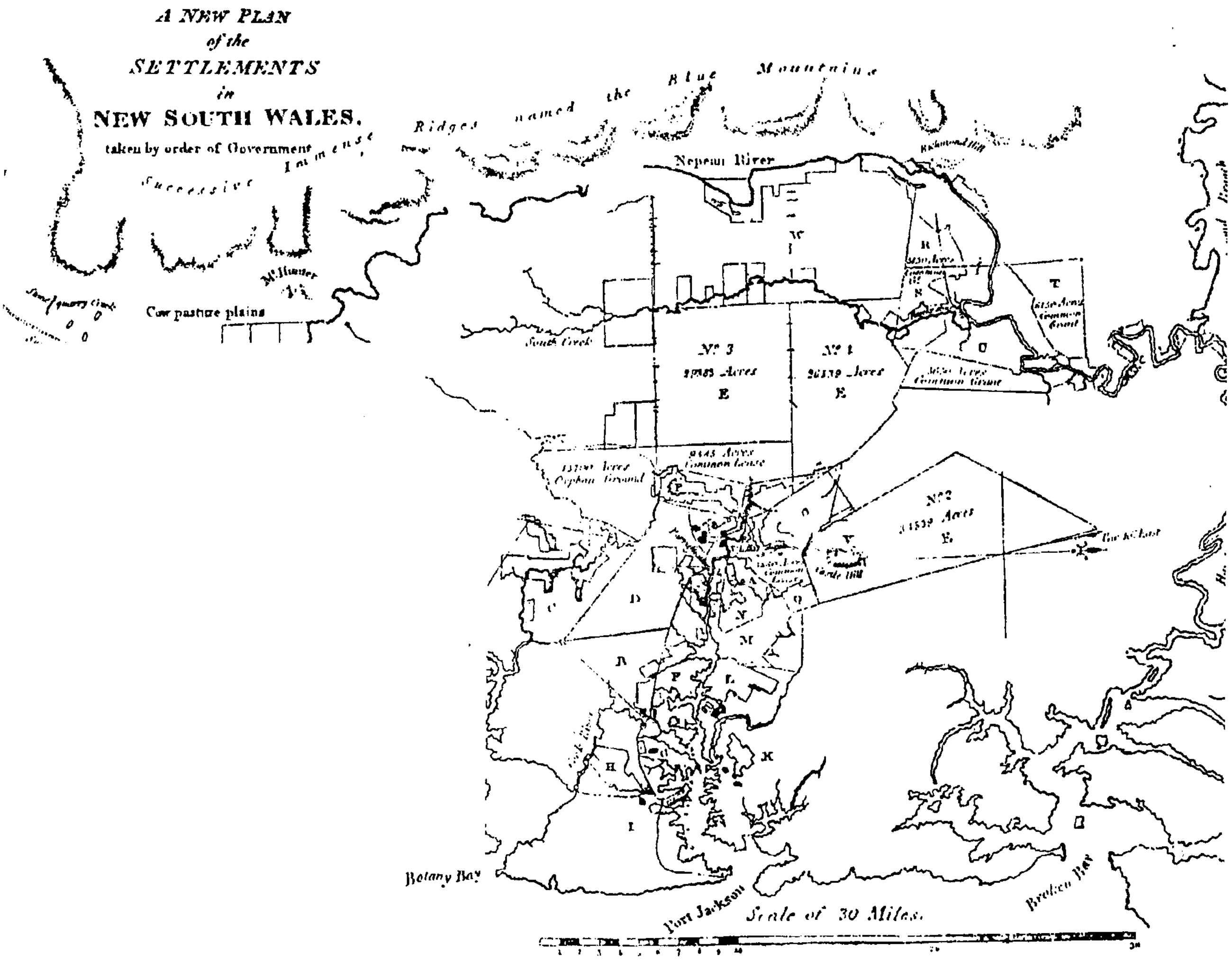
GPS-CONTROLLED PHOTOGRAPHY: THE DESIGN, DEVELOPMENT AND EVALUATION OF AN OPERATIONAL SYSTEM UTILISING LONG-RANGE KINEMATIC GPS

GREG DICKSON



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Foreword

GPS-controlled aerial photography is a relatively new application. The theory and mathematics supporting the methodology has been known for some time, however, there are many challenges associated with developing a reliable, day-to-day operational platform and support infrastructure. This thesis describes the experiences of the author in developing and implementing this concept within the NSW Department of Lands & Property Information (as it is now known -- at the time this research was carried out it was the NSW Surveyor General's Department). There are two parts to this research. One is tackling all the engineering issues involved with integrating GPS hardware into an aircraft, operating the system so that GPS could contribute to efficient aerial photography, and the design and development of the software system necessary to ensure the GPS data was collected and could support the processing of the aerial photography. The second part of the research was conducting tests using long-range kinematic GPS techniques to see if it were feasible to use reference receivers located many hundreds of kilometres away from the area of photography.

Quoting from the Abstract. "The NSW Surveyor General's Department introduced this technology as a cost effective solution to its current topographic mapping program in the Western Region of New South Wales. As well as the substantial cost savings that result from reduced ground control, further savings can be made by centralising the GPS ground (reference) station which supports airborne GPS-controlled photography. In New South Wales this introduces the scenario of Kinematic GPS operations over distances exceeding 900 km. The successful determination of GPS integer ambiguities over these distances is still the subject of ongoing research, but in the aerial triangulation process this problem can be avoided by modelling the drift behaviour of phase locked, or cycle slip free, GPS data."

The research was conducted and carried out to a successful conclusion. This report describes the background and development of GPS-controlled photography and its role in the aerial triangulation process. It outlines the conceptual design, implementation of hardware and software, and the ongoing development and refinement of a system. The performance of long-range kinematic GPS and the effectiveness of GPS-drift modelling is evaluated in two test scenarios.

Comparisons are made between GPS "drift corrected" long-range kinematic GPS trajectories (up to 1500 km), and fixed-ambiguity short-range trajectories. Results show that the differences in the corrected trajectories for camera stations are better than 0.1 m. These results are supported by aerial triangulation adjustments of 1:50000 photography using various kinematic trajectories where comparisons of adjusted image points are generally better than 0.1 m in X, Y and Z.

This report describes, in a step-by-step fashion, how this innovative procedure was tested and how it has proven to be a reliable support platform for routine GPS-controlled aerial photography in NSW. The results indicate that the system described in this report is capable of supporting mapping scales as large as 1:4000 anywhere within NSW. Anyone with an interest in GPS-controlled photogrammetry would find this report of great interest.

C. Rizos

November 2000

Acknowledgements

Aerial photography is an expensive business. I consider myself to be extremely fortunate to have been involved with the implementation of a GPS navigation and camera control system for the aerial photography aircraft of the Surveyor General's Department of NSW. For a research student, this has been a unique opportunity.

It could not have happened without the commitment of the Department to the needs of the Western Division Legal Road Network Project. Although I initiated my involvement in the project I must acknowledge the support given to me by a number of people.

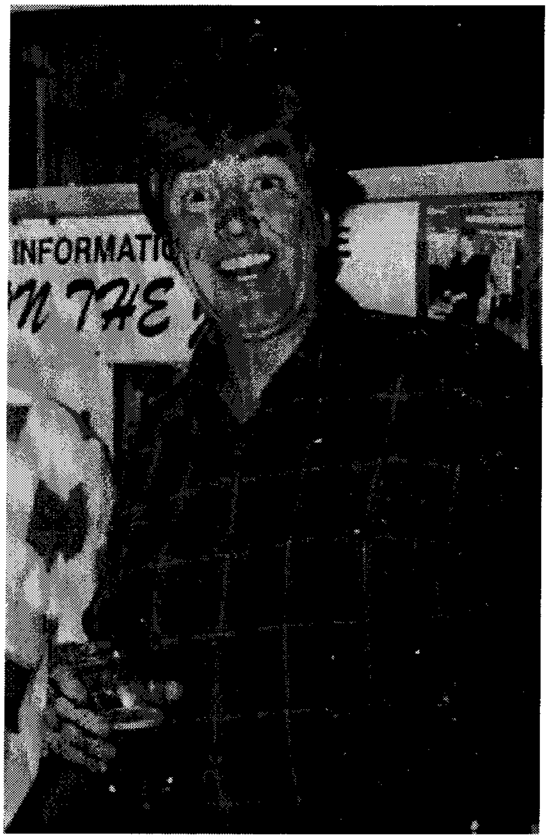
I must thank the late Mr John Perry for his unwavering enthusiasm and his desire to make this project happen. He has supported my judgement throughout which has made my job much easier. I must also thank photogrammetrists Mr Greg Burgess and Mr Graeme Thompson for their affirmative attitude and the odd question which made me delve a little deeper for the right answer.

Hugh Gould, Peter Purcell, Ken Foody, Ralph Millard and Neil Macarthur of the Aerial Survey Unit who have had to work with my software and system design. Their feedback has been appreciated.

I would also like to thank my supervisor, Associate Professor Chris Rizos of the School of Geomatic Engineering, UNSW, for his patience and positive criticisms of my work.

My family, Maureen, Kurtis and Brent have contributed significantly to this work with their tolerance, for which I thank them.

Dedicated to the memory of John Perry



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Abstract

GPS-controlled aerial photography is a relatively new application. The theory and mathematics supporting the methodology has been known for some time, however there are many challenges associated with developing a reliable, day to day operational platform and support infrastructure. The New South Wales Surveyor General's Department has introduced this technology as a cost effective solution to its current topographic mapping program in the Western Region of New South Wales.

As well as the substantial cost savings that result from reduced ground control, further savings can be made by centralising the GPS ground (base) station which supports airborne GPS-controlled photography. In New South Wales this introduces the scenario of Kinematic GPS operations over distances exceeding 900km. The successful determination of GPS integer ambiguities over these distances is still the subject of ongoing research, but in the aerial triangulation process this problem can be avoided by modelling the drift behaviour of phase locked or cycle slip free GPS data.

This document describes the background and development of GPS-controlled photography and its role in the aerial triangulation process. It outlines the conceptual design, implementation of hardware and software, and the ongoing development and refinement of a system. The performance of long-range Kinematic GPS and the effectiveness of GPS-drift modelling is evaluated in two test scenarios.

Comparisons are made between GPS "drift corrected" long-range Kinematic GPS trajectories (up to 1500km), and fixed-ambiguity short range trajectories. Results show that the differences in the corrected trajectories for camera stations are better than 0.1m. These results are supported by aerial triangulation adjustments of 1:50000 photography using various Kinematic trajectories where comparisons of adjusted image points are generally better than 0.1m in X, Y and Z.

A unique installation is proven as a reliable support platform for GPS-controlled aerial photography. The results support the initial concept that aerial triangulation results based on drift corrected long-range Kinematic GPS should not deteriorate with distance from a base station. The results also indicate that the system described here is capable of supporting mapping scales as large as 1:4000 anywhere within NSW.

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1. Introduction

The Surveyors General's Department (SGD) of New South Wales, formerly the Land Information Centre (LIC) of New South Wales and even earlier, the Central Mapping Authority of New South Wales has traditionally been the State Government's principal map production agency.

The manufacture of mapping products has slowly migrated since the early 70's from the established analogue capture and production techniques to the current digital methods performed on photogrammetric and cartographic workstations. The SGD, because of the size and scope of its mapping programs, has always sought to introduce modern and innovative techniques to its production processes.

At the time of the completion of the Standard Mapping Program in the late 1980's the SGD used its own:

- aerial survey aircraft
- geodetic and mapping control survey branch
- photogrammetric branch using a number of analogue stereo plotters and ortho-rectification machines
- extensive and capable cartographic personnel
- computer systems and support branch which included research and development staff
- printing and film processing branches

to support its mapping activities.

The various branches and processes mentioned maintained an ethic of best practice which ensured that the latest technology, if not always adopted, was always considered. Digital technology had been introduced in a number of areas within the SGD. The benefits and uses of digital data had already been acknowledged. The completion of the Standard

Mapping Program, changes in the requirements of government at the time and the emergence of digital techniques, changed the way that information could be presented and stored and migrated the SGD from the familiar mapping processes to the new world of Geographic, Land and Spatial Information Systems (GIS, LIS and SIS).

One area of LIS identified as appropriate for the SGD was the then proposed Digital Cadastral Data Base (DCDB). The benefits of data basing the cadastre and presenting it in a graphical form had been demonstrated to be politically advantageous, and could be used as a base planning tool throughout all levels of government.

The SGD was funded to complete the Digital Cadastral Data Base (DCDB) for the whole of New South Wales. Within the SGD this created major changes. The process of map production, revision and expansion was curtailed as nearly all resources were migrated to the demands of the DCDB. The ability to produce maps to the degree that was previously achievable was slowly eroded away. A small portion of the Photogrammetric Branch was retained which was, by the early 90's, only a token representation of the SGD's former capability.

In 1993, as a result of the Roads Act 1993, the Department of Land and Water Conservation (DLWC) identified the need to update the spatial data sets of the Western Division of New South Wales. Lack of information about the nature of this semi-arid land resource and the identification of land use problems which include infestation with woody shrubs and weeds, grazing pressures from domesticated, native and feral animals, salinity, water quality and the public's uncontrolled right of access and subsequent impact on this fragile region.

A major undertaking to arise from the implementation of the Roads Act and the need for corrective action in the Western Division is the Western Division Legal Road Network Project (WDLRN). In the Western Division of NSW the majority of roads and tracks have never been formally constituted as public roads. These tracks and roads which are often constructed and maintained at public expense include parts of highways and regional and council roads.

In the absence of a rational, legal road network of public roads, public access rights across the Western Division were accommodated through inclusion of a clause in each lease which required the lessee "not to obstruct or interfere with any reserves, roads or tracks or the use thereof by any person".

Traditionally the clause was interpreted by the Department (and most if not all lessees) as conferring unfettered rights on members of the public to use any track or constructed road within the boundaries of a Western Lands lease. This unrestricted access has proved increasingly impotent as a means for balancing the rights of the public to those of the lessees to manage the security of their properties.

Legislative and administrative action has been taken to establish a rational legal road network. The scope of the project is to identify the status of all existing legal roads in the Western Division. There are some 4700 rural Western Lands leases in the Western Division encompassing about 7000 lots. It is estimated that 300 plans will need to be compiled and about 3000 dealings prepared.

The challenge of the project was to identify the position of the access routes in a cost effective and accurate manner. Traditional land survey techniques could not be considered owing to the costs and the scope of the project.

The solution to this problem lay in new photogrammetric processes which use Global Positioning System (GPS) controlled photography and analytical plotters interfaced to Computer Aided Design (CAD) software capturing planimetric digital topographic and cultural detail.

The SGD was charged with the digital capture process for this project. Although driven by the Legal Road Network the data sets captured would provide base mapping data to an accuracy that was previously un-achievable considering the scale of photography selected for this project. These data will be the beginnings of a seamless photogrammetric control data set for New South Wales. (Dickson, Burgess & Moss, 1998)

The proposed technology was new and its execution was somewhat clumsy. In 1993 the SGD initiated a joint venture with interested survey and aerial survey companies. The joint venture was to evaluate the proposed technology over a 1:250000 mapping tile which would be indicative of a typical map coverage in the Western Division Legal Road Network Project. This technology had never been used on a project of this magnitude.

The nominated pilot area was the 1:250000 map sheet SH/55-7, Angledool, adjoining the NSW - Queensland border. This pilot project has been the subject of a number of publications (Mitchell & Dickson, 1996; Fraser, 1994) but its results supported the premise that 1:50000 GPS controlled photography could deliver ±2m three dimensional control data based on a bare minimum of ground control.

Some of the results and savings from this pilot are as follows:

- Reduction in ground survey point requirements from approximately 70 to 4 for a 1:250000 map tile.
- Relative GPS air station coordinates better than 1m.
- Aerial triangulation precision ±2 metres in X, Y and Z using un-targeted photo points.

The outcomes of the proof of concept and the scope of the WDLRN project: 22 x 1:250000 map tiles and positional accuracy requirements of ±5m in data capture (±2m in derived coordinates from aerotriangulation) posed a challenging task for the SGD.

The WDLRN project required the introduction of new operational systems to current capture and production processes. The proven results of the Angledool pilot project demonstrated that GPS supported camera station coordinates in an aerial triangulation adjustment was a cost effective solution in reducing production costs and enhancing the quality of digital map data. A major operational difference between the pilot project and the WDLRN project was the size of the project area to be mapped and anticipated operational changes.

Most published GPS controlled photography projects have been based on short kinematic baselines and large scale photography. For the SGD's mapping programs it was proposed to use one centrally located base station to support photographic operations anywhere within the State. This could result in the determination of kinematic trajectories over baselines exceeding 900km. There are a number of problems in attaining high precision positioning results using long range kinematic GPS. The major challenges are nullifying the effect of the ionosphere and the determination of carrier cycle ambiguities. The development of the GPS receiver and solutions to the positioning problem are examined in Chapters 2 and 3.

The process of aerial triangulation has always been an intensive and costly process for the production of mapping and ortho-rectified image products. Various techniques and processes have been explored that could reduce the associated overheads of these products. Substantial cost savings can be made through the reduction of ground control requirements.

Ground control requirements for traditional photogrammetry can be reduced, sometimes even eliminated, through the introduction to the aerial triangulation adjustment of what is referred to as exterior camera orientation elements or "**auxiliary data**" (Ackermann, 1984; Friess, 1986a).

Auxiliary data is information about exterior camera position and orientation parameters (X_{PC}, Y_{PC}, Z_{PC}, ω, ϕ, κ) at the time of exposure. Within the photogrammetric adjustment this data, when X_{PC}, Y_{PC}, Z_{PC} are known, simplistically inverts the determination of image points from **resection** to **intersection** solutions strengthening the adjustment.

Sources of this auxiliary data have been many and varied but none have displayed the potential of the Global Positioning System (GPS) in delivering the airborne camera position parameters (X_{PC}, Y_{PC}, Z_{PC}) and , if taken to higher levels of development, the attitude parameters (ω, ϕ, κ) as well. Chapter 4 discusses aerial triangulation strategies using auxiliary GPS data. These strategies are not reliant on the determination of carrier cycle ambiguities but demonstrate how cycle slip free GPS data can be corrected for linear trajectory errors, commonly referred to as drift.

The common element between the aerial photograph and the GPS receiver observation is time. GPS controlled photography is only possible by linking the two events through a common time frame. This is generally achieved through accurately recording camera events in the GPS timing system. Timing and other errors which impact upon aerial triangulation and flight navigation systems are reviewed in Chapter 5.

The SGD's CESSNA 412 Golden Eagle flies photography seven days a week, weather permitting. Although not a technical issue, the monetary resources available to resource a data collection and production system impacts directly on any conceptual system designs. Chapters 6 and 7 examines the type of operational systems supporting GPS controlled photography/photogrammetry given cost and technical restrictions. An outline is given of the equipment acquisition process to highlight the level of integration required to realise an operational system.

It is not a trivial exercise fitting ancillary equipment into an aircraft. Many aspects of its operation and ergonomics have to be considered, non more important than adhering to engineering guidelines defined by the aviation authorities . The fitting of hardware and software into the SGD's aircraft is outlined in Chapter 8. Considerations are not restricted to the physical aspects of the installation but also include the interface between the crew and the computer /camera systems. Supporting the aircraft operation is a number of other sub-systems. The automated base station operation and data collection and flow system is described in Chapter 9. An important aspect of the design and operation of these processes is that they are simple to operate, reliable and have redundancy capability.

Chapters 10 and 11 describe the performance of an operational system. The problems encountered and their solutions illustrate the difficulty in creating prototype robust systems. A major consideration in the development of this system was the funding available for testing and development. The system was declared operational with very little testing due to the high operational costs of the aircraft and crew. These chapters demonstrate that low cost and high performance can be realised if careful research and development is ongoing.

The realisation of high accuracy camera air stations is fulfilled when the aircraft GPS data and the base station GPS data are brought together and post processed to determine the trajectory of the aircraft antenna. This process is also subject to quality control and is evident in the data flows and post processing strategies. Chapter 12 describes these methods from the point of collation through to the interpolated positions of the aircraft GPS antenna. This process has been automated as much as possible through the development of software utilities. These utilities are designed to minimise operator error through the use of standardised interfaces and data structures.

The Angledool pilot project had demonstrated that GPS camera stations can be successfully included in the aerial triangulation adjustment. Chapter 13 is an evaluation of long range kinematic GPS. Comparisons are made of derived trajectories based on baseline distances up to 1500km. Comparisons are made of aerial triangulation adjustments using trajectories based on different baseline lengths. GPS linear drift models are evaluated through differencing combinations of trajectories and various aerial triangulation adjustment models.

A consequence of creating real time digital data flows supporting both the storage of raw GPS data and real time navigation functions was the opportunity to extend the functionality of the RC30 camera system. The camera's computer control was extended to include the recording, both on and off the film, meta data about each camera exposure. Chapter 14 describes the development of the photography management system which was implemented to complete the operational GPS/camera combination package.

The report concludes with reference to future developments and confirmation of the operational and computational methodologies adopted to meet the airborne positioning requirements of a systematic mapping process and program.

2. GPS Evolution with Respect to Photogrammetry

2.1 The developmental time scale

Knowing the position and orientation of the perspective centre of an aerial camera at the instant of exposure has substantial benefits for the photogrammetric process and to the achievable accuracies. Consequently, research work on this aspect was advanced before the introduction of the Global Positioning System.

"The concept of deploying a GPS receiver in an aircraft to provide the precise position of airborne instrumentation packages was first seriously considered by investigations in the National Geodetic Survey in 1982" (Lucas & Mader 1989)

Early experiments by Duane Brown in 1969 are reported by Merchant (1993) to support the concept that an aerial, film-based, photogrammetric system can promise the resolutions and stability required to extend the aerial control resulting from GPS measurements, to the ground detail.

Brown's work demonstrated that internal spatial accuracies nearing one part in three hundred thousand could be achieved using a reseau[1] based camera at 3700 metres over a controlled test range. The position of the aircraft at the time of exposure was determined by three ground based terrestrial cameras.

Probably closer to the concepts of GPS-controlled photogrammetry are the lunar space missions of the Apollo series. Doppler tracking of the spacecraft produced an ephemeris -

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[1] The camera reseau is a precise grid etched on a glass pressure plate , or inscribed on a platen locating back whose surface is in contact with the film as it moves over the focal plane. The grid intersections are spaced at approximately equal intervals, usually 1 or 2 centimetres. The principal function of the reseau is to provide a precisely calibrated grid which is superimposed on the negative during exposure. The extent of film shrinkage or expansion may be determined by comparing the grid on the photograph with the known dimensions of the reseau. (Slama, 1980)

knowledge of the spacecraft's position with respect to a reference system and time; a stellar camera provided information about the spacecraft's attitude with respect to the reference system; an altimeter provided the distance above the lunar surface.

This data was combined with the information from the mapping camera and was all that was required for satellite photogrammetry. Obviously, no surveyed ground control was used.

The value of being able to produce mapping without ground control, or a minimal amount of ground control, has been identified as being highly desirable, due to the cost savings in map production.

Many researchers have identified the potential of dynamic positioning systems for this purpose. There are a number of systems that can be used for dynamic positioning although most suffer from limitations in respect to photogrammetric requirements.

Any system which adds to the knowledge of the camera position or orientation at the time of exposure is commonly referred to as "auxiliary data". Auxiliary data for aerial triangulation dates back more than 50 years. Data at that time was provided by statoscope, horizon camera and solar periscope. These systems were revived during the 1950s along with the introduction of airborne profile recorders (APR) and gyroscopes. Only the statoscope and APR are still used in practical application, (Ackermann, 1984).

During the 1950s horizontal positioning systems such as SHORAN, HIRAN and SHIRAN were adapted to airborne determination of large aerotriangulation blocks but these also disappeared due to drawbacks of economics and accuracy (Ackermann, 1986).

Other horizontal positioning systems such as LORAN C, for example, can position at distances up to 1500km to accuracies between 100 to 500 metres (95%) dependent on geometry and range. The DECCA Navigator System is one of the oldest electro-magnetic positioning systems, first introduced in the 1940s. DECCA works at ranges up to 450km, giving positioning accuracies of between 50 to 200m (95%) for reasonable geometry (Ackroyd & Lorimer, 1990).

Although capable of real-time position determination, these systems are not capable of the accuracies required by even the smallest scale photogrammetric project. This does not mean that they cannot play a supportive role in contributing coarse information in support of other systems.

Inertial Navigation Systems (INS) measure continuous changes in position and velocity with time through the use of gyroscopes and accelerometers. In simple terms, any instantaneous position information is the result of some initial position plus some time-based acceleration or velocity data. Unfortunately, the long-term performance of standalone INS is poor and requires operational procedures that are not all that suitable for photographic flights. The effect of these errors can be reduced by inputting external control measurements such as GPS information into a Kalman Filter. The outputs of the Kalman Filter are optimal real-time estimates of velocity, position and attitude. The strength of the INS is the short term contribution that can be made to other auxiliary data.

The INS platform can also be coupled to the camera reference frame allowing information to be derived regarding the tilts and rotations of the camera, and hence of the photographic image. This is of little value as the inherent strength of the relative orientation between photographs renders additional attitude data ineffective unless the data is known to be accurate to more than 10 arc seconds (Schwarz et al, 1984).

The greatest technical innovation, in the form of auxiliary data, that has been introduced to photogrammetry has been GPS. As early as 1984 simulations had shown the viability of the NAVSTAR GPS system to deliver the accuracies required for air station coordinates.

Development of this technology for photogrammetry appears to have taken two very different courses to achieve the same end. There is a core of researchers based in European Photogrammetric Schools, particularly in Germany, who treat the auxiliary data as just *auxiliary data.* The fact that it is GPS, and has associated problems with it, is not considered detrimental to their approach to the problem. In most European research the limitations of the GPS system are addressed in the photogrammetric aerial triangulation solution, where auxiliary data tends be treated in the *relative* sense.

On the other hand studies in North America tended to concentrate on the more difficult problems associated with the GPS data, the purpose being: photogrammetric mapping without ground control. Consequently North American research does not appear to consider the overall goal of mapping, but only to solving the problems associated with kinematic GPS in order to derive *absolute* position. Solutions are not seen to lie in aerial triangulation adjustment techniques.

Although Ackermann (1984) is concerned with auxiliary data (non GPS) he makes the reference *"the use of GPS satellites for flight navigation will have to be considered soon".* In the system described here the CPNS (Computer Controlled Photo Navigation System) is used to direct the aircraft, control pinpoint photography and supply auxiliary data. The CPSN system is based on the high frequency Thomson-CSF-Trident III airborne ranging system, which is of the aircraft interrogator/ground transponder variety.

Ackermann (1984) addresses the error problems associated with this auxiliary data in the photogrammetric aerial triangulation adjustment. The inherent strengths of the aerial triangulation adjustment are used to extract the quality information concerning the auxiliary data. This is done by solving for drift and translation parameters, and making a few assumptions about the behaviour of the auxiliary data. His paper outlined the approach of using only four ground control points for a rectangular block and using auxiliary data only. His CPSN data outcomes indicate marginal differences between results where auxiliary data was included or excluded. The problem being the poor positioning results of the CPSN system. Other associated problems of auxiliary data, timing systems and spatial offset vectors will be examined in subsequent chapters.

At the same time, North American researchers were addressing the problem of GPS positioning limitations. In that sense if all information about camera position and attitude is known within a reference frame at the time of exposure, then the need for ground control is no longer there.

Schwarz et al (1984) acknowledged that the standard tool for topographic mapping is the photogrammetric aerial triangulation adjustment. But they point out that there are a number of operational problems associated with this process.

Although the quality of the aerial triangulation adjustment is generally good, the same cannot always be said for the quality of geodetic control. The establishment of ground control is expensive and time consuming, and in addition, the availability of control may restrict the flight pattern.

Moving the control from ground level to flight level promises homogenous control coordinates at flying height, avoids targeting problems and permits complete freedom in the choice of flight pattern. Instantaneous positioning would mean that aerial triangulation could be repeated at any time, with the same accuracy, but without reference to a fixed set of control points.

Ibid (1984) proposed that such a positioning system could be realised by a combination of inertial and satellite techniques. The satellite system provides *absolute position* and repeatability, while the inertial system contributes very accurate relative positioning information.

The Ibid (1984) paper concentrates on the *"complete elimination of ground control"*. In 1984 there were four usable GPS satellites in orbit providing about 2 hours duration of instantaneous positioning capability in many parts of the world. Three satellites could be used in conjunction with a cesium clock.

Some receiver performance specifications are noted here. The speed of the satellite receiver switching rate is directly related to the combined performance of the GPS/INS combination. GPS Position updates varied between 1 and 60 seconds in 1984. A slow switching receiver (60sec) could be expected to position within an accuracy range of 8 to 12m (1σ). An accuracy of about 2m could be expected from a fast switching receiver (1sec). So much for Selective Availability of today!

Further improvements could be made by differential techniques.

Results of photogrammetric aerotriangulation adjustments using simulated GPS/INS data demonstrated the potential of this technology, satisfying requirements of 1:50000 photography. The results presented use aerotriangulation adjustment software modified to accept camera station coordinates.

Goldfarb & Schwarz (1985) used INS and GPS to complement the best features of both systems. Figure 2.1 illustrates one of two strategies - a stable platform INS is used along with differential pseudo-range (P-code) measurements. The second strategy is to augment GPS carrier phase difference measurements with strapdown INS data.

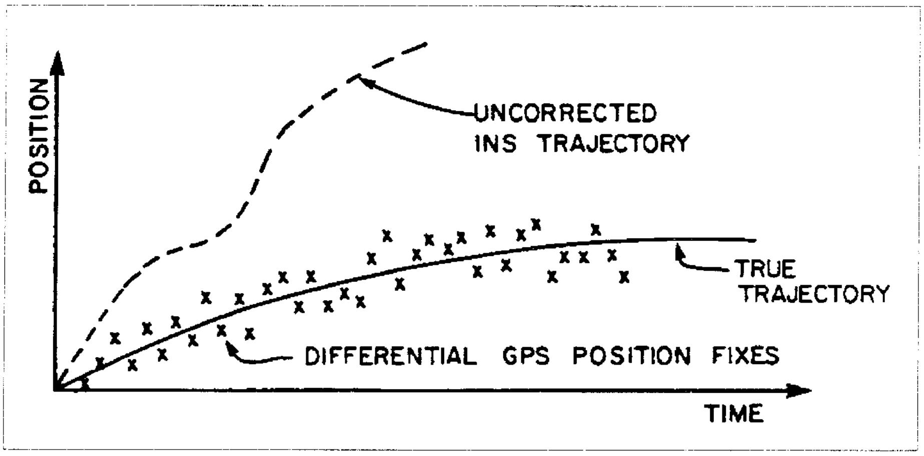

Figure 2.1 Combination of GPS pseudo-range and INS (Goldfarb & Schwarz, 1985).

A computer program was developed to simulate INS and GPS data for an aircraft in flight and for a number of ground GPS stations. Schwarz et al (1984) has shown that for an image scale of 1:50000, standard errors of about 1m can be derived for ground points if the airborne camera can be positioned with a standard error of 1 to 2m.

Goldfarb & Schwarz (1985) models an eighteen satellite constellation, with the assumption that receivers can only track four satellites at a time (the four satellite constellation producing the minimum GDOP at the average ground station position is used at all times). Satellite ephemeris data was simulated to reflect broadcast quality. Other error sources such as single frequency ionospheric delay, receiver clock flicker, and correlated or uncorrelated noise contributed to the range noise.

"The nature of the local-level INS mechanization requires some form of real- time error control. Usually, external measurements are incorporated by means of Kalman filtering. A simple filter using P-code pseudo-ranges as update measurements is in this case sufficient to assure the linearity of the error equations." (Goldfarb & Schwarz, 1985)

The carrier phase solution is not as flexible, although initial integer ambiguities can be determined before the start of a mission, changes in the satellite tracking complicates the situation!

Their results highlight the improvement which is obtained when the differential GPS technique is used. Single receiver pseudo-ranges produced rms coordinate errors of 8 to 21m. This dropped to 3 to 8m when one ground station is used in conjunction with the aircraft data. This is in the case of P-code data! It is interesting to note that some improvement were gained by using two ground receivers in the solutions. In all solutions, height was the weakest component.

The combined solutions, differential GPS plus INS, demonstrated a marked improvement, one order of magnitude over the GPS only results. No improvement was made to single receiver P-code results. The second scenario, differential phase, was only a slight improvement on the differential code plus INS solution.

Both strategies achieved coordinate accuracies at the 0.5m level. This example also highlights the *absolute position* solution to the photogrammetric problem.

The previous simulations were proof of concept. They did not address the spatial relationships between antenna phase centre, INS reference point, camera perspective centre and common timing systems.

In Europe, simulations testing the accuracy requirements of auxiliary data to deliver specific photogrammetric accuracies had been performed by Friess (1986). His work involved extensive simulations of aerial triangulation adjustments using varying levels of auxiliary data and ground control accuracies.

Friess (1986) acknowledges the simulation work of Schwarz et al (1984), using these results as guidelines for his research. The difference was that Friess (1986) determines the auxiliary data accuracy required for a particular photogrammetric application, whereas Schwarz et al (1984) determined that GPS/INS has a particular accuracy, therefore a certain photogrammetric application is possible.

Friess (1986b) simulations are based on greatly simplified assumptions: *"flat terrain, ideal overlap, a regular pattern of points, constant flying height and strictly vertical photographs. All detailed considerations of drift, systematic errors and correlation of observations are omitted".*

A number of configurations are presented:

- All exterior orientation elements, no ground control. If all six camera orientation elements X_{PC}, Y_{PC}, Z_{PC}, ω, ϕ and κ are observed the blocks are determined and stable without any ground control (in the satellite reference system). Even with poor auxiliary data (±10m) adjustment accuracies are $\mu_{x,y}=2\sigma_0$, $\mu_z=3\sigma_0$ where

σ_o=15μm which is sufficient for 1:60000 photo scale (σ_o is 0.9m in terrain). The same accuracy without auxiliary data would require ground control every 8 base-lengths. These results can be extrapolated to higher auxiliary data accuracies where the limitation becomes the photogrammetric measurement limitations.

- Ground Control. Results demonstrate that additional ground control to the auxiliary data does not lead to any significant improvements. *"It is obvious that aerial triangulation does not require ground control if all six exterior orientation elements are available as auxiliary data. In cases where only camera position coordinates or attitude parameters are observed, additional ground control is necessary to stabilise the block".* Not having ground control introduces a datum problem as the map may not be required in the auxiliary data reference system. Four ground control points present a practical solution.

- Positioning data versus attitude data. Results indicate that camera position data are more effective auxiliary data than angular data. Positional data alone are improved less than 10% by the addition of attitude data.

Significant conclusions are:

- that the application of auxiliary data in the aerial triangulation adjustment is promising, especially the reduction of ground control to a minimum.

- that the direct use of navigation data for the orientation of aerial photographs will be possible if the exterior orientation elements can be determined to ±0.1m (X_{PC}, Y_{PC}, Z_{PC}) and 0.03sec (ω, ϕ and κ), i.e. aerial triangulation can be dispensed with. In this case the accuracy of the image point coordinates would be a function of the observational accuracy and the photography scale, e.g. a σ_0 of 8μm on 1:50000 photography would imply a point accuracy of 0.4m.

First attempts to actually capture experimental data was reported in Lucas (1987). His first planned experiment was scheduled for July 1985, but there were difficulties with limited receiver and aircraft availability, and weather was uncooperative. A second experiment was scheduled for December 1985. Adequate photography and accompanying GPS observables were acquired on four of the five scheduled days. Unfortunately this was the same week the U.S. Air Force had chosen to relocate one of its satellites, rendering the experimental data useless.

Lucas (1987) does address the problem of antenna - camera centre offset. GPS cannot provide the direct coordinates of the exposure station as the GPS antenna and the rear nodal point of the camera lens cannot occupy the same point in space.

Generally, the position of the camera with respect to any fixed point on the aircraft is continually changing as the camera is rotated for drift or tilted for verticality. These changes can be determined with auxiliary data but a simpler solution is to lock the camera in position and plan for more overlap to compensate for variations in coverage.

In this case the vector between the camera and the antenna will remain constant within the camera reference system. The solution then is to use the orientation matrix that relates object space to image space to relate the GPS determined antenna positions to the photogrammetrically determined camera positions.

There is also the separation in time, as the camera exposes independently of the GPS positions. The time of camera exposure has to be mapped on the GPS time scale. This is seen as a hardware problem.

Again simulated data demonstrates how air station coordinates match or exceed the accuracies of the same aerial triangulation adjustment using ground control. Tables 2.1 and 2.2 (Lucas, 1987) highlight the precisions obtainable for GPS determined camera station coordinates. The simulated data is based on a model of 49 photographs in a 7 x 7 formation, approximating 1:24000 photography using 67% forward and side overlap. Image coordinate observations are assumed to be 3μm, five ground control points, assigned a standard error of 5cm, were used giving a minimum control network of seven photographs between control. GPS observations and the offset vector were assigned 10cm standard errors in all components.

Table 2.1 Standard errors in centimetres of horizontal position as a function of position within the network. Top entry in each cell obtained using ground control; bottom entry from inclusion of GPS observations without ground control (Lucas, 1987).

4.9 14.7	8.5 12.2	10.0 11.1	10.5 10.9	10.0 11.1	8.5 12.2	4.9 14.7
8.5 12.2	7.4 9.7	8.1 8.7	7.8 8.5	8.1 8.7	7.4 9.7	8.5 12.2
10.0 11.1	7.9 8.7	7.3 7.6	7.3 7.3	7.3 7.6	7.9 8.7	10.0 11.1
10.5 10.9	8.1 8.5	7.3 7.3	7.2 7.0	7.3 7.3	8.1 8.5	10.5 10.9
10.0 11.1	7.9 8.7	7.3 7.6	7.3 7.3	7.3 7.6	7.9 8.7	10.0 11.1
8.5 12.2	7.4 9.7	8.1 8.7	7.8 8.5	8.1 8.7	7.4 9.7	8.5 12.2
4.9 14.7	8.5 12.2	10.0 11.1	10.5 10.9	10.0 11.1	8.5 12.2	4.9 14.7

"Edge effects, larger errors in ground points along the edge of the network caused by fewer rays intersecting these points, are obvious in both horizontal and vertical errors of both adjustments. These effects are the greatest in the corners as seen in the GPS results, and provide the largest differences because the corner ground control points were constrained to 5cm in the ground control case.

Table 2.2 Standard errors in cm of elevation as a function of position within the network. Top entry in each cell obtained using ground control; bottom entry from inclusion of GPS observations without ground control (Lucas, 1987).

5.0 19.5	21.9 16.2	25.5 15.5	27.1 15.2	25.5 15.5	21.9 16.2	5.0 19.5
21.9 16.2	17.6 13.5	18.1 12.6	18.1 12.3	18.1 12.6	17.6 13.5	21.9 16.2
25.5 15.5	18.1 12.6	14.7 11.5	12.6 11.1	14.7 11.5	18.1 12.6	25.5 15.5
27.1 15.2	18.1 12.3	12.6 11.1	5.0 10.8	12.6 11.1	18.1 12.3	27.1 15.2
25.5 15.5	18.1 12.6	14.7 11.5	12.6 11.1	14.7 11.5	18.1 12.6	25.5 15.5
21.9 16.2	17.6 13.5	18.1 12.6	18.1 12.3	18.1 12.6	17.6 13.5	21.9 16.2
5.0 19.5	21.9 16.2	25.5 15.5	27.1 15.2	25.5 15.5	21.9 16.2	5.0 19.5

Table 2.2 shows that GPS has a definite advantage over ground control in precision of elevation determination. All except the five constrained points are less precisely determined in the ground control case. There are two factors at work here. First, edge effects degrade the precision of elevation determination more severely than they do horizontal precision (compare tables 2.1 and 2.2). This is due, in part, to the greater uncertainty in the elevations of the exposure stations along the edge of the network, which are resected by fewer ground points. The GPS observations of these exposure station positions play an important role in counteracting this component of edge effects. Secondly, it has been pointed out by Slama (1980) that elevation errors in triangulation tend to grow with distance from control at a much greater rate than do horizontal errors. Because each exposure station acts as a control point when GPS observations are included, distance from control is no longer a factor." (Lucas, 1987)

This sample is a practical illustration of the influence of external orientation parameters within an aerial triangulation adjustment.

It was not until 1987 that experimental data was becoming available. Lucas & Mader(1989) were able to collect data in two test experiments through cooperation between the Texas Department of Highways and Public Transportation (TDHPT) and the Washington State Department of Transportation (WDOT).

In Europe, in June 1987, the Survey Department of Rijkswaterstaat in cooperation with KLM-Aerocart, the University of Stuttgart and the Delft Technical University executed a research project with two objectives:

1. Establish the attainable accuracy of camera positions measured during a flight with differential GPS techniques.

2. Establish the likely reductions in ground control through the introduction of GPS camera positions into a photogrammetric aerial triangulation adjustment.

For the Dutch experiment a test field was established over a regular grid of approximately 400m containing a total of 80 accurately surveyed ground control points and targeted tie-points. The test area covered 4km x 4km. The overall precision of the control was 2-3cm (1σ). It should be noted that all points were computed relative to one fixed base point, the same as that used for the differential receiver during the test flights.

The basis of the first objective was to compare results of GPS computed perspective centres with those of the ground controlled aerial triangulation adjustment. The second objective was to incorporate the observed GPS positions into a minimal controlled aerial triangulation adjustment and assess the results.

For this test the aircraft was fitted with a Sercel TR5S GPS receiver. It is a receiver capable of continuously tracking five satellites. It is a C/A-code, single frequency (L1) receiver with an update rate of 0.6 sec which can simultaneously output raw data and position data on two output ports. A portable computer was used to log raw data and the GPS antenna was mounted slightly eccentric to the camera on top of the fuselage.

A WILD RC-10 camera was used for the test. The camera was modified so that a pulse could be generated and recorded against the GPS time scale. In this case a photo sensor generates a pulse 0.2 milliseconds long at the exact instant the shutter reaches it maximum aperture. This pulse is then recorded in the data logging computer and recorded with the raw data in the GPS time frame. Figure 2.2 illustrates the timing relationship between GPS time pulses and each camera event.

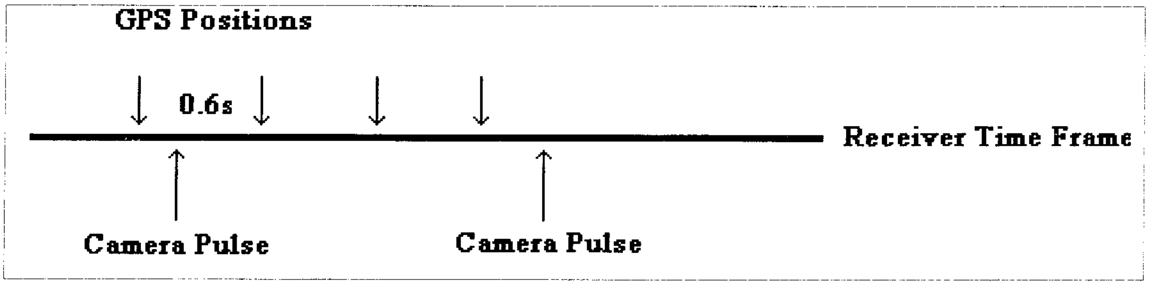

Figure 2.2 Relationship between camera pulses and GPS time.

Throughout the test flights the camera was "locked down" so that the spatial vector between the camera and the antenna remained constant within the aircraft reference frame.

A Sercel Nr52 receiver was used at the fixed ground station. This is a similar receiver to the TR5S except that it does not provide real-time position fixes.

Two test flights over two days resulted in 16 parallel strips, 360 photographs of 70% forward and 50% side overlap. The photography was captured at a scale of 1:3700 (flying height 770m, focal length 213.67), was flown in alternate directions to trace possible biases in the results and only during periods of favourable geometric dilution of precision (GDOP <5). An important aspect is that satellite tracking started 10 minutes before take-off to allow *"receiver calibration"*.

The GPS data was processed using a smoothed pseudo-range technique to make use of the millimetre level carrier phase observable. The approach is based on the assumption that at each epoch I the difference between the pseudo-range measurement P(I) and the integrated phase observable D(I) is a constant but arbitrary value A. As soon as this value is computed from n measurements P(I) and D(I) at n different epochs, a smoothed pseudo-range $\underline{P(I)}$ can be computed for all subsequent epochs from:

$\underline{P(I)} = A + D(I)$The precision is determined by D(I) (Van Der Vegt, 1989)

The relative coordinate precision of these results for all strips was at the 5cm level but there existed drifts and offsets in the GPS positions as a result of the processing techniques.

The second objective of the researchers was the use of minimal ground control to support GPS-controlled photography. Simulations here support previous comments that only four (H&V) ground control points are required when projection centre coordinates are available from GPS.

Conclusions drawn from these results are that the feasibility of reducing ground control to four H&V control points at the block corners is possible when GPS drift can be eliminated. In order to obtain an operational system, aerial triangulation adjustment software requires refinements to accommodate linear drift in GPS positions.

Lucas & Mader (1989), on the other hand, used differential phase measurement techniques to determine the instantaneous GPS antenna coordinates. It required an operational procedure to be followed whereby the aircraft antenna remained fixed over a known point for a few minutes before and after the mission.

Their tests used a modified (shutter pulse) Wild RC-10, Ziess Jena LMK cameras and TI-4100 GPS receivers. The Texas test aircraft positioned the antenna behind the cabin but as far forward of the tail as possible, the Washington test aircraft had the antenna positioned on the tail.

The constraints on this experiment were quite tight, both receivers must track the same four satellites continuously, without a single loss of lock, from the time the air plane departed from the known reference point. They required that all four satellites be above a minimum elevation of 20° and that the GDOP be less than 10. This scenario created a degree of urgency for the flight crew within a window of approximately one hour.

For these tests, as in Europe, the camera was "locked down" and turns were restricted to minimum bank angles to avoid loss of lock. The resulting photo scale was approximately 1:3000.

After data collection triangulation was observed as per normal procedures, 18 photos for the Texas test (3 strips of 6 photos) and 20 photos for the Washington test (2 strips of 10). The small size of the data sets is the result of a number of unrelated occurrences.

The GPS data was processed using software based on the observation models of Mader (1986). The known starting position of the antenna is forced to be the solution yielding the unknown integer biases for each double difference. These are then fixed in the solution and remain so as long as no loss of lock occurs.

"The mobile antenna's terminal position (at the end of the flight) is also known and should match the coordinates obtained from the solution, but the realisation of these ideal circumstances is never realised. The accumulation of errors with time will result in the computed terminal position of the antenna departing from its known location by a metre or two." (Lucas & Mader 1989).

It is suggested that GPS and photogrammetry could be combined into one adjustment so that the photogrammetry could be used to assist in the determination and fixing of cycle slips. Although feasible the author claims that it would be seldom necessary, and it is expensive.

From these early tests, the feasibility of using GPS in support of aerial triangulation had been established. It was proving to be an observational resource which offered to be highly adaptive to the science of photogrammetry.

3. Associated problems with current technology

3.1 Receiver technology

Today's GPS receiver, be it a hand held navigator or a sophisticated high precision "geodetic" quality unit, is a vastly different apparatus from those first manufactured in the early 1980s. Early receiver designs, although cumbersome, heavy and power hungry, were quite adequate for the developmental and testing requirements of the day. These designs validated the performance of the GPS concept more than lending themselves to innovative survey or positioning techniques.

Designs had to be capable of tracking four satellites, as that was the requirement to determine the four unknowns X, Y, Z position and time (clock offset). The STI5010 (1980, $200,000) receiver was a single channel design which operated by tracking sequentially between satellites. This design was limited when used in dynamic states, requiring external sensor support to aid the GPS pseudo-range measurements. Continuously integrated phase measurements were not available from this design, position being derived solely from pseudo-range measurements.

1982 saw the introduction of the 'Texas Instruments' TI 4100 (cost:$150,000). This was a P-code (Precise Code), fast multiplexing design which had basically the advantages of a four channel receiver. The initial navigation problem of requiring four satellites to calculate a position was reflected in receiver design. The TI 4100 used different data rates for different dynamics. In "User Dynamics mode 2" the receiver could record data at a rate of 1.2 seconds with the advantage of P-code measurements rather than C/A-code (Coarse Acquisition Code) (Leick, 1995). Its bulky design, heavy weight and difficult interface is in stark contrast to today's modern designs.

In April 1985 at the First International Symposium on Precise Positioning with the Global Positioning System (Brown, 1985) four new receivers were announced, the Litton GPS

Survey Set, the Sercel TR5S, the Trimble 4000S (an improved version of the 4000A) and the Wild-Magnavox WM101. The Litton design was said to be capable of tracking up to 8 satellites simultaneously, with pseudo-range and carrier phase output, and onboard storage (available 1986, \$40,000). The Sercel TR5S was a 5 channel design capable of C/A pseudo-range and carrier phase at a sample rate of 0.6 seconds.

The Trimble receiver was a five channel design with some innovations. Unlike other GPS receivers, the 4000S did not depend on the use of an ultra stable local oscillator. Accurate timing is generated by the GPS satellite clocks, transferred through the position and clock offset solution of code phase measurements to four satellites (cost:\$39,500). The WM101, like the other receivers mentioned here, tracked the C/A-code to reconstruct the L1 carrier phase and extract the broadcast satellite messages. Wild-Magnavox introduced the WM102 which offered a dual frequency model capable of full L2 reception by tracking the P-code. During periods of P-code encryption a squaring technique was used to recover a modified second frequency ($L2^2$, $\lambda/2$). The combination of the L1 and L2 frequencies, known as the *ionosphere free linear combination*, reduced the effects of the ionosphere as baselines exceeded 40 to 50kms.

Although various researchers had demonstrated, in somewhat limited form, the dynamic positioning capability of these early designs, the photogrammetric capability lay in future receiver design and development.

Figure 3.1 is the real-time navigation system, implemented by NORTECH Surveys Inc. of Canada and operated by the author in 1987. It was a complex mix of, by today's standard, rather out of date technology. Much of what is


Figure 3.1 Navigation rack undergoing office tests. The LORAN receivers are the two units sitting on top of the TRIMBLE which is on the bottom.

displayed here is built into today's modern multi-channel receivers. This system was used as a guidance platform in support of offshore aircraft magnetometer surveys. It provided real-time guidance to the pilot along pre-planned survey lines and collected raw pseudo-range data by way of digi-tape for subsequent differential post processing, thus providing a system of quality control.

This serves as an example of the crude technology that could be utilised for photogrammetric applications in 1987.

This system illustrates some of the limitations, at that time, of the receiver technology. The receiver used here is the Trimble 4000A, a basic four channel GPS receiver capable of tracking four satellites, outputting pseudo-range and range-rate data at an update rate of 1 sec. This receiver had an acquisition time of 20 minutes from a cold start, 5 minutes from a warm start. Its maximum tracking dynamics limited it to a velocity of 100 metres/second and 0.5g. Position and velocity was generated at a rate of once every 10 seconds.

NORTECH's R&D people had developed their software to calculate position and velocity information from the raw pseudo-ranges. This enabled the calculation of position and velocity in near real-time. The GPS receiver in this case delivering the time-tagged raw ranges to a computer which did the bulk of the positional computation. This process was supported by other navigation data such as the LORAN dual chain receivers as depicted in figure 3.1. A Computer Addressable Precise Timing System (CAPTS - Rubidium Clock) is used to generate a 5 MHZ frequency to standardise and monitor the timing of the system. All sources of data were accordingly weighted and combined in a least squares navigation solution.

Although a minimum of four GPS satellites is required to determine a unique position solution, the NORTECH system was versatile enough to generate 2-D positions when only tracking two satellites. This was achieved by using auxiliary data. During periods of only three satellite coverage radar and barometric altimeter data, corrected for a geoid model, provided height information, the remaining unknowns latitude, longitude and receiver clock offset (the external rubidium clock) could be determined from the three satellites. Furthermore, the established clock offset and drift rate of the external rubidium clock could be constrained allowing for navigation solutions when only two satellites were available, again height was sourced from radar and barometric altimeter data.

Conceptually all this was very innovative, enabling 1 second update rate pseudo-range position solutions from a minimum of two satellites. For the operator it was a challenge to keep it running. Modelling the clock offset and its drift rate was always difficult.

To be initialised, the Trimble would have to be stationary and tracking four satellites until a position was computed, this process also established GPS time. At the time (1987) this procedure and the technology were in conflict; the project satellite window was very small and much useful window time was lost initialising the system; any delays impacted on the overall performance. Procedures were designed to make the best of the current situation.

The receiver was turned on, locking onto one or two satellites, downloading satellite almanac data, before suitable geometry and satellite numbers were available: the constellation was still developmental and limited. Once that first position fix was computed and GPS time established then navigation was possible, calculated from the pseudo-range data being output from the receiver's RS-232 port.

The four channel receiver design of the Trimble created problems when constellation changes were required. The receiver and navigation computer was not tolerant of extended data outages such as searching for the new satellite and down loading a satellite ephemeris, tending to become quite "lost". Changing satellite constellations, which always produced a period of "dead reckoning", was a harrowing experience. A number of missions were aborted because the system had become disorientated.

If the operator could keep all this going for an entire mission, including periods of two satellite coverage, then all the raw observation data collected on the aircraft was post-processed for quality control. This process used the differential correction data generated by another receiver established at the working office of the project team.

Although cumbersome, sensitive and temperamental, this technology demonstrated the potential of GPS for position determination of dynamic platforms.

In contrast, the modern GPS receiver carries out these procedures in the background, invisible to the user!

Around this time manufacturers had identified the value, and developed the capability of tracking multiple satellites. The GPS constellation was growing, new satellites were steadily coming on line. A trend was also developing in the design of receivers. Manufacturers had identified two very different types of applications, navigation and survey. 1987 saw the introduction of the WM101 surveying receiver to Australia. The Wild Survey Company's background was reflected in this receiver, designed primarily for the survey market. It was a single frequency, four channel, sequencing receiver capable of tracking six satellites with the benefit of onboard data storage. This unit was truly portable.

Table 3.1 is a receiver comparison chart taken from the promotional brochure produced for the NORSTAR 1000 GPS receiver (circa 1987). The versatility of designs is emerging in this comparison. The ability to store data onboard the receiver was seen as a great step forward.

Data logging systems had been one of the more undesirable aspects of the technology. It is interesting to note the comments of Collins (1986):

"To date, our single greatest problem in using the 4000S has been the reliability of the laptop computer which logs the observed data. We have been using Kaypro 2000 computers because they cost about one-half the price of GRID laptop computers which others often use. Actually, neither the Kaypro or GRID is ideally suited to field use, but they will have to do until something better comes along."

Table 3.1 Nortech brochure of available receiver technology (NORTECH Surveys Inc of Canada, circa 1987).

NORSTAR 1000 Feature Summary

9.0 GPS Receiver Comparison

Feature	**NORSTAR 1000**	**Trimble Navigation 4000SX**	**Texas Instruments TI-4100**	**Wild-Magnavox WM-101**
Technical:				
No. of channels	5 or 7	5	1	4
Type of receiver	Dedicated	Dedicated	Multiplexing	Sequencing
Weight (kg)	8	20.5	22	14.4
Dimensions (inches)	5.25x17x12	7x18x19	8.3x17.5x14.7	6.5 x 15.3 x 20
Volume (cubic inches)	1071	2394	2135	1990
Power(watts)	60	60	110- 170	20
Operation @ -40C	YES	NO	NO	NO
Operating temperature	-40C to +50C	0C to +50C	-20C to +50C	-25C to + 55C
Display size	4x40= 160 char	2x16=32 char	2x16=32 char	3x20=60 char
Main CPU	68010/16 bits	?	9990/16 bit	8086/16 bit
FP Math Coprocessor	YES/68881	NO	?	8087
No. of serial ports	4	2	1	2
Oscillator:				
Oscillator in	YES	YES	YES	NO
External frequency	3.41,5,10,10.23 MHZ	5 MHZ	5 MHZ	- - -
I PPS (Pulse/Sec) Out	YES	OPTIONAL	YES	NO
Mark Position Key	YES	NO	YES	NO
Mark Position Input	YES	NO	NO	NO
Navigation:				
Navigation application	YES	NO	LIMITED	LIMITED
No. of way-points	1000	-- -	9	
Event scheduling	1000	NO	NO	NO
Steering display	YES	NO	NO	NO
Modes:				
Mode configurable	YES/static,low,med,hi	NO	YES	NO
Mode accelerations	OG,0.6G,1.5G,4G	0.5G max	YES	?
Differential:				
Real-time differential	YES	NO	NO	NO
Dynamic differential	YES	NO	NO	NO
Measurements:				
Pseudo-range	YES	YES	YES	YES
Integrated Doppler	YES	YES	YES	YES
Carrier phase	YES	YES	YES	YES
Smoothing filter	YES	YES	YES	YES
Filter user-configurable		YES	NO	NO
NO				
Other:				
Software maintenance	YES	YES	YES	YES
Datalogger capabilities	YES	YES	YES	YES
Display update rate	I second	I second	1.2, 3 seconds	7.5 seconds
Internal data storage	YES	NO	NO	TAPE
Solid state MMU	YES(option)	NO	NO	NO
Internal batteries	YES/data backup only	YES(option)	YES(option)	YES
Soft key functions	YES	YES	NO	YES
Remote control	YES	LIMITED	POSSIBLE	NO
Internal undulate table	YES	NO	YES	NO
Alert utility	YES	YES	NO	NO
Datum configurable	YES	YES	YES	NO
Units configurable	YES	NO	YES	NO
POns configurable	YES	LIMITED	NO	YES
Post Processing Sftwre	NOVAS	TRIMVEC	GEOMARK	POPS

The data contained in this receiver comparison has been obtained from the respective manufacturer's marketing brochures and is subject to change without notice. Norstar Instruments will not be responsible for publishing errors or specification changes of the receivers listed herein.

The alternative to direct logging to a computer was some sort of tape drive mechanism. Both strategies had their drawbacks.

The introduction of non-volatile memory within the GPS receiver was another major advance in the technology. The satellite almanac data could be retained within the receiver's memory reducing the time to satellite lock from 15-20 minutes to 2 minutes or less. The inclusion of onboard RAM negated the need for tape drives and data loggers. This was generally the case for survey applications.

For high dynamic situations, generating large volumes of data, data logging systems were still required, and are still used today.

The period 1988 through 1990 saw the introduction of the versatile multi-channel GPS receiver. The introduction of Selective Availability had reduced the positioning power of the GPS system to the public user. Enterprising manufacturers were promoting the Real Time Differential or post-processed differential solutions using phase smoothing techniques. In support of this, the survey receiver and precise navigation receiver had become one, with models like the ASHTECH X-II 12 channel and the Trimble 4000ST nine channel receivers.

Receivers such as these were the forerunners of today's modern designs. These receivers were self-contained units, tracked multiple satellites on parallel channels with little or no inter-channel biases. They could be purchased with multiple communication ports and output a selection of data types and formats. For survey applications the onboard RAM reduced logistics of a survey considerably but was still not foolproof. Features such as 1 Pulse Per Second (PPS) out and event marking capability lent itself to the dynamic instantaneous position problem.

The link between an event and the position could be solved by various techniques. In photogrammetric applications a frequency counter could be used as a precise stopwatch to measure the time difference between the pulse generated by a camera at the instant of exposure and the 1PPS output from the GPS receiver (Kinlyside, 1988). This is difficult as the pulses are not time-tagged, which makes later processing problematic.

An alternative is the approach used by NORTECH with their CAPTS system. This is in fact an enhanced frequency counter capable of actually time-tagging the data. This data can then be interpolated against the sequential position data that has been logged for post-processing.

Although the advantages of dual frequency receivers had been identified in the design stages of the GPS program, the use of commercial dual frequency receivers had been limited, firstly due to cost and secondly the techniques used to recover the L2 carrier phase. For survey applications dual frequency data helped to overcome the effects of the ionosphere and within the processing software could be used as an aid to the repair of cycle slips or the resolution of integer cycle ambiguities needed to determine precise range data.

A number of manufacturers began to offer dual frequency P-code models but their advantages were short lived with the introduction of Anti-Spoofing (AS) on the 31 January 1994. AS is a modification of the mathematical algorithm which generates the P-code. The encrypted P-code is referred to as the Y-code. A solution to overcome AS was to offer dual frequency receivers which tracked the C/A-code recovering the L1 phase data and pseudo-ranges, and using a squaring technique to recover the L2 phase data. This process reduces the L2 observable to half the L2 wavelength, substantially reduces the signal-to-noise ratio and lacks any P-code range information. This technique was used on the Ashtech MD-XII and the Trimble 4000SST receivers (Seeber, 1993). The newly released LEICA System 200 (1991) was designed to track the P-code when it was available (P-code was always available on Block 1 satellites). During periods of AS (Block II satellites and onwards) it could still recover the L2 P-code range through a code-correlation squaring technique (Hatch et al, 1992; Ashjaee & Lorenz, 1992; Leick 1995). The P-code range is important in the process of ambiguity determination in kinematic or carrier phase differential positioning. A drawback with code-correlation squaring is that it still results in a L2 half wavelength observable but there is a significant improvement in the signal-to noise ratio over simple squaring. Signal-to-noise ratios are important because the higher the ratio the shorter the correlation time or time that is required to average the signal. Kinematic applications benefit from high signal-to-noise ratios.

Associated with the new Leica model were new processing algorithms which depended on the design specification of the receiver. Signal-to-noise ratios had been increased and the Leica receiver employed clock steering to reduce post-processing noise associated with mismatched data. These same algorithms were influencing dynamic applications as well.

The dependence of the sub-metre/sub-decimetre dynamic solution on a static observation initialisation period was nearing its end. Goad (1992b) had demonstrated sub-decimetre solutions over 1500km to a buoy without any initialisation.

Today's high-end GPS receiver, driven by the algorithms of the surveyor, the navigator or the geodesist, is a sophisticated device.

"A major accomplishment in the continued development of GPS technology, and at the same time a clear sign of an innovation-happy GPS industry, are the various solutions that have become available over the last couple of years for dealing with AS." (Leick, 1995)

Other techniques have also been developed to recover the P-code range and the full L2 carrier wavelength under AS. These two observables are important in decreasing the time or observation window required to determine the L1 and L2 carrier cycle ambiguities. The technique used by Trimble in its *4000SSE* model is a cross correlation tracking process. This method utilises the fact that the Y-codes on each frequency are the same. The correlation between the two signals is maximised by measuring the time delay between the two frequencies. The resulting observables are the range differences and the beat-frequency carrier (L2 - L1) (Ashjaee and Lorenz, 1992). This results in the recovery of full wavelength L2 and a P(Y)-code range difference. The direct range can be obtained by adding the C/A-code range. This technique suffers from poor signal-to-noise ratios.

Z Tracking was introduced by Ashtech on its Z12 receiver. Under AS this technique recovers full L2 wavelength, L1 and L2 Y-code ranges. The methodology correlates the incoming L1 and L2 signals with the receiver generated P-code deriving an estimate of the encryption bit which is applied to the opposite frequency signal processing. As Y-code ranges are determined full wavelength L1 and L2 carrier phases are available (Ibid, 1992, Leick, 1995). In comparison to other signal processing techniques under AS Z tracking returns the highest signal-to-noise ratio.

In 1991 Novatel Communications introduced their Narrow Correlation receiver design. The new C/A-code tracking technique produces range accuracies approximately a factor $\sqrt{5}$ worse than P(Y)-code receivers. The methodology is based on increasing tracking bandwidth and decreasing the chipping width. Instead of aligning on one C/A-code chip, alignment is made on a number of chips which reduces the observation variance.

"Despite the increased bandwidth and data processing burden, narrow-correlator technology offers several substantial advantages in GPS receiver performance, as compared to a conventional one-chip correlator spacing GPS receiver, notably:

- *Significant improvement in range resolution*
- *Reduced susceptibility to multipath effects*
- *Shorter recovery time after loss of track (lock)*
- *Fewer computations required for solving wavelength ambiguities in applications where carrier phase is used for ranging."* (Karels et al, 1994)

The introduction of Cross Correlation, Z and Narrow Correlation Tracking have decreased what would have been 1 to 2 hours observation time to 5 minutes or less, with the bonus of increased solution confidence. Sub-metre dynamic solutions, in concert with smart software, are now a reality benefitting from the high quality data and reliability available from the modern GPS receiver.

3.2 Kinematic principles

Positioning a dynamic airborne antenna for photogrammetric purposes brings with it the problem of locating or developing software capable of converting the numerous measurements of the GPS receivers to positions. Like the development of the hardware, software has evolved in such a way that it makes it possible to realise this goal. Software development has not only benefitted from receiver improvements but also from gains in the personal computer environment.

Processing techniques have evolved from the first single point pseudo-range position solutions to today's *"on the fly"* (OTF) centimetre level solutions.

The most basic navigational function is to measure pseudo-ranges between a GPS receiver and a constellation of at least four GPS satellites for the determination of receiver location and clock offset. By measuring the rate of change of range to four GPS satellites, the receiver velocity and clock error rate can also be determined.

Basic GPS receiver measurements are (Leick, 1995, Seeber, 1993):

- Pseudo-range - is derived from the time shift necessary to correlate the code modulations of the received signal with those of the signal generated within the receiver. C/A-code is measured on the L1 frequency, P-code can be measured on both frequencies.

- Carrier Phase - is the difference between the received satellite carrier phase at the receivers antenna and the phase of the internal receiver oscillator measured at equally spaced nominal receiver clock epochs. Carrier phases can be measured on either GPS signal frequency.

- Doppler Measurement - The difference between the received signal's frequency and the receiver generated frequency (nominal frequency) during a given time interval.

3.2.1 Code Pseudo-ranges

Code phases (pseudo-range measurements from code measurements) and carrier phases (pseudo-ranges from carrier phases) are the two fundamental observations used to determine satellite to receiver range.

Let t^S be the reading of the satellite clock at the time of transmission and t_R be the receiver clock reading at the time of reception. Both the satellite and receiver clocks will contain delays, δ^S and δ_R, with respect to GPS system time. The difference between the clock readings is equivalent to the time shift Δt, the time it takes to align the codes within the receiver. Thus:

$$\begin{aligned}\Delta t &= t_R - t^S = [t_R(GPS) - \delta_R] - [t^S(GPS) - \delta^S] \\ &= \Delta t(GPS) + \Delta\delta\end{aligned} \tag{3.1}$$

where $\Delta t(GPS) = t_R(GPS) - t^S(GPS)$ and $\Delta\delta = \delta_R - \delta^S$ (Hofmann-Wellenhof et al, 1992). The error in the satellite clock δ^S can be modelled by a polynominal whose coefficients are transmitted in the satellite navigation message. For navigation applications the modelling of the satellite clock error removes δ^S leaving the remainder $\Delta\delta$ representative of the receiver clock error. Multiplying Δt by the speed of light, c, determines the pseudo-range PR.

$$PR = c\Delta t = c\Delta t(GPS) + c\Delta\delta \tag{3.2}$$

In the above $c\Delta t(GPS)$ corresponds to the true distance between the satellite at $t^S(GPS)$ and the receiver at $t_R(GPS)$. Let ρ be the true distance between the satellite at time $t^S(GPS)$ and the receiver at time $t_R(GPS)$. Then the pseudo-range in metres is:

$$\begin{aligned}PR_R^S &= c\Delta t(GPS) + c\Delta\delta = \rho_{t\,(GPS)} + c\Delta\delta \\ PR_R^S &= \sqrt{(x^S - x_R)^2 + (y^S - y_R)^2 + (z^S - z_R)^2} + c\Delta\delta\end{aligned} \tag{3.3}$$

The above holds true if the propogation medium were a vacuum and no other biases were present. The complete expression for pseudo-range with respect to the nominal receiver time t_R in metres is (Leick, 1995):

$$PR_R^S(t_R) = \rho_R^S(t_{R_{GPS}}) - c(\delta_R - \delta^S) + I_{R,P}^S(t_R) + T_k^S(t_R) + d_{R,P}(t_R) + d_{k,P}^S(t_R) + d_P^S(t_R) + \epsilon_P \tag{3.4}$$

where:

$\rho_R^S(t_{R_{GPS}})$	the true range from the satellite to the receiver
$I_{R,P}^S(t_R)$	the range error caused by (dispersive) ionospheric signal delay
$T_R^S(t_R)$	the range error caused by tropospheric signal delay
$d_{R,P}(t_R)$ and $d_{R,P}^S(t_R)$	the range error caused by receiver and satellite harware code delays
$d_{R,P}^S(t_R)$	the range error caused by code signal multipath
ϵ_P	the range error caused by random measurement noise

The units of all the terms in (3.4) are in metres. The subscript P identifies all terms whose evaluation is associated with pseudo-ranges. In applications where low accuracy is required the receiver location and receiver clock offset are the unknowns. The satellite clock errors can be modelled from the coefficients in the satellite message, ionospheric and tropospheric delays can be approximated from models and hardware and multipath errors can be negelected for navigation solutions. There remain four unknowns x_R, y_R, z_R and δ_R. These can be determined by simultaneously measuring pseudo-ranges to four GPS satellites resulting in the following equations:

$$PR_R^1 = \sqrt{(x^1 - x_R)^2 + (y^1 - y_R)^2 + (z^1 - z_R)^2} + c \cdot \delta_R \tag{3.6}$$

$$PR_R^2 = \sqrt{(x^2 - x_R)^2 + (y^2 - y_R)^2 + (z^2 - z_R)^2} + c \cdot \delta_R \tag{3.7}$$

$$PR_R^3 = \sqrt{(x^3 - x_R)^2 + (y^3 - y_R)^2 + (z^3 - z_R)^2} + c \cdot \delta_R \tag{3.8}$$

$$PR_R^4 = \sqrt{(x^4 - x_R)^2 + (y^4 - y_R)^2 + (z^4 - z_R)^2} + c \cdot \delta_R \tag{3.9}$$

It should be pointed out that the solution is an iterative one due to the difference between the satellite transmission and receiver reception times, and the effect this has on the calculated satellite positions. If more than four satellites are observed then a least squares solution can be derived. A more common simplified form of equation (3.4) using different notation is (Seeber, 1993):

$$PR_{CD} = c(t_r - T_t) = R + cdt_u + cdt_a + cdt_s + \epsilon_R \tag{3.10}$$

where:

dt_s	satellite clock error with respect to GPS time
dt_u	clock synchronization error
dt_a	atmospheric propagation delay
ϵ_R	observation noise
R	slant range

The subscript *CD* denotes code observations. Variations to the navigation solution can be made, for example, in ship borne applications where the height of the receiver is reasonably well known. External clocks, synchronised to GPS time, can also be used. Both these situations reduce the number of unknowns to be estimated, increasing the GPS performance (in the early testing years), beyond its limited four satellite window.

The accuracy of the pseudo-range technique depends on the quality of the satellite ephemeris. Before the introduction of Selective Availability (SA) the navigation solution was accurate to 10 to 20 m using P-code. SA has reduced this to around 100m horizontal (95% C.I.). Before SA the navigation solution may have been just adequate enough to control small scale mapping applications, but other operational factors would have still complicated the situation.

Current positioning accuracy is subject to selective availability.

3.2.2 Pseudo-range enhancements

Improvements to the accuracy of the navigation solution can be made through the use of a number of techniques. One of the first developments in this area was proposed by Hatch (1982), described as "phase smoothing". This process utilises the uninterrupted or unbroken phase counts and fractional phase readings to smooth the changes in the raw pseudo-ranges.

Ibid (1982) demonstrates, using dual frequency data, the use of integrated Doppler measurements in improving the pseudo-range precision. The integrated Doppler can be determined by (Seeber, 1993):

$$N_{jk} = \int_{t_j}^{t_k} (f_g - f_r)\ dt \tag{3.11}$$

where

f_r	is the received carrier frequency
f_g	is the reference frequency within the receiver
N_{jk}	is the integrated Doppler count between epochs t_j and t_k. It can be considered as a measure of the range difference between the receiver antenna and two consecutive orbital positions of the same satellite at two different epochs t_j, t_k.

The basic observation equation can be written in metres as (Ibid, 1993):

$$\Delta R_{ij} = \frac{c}{f_0}\ (N_{jk} - (f_g - f_s)\ (t_k - t_j)) \tag{3.12}$$

or as a function of the unknown station coordinates and unknown frequency difference:

$$\begin{aligned} N_{ij} = \frac{f_g}{c} & (\{(X_k - X_i)^2 + (Y_k - Y_i)^2 + (Z_k - Z_i)^2\}^{1/2} \\ & - \{(X_j - X_i)^2 + (Y_j - Y_i)^2 + (Z_j - Z_i)^2\}^{1/2}) \\ & + (f_g - f_s)(t_k - t_j) \end{aligned} \tag{3.13}$$

where

ΔR_{ij}	is the change in range between consecutive satellite positions S_j, S_k and the

receiver between epochs t_j and t_k

f_s is the frequency of the signal transmitted by the satellite

f_0 is the nominally constant receiver generated reference frequency

X_k, Y_k, Z_k and X_j, Y_j, Z_j are the known satellite coordinates at epochs k and j

X_i, Y_i, Z_i are the unknown receiver station coordinates

The integrated Doppler count is a vastly improved determination of the change in satellite - receiver range then successive pseudo-ranges. Hatch (1982) suggests combining the pseudo-range and the Doppler count measurements to determine an improved "smoothed" pseudo-range. Ibid (1982) illustrates *"Assume that we have two sequential unbiased range measurements from a GPS satellite already corrected for ionospheric effects. (The bias and ionospheric effects are dropped temporarily simply to avoid obscuring the concept with more complex equations.) It is obvious that recasting the two equations into the sum(or average) and the difference results in no loss or gain in the information content."*

Let there be a whole group, N, of refraction corrected pseudo-range measurements $PR_R^S(t)$, then the average pseudo-range measurement is:

$$\overline{PR_R^S} = \sum_{t=0}^{N-1} \frac{PR_R^S(t)}{N} = \overline{R_R^S} \quad \text{(average range)} \tag{3.14}$$

where

$\overline{R_R^S}$ and $\overline{PR_R^S}$ denote averaged values

there are also N pseudo-range differences (from the average)

$$PR_R^S(t) - \overline{PR_R^S} = PR_R^S(t) - \sum_{t=0}^{N-1} \frac{PR_R^S(t)}{N} = R_R^S(t) - \overline{R_R^S} \tag{3.15}$$

(for simplicity the clock errors have been dropped)

Let there also be a group, $N\text{-}1$, refraction corrected Doppler count measurements, $D(t)$, which measure the range change between $PR_R^S(t-1)$ and $PR_R^S(t)$ measurements.

Ibid (1982) states *"it is shown that the N-1 Doppler counts D_i can be mapped into N measurements M_i such that:"*

$$M_i = R_i - \overline{R}$$

or in the current notation:

$$M(t) = R_R^S(t) - \overline{R_R^S} \tag{3.16}$$

Equations (3.15) and (3.16) are of exactly the same form. However, the Doppler accuracy is two orders of magnitude greater than the code derived measurements. Given the availability of the Doppler measurements the change in range derived from the pseudo-range measurement is useless. The value is in the pseudo-range measurement itself as there is no equivalent Doppler equation to (3.14).

Equations (3.14) and (3.16) are then combined to give:

$$M(t) + \overline{PR_R^S} = R_R^S(t) \tag{3.17}$$

Ibid (1982) goes on to state that *"from the cumulated Doppler count measurements a relatively noise free value can be computed which maps the code measurements back to an equivalent initial measurement. The code measurement information is then extracted by forming the average value of this initial measurement which becomes increasingly accurate"*:

$$\overline{PR_{R_0}^S} = \sum_{t=0}^{N-1} \frac{(PR_R^S(t) - \sum_{j=1}^{t} M(j)}{N} \tag{3.18}$$

"It should be noted that for post processing of a group of measurements the averaging which occurs is performed across the entire data set." Hatch (1982). The precision of this technique for C/A-code receivers approaches 1m, but today the accuracy will be a function of the SA noise.

For real-time data, or in the case of a moving antenna, the only option is to average across the data up to the current measurement. Ibid (1982) proposes the recursive form where *i* is time dependent:

$$PR_R^S(i+1) = \frac{N}{N+1}\,(PR_R^S(i) + M(i+1)) + \frac{1}{N+1}\,PR_R^S(i+1) \tag{3.19}$$

Equation (3.19) makes a linear combination of the *i*th Pseudo-range smoothed by the *i-1* to *i*th Doppler measurement plus the *i+1* pseudo-range. Hatch (1982) also states that *"It is also apparent in this form that the Doppler measurement is assumed to be an infinitely more accurate measurement than the code measurement. Since the Doppler is actually only about 100 times more accurate it is wise to use variance ratios if the number of measurements approaches 10,000 (100 squared)".*

The same form is defined by Seeber (1993) and used by Lachapelle et al (1986):

$$PR_\Phi(t) = \omega_{PR}(t)PR_r(t) + \omega_\Phi(t)(PR_\Phi(t-1) + (\Phi(t)-\Phi(t-1))) \tag{3.20}$$

where

$PR_r(t)$	is the raw observed pseudo-range at t
$PR_\Phi(t)$	is the phase-smoothed pseudo-range at t
$\omega_{PR}(t)$	is the weight of raw pseudo-range at t
$\omega_\Phi(t)$	is the weight of $(PR_\Phi(t-1) + (\Phi(t)-\Phi(t-1))$ $\omega_\Phi(t) = 1 - \omega_{PR}(t)$

The outcome of this form is excellent relativity between successive epochs, but position is propagated from the initial code determination. The effectiveness of this technique has been somewhat defeated through the introduction of SA.

This process has been used in photogrammetric applications (Cortes & Heimes, 1988). Ibid (1988) demonstrated that very high relative accuracy of the GPS data after the removal of X, Y and Z shifts (zero degree polynomial), linear (first degree polynomial) and quadratic trends (second degree polynomial).

These equations are a means to improve the overall pseudo-range positions, but they are subject to systematic errors, the most prevalent of which is multipath. Multipath errors result from reflected signals in the vicinity of the antenna. This effect can cause the pseudo-ranges to be distorted by several metres and can vary over a time scale of minutes. Phase smoothing does not eliminate the dispersive effects of the ionosphere. The ionosphere affects the pseudo-range and the phase with opposite signs, thereby doubling the impact of the ionosphere on the final position determination (Mader, 1996).

This had demonstrated the versatility of a single receiver operation but further improvements could be made to the position accuracy through the use of differential corrections. There are basically two techniques in applying differential corrections to GPS measurements. The simplest is to implement position corrections. A reference receiver is located on a site whose position is known. Position corrections are generated by comparing the receiver's calculated position to the known site values, producing $\Delta\phi$, $\Delta\lambda$ and Δh or ΔX, ΔY and ΔZ. These corrections are passed to the remote receiver resulting in a corrected location. The disadvantage of this technique is that both the reference and remote receivers have to track the same constellation of satellites. The method degrades as distance increases (significantly beyond 500km, Ackroyd & Lorimer, 1990) because the satellite geometry of the position calculation changes.

The second and more sophisticated technique is to generate corrections to the pseudo-range observations at the reference receiver by comparing the observed pseudo-range to the known satellite range (based on the satellite ephemeris and the known reference position). The main advantage of the pseudo-range differential method is that the remote receiver's satellite selection is independent of the reference receiver. In addition the pseudo-range corrections are valid over longer distances.

Table 3.2 from Blackwell (1985) summarises errors associated with differential GPS.

Friess (1988) has studied differential GPS for photogrammetry using phase and pseudo-range observations. Ibid (1988) determines the initial unknown phase ambiguities for the

Table 3.2 Differential GPS Error Budget* (Blackwell, 1985)

Error Source	Predicted Error (m)	
Residual satellite clock error	0	
Residual ephemeris error	0	
	P-code	C/A-code
Residual ionospheric/tropospheric delay error	0.15	0.15
Receiver inter-channel bias	0.15	0.6
Receiver noise	0.25	2.4
Multipath	1.2	3.05
UERE (RMS)	1.3	4.0
Resulting Position Accuracy		
RMS horizontal position error (assume HDOP = 1.5)	1.9	5.9
RMS vertical position error (assume VDOP = 2.5)	3.2	9.9

*Assume 50nmi separation between remote and reference receivers

reference receiver based on the known reference station coordinates, and then determines those for the aircraft data set based on the initial pseudo-range coordinates.

A number of assumptions are made and this model disregards a number of error sources. Of course the initial ambiguity determination may be well off the "correct value" but this process appears to make use of the continuous phase tracking of the receivers. The methodology then appears to follow a position correction process:

"As *a result of this process one obtains for each observation epoch i, i.e. every 0.6 sec, the coordinates of the stationary receiver antenna in the geocentric coordinate system WGS84. The variance-covariance matrices of all epochs were also obtained:*

$$X_{ref}(t_i);\ Q_{ref}(t_i) \text{ and } X_{air}(t_i);\ Q_{air}(t_i) \qquad (3.21)$$

where:

$X_{ref}(t_i)$ *is the position vector of the GPS antenna at the reference point at observation epoch t_i in WGS84*

$X_{air}(t_i)$ *is the position vector of the GPS antenna on the aircraft at observation epoch t_i in WGS84*

$Q_{ref}(t_i)$, $Q_{air}(t_i)$ *the corresponding variance-covariance matrices*

These single epoch positions are influenced by the above neglected systematic effects. Assuming that the systematic effects on the positions of both receiver antennae are identical or rather similar, these effects can be reduced by calculating relative positions of the aircraft GPS antenna with respect to the stationary GPS antenna.

$$X_{relair} = X_{ref} + [X_{air}(t_i) - X_{ref}(t_i)] \tag{3.22}$$

$$Q_{relair}(t_i) = Q_{ref}(t_i) + Q_{air}(t_i) \tag{3.23}$$

where:

X_{ref}	*is the nominal position vector of the stationary receiver antenna*
$X_{relair}(t_i)$	*is the relative position vector of the GPS aircraft antenna in WGS84*
$Q_{relair}(t_i)$	*is the corresponding variance-covariance matrices"*

This demonstrated use of GPS for photogrammetric applications used the early prototype satellite constellation, limited to satellite numbers 6, 8, 9, 11 and 12. To achieve this level of positioning using phase smoothed position corrected differential GPS would require special procedures. The most important aspect would be the continual phase tracking of a minimum of four satellites for the entire photographic run. Friess (1988) reports that results were poor for one run but this was due to poor PDOP (40). His paper does not refer to the importance of phase lock in this process.

Friess'(1988) test results are exceptional. The initial results indicate a positioning accuracy better than ±10cm in comparison to the photogrammetrically determined photograph centres. Obviously advantage is taken of the relative nature of successive position solutions resulting from the continued phase tracking. This is further exploited by removing linear drift parameters similar to Cortes and Heimes (1988). Operational considerations to achieve such results are (Ibid, 1988):

"(h) In survey flight missions with GPS positioning in absolute mode, the following precautions should be taken:

- *i)* *Do not change the satellite configuration during a flight line;*
- *ii)* *Use, if possible, the same configuration of satellites; any change produces a discontinuity in the GPS data (in differential mode it is compensated).*
- *iii)* *If a change of the satellite configuration is unavoidable, apply it during the turn of the air plane from one line to the next.*
- *iv)* *If the flight mission cannot be completed in one day, use (if possible) the same satellite configuration in the next flight(s)."*

These results demonstrate the positioning quality embedded in the carrier phase data.

3.2.3 Relative positioning

The use of combined code pseudo-range - phase observations (Doppler) has its merits but the real gains in positioning accuracy lie in the processing of phase data itself. *"The carrier phase is derived from a phase comparison between the received Doppler-shifted carrier signal f_{CR} and the (nominally constant) receiver-generated reference frequency f_0"* (Seeber, 1993). The observation equation for the carrier phase observable $\varphi_k^p(t)$ for station k and satellite p can be written as (Leick, 1995):

$$\begin{aligned}\varphi_k^p(t) &= \varphi_k(t) - \varphi^p(t) + N_k^p(1) + I_{k,\varphi}^p(t) + \frac{f}{c}T_k^p(t) \\ &\quad + d_{k,\varphi}(t) + d_{k,\varphi}^p(t) + d_{\varphi}^p(t) + \epsilon_{\varphi}\end{aligned} \tag{3.24}$$

where:

$\varphi_k(t)$ and $\varphi^p(t)$	represent the receiver's phase and the received satellite phase at the nominal reception time t.

$N_k^p(1)$	represents the initial integer ambiguity. It is the arbitrary counter setting of the tracking register when observations begin when phase lock is established.
$I^p_{k,\varphi}(t)$ and $T^p_{k,\varphi}(t)$	represent the ionospheric and tropospheric effects.
$d_{k,\varphi}(t)$ and $d^p_{\varphi}(t)$	refer to hardware delays of the receiver and satellite.
$d^p_{k,\varphi}(t)$	is the multipath effect.
ϵ_φ	represents random carrier phase noise

Terms with the subscript φ are expressed as units of cycles (2π). The tropospheric delay is converted to cycles by the factor f/c, where f is the nominal carrier frequency. The receiver shifts its own phase signal to lock with incoming signal, from that point the receiver tracks the cycle increases and decreases in the incoming signal. If the signal is interrupted then a cycle slip is said to have occurred. Phase lock is re-established and the count is re-initialised.

Equation (3.24) is developed by introducing the clock errors, modelling the satellite frequency and relating signal travel time to the topocentric range. The fully developed expression for the undifferenced carrier phase is (Leick, 1995):

$$\begin{aligned}\varphi_k^p(t) &= \frac{f}{c}\rho_k^p(t) - f\left[1-\frac{\dot{\rho}_k^p(t)}{c}\right]dt_k + f\,dt^p + N_k^p(1) + \frac{a^p}{c}\rho_k^p(t) \\ &\quad + I^p_{k,\varphi}(t) + \frac{f}{c}T_k^p(t) + d_{k,\varphi}(t) + d^p_{k,\varphi}(t) + d^p_{\varphi}(t) + \epsilon_\varphi\end{aligned} \qquad (3.25)$$

In equation (3.25) the receiver clock error contributes in two ways, via the terms $f\ dt_k$ (which is large) and the term $\dot{\rho}_k^p$ (the topocentric range rate). A phase measurement accuracy of 0.01 cycles requires a receiver clock accuracy of about 0.01 nsec. The effect of the topocentric range rate $\dot{\rho}$ is negligible if the station clock error does not exceed 0.1 μsec.

Satellite clock errors contribute to the phase observable through the large term $f\ dt^p$ and the small frequency offset term $a^p\rho_k^p/c$ (a^p is the coefficient of the modelled satellite frequency offset).

A more familiar presentation of equation (3.25) in units of metres for one satellite and one receiver is given by Seeber (1993):

$$PR_{CR} = R + cdt_u + cdt_a + cdt_s + c\left(\frac{N}{f_{CR}}\right) + \epsilon_R \tag{3.26}$$

where:

PR_{CR}	is the pseudo-range from the nominal carrier phase.
R	is the slant range
dt_u	is the clock synchronization error
dt_a	is the atmospheric propagation delay
N	is the ambiguity term, the unknown integer number of cycles where: $c \,.\, \frac{N}{f_{CR}} = N \,.\, \lambda_{CR}$ (3.27) defining f_{CR} and λ_{CR} as the frequency and wavelength of the carrier signal respectively.
ϵ_R	is the observation noise.
c	is the signal propagation velocity (speed of light)

The greatest difficulty with this method is the determination of the cycle ambiguity, N, because the observation is only a fraction of the cycle, the number of cycles within the satellite - receiver range is unknown. Many techniques are used to determine N and some of these will be described in subsequent pages. Alternatively, the range must be known within half a cycle length (~10cm).

In equation (3.26) the carrier phase observations can be used to determine the range to a satellite, but a number of terms must be resolved before this can be done. Some of the terms are common to a number of different combinations. Two receivers observing the same satellite are subject to the same error dt_s, one receiver observing a number of satellites is subject to the same error dt_u.

Data combinations are (Seeber, 1993):

- between observations at different stations
- between observations of different satellites
- between observations at different epochs
- between observations of the same type, and
- between observations of different type.

Single-differences can be formed between receivers

$$\Delta(\bullet) = (\bullet)_{receiver\ j} - (\bullet)_{receiver\ i} \tag{3.28}$$

Single-differences can be formed between satellites

$$\nabla(\bullet) = (\bullet)^{satellite\ q} - (\bullet)^{satellite\ p} \tag{3.29}$$

Single-differences can be formed between epochs

$$\delta(\bullet) = (\bullet)_{epoch\ 2} - (\bullet)_{epoch\ 3} \tag{3.30}$$

Using (3.2.3.5), then the single-difference (in metres), for carrier phase, formed between two receivers i and j is:

$$\begin{aligned} \Delta PR_{CR_{ij}} = {} & \Delta R_{ij} + c(dt_{u_j} - dt_{u_i}) + c(dt_{a_j} - dt_{a_i}) \\ & + c(dt_s - dt_s) + \lambda_{CR}(N_i - N_j) + \epsilon_{\Delta CR} \end{aligned} \tag{3.31}$$

The satellite clock errors cancel. Simplifying the equation:

$$\Delta\Phi = \Delta R + cdt_u - \Delta d_{ion} + \Delta d_{trop} + \lambda \Delta N + \epsilon_{\Phi} \tag{3.32}$$

The propagation delay dt_a in equation (3.31) is a now a differential value and can be disregarded for receivers close together.

Double-differences are formed by differencing between receivers and satellites. Using (3.29), then the double-difference, for carrier phase, formed between two single-differences between two satellites p and q is:

$$\begin{aligned}\nabla\Delta PR_{CR} = (\Delta R_{ij}^{p} - \Delta R_{ij}^{q}) + c(\Delta t_{u_{ij}} - \Delta t_{u_{ij}}) + c(\Delta t_{a_{ij}^{p}} - \Delta t_{a_{ij}^{q}}) \\ + \lambda_{CR}(\Delta N_{ij}^{p} - \Delta N_{ij}^{q}) + \epsilon_{\nabla\Delta}\end{aligned} \tag{3.33}$$

The receiver clock terms dt_u cancel. Simplifying (3.33) :

$$\nabla\Delta\Phi = \nabla\Delta R - \nabla\Delta d_{ion} + \nabla\Delta d_{trop} + \lambda\nabla\Delta N + \epsilon_{\phi} \tag{3.34}$$

"The double-difference observables are free from satellite and receiver clock errors and include only reduced propagation and orbit errors. The double-difference observable is the basic observable in many adjustment models for GPS observations." (Ibid, 1993)

The next combination is the triple-difference. This differences double-differences over a period of time. This combination cancels out the initial cycle ambiguity, *N*, from the observation equation. What remains is a linear combination of all pseudo-ranges and the residual propagation biases as well as un-modelled orbital biases (Seeber, 1993).

The simplified notation is:

$$\delta\nabla\Delta\Phi = \delta\nabla\Delta R - \delta\nabla\Delta d_{ion} + \delta\nabla\Delta d_{trop} + \epsilon_{res} \tag{3.35}$$

Triple-differences are useful in the detection of cycle slips (loss of phase lock in the receiver) , being used in post processing software for automatic editing processes.

3.2.3.1 Detection of Cycle Slips

Detection of cycle slips in observation data streams is important as their presence limits the usability of the data. Differencing is a standard method of cycle slip detection in both single and dual frequency applications. Cycle slips in dual frequency data can also be detected by monitoring temporal variations in the ionospheric residual (Hofmann-Wellenhof et al, 1992):

$$\Phi_{L1}(t) - \frac{f_{L1}}{f_{L2}}\Phi_{L2}(t) = N_{L1} - \frac{f_{L1}}{f_{L2}}N_{L2} - \frac{A(t)}{\lambda_{L1}\, f_{L1}^{2}}\left(1 - \frac{f_{L1}^{?}}{f_{L2}^{2}}\right) \qquad (3.36)$$

The right hand side of (3.36), the ionospheric residual, does not contain any time dependent terms except for ionospheric refraction. For short baselines, cycle slips are indicated by sudden jumps in the ionospheric residual. The remaining problem is determining whether the slip occurred on L1, L2 or both.

Cycle slips can also be detected through differencing phase, $\lambda\Phi_i^{\,j}(t)$, and code, $PR_i^{\,j}(t)$,range observations.

$$\lambda\Phi_i^{\,j}(t) - PR_i^{\,j}(t) = \lambda N_i^{\,j} - 2\Delta^{Iono}(t) \qquad (3.37)$$

Evident here is the doubling of the ionospheric effect due to the different propagation delays of the code and the carrier. A drawback with this testing quantity is the time dependent term of the ionosphere and the noise level of the code measurements in comparison to the phase measurements. If code range noise levels approach a few centimetres then this technique would be a viable test quantity.

3.2.3.2 Solving Ambiguities

In equation (3.26) it is evident that if N (initial ambiguity) and other parameters can be determined with sufficient confidence then the satellite range will be very accurate (<0.19m for L1).

"This initial ambiguity has to be determined with the appropriate techniques to exploit the full accuracy potential of the GPS carrier phase measurements. Ambiguity determination is one of the most demanding problems in the geodetic technique of evaluating GPS observations. On the other hand it is the integer nature of the phase ambiguities that guarantees the high accuracy of relative positioning with GPS. The best and simplest possibility for determining the ambiguity would be the use of additional frequencies or

signals, as is the case for terrestrial electronic distance measurements. Unfortunately, GPS does not provide more than two frequencies, hence particular strategies were developed to solve the ambiguity problem". (Seeber, 1993)

"The cycle ambiguity is an integer number. However, this cycle ambiguity cannot be separated from receiver and satellite clock errors in one-way phase observations between a receiver and a satellite (3.26). *But in station-satellite double-difference observations, both receiver and satellite clock-related errors are cancelled in the differencing process. To resolve ambiguities, therefore, one should work either explicitly or implicitly with the double-difference phase observable" (Abidin, 1994)*

The *geometric method (Coordinate Domain Search, Han & Rizos, 1997)* of ambiguity determination has the clearest and simplest modelling. It is reliant on the continuous tracking of the carrier phases which maintains the unknown initial ambiguity, *N*. From the continuous tracking of the phases, ambiguity-free range differences can be determined that are used in a Doppler solution to determine the coordinates of the user antenna. From the Doppler solution, ambiguity-free pseudo-ranges are derived and compared with the ambiguous range observations. From this comparison, ambiguities are derived.

This technique is dependent on large changes in satellite geometry, i.e. long observation periods, and no loss of satellite lock. The estimated ambiguities are real numbers that can be fixed to integer numbers if the estimated values are close to whole numbers. Generally if the estimated value is less than half a cycle. The observation time can be reduced if more satellites are observed, the satellite geometry is improved or observing signals with longer wavelength.

The technique is limited as the inter-station distances increase, which introduces problems arising from the troposphere, ionosphere and satellite orbits. The effect of changing satellite geometry is evident in figure 3.2.

The *ambiguity function* technique uses the single-difference observables between two stations where the coordinates of one station are taken as known. A search volume is established around an initial estimate of the unknown station. The search volume is then divided into a narrow grid of points with equal spacing. Each point is tested using the ambiguity function:

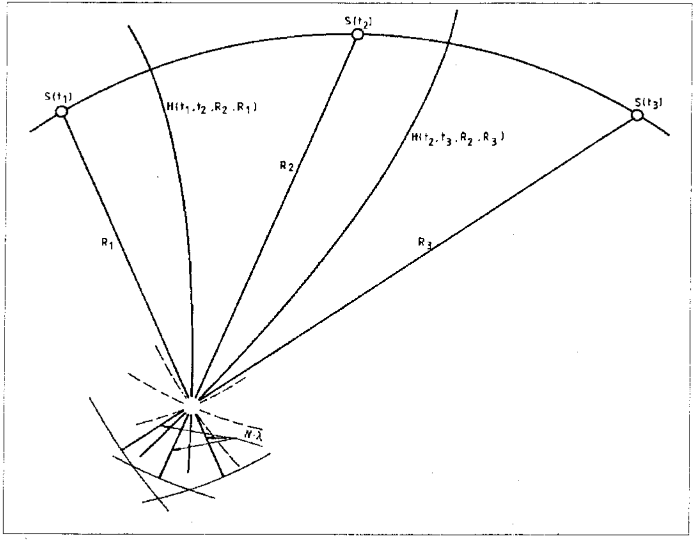

Figure 3.2 Geometric method of ambiguity resolution (Seeber, 1993).

$$\left\| \sum_{j=1}^{n_j} e^{i\{\Phi_{AB}^{j}(t) - \frac{2\pi}{\lambda}\rho_{AB}^{j}(t)\}} \right\| = n_j \cdot 1 \qquad \text{(Hofmann-Wellenhof et al, 1992)} \quad (3.38)$$

Consider an error free example with 4 satellites ($n_j = 4$) and correct coordinates for the points A, the known station, and B, the position to be tested. The evaluation of the left hand side of (3.38) should yield 4 (disregarding measurement errors and incomplete modelling) where $\Phi_{AB}^{j}(t)$ are the single differences of the measured phases and $\rho_{AB}^{j}(t)$ can be calculated from the known satellite and point coordinates.

Each point is tested for the ambiguity function, the candidate which returns the maximum value for the ambiguity function and minimises the weighted residuals ($V^T PV$) is determined to be the solution. In the above example if the wrong point coordinate is tested then the value will be less than 4.

Combinations of *dual frequency data can provide solutions to the ambiguity problem.* There are a number of linear combinations that can formed with dual frequency phase observations. The most common being the wide lane and narrow lane combinations. The wide lane can be denoted as (Ibid, 1992):

$$\Phi_{\Delta} = \Phi_{L1} - \Phi_{L2} \tag{3.39}$$

The signal, which has a signal to noise ratio which is 6 times greater than the base carriers, has a wavelength of 86.2cm which provides an increased ambiguity spacing. Ibid (1992) shows that the phase models for carriers L1 and L2 can be combined and differenced, leading to the equation (in units of cycles):

$$\Phi_{\Delta} = \frac{f_{\Delta}}{c}\rho + f_{\Delta}\Delta\delta + N_{\Delta} - \frac{A}{c}\left(\frac{1}{f_{L1}} - \frac{1}{f_{L2}}\right) \tag{3.40}$$

where :

$f_{\Delta} = f_{L1} - f_{L2}$

$N_{\Delta} = N_{L1} - N_{L2}$

A is a function of the differential ionosphere and $\Delta\delta$ is the differential receiver clock error. The wide lane ambiguities are more easily solved than the base carrier ambiguities. The ambiguities for the measured phases (e.g. L1) can be derived from manipulating (3.40) to give:

$$N_{L1} = \Phi_{L1} - (\Phi_{\Delta} - N_{\Delta})\frac{f_{L1}}{f_{\Delta}} + \frac{A}{c}\frac{f_{L1} + f_{L2}}{f_{L1}\,f_{L2}} \tag{3.41}$$

Note that the distance term ρ and the clock bias $\Delta\delta$ have dropped out. These terms are still embedded in the term N_{Δ}. The ionosphere term still makes it difficult to determine carrier ambiguities as baseline lengths grow.

The narrow lane

$$\Phi_{\Sigma} = \Phi_{L1} + \Phi_{L2} \tag{3.42}$$

has a wavelength of 10.7cm, the lowest noise level and yields the best results, however its ambiguity is difficult to resolve.

Other linear combinations have been tried such as the ionosphere-free Φ_{L3}. The disadvantage of this combination is that the corresponding ambiguity is no longer an integer (Ibid, 1992).

Another approach to the problem of solving for cycle ambiguities is the *combination of* *code and carrier phase (Observation Domain Search, Han & Rizos,1997). "The non-ambiguous code phase measurements are used as an additional wavelength to resolve the carrier phase ambiguity"*(Seeber, 1993)

The technique depends on the observation of code measurements until such time as the noise level of the code solution is less than half the wavelength of the carrier wave. This has not been considered feasible until the appearance of the modern low noise code measuring receivers. For dual frequency observations this technique can be used as an extension of the wide laning process previously outlined. An advantage is that the ionosphere effect evident in (3.40 and 3.41) can be eliminated by a combination of dual frequency phase and code data.

Unlike geometric methods this technique is independent of the observation geometry, satellite and receiver clocks and the atmospheric delays. This technique can estimate ambiguities in a very short observation time, and is suitable for long baselines and kinematic applications.

The derivation by Hofman-Wellenhof et al (1992) denotes the wide lane ambiguity as:

$$N_\Delta = \Phi_\Delta - \frac{f_{L1} - f_{l2}}{f_{L1} + f_{L2}} (R_{L1} + R_{L2}) \tag{3.43}$$

This equation is independent of the baseline length and ionospheric effects but is susceptable to multipath effects. For this reason it is suggested to average over a longer period. Ionospherically free ambiguities for L1 and L2 phases can then be determined from (Ibid, 1992):

$$N_{L1} = \frac{f_{L1}}{f_\Delta} \Phi_{L1} - \frac{f_{L2}}{f_\Delta} (\Phi_{L2} + N_\Delta) - (\frac{\rho}{c} + \Delta\delta)(f_{L1} + f_{L2}) \qquad \text{(for L1) (3.44)}$$

It is best to calculate N_Δ and N_{L1} in a two step process so that the integer nature of the ambiguities is not lost

Properties of the narrow and wide lane ambiguities include:

$$N_\Delta = N_{L1} - N_{L2} \qquad\qquad N_\Sigma = N_{L1} + N_{L2} \tag{3.45}$$

These are not independent. When N_Δ is even N_Σ has to be even and visa versa for the odd case. As an example, if the wide lane ambiguity is estimated to be 0.6 cycles and rounded to a value of one, then the narrow lane ambiguity will be estimated to be 8 cycles because:

$$\lambda_\Delta \approx 8\lambda_\Sigma \tag{3.46}$$

This result does not agree with the even-odd condition so the wide lane ambiguity is incorrect and should be fixed to zero. The exploitation of this methodology leads to dramatic savings in observation times and is advantageous for *"on-the-fly"* techniques in kinematic survey applications.

Ambiguity Domain Search methods introduce another technique to determine the ambiguity associated with each phase observation. Overall this process requires a large amount of mathematical operations because of the nature of the search technique. This search algorithm usually begins with an approximate position estimate based on a float ambiguity solution. A routine based on an optimised search process then restricts the search area or "ambiguity-space" that tests the ambiguity solutions. Figure 3.3 illustrates the ambiguity-space for the two and three satellite case.

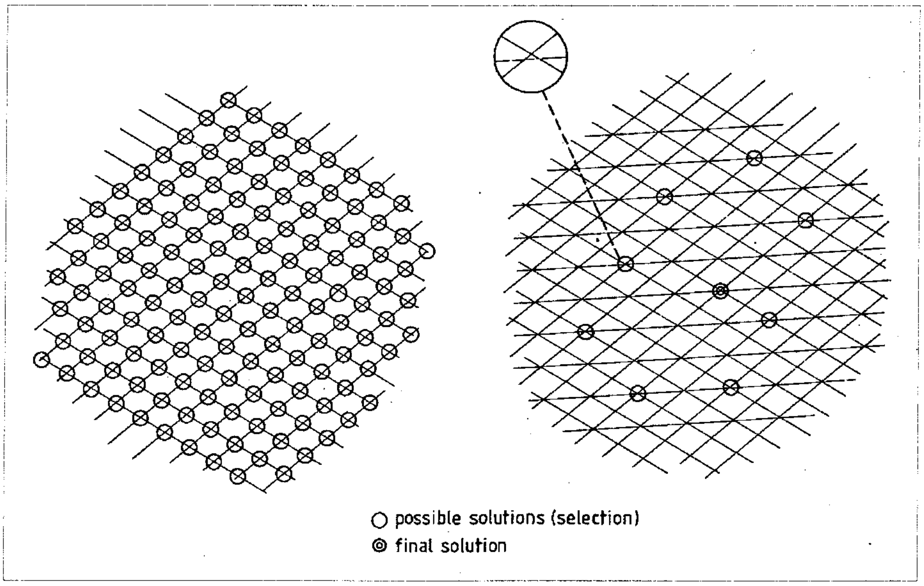

Figure 3.3 Ambiguity search patterns for 2 satellites (left) and 3 satellites (right) (Seeber, 1993).

The technique is highly dependent on statistical testing, based on the initial estimate of the ambiguities. If a confident initial estimate is made then the number of required ambiguity combination tests to be made will be small based on the test space, but if the initial estimate is poor then the technique may fail. It is more robust as the number of satellites and frequencies observed increases.

The techniques and processes outlined here are solutions to the measuring time frames associated with static GPS observation methods. Table 3.3 summarises the advantages and disadvantages associated with some of the processing techniques which ultimately try to determine the greatest accuracy baseline determination in the shortest possible time observation time.

Table 3.3 Summary of ambiguity estimation methods (Seeber, 1993).

Technique	Advantages	Disadvantages
Geometric Methods	-basically simple and clear modelling -works with few satellites -usable for short, long and very long distances -the ambiguity float solution rapidly provides approximate results	-long observation time necessary for sufficient geometric rigour -influenced by un-modelled effects like ionosphere, orbits etc. -no a priori use of the integer nature of ambiguities -sensitive to unrecovered cycle slips
Code/Carrier Methods	-independence of geometry -kinematic application -long and very long baselines possible	-dual frequency P-code receiver necessary -sensitive to multipath -only wide lane ambiguities are resolved

Ambiguity search methods	-allows fast ambiguity resolution (e.g. in rapid static applications -true kinematic applications possible -uses the integer nature of ambiguities	-sensitive against systematic errors -requires the observation of as many satellites as possible

The results and processes are very encouraging but for GPS to be of any benefit for the control requirements of airborne positioning in support of medium to large scale mapping the resolution of ambiguities is desirable.

Not mentioned in any of the previous search methodologies is the "Antenna Swap" technique to determine the cycle ambiguities before the beginning of a kinematic survey. This method uses two receivers one located on a known point and the other close by. Observations are made on both receivers for a short time, then both antennas are swapped to the location of the other but remain connected to their initial receivers. Observations are made for another short period. The double-difference phase observation equations are:

Position 1. $\nabla\Delta\phi(t_1) = \nabla\Delta R(t_1) + \lambda\nabla\Delta N$ (3.47)

Position 2. $\nabla\Delta\phi(t_2) = -\nabla\Delta R(t_2) + \lambda\nabla\Delta N$ (3.48)

Subtracting the observation equations yields:

$$\nabla\Delta\phi(t_1) - \nabla\Delta\phi(t_2) = \nabla\Delta R(t_1) + \nabla\Delta R(t_2) \qquad (3.49)$$

From equation (3.49) the baseline can be determined and the result then used in the *known baseline* technique to derive the ambiguity term $\nabla\Delta N$.

This process of initialisation is not feasible for the beginning or end of a photographic mission mainly because the aircraft antenna is generally a fixture on the airframe. The next option, which has been used in early GPS controlled photogrammetry, is the known baseline technique to resolve the ambiguities before beginning the survey mission. Before the survey begins the roving receiver antenna and the stationary receiver antenna must occupy stations with known coordinates. This implies the baseline is then known. This condition leads to the observation equation:

$$\nabla\Delta N = (\nabla\Delta\phi - \nabla\Delta R)/\lambda \tag{3.50}$$

This condition solves for the double-differenced ambiguity and the survey can begin.

The remaining technique to resolve ambiguities before beginning a mission is to observe a static session, between the initialisation point and a known point, for a time sufficient to determine ambiguities before moving.

Lucas & Mader (1989) used the known baseline technique to initialise their experiments in Texas and Washington. Others to refer to the same technique are Curry & Schuckman (1993), Gruen et al (1993), Burman & Torlegard (1994), Collins (1994) and Friess (1991).

For photogrammetric applications, these classic initialisation methods have been superseded by the on-the-fly (OTF) results which result from code/carrier and ambiguity search methods and others. This has been referred to by Collins (1994), Corbett (1995), Curry & Schuckman (1993), Hothem et al (1994), Kletzli (1994) and Jacobsen (1993).

According to DeLoach et al (1995) "*Recently, three important improvements in the Global Positioning System have contributed to making the OTF process reliable and ready for production use:*

(1) The GPS constellation has been filled in, so that all-in-view receivers can usually track more than five and sometimes as many as ten satellites at a time;

(2) Civilian GPS receivers have been developed that do not depend on knowing the chip sequence of the encrypted P-code, but which still provide full-wavelength L1 and L2 carrier-phase measurements: and

(3) The C/A-code measurement noise level in some recently developed receivers

> *has improved by almost two orders of magnitude.*
> *Consequently, during the past year, a selection of OTF-capable hardware has become available and at least nine different organisations have their own versions of OTF software."*

The tidal monitoring results reported by DeLoach et al (1995) using OTF capable equipment and software are testimony to the capability of this technology.

Even if the wrong ambiguities are estimated, for the photogrammetric problem when GPS drift is modelled and minimal ground control is used, the consequences are not disastrous. Accommodating this situation is addressed by Han & Rizos (1997) under the scenario - "Single-Receiver Relative Positioning". In this situation initial ambiguity errors are linearly adjusted out based on the constraining start and finish points. This is valid whilst phase lock is maintained on a minimum four satellites throughout the unknown period of the survey. This method can be identified with that proposed by Ackermann (1992, 1994a,1994b).

In photographic applications where auxiliary data requirements approach the upper limits of kinematic GPS positioning and GPS drifts are not considered as parameters within the aerial-triangulation adjustment, then observations should be of such a quality that the carrier phase ambiguity estimates are indeed the correct value. If they are not, then the induced errors after adjustment will impact directly on the quality of the image point coordinates.

3.3 GPS system limitations

When first introduced, the GPS constellation of satellites was very limited in its usefulness except for large scale high profile companies/agencies or those users engaged in research and development. Three system limitations were identified (Kleusberg & Langley, 1990):

3.3.1 GPS signal reception

GPS is a space based signal so it is obvious that its reception will only be possible in areas where receiver antennas have a direct uninterrupted view of the satellite. This precludes its use for sub-surface marine navigation or underground applications such as mining or tunnelling. Signal shading can occur due to topography, high rise buildings and overhead foliage. In navigation applications for example ,a ship's superstructure can interrupt GPS signal reception, and the fin on an aerial survey aircraft can shade GPS reception. The options, in these cases, are to plan accordingly, to minimise the effects for a particular survey configuration, or provide an independent backup system to support the process through the outage periods.

3.3.2 GPS signal integrity

It is all very well to receive the GPS signals but how correct is the information embedded in the "satellite message"? In a solution using four satellites a unique coordinate will result. Wrong information about the GPS system will affect that position solution. Wrong information could be a corrupted satellite ephemeris, incorrect satellite clock or satellite health information. If faulty information is not detected, the user will be unawares.

To combat this problem at the user end, proposals such as the implementation of a GPS Integrity Channel (GIC) or Receiver Autonomous Integrity Monitoring (RAIM) have been suggested for integrity monitoring. GIC is a proposal that requires a monitoring body and a means to provide instantaneous information about the status of the GPS system. It is proposed to provide this information via a separate satellite communication link. RAIM, on the other hand, can be built into the receiver. It is based on redundancy which occurs when more than four satellites are observed. An abnormality prompts an alert that the system integrity has failed. This is particularly important for the aviation community which is becoming more reliant on GPS as a navigational aid. The consequences of GPS integrity failure in the aviation area could be catastrophic.

3.3.3 GPS signal accuracy

A GPS receiver measures the time it takes for the signal to travel from the satellite to the receiver. Along the way the signal is subject to many disturbances. So what the receiver actually recovers is a waveform that has been subject to various delays and biases that have effected its propagation velocity since it initially left the satellite. How well corrections for these delays and biases are made will determine the quality of the measurement.

The measurements are subject to errors in the satellite ephemeris, the satellite clock, the effects on signal propagation through the ionosphere and the troposphere, and the errors which are within the receiver, such as the receiver clock error and measurement noise. Ultimately the quality of the position determinations are still a function of the satellite geometry at the time of observation. The U.S. Department of Defense has introduced artificial errors due to Selective Availability which corrupt the satellite ephemeris or the satellite clocks, or both. All the processes described in this chapter are ways and means to limit the effects of errors and biases on the user.

Other limitations exist at the user end regarding the application of GPS to photogrammetry. These limitations are basically in the receiver designs and have been highlighted in the descriptions of the experiments. Nowadays, it is more or less the "gremlins" that exist within the receiver firmware that cause most problems. There is no question that the benefits of low-noise code and phase tracking have contributed significantly to on-the-fly developments, but the ability to carry out multi tasking that is now demanded of the top-of-the-line receivers can be a limiting factor on performance, and could compromise survey missions. For most researchers the interfacing a GPS measurement to a camera event is no longer an issue and the photogrammetric processes have been proven. The challenge is to make the small steps that will increase the reliability of the products and processes.

Although not commonly acknowledged, receiver manufacturers within the U.S. have to comply with operational limitations as specified by the Department of Defense. These limitations take the form of speed (1,000knts[2]) and height (60,000ft[2]) restrictions where the receiver is to become inoperable beyond these defined boundaries. For operational airborne positioning using general aviation aircraft these limitations are of no consequence

3.4 Costs

In the implementation of any new process or introduction of new technology, a cost-benefit study is paramount in the decision making strategy. The tests conducted by Lucas & Mader (1989), van der Vegt (1989) and Hothem et al (1994) are very expensive undertakings. In the Hothem et al (1994) Utah test three base station receivers and two aircraft receivers were used. Apart from the hardware costs, whether owned or leased, the logistics of an operation are expensive. Anything that has something to do with the operation of an aircraft is extremely expensive. Modifications to that aircraft only make the costs spiral. To evaluate any system requires enough ground control to realise the camera exposure stations within an accuracy consistent with the estimates of the GPS positioning. This is an expensive undertaking.

The rewards, though, are substantial. The proven techniques lead to the reduction in ground control requirements, in some cases, eliminating ground control entirely. The investment in a GPS receiver for an aerial survey operation is a significant oncost, particularly if that receiver is used for "value adding" to the photogrammetric process, i.e. support pattern photography, aircraft navigation etc. A generic system can be operational for around $200,000, whereas a dedicated system from a camera manufacturer may double this cost when the full infrastructure to support the installation is considered. If automated support processes are implemented then this cost can be recouped in direct savings made in the mapping processes, e.g. cost savings in ground survey, photo preparation, digital photographic indexing.

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[2] *Higher altitude and velocities up to 25,000 nautical miles-per-hour options are available in the U.S. and under validated export license for other countries* - Z12 specification brochure 1995

3.5 Operational limitations

Operational limitations are those that may impact on the success of a photographic mission. Data collection is the number one priority, lost data is to be avoided, it is expensive and from a management viewpoint puts a question mark over any high-tech operation. Lost data can only be avoided by ensuring that all components of the installations both on the ground and in the air are as reliable and as simple as can be designed. This requires dedicated logging systems, **reliable power supplies**, secure cabling, foolproof operations, knowledge of known "bugs" and thorough testing of the installation. This ensures that the system will perform and that the equipment dedicated to a particular task is operating to the best of it's ability.

Operational limitations impact directly on the data gathering stage, beyond that point nothing can be done to improve the situation regarding the outcome of the mission, except for repeating it and accepting the losses. Before the introduction of on-the-fly ambiguity resolution the loss of phase lock was critical to the post-processing stage. This required special procedures on the ground and limitations on manoeuvring in the air. Even if ambiguities are not fixed, which is generally the case for longer kinematic baselines, continuous phase lock is desirable, particularly on a photo run. This can be enhanced by collecting as much data as possible, generally at 1Hz rate and down to 5° satellite elevation above the horizon. This ensures that tracking is maintained to as many satellites as possible during manoeuvring. This also increases the operational range from the reference station substantially - greater than 1000km with careful planning.

Because of the fin design on most aircraft, it is prudent to fly from south to north in the southern hemisphere for those photo runs along meridians, as this will reduce the impact of signal shadowing.

For a mission to be successful requires the weather to be ideal, and the aircraft and GPS system to be fully operational. Today's complete GPS constellation and a 5° elevation cutoff is significant in that the photo mission can proceed without satellite availability planning.

3.6 Those problems not identified

This heading is reserved for cases of the "unexplained". They generally fall into the "one off" category and are associated with the question "why did this happen?". Some of these problems are not evident until the post-processing stage and the question, "what is going on here?" suggests itself.

Some authors comments:

Earls & Byrne (1996) - *"the technology requires a high level of competence in photogrammetry, surveying science and adjustment theory. It does not lend itself to practitioners who do not have these essential foundations".*

Andersen (1994) - *"to those who have not yet begun with GPS-supported block adjustment, the recommendation is to use qualified people, both for the GPS processing and for the block adjustment. The technique is not developed so far that you can say "just push a button and get the answer". It is necessary to understand the underlying theory".*

MAPPS (1997) - *"Planning was emphasized as the most critical aspect of successful Airborne GPS (ABGPS) projects. The complex nature of ABGPS technology requires competent staff, careful planning, excellent communication and coordination, and quality equipment and software. Prudent practitioners rely on ground control for QA/QC. Although aero-triangulation solutions can be achieved without known ground control, it is dangerous to rely entirely on airborne GPS without a means of quality control checks. Some of the key elements for success that were mentioned: 1) use high quality equipment and software; 2) hire smart people: and 3) prepare detailed plans and checklists for every aspect of the operation."*

4. Principles of Aerial Triangulation

Aerial triangulation is defined as (Slama,1980):

> *"The process for the extension of horizontal and/or vertical control whereby the measurements of angles and/or distances on overlapping photographs are related into a spatial solution using the perspective principals of the photographs. Generally this process involves using aerial photographs and is called* aerotriangulation *or* aerial *triangulation."*

The basic steps are:

1. relative orientation of each stereo model.
2. connect the adjacent models to form a continuous strip or block.
3. adjust the strip or block to photo identified surveyed ground control points.

Photography taken for mapping purposes is generally referred to as vertical photography. In normal operating conditions this photography will contain small tilts away from the true vertical. The size of these tilts rarely exceed 3° but they introduce errors in the determination of measurements made on the photograph, particularly elevation measurements.

4.1 The mathematics of photogrammetry

The *space position* and *angular orientation* of a tilted photograph is expressed in the *elements of exterior orientation* (Wolf, 1983). The spatial position of the aerial photograph is expressed in terms of X_L, Y_L and Z_L where L denotes the perspective centre of the photograph. The angular orientation of the aerial photograph is expressed in terms of quantities ω, ϕ and κ defining the angular relationship between the three axes of the image coordinate system and the three axes of the ground coordinate system.

4.1.1 The collinearity condition

The elements of exterior orientation can be determined by the method of space resection based on the principles of collinearity. This is a numerical condition which if satisfied can be used to determine the six elements of exterior orientation. This is the preferred method of resolution of the orientation problem as it can be easily programmed for computer solutions.

"Collinearity is the condition in which the exposure station of any photograph, an object point, and its photo image all lie on a straight line." (Wolf, 1983)

This condition is illustrated in figure 4.1 where the exposure station *L*, image point *a* and object point *A* lie on a straight line. *L* and *A* have coordinates in the ground coordinate system and *a* has coordinates in the image coordinate system. The two coordinate systems are not coincident because the photograph is tilted and rotated. The relationship between these two coordinate systems is expressed by a 3 x 3 orthogonal matrix designated as **M**. The nine elements of **M** are functions of the rotation elements ω, ϕ and κ (Moffitt & Mikhail, 1980).

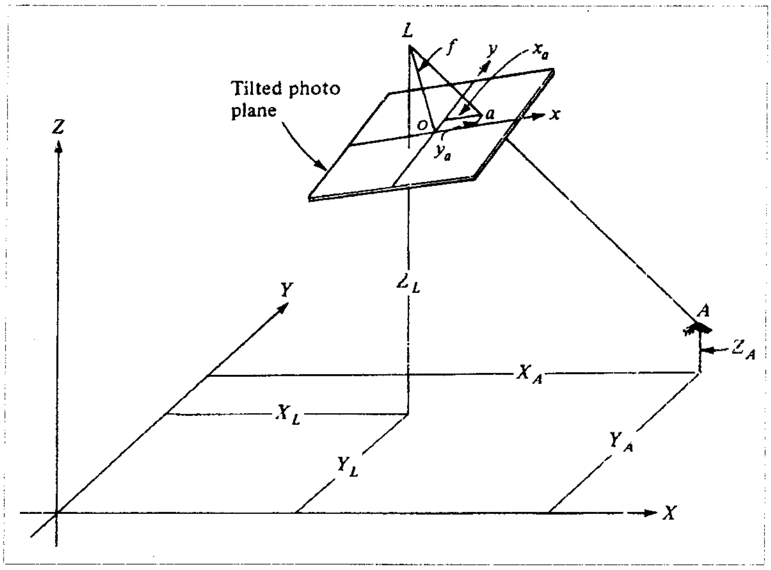


Figure 4.1 The tilted photograph. (Wolf, 1983)

Let x'_a, y'_a and z'_a represent the rotated image point coordinates x_a, y_a and f into coordinate system *XYZ*. The rotation formulas are then (Wolf, 1983):

$$
\begin{aligned}
x_a &= m_{11}x_a^{\prime}+m_{12}y_a^{\prime}+m_{13}z_a^{\prime} \quad (a)\\
y_a &= m_{21}x_a^{\prime}+m_{22}y_a^{\prime}+m_{23}z_a^{\prime} \quad (b)\\
z_a &= m_{31}x_a^{\prime}+m_{32}y_a^{\prime}+m_{33}z_a^{\prime} \quad (c)
\end{aligned}
\qquad (4.1)
$$

Note that z_a is equal to $-f$.

Using similar triangles the collinearity condition equations are developed (Ibid, 1983):

$$\frac{x_a^{\prime}}{X_A-X_L}=\frac{y_a^{\prime}}{Y_A-Y_L}=\frac{z_a^{\prime}}{Z_A-Z_L} \qquad (4.2)$$

reducing,

$$x_a^{\prime}=\left(\frac{X_A-X_L}{Z_A-Z_L}\right)z_a^{\prime} \qquad (4.3)$$

$$y_a^{\prime}=\left(\frac{Y_A-Y_L}{Z_A-Z_L}\right)z_a^{\prime} \qquad (4.4)$$

and by identity,

$$z_a^{\prime}=\left(\frac{Z_A-Z_L}{Z_A-Z_L}\right)z_a^{\prime} \qquad (4.5)$$

Equations (4.3), (4.4) and (4.5) are substituted into equations (4.1) (a), (b) and (c). The term $\left(z_a^{\prime}/Z_A-Z_L\right)$ is factored from each equation then equation (a) and (b) is divided by (c). $-f$ is substituted for z_a. The derived collinearity equations are :

$$x_a=-f\left[\frac{m_{11}(X_A-X_L)+m_{12}(Y_A-Y_L)+m_{13}(Z_A-Z_L)}{m_{31}(X_A-X_L)+m_{32}(Y_A-Y_L)+m_{33}(Z_A-Z_L)}\right] \qquad (4.6)$$

$$y_a = -f\left[\frac{m_{21}(X_A - X_L) + m_{22}(Y_A - Y_L) + m_{23}(Z_A - Z_L)}{m_{31}(X_A - X_L) + m_{32}(Y_A - Y_L) + m_{33}(Z_A - Z_L)}\right] \tag{4.7}$$

These equations may also be written in different forms such as (Moffitt & Mikhail,1980):

$$\begin{bmatrix} X_A - X_L \\ Y_A - Y_L \\ Z_A - Z_L \end{bmatrix} = \frac{1}{k}\mathbf{M}^{\mathrm{T}} \begin{bmatrix} x_a - x_0 \\ y_a - y_0 \\ z_a - z_0 \end{bmatrix} \tag{4.8}$$

where x_0, y_0 and z_0 (f) are three elements of interior orientation (determined by camera calibration), k is a scalar that is equal to the ratio of lengths L to a and L to A and **M** is the 3 x 3 orthogonal matrix of rotation. These equations are fundamental to all procedures in photogrammetry (Ibid, 1980).

The equations are non-linear and contain nine unknowns, consisting of the rotation parameters ω, ϕ and κ embedded in the rotation matrix, the exposure station coordinates X_L, Y_L and Z_L and the object point coordinates X_A, Y_A and Z_A. The linearised form of these equations is as follows (Wolf, 1983):

$$v_x = b_{11}(d\omega) + b_{12}(d\phi) + b_{13}(d\kappa) - b_{14}(dX_L) - b_{15}(dY_L) - b_{16}(dZ_L) + b_{17}(dX) + b_{18}(dY) + b_{19}(dZ) + J \tag{4.9}$$

$$v_y = b_{21}(d\omega) + b_{22}(d\phi) + b_{23}(d\kappa) - b_{24}(dX_L) - b_{25}(dY_L) - b_{26}(dZ_L) + b_{27}(dX) + b_{28}(dY) + b_{29}(dZ) + K \tag{4.10}$$

In the above $v_{x,y}$ represents the observation residuals, $b_{11,12,\ldots}$ represent the coefficients of the unknowns and J and K are the constant terms computed using approximate values for the unknowns. The solution is an iterative one as these two equations are only linear approximations of the exact equations (4.6) and (4.7). As the approximations approach their corresponding true values the differences between the two equations becomes negligible.

In matrix notation (4.9) and (4.10) can be combined to form:

$$\begin{bmatrix} V_{x_{ij}} \\ V_{y_{ij}} \end{bmatrix} + \begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} & b_{15} & b_{16} \\ b_{21} & b_{22} & b_{23} & b_{24} & b_{25} & b_{26} \end{bmatrix} \begin{bmatrix} \Delta\omega_i \\ \Delta\phi_i \\ \Delta\kappa_i \\ \Delta X_i^c \\ \Delta Y_i^c \\ \Delta Z_i^c \end{bmatrix} + \begin{bmatrix} b_{17} & b_{18} & b_{19} \\ b_{27} & b_{28} & b_{29} \end{bmatrix} \begin{bmatrix} \Delta X_j \\ \Delta Y_j \\ \Delta Z_j \end{bmatrix} = \begin{bmatrix} -f_x^0 \\ -f_y^0 \end{bmatrix} \tag{4.11}$$

The simplified notation of equation (4.11) for the ground coordinates of the exposure centre of photo i and the ground coordinates of point j is (Slama, 1980):

$$\underset{(2,1)}{\mathbf{V}_{\mathrm{ij}}} + \underset{(2,6)(6,1)}{\dot{\mathbf{B}}_{\mathrm{ij}}\ \dot{\Delta}_{\mathrm{i}}} + \underset{(2,3)(3,1)}{\ddot{\mathbf{B}}_{\mathrm{ij}}\ \ddot{\Delta}_{\mathrm{j}}} = \epsilon_{ij} \tag{4.12}$$

In equation (4.12) $\mathbf{V}_{\mathrm{ij}}$ are the corrections to the observed values, $\dot{\mathbf{B}}_{\mathrm{ij}}$ and $\ddot{\mathbf{B}}_{\mathrm{ij}}$ are the design matrices, $\dot{\Delta}_i$ refers to corrections to the exterior orientation parameters, $\ddot{\Delta}_j$ refers to corrections to the ground coordinates and ϵ_{ij} are the constant terms.

For the single photograph case there are six unknowns, the three photo exposure centre coordinates and the three rotation parameters. To solve for these unknowns requires the formation of six equations by observing three ground control points (two equations for each point yield a unique solution). If more than six equations are formed then their solution can be obtained by the method of least squares.

Equation (4.12) is extended for n image coordinate observations on m photographs leading to the general form of the collinearity equations:

$$\underset{(2mn,1)}{\mathbf{V}} + \underset{(2mn,6m)(6m,1)}{\dot{\mathbf{B}}\ \dot{\Delta}} + \underset{(2mn,3n)(3n,1)}{\ddot{\mathbf{B}}\ \ddot{\Delta}} = \underset{(2mn,1)}{\epsilon} \tag{4.13}$$

4.1.2 Introducing ground control equations

Let the point j have ground control coordinates X_j^{00}, Y_j^{00} and Z_j^{00} and V_x, V_y and V_z be the unknown residuals associated with these coordinates. The ground coordinates of point j can be expressed as (Trinder, 1995; Slama, 1980):

$$\begin{aligned} X_j &= X_j^{00} + V_{x_j} \\ Y_j &= Y_j^{00} + V_{y_j} \\ Z_j &= Z_j^{00} + V_{z_j} \end{aligned} \tag{4.14}$$

The ground coordinates of point j can also be expressed in terms of the approximate values

$$\begin{aligned} X_j &= X_j^{0} + \Delta X_j \\ Y_j &= Y_j^{0} + \Delta Y_j \\ Z_j &= Z_j^{0} + \Delta Z_j \end{aligned} \tag{4.15}$$

where ΔX_j, ΔY_j and ΔZ_j are corrections to the approximate values. The equations are combined and rearranged to give:

$$\begin{bmatrix} V_{x_j} \\ V_{y_j} \\ V_{z_j} \end{bmatrix} - \begin{bmatrix} \Delta X_j \\ \Delta Y_j \\ \Delta Z_j \end{bmatrix} = \begin{bmatrix} X_j^0 - X_j^{00} \\ Y_j^0 - Y_j^{00} \\ Z_j^0 - Z_j^{00} \end{bmatrix} \tag{4.16}$$

or in matrix notation:

$$\underset{(3,1)}{\ddot{\mathbf{v}}_j} - \underset{(3,1)}{\ddot{\mathbf{\Delta}}_j} = \underset{(3,1)}{\ddot{\mathbf{c}}_j} \tag{4.17}$$

where the double dot refers to corrections to the ground coordinates.

4.1.3 Introducing exterior orientation parameter equations

The same approach used to introduce control coordinates is used to introduce exterior orientation parameters. The same principle of adopting measured values of exterior orientation and their associated unknown residuals, and equating them to approximate values of the exterior orientation parameters and their corrections is used to create the matrix:

$$\begin{bmatrix} V_{\omega_i} \\ V_{\phi_i} \\ V_{\kappa_i} \\ V_{X_i^c} \\ V_{Y_i^c} \\ V_{Z_i^c} \end{bmatrix} - \begin{bmatrix} \Delta_{\omega_i} \\ \Delta_{\phi_i} \\ \Delta_{\kappa_i} \\ \Delta X_i^c \\ \Delta Y_i^c \\ \Delta Z_i^c \end{bmatrix} = \begin{bmatrix} \omega_i^0 - \omega_i^{00} \\ \phi_i^0 - \phi_i^{00} \\ \kappa_i^0 - \kappa_i^{00} \\ (X_i^c)^0 - (X_i^c)^{00} \\ (Y_i^c)^0 - (Y_i^c)^{00} \\ (Z_i^c)^0 - (Z_i^c)^{00} \end{bmatrix} \tag{4.18}$$

The single matrix equation is represented as:

$$\underset{(6.1)}{\dot{\mathbf{V}}_{\mathrm{i}}} - \underset{(6,1)}{\dot{\Delta}_{\mathrm{i}}} = \underset{(6,1)}{\dot{\mathbf{C}}_{\mathrm{i}}} \tag{4.19}$$

Equations (4.13), (4.17) and (4.19) combine to give a complete mathematical model of the photogrammetric problem (Slama, 1980):

$$\begin{array}{lllllll} V & + & \dot{B}\dot{\Delta} & + & \ddot{B}\ddot{\Delta} & = & \epsilon \quad \text{Collinearity equations.} \\ \dot{V} & - & \dot{\Delta} & & & = & \dot{C} \quad \text{Exterior orientation equations (auxiliary data).} \\ \ddot{V} & & & - & \ddot{\Delta} & = & \ddot{C} \quad \text{Ground control equations.} \end{array} \tag{4.20}$$

Each of these equations is associated with an appropriate weight matrix.

4.2 Introducing GPS camera station coordinates

4.2.1 The function of kinematic differential GPS in the context of aerial triangulation

Sources of auxiliary data and their use in the photogrammetric processes go back to the earliest days of aerial photography (Ackermann, 1984). The problems associated with this data being mainly the dynamic nature of the camera platform, the quality of the data and its relationship to a reference system. The mathematics of aerotriangulation using auxiliary data is far easier than the data collection itself.

The reference system can be either local or global. Inertial platforms, barometric and visual reference systems can be considered as local reference systems as the data is not treated in an absolute sense. The value in this data is drawn from the observational changes in subsequent data points. These observations are generally utilised by either differencing the current observation against the initial observation or differencing sequential observations.

Global reference systems have been introduced where it has become possible to determine dynamic positional information relative to an external reference frame. Examples of some of these systems are ground based radio systems such as SHORAN or LORAN through to satellite based systems like TRANSIT Doppler and NAVSTAR Global Positioning System (Ackroyd & Lorimer, 1990; Ackermann, 1984). Some of these systems can return camera positional data in a reference frame external to the aircraft, such as global geocentric or national mapping datums.

Irrespective of which reference system type is used the photogrammetric requirement is that the auxiliary data collection technique has dynamic or kinematic capability.

The use of auxiliary data in the photogrammetric adjustment has been limited up until now by the quality of the data available from the various sources, some of which have been mentioned.

GPS has been developed to support military navigation and timing requirements. Today, receivers can determine their position within a global reference system (WGS84) almost instantaneously whilst stationary or moving. This dynamic positioning ability, its portability and operational flexibility has made the technology attractive to the photogrammetric process.

The technology has evolved from the initial excitement of static and dynamic single point positioning of the early eighties to today's differential range and phase processing techniques. The term "kinematic GPS" was introduced by Remondi (1985) to differentiate between the extended observation times of traditional relative static GPS surveys and the new prospects of centimetre level surveys in seconds resulting from the continuous carrier phase tracking of a moving antenna.

*"We use the terms **Kinematic GPS Positioning** or **Kinematic GPS Surveying** for those procedures, which allow the instantaneous determination of differential positions at the much higher surveying accuracy level of a few ppm. In this context, instantaneous means based on a single epoch measurements only. Obviously, this leads to an enormous reduction of observation time compared to conventional static GPS surveying. Moreover, Kinematic GPS Positioning can also determine positions along the trajectory of a continuously moving vehicle. The term Kinematic GPS is used for both real-time and post-mission applications"* (Kleusberg, 1991).

Differential kinematic GPS positioning uses the code range, either P-code or C/A-code, corrected for range error using differential range corrections from a receiver located at a known location to determine the position of the moving receiver. There are a number of variations on this technique to improve the quality of results.

Kinematic and Differential GPS positioning are superior to other dynamic positioning systems due to the autonomous nature of the receivers. It is a passive system that is dependent on transmitted signals provided free to air by the United States Department of Defense.

The fact that it is available 24 hours a day worldwide and is capable, with the right tools, of providing high quality positioning results makes GPS the ideal application for airborne sensor positioning. It is this capability that has proved so attractive to the photogrammetrist. It is now possible to determine X_{PC}, Y_{PC}, Z_{PC} to an accuracy which, in some cases, will support aerial triangulation adjustments without ground control.

No other positioning system can provide a comparable service for a better cost.

4.2.2 Accuracy requirements for different photographic scales

Aerotriangulation accuracy is firstly the direct result of the observation of image points, and secondly, dependent on the "control", be it ground control or auxiliary data. It can be likened to the terms class and order as applied to survey adjustment.

The ability to observe image points does not change with photo scale. Consequently, the absolute accuracy of an adjusted block, if all external errors are zero, is ultimately determined by the ratio of the image point observing accuracy to the photo scale. For example, the block accuracy of 1:50000 photography observed at 10μm cannot be better than 0.5m. External control errors which exceed the precision/scale function will distort the aerial triangulation model.

Geometrically, auxiliary data has a different impact than ground control on the aerial triangulation adjustment. Adjustment precision does not decline adversely as a direct result of a decrease in auxiliary data accuracy. Friess (1986a), through various simulations demonstrates how block accuracy is related to auxiliary data, attitude and position precision (See Table 4.1).

The table is for a block size of 10 x 41 photographs. According to his simulations block size exerts a slight influence on block accuracy. *"The larger the block the more effective are auxiliary data on the same level of precision. The effect is especially visible as long as precision of auxiliary data is poor (>1m) and if no ground control is used. The* *deterioration of smaller blocks is quite insignificant, however, and may be disregarded in the first instance."*

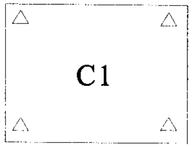
It is interesting to note the requirements of attitude auxiliary data. To attain block accuracies where $\mu_{x,y}$, μ_z approaches σ_0, attitude data better than 1 second is needed. On small conventional aircraft this level of attitude determination is not readily possible, particularly from GPS sources. The table highlights the fact that attitude data alone is not sufficient to triangulate without ground control.

Table 4.1 also illustrates how the link between the standard deviation of positional navigational data $\sigma_{X_{PC}, Y_{PC}, Z_{PC}}$ and the overall block accuracy $\mu_{X,Y} / \sigma_0$ is related. It can be seen that the relationship is not linear in terms of magnitudes. Friess (1986b) points out in his conclusion *"The influence of camera position data on the accuracy of photogrammetric blocks is considerable. They always allow reduction of control to the minimum case with 4 ground control points in the corners of the block. Camera position coordinates observed with low accuracy (±10m) already allow aerial triangulation with minimum ground control and provide ground point position accuracies which could otherwise only be reached with quite dense ground control."*.

Table 4.2 (Ackermann, 1992) illustrates the relationship between mapping requirements and GPS camera positioning. This illustration is derived from position information only, attitude data is not considered here. Critical values are apparent, particularly in the vertical, when large scale mapping is required. This can be somewhat reduced by decreasing the $\text{scale}_{\text{photo}}$ to $\text{scale}_{\text{map}}$ ratio.

Table 4.1 Simulation results, block size 10 x 41 photographs (Friess, 1986a).

Case	standard deviation of navigation data		without ground control (m)				4 ground control points (m) C1				2 ground control chains (m) C2			
	$\sigma_{X_{PC}, Y_{PC}, Z_{PC}}$	$\sigma_{\omega,\phi,\kappa}$	μ_X/σ_0	μ_Y/σ_0	μ_Z/σ_0	$\mu_{X,Y}/\sigma_0$	μ_X/σ_0	μ_Y/σ_0	μ_Z/σ_0	$\mu_{X,Y}/\sigma_0$	μ_X/σ_0	μ_Y/σ_0	μ_Z/σ_0	$\mu_{X,Y}/\sigma_0$
camera position and attitude data	0.0m	0.0sec	0.50	0.56	1.00	0.53	0.50	0.56	1.00	0.53	0.50	0.56	1.00	0.53
	0.1m	2.3sec	0.52	0.59	1.00	0.56	0.52	0.58	0.98	0.55	0.52	0.58	0.99	0.55
	1.0m	23.0sec	0.71	0.79	1.32	0.75	0.70	0.77	1.29	0.74	0.70	0.77	1.28	0.74
	3.0m	68.7sec	1.08	1.07	1.73	1.08	0.96	1.02	1.65	0.99	0.94	1.01	1.60	0.98
	6.0m	137.4sec	1.40	1.51	2.24	1.46	1.28	1.41	2.20	1.35	1.24	1.39	2.10	1.32
	10.0m	229.1sec	1.91	2.23	3.10	2.08	1.73	2.06	3.03	1.90	1.64	2.02	2.89	1.84
camera position coordinates only	0.1m	-	0.78	0.91	1.37	0.85	0.74	0.86	1.31	0.80	0.72	0.84	1.29	0.78
	1.0m	-	0.86	0.98	1.49	0.92	0.80	0.91	1.41	0.86	0.79	0.90	1.41	0.85
	3.0m	-	1.17	1.24	1.92	1.21	1.10	1.15	1.84	1.13	1.03	1.09	1.72	1.06
	6.0m	-	1.51	1.57	2.55	1.54	1.36	1.46	2.47	1.41	1.30	1.43	2.36	1.37
	10.0m	-	1.98	2.06	3.08	2.02	1.75	1.73	2.92	1.74	1.72	1.70	2.66	1.71
attitude data only	-	1.0sec					0.87	1.05	1.55	0.96	0.88	0.99	1.44	0.94
	-	20.7sec					2.28	1.24	2.02	1.84	2.26	1.24	1.52	1.82
	-	62.2sec					2.20	3.07	2.92	2.67	2.20	3.15	2.16	2.72
	-	137.4sec					3.19	3.41	4.71	3.30	3.22	3.36	3.86	3.29
	-	412.5sec					8.51	5.08	9.88	7.01	8.66	5.16	9.24	7.13



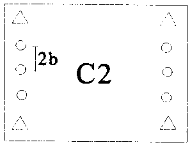


Table 4.2 GPS blocks for mapping, required accuracy of GPS camera positioning (Ackermann, 1994).

Map Scale 1:	*Photo Scale 1:*	*Required AT accuracy*		*Contour Interval*	*Required σ_{GPS}*							
					(1)		*(2)*		*(3)*		*(4)*	
		$\mu_{x,y}$ *(m)*	μ_z *(m)*	ΔH *(m)*	*x,y (m)*	*z (m)*	*x,y (m)*	*z (m)*	*x,y (m)*	*z (m)*	*x,y (m)*	*z (m)*
100000	100000	5	4	20	39	16	21	11	19	8.5	27	6.2
50000	65000	2.5	2	10	18	6.9	9.2	4.5	7.5	2.8	11	2.4
25000	40000	1.5	1.0	5	11	2.8	5.4	1.8	4.4	0.7	6.8	0.9
10000	25000	0.6	0.6	2.5	3.6	1.6	1.3	1.0	0.6	0.4	1.7	0.5
5000	12000 SWA(1)	0.3	0.25	1	1.9	0.3	1.0	0.2	0.3	-	0.9	0.05

$\sigma_0 = 10\ \mu m$

(1) $\sigma_0 = 12\ \mu m$ for z

(1) control case a, no drift parameters

(2) control case a, drift parameters per block

(3) control case a, drift parameters per strip

(4) control case b, drift parameters per strip (2 cross strips)

Figures 4.2 and 4.3 below indicate the expected aerial triangulation adjustment precision as a function of GPS positioning accuracy and photo scale using the control configurations **a** and **b** and the 4 different solution types (1 through 4) listed in table 4.2. By using the information in these figures and tables the required GPS accuracies can be derived for a given photo scale and specified aerotriangulation precision.

In the light of these results, kinematic GPS data can be considered as highly adaptable for the purposes of aerotriangulation, be it

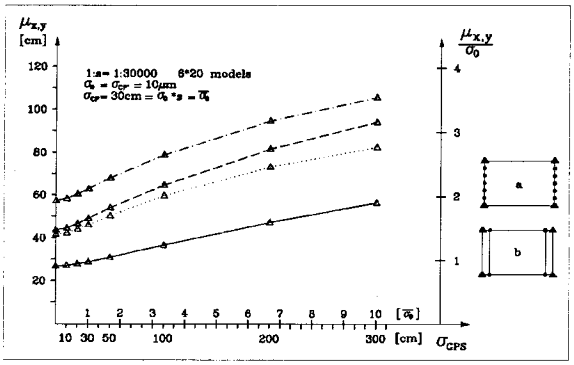


Figure 4.2 Influence of GPS camera positioning accuracy (σ_{GPS}) and drift parameters on horizontal accuracy ($\mu_{x,y}$) of adjusted blocks (Ackermann, 1992).

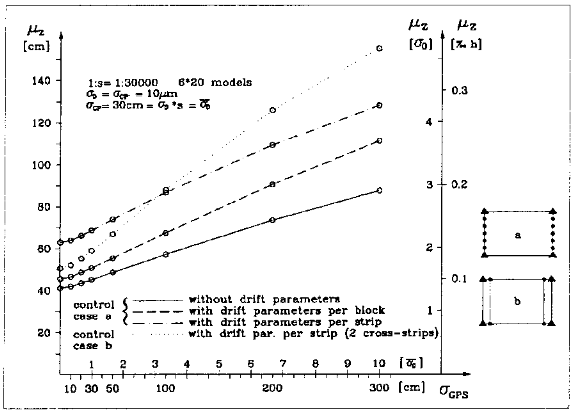


Figure 4.3 Influence of GPS camera positioning accuracy (σ_{GPS}) and drift parameters on vertical accuracy (μ_z) of adjusted blocks (Ackermann, 1992).

differentially corrected range positions or double differenced phase data. Simulated aerotriangulation results by Friess (1986b) using only positions (±10m of the true position) and attitude data (227sec) for control is sufficient for small scale mapping if interior camera calibration errors are not considered; $\mu_{x,y}=2\sigma_0$ and $\mu_z=3\sigma_0$ where σ_0 is the unit weight of image point observation (in 1:60000 photo scale a σ_0 of 10μm corresponds to 0.6m in the terrain units). Generally, this case, although meeting the required aerial triangulation block accuracy, does not solve the datum problem.

Obviously, from these simulations, to achieve the best block accuracy requires that $\sigma_{GPS} \leq \sigma_0$ x s and $\sigma_{CP'} = \sigma_0$, $\sigma_{CP} \leq \sigma_0$ x s. A case that becomes more difficult to maintain as photo scales increase.

The work of Friess (1986b) in contrast to Ackermann (1992) demonstrates the impact of processing and technology developments in the GPS disciplines. Friess (1986b) considered the use of attitude data in combination with GPS. At the time the combination of INS and GPS did appear to be the solution to a number of the associated problems in determining auxiliary data suitable for photogrammetry without or minimal ground control. Later simulations and research work look at GPS solutions only in meeting these needs.

4.2.3 Drift

It has been established that auxiliary data has a substantial impact on the modern aerial triangulation adjustment process. The basic concept of GPS aerial triangulation is the inclusion of GPS camera station coordinates into an aerial triangulation adjustment as observations of the unknown perspective centres of the aerial photographs, together with the conventionally measured image coordinates. This is a similar approach to what was formally referred to as aerial triangulation adjustment with auxiliary data.

The ideal scenario for GPS camera positioning in support of aerial triangulation would be the determination of all camera perspective centres to an absolute accuracy better than the achievable image point observation variance in terrain units - $GPS_{Abs} < \sigma_0 * s$, where s is the photo scale. In reality the ideal scenario is rarely achieved. To achieve this level of accuracy from GPS requires the determination of the unknown number of carrier phase wavelengths or cycle ambiguities, *N*, associated with each observation of carrier phase to numerous satellites. In the case of GPS camera positioning this requires kinematic techniques which will lead to fixed ambiguity trajectory solutions.

Although such solutions have been demonstrated the techniques suffer when signal interruptions occur and as distance increases away from the reference station. To avoid these situations special limitations are placed on operational procedures to limit the chances of signal interruption. These limitations may include limiting the angle of bank in turns and flying photography in particular directions. P-code and narrow correlator C/A-code receivers have contributed greatly to "ambiguity resolution on the fly" techniques which overcome the problems of loss of signal to some extent, but recovery times and the operational range from the reference station still remain as issues. Ackermann & Schade (1993) suggest that a simpler solution is to establish approximate ambiguities based on an initial C/A-code or P-code position and accept that these solutions generate GPS drift errors. This is the same methodology suggested by Han & Wong (1996) for land survey applications.

Although approximate ambiguities do not yield positions of any *true* value the systematic errors in the solutions can be corrected at a later stage in combination with aerial triangulation. The assumptions and drawbacks with this approach are that the drift errors which result from the approximate ambiguity solutions are linear in behaviour and the removal of these drift errors will also include other unmodelled errors. Included in unmodelled errors is the relationship between the camera and the GPS antenna. Ackermann & Schade (1993) suggest that for test results over photo strips which take 5 to 15 minutes to cover, drift errors are generally quite linear. They continue suggesting that the accuracies achieved with this technique do not appear to deteriorate as the distance from the reference station increases. This has proven to be the case as results conducted by the SGD in chapter 13 confirm.

Another aspect of this technique is that continuous phase lock is only necessary whilst on the photo strip, restrictions in the turns can be dispensed with. In fact the receiver needs only to be operating or recording data whilst on the photo strip.

GPS drift can only be determined through the identification of ground control in the aerial triangulation model. The amount of control required is dependent on the drift model adopted.

(a) If it is assumed that for a photographic sortie the difference between the true camera position, $C_{x,y,z}$, and the observed GPS camera position, $G_{x,y,z}$, (corrected for the antenna camera vector) is zero then in principle the aerial triangulation adjustment can be executed without ground control. In practice an approximate ground point is required to orientate the models the right way up. This methodology is limited by interior camera orientation errors, that GPS isn't always in the local datum and GPS signal and data interruptions do occur making $C=G$ difficult to realise.

(b) If it is assumed that for a photographic sortie the difference between the true camera position, $C_{x,y,z}$, and the observed GPS camera position, $G_{x,y,z}$, remains constant then only one ground control point is required to determine the three translations between C and G. There are also no special requirements for cross (tie) strips or extra vertical control which is demanded of standard aerial triangulation. The methodology does overcome local datum effects but is limited by interior camera orientation errors and suffers from GPS signal and data interruptions.

(c) If it is assumed that for a photographic sortie the difference between the true camera position, $C_{x,y,z}$, and the observed GPS camera position, $G_{x,y,z}$, drifts at a constant rate then control points placed at the block corners (4) are sufficient to determine one set of linear correction parameters. There are still no special requirements for cross (tie) strips or extra vertical control. The methodology overcomes interior camera orientation errors and local datum effects but suffers from GPS signal and data interruptions.

(d) Blocks of aerial photography are not always completed in the one sortie. This creates the scenario where each photographic line is subject to its own set of GPS drift parameters. In this case, for a standard block using 20% side overlap, just four ground control points located in the block corners is insufficient to determine the drift parameters.

"However, their numerical solution can become difficult, if the block has standard overlap and if only four ground control points are used" (Ackerman and Schade, 1993)

"Four ground control points are not sufficient, however, for a block with standard (20%) side overlap, to solve for all drift parameters if each strip is given a separate set of parameters" (Ackermann, 1992)

There are a number of solutions to this problem.

- Fly the block with 60% side overlap
- Use two chains of vertical control points as in figure 4.4
- Use two cross strips at each end of the block as in figure 4.5

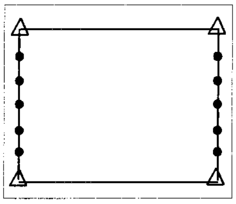


Figure 4.4 Layout using two chains of vertical control.

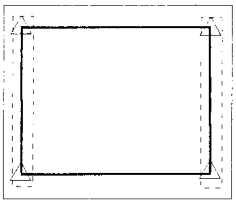


Figure 4.5 Layout using cross strips.

The most economical option of the three is the case with two cross strips. Standard photography capture is far cheaper than establishing ground control, particularly vertical control. 60% side overlap only increases the amount of photography unnecessarily and increases the amount of image point observations significantly.

4.2.4 Introducing GPS Observations to the aerial triangulation adjustment

There are now three observation types to introduce to the aerial triangulation or combined block adjustment, the GPS camera station coordinate observations, the image point observations and the ground control observations. Ground control observations are required to introduce the local datum and provide the control basis to determine the GPS drift parameters. Using the GPS drift model the amount of ground control can be reduced to as little as four control points located in the corners of the block.

Assuming that the drift behaviour of the adopted GPS solutions is linear, the following observation equations for the GPS coordinates, relating to camera station *i* in photo strip *k* are:

$$\begin{aligned} V_{X_{ik}}^{GPS} &= X_{ik} - (a_{0k} + a_{1k}\,\bar{x}_{ik}) - X_{ik}^{GPS} \\ V_{Y_{ik}}^{GPS} &= Y_{ik} - (b_{0k} + b_{1k}\,\bar{x}_{ik}) - Y_{ik}^{GPS} \\ V_{Z_{ik}}^{GPS} &= Z_{ik} - (c_{0k} + c_{1k}\,\bar{x}_{ik}) - Z_{ik}^{GPS} \end{aligned} \tag{4.21}$$

This is a modification of the perspective centre elements of equation (4.18) by the addition of the linear terms for GPS assisted photography.

The equations contain the observed GPS camera station coordinates $(X,Y,Z)_{ik}^{GPS}$ and their least squares corrections $V_{(X,Y,Z)_{ik}}^{GPS}$, the unknown coordinates of the perspective centres $(X,Y,Z)_{ik}$ and the linearised datum transformations and corrections for systematic errors per photo strip k which includes the offset between the camera and GPS antenna $(a_{0k}.........c_{1k})$. The coordinate $\bar{x}_{ik}$ refers to an auxiliary flight axis coordinate of camera station *i* on strip *k*. This value can also be an arbitrary incremental value $\bar{i}_{ik}$ (e.g. observation number) or based on the sequential exposure time $\bar{t}_{ik}$.

The three observation groups are combined as follows into the block adjustment (Ackermann, 1988):

- xy image coordinates (vector x), weights 1 (Collinearity)
- $(XYZ)^C$ ground control points (vector $\underline{X}^C$), weights p^C (Ground control)
- $(XYZ)^G$ GPS coordinates (vector $\underline{X}^G$), weights p^G. (Perspective centre)

The mathematical model of the combined block adjustment contains 3 groups of unknowns:

- the camera orientation parameters $\dot{\Delta}$, including the coordinates of the camera stations
- the coordinates $\ddot{\Delta}$ of all the terrain points of the block, including ground control points
- drift parameters $\dddot{\Delta}$ for the GPS observations

The model can be extended to 4 groups of unknowns with the inclusion of additional parameters $\hat{\Delta}$ for self calibration

Thus the complete set of linearised observation equations for the combined bundle adjustment is:

$$\begin{array}{lllllllll} \boldsymbol{V} & + \dot{\boldsymbol{B}}\dot{\Delta} & + \ddot{\boldsymbol{B}}\ddot{\Delta} & & + \hat{\boldsymbol{B}}\hat{\Delta} & = \epsilon & \text{Weights} & 1. & \text{(a)} \\ \ddot{\boldsymbol{V}} & & - \ddot{\Delta} & & & = \ddot{\boldsymbol{C}} & & P^{G}. & \text{(b)} \\ \dot{\boldsymbol{V}} & - \dot{\Delta} & & - \dddot{\boldsymbol{B}}\dddot{\Delta} & & = \dot{\boldsymbol{C}} & & P^{C}. & \text{(c)} \end{array} \qquad (4.22)$$

Note the inclusion of the term $\dddot{\boldsymbol{B}}\dddot{\Delta}$ to cater for GPS drift. For equations (4.22) (b) and (c) the coefficient matrices for the parameters $\dot{\Delta}$ and $\ddot{\Delta}$ only have the elements one in the respective columns.

The introduction of GPS drift parameters into the aerial triangulation adjustment does not guarantee instant success and highly desirable results. The determination of drift might not be possible because of adjustment singularities which may result from control or adjustment configuration deficiencies.

4.2.5 Aerial triangulation without ground control

Aerial triangulation without ground control is an attractive option as it can reduce production costs even further. It also offers the capability to operate "over the horizon" so to speak, such as mapping in hostile environments without having to "set foot there". The technique does require that the trajectory solution be precise and free from any drift.

"The photo block is then tied only to the camera air stations. It is controlled at the perspective centres, so to speak. In that case all derived ground coordinates are affected by errors of interior camera orientation, the effects of which can be quite considerable. The error effects of interior orientation are always present in aerial triangulation. However, in conventional methods the blocks are tied to ground control points, and the error effects are pushed by the block adjustment into the photo orientation parameters, where they do not show up directly and do no harm" (Ackermann and Schade, 1993)

One must also address the datum problem when mapping without ground control. Two effects must be considered in this case: the transformation from the WGS84 ellipsoid to the local datum and the datum propagation effects as the length of the kinematic GPS baselines grow. Using GPS for aerial triangulation has introduced the issue of "ellipsoid height". The accuracy of derived image point orthometric heights will always be limited by the quality of the geoid model.

An explanation of some of the limitations of GPS aerial triangulation lies in the way the aerial triangulation adjustment block is built up. The adjustment block without any ground control or GPS camera stations is very weak. In profile it can be considered as a truss bridge without the top braces. This is illustrated in figure 4.6. In the traditional aerial triangulation adjustment without GPS camera centres or vertical control the determination of the block is distorted as in figure 4.7. The block in this case only has minimal ground control but without any vertical control the block will "sag" and the perspective centres will lose their true relativity. The image point observations and

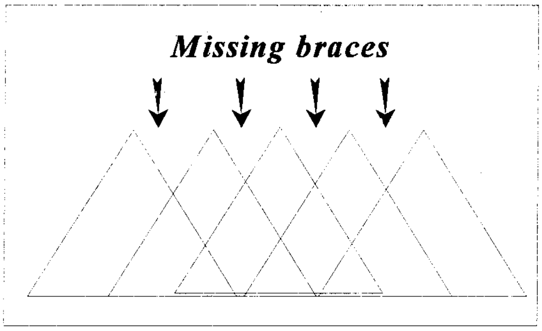


Figure 4.6 Profile of overlapping images illustrating lack of bracing at the camera centres within the simple model.

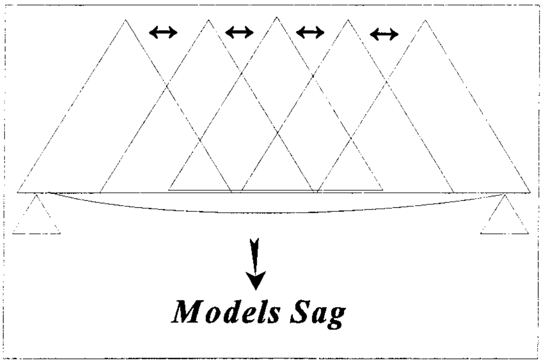


Figure 4.7 Strip derived from models tends to sag without vertical support, camera centres lose relativity.

the geometry of the model is not strong enough to prevent this happening.

Adding vertical control, figure 4.8, throughout the block overcomes this sagging effect, but the cost of establishing the vertical control, or for that matter any ground control, is substantial.

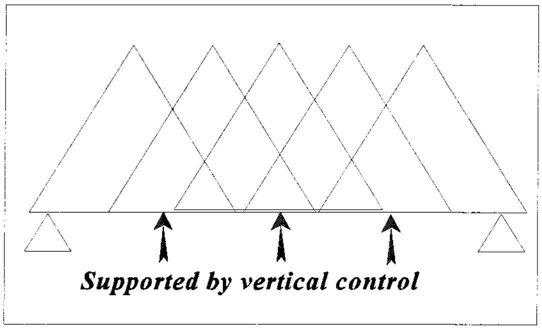


Figure 4.8 Vertical control supports the models, camera centre relativity restored.

Introducing GPS to this model can be viewed in two ways. In the first case the GPS observations are treated as "relative" and drift is an accepted by-product of the process. This is illustrated in figure 4.9, where the strip of models becomes braced at the perspective centres but the absolute position and orientation can be considered as unknown.

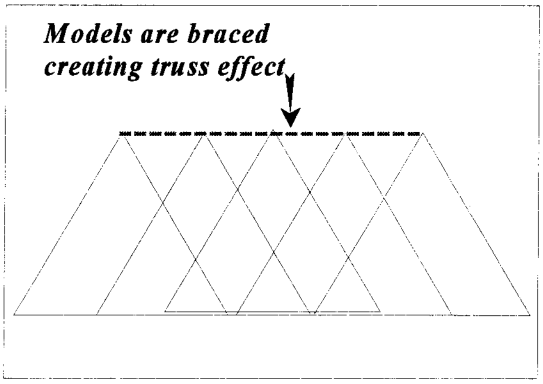


Figure 4.9 Truss effect created by adding GPS observations at perspective centres.

The second case is where the GPS camera station coordinates are considered as "absolute" and error free. It is this situation that promises to support aerial triangulation without ground control. There are concerns that interior camera orientation errors associated with the relationship between the position of the perspective centre and the image coordinate system x_0 , y_0 and f and the errors due to lens distortion combine to make aerial triangulation without ground control difficult to realise. The collinearity condition is based on the rule that the exposure station, any object point and its image point all lie on a straight line. Within the aerial triangulation adjustment, ground control indirectly ensures that this condition is enforced. Without ground control any errors in the lens system will be projected directly into the derived image coordinate system, as in figure 4.10. There is also the possibility that incorrect GPS camera centre coordinates will go undetected.

Solutions to this aspect of GPS aerial triangulation require the precise calibration of the camera system. The modelling is not perfect and suffers from many uncertainties.

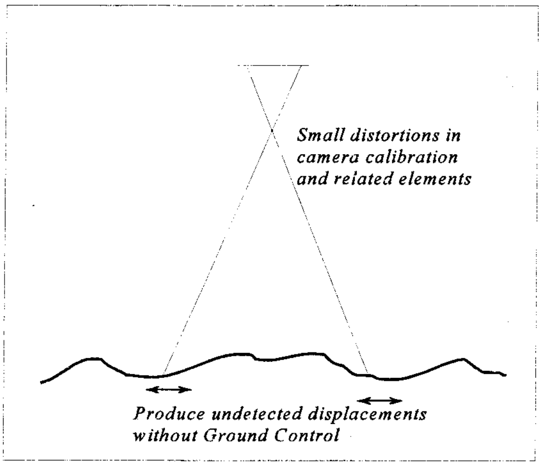


Figure 4.10 Interior orientation errors produce undetected errors in object points without ground control.

Figure 4.11 illustrates how GPS drift is accounted for between two adjoining strips. The relative orientation of adjoining photographs in a strip is considered known in this example. Adjacent strips are connected to one another via the common image tie points between the strips. This identifies along track, cross track and vertical GPS differences, or the constant terms of the components, a_{0k}, b_{0k} and c_{0k}, and also the three orientation elements of the GPS trajectory, which are the linear terms, a_{1k}, b_{1k} and c_{1k}. By joining one strip to another these values will only be relative to the first strip.

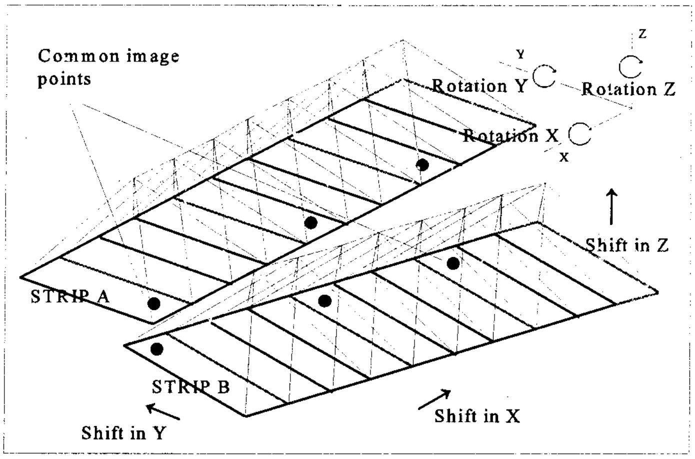


Figure 4.11 Illustration of how strip B is rotated and translated into strip A. The rotation around the Z axis and the shifts in X and Y are the strongest in this case.

This situation can be built up by the addition of further strips, but the block remains weak due to the relative rotations around the X axis (roll, ω) between adjoining strips and rotations around the Y axis (pitch, ϕ). These weaknesses are overcome by the addition of cross strips at the ends of the block.

The adjustment integrity is not complete without the addition of ground control. The requirement of four ground control points, H & V, located in the corners of the block, provides the datum to determine the absolute drift values of the GPS perspective centres.

Within the aerial triangulation adjustment, GPS camera centres adopted in this methodology provide a bridging function by increasing the integrity of the photogrammetric model. Ground control provides the means to introduce datum information into the adjustment, validates self calibration procedures and minimises the effects of interior orientation errors. The image point observations link the datum points (control) to the object points simultaneously relocating the GPS camera centres by removing systematic errors (drift).

4.3 Performance outcomes with respect to operational aspects.

Simulations by Friess (1986b) and Ackermann (1992) demonstrated that the inclusion of GPS auxiliary data can be extremely advantageous in reducing costs associated with establishing photogrammetric ground control. The quality of available data has steadily improved, particularly in the late 1980s and early 1990s.

Processing techniques have progressed from single point 30m position accuracies based on four pseudo-range observations, to combined dual frequency code/phase real time dynamic solutions capable of 1cm accuracy. The latter has only been available in recent years.

The results of Friess (1986b) and Ackermann (1992) point out that small scale **mapping** capability is easily achievable. Most differential code techniques are capable of sub-10m accuracies both in a relative and absolute sense. However, this capability is still dependent on good observation practice. Accuracies can quickly deteriorate if simple operational procedures are neglected.

The introduction of this technology into photogrammetric operations is sensitive to costs versus the benefits. Aerial photography is an expensive business, and the mapping process, in addition, includes the ground survey component, aerotriangulation and plotting. Even in its developmental period, GPS-controlled photography promised substantial cost savings.

The elimination of the associated costs of ground control and some of its problems - access difficulties, selection of suitable control points and targeting - were powerful motivating factors for this new technique. Proof-of-concept studies required the establishment of test ranges, though in some cases these may have already existed to support camera calibration studies.

Operationally, the deployment of this technology has only fulfilled its potential with the full operational capability of the GPS constellation in 1994. Aerial photography is primarily dependent on the prevailing weather - regardless of anything else, if the weather is unsuitable - no flying. Other influencing factors are the aircraft and the associated equipment status. Now add to this the suitability and availability of the GPS constellation and, for high accuracy, the dependence on a GPS base station.

Regardless of GPS accuracy, performance is limited by some operational aspects.

(a) GPS base station

To provide the high accuracy positional performance stated in table 4.2 (for 1:10000 mapping and better) requires the use of a GPS base station operating within close proximity to the project area (for high accuracy). An alternative is a remote base station established in a convenient location for the project (usually for lower accuracy). The success of a photo mission is dependent on the performance of this station. It also introduces a further cost as it needs to be maintained and its operation monitored.

A GPS base station needs to be very reliable. Communication with the aircraft may not be possible, and a day's photography may be lost due to loss of base data.

"In the aircraft two TI4100 and on a reference station in the test site also two TI4100 receivers have been used, attached to the same antenna." - "By bad luck two GPS receivers have not operated well, one of these has been in the aircraft and one on the ground. In addition these have been not the receivers operating with the satellites. The quality of relative GPS

positioning has been reduced by this"

- A synopsis as written by Jacobsen (1991) of European tests up to 1990.

"In the Washington experiment, the operator of the mobile receiver had difficulty locking onto one of the satellites. When he was finally successful, we were already behind schedule so the pilot was quickly given permission to proceed. The air plane departed from the index mark and moved about 10 metres down the taxiway before word was received that the fixed receiver had not acquired the fourth satellite."

- A description of complications (Lucas & Mader, 1989)

"Missing data was caused by power failures, insufficient storage capacity in the data logging devices, or unexplained lock-up of the data logging software."

"At some reference stations, problems with data collection were experienced during a few missions"

- Flight mission experiences (Hothem et al., 1994)

These are a sample of problems that have occurred before the potential of the technology was even fully realised.

(b) Antenna - camera offset

The GPS positions recorded on a flight are not those of the camera reference point, but those of the antenna phase centre. The magnitude of this error in the final aerotriangulation analysis is dependent on how well the eccentricity vector between the camera and the antenna in the aircraft local reference system, is known, or if it is ignored, how small the eccentricity vector is.

"The GPS antenna is placed somewhere on the roof of the aircraft as the

radio signals must have an uninterrupted direct path from the satellites to the antenna. For high precision measurements one has to consider this eccentricity between the antenna and the projection centre of the camera. The spatial offset reduction should refer to the external coordinate system. Hence, in principle, the eccentricity and the aircraft attitude have to be taken into account" (Burman & Torlegard, 1994)

The determination of this vector is usually by a close range survey which yields the offset components within the aircraft local reference system. The survey is usually determined with the aircraft in a level attitude although there are variations on this.

"A L1/L2 antenna was required on the aircraft and needed to be positioned directly above the nadir point of the camera. To accomplish this the aircraft was labelled in flight during a period of calm weather and the camera mount was levelled (i.e. the proposed antenna position was determined on the aircraft inner fuselage in flight based on a typical aircraft attitude and vertical camera alignment). *The plane landed leaving the camera in this levelled position."* (Kletzli, 1994) This situation only holds true for a particular aircraft configuration and attitude (aircraft pitch is sensitive to speed, altitude and wing flap position) but it is the best technique to reduce to a minimum the eccentricity effects of pitch, roll and yaw.

The eccentricity vector error is best minimised by positioning the GPS antenna as close as possible to vertically above the camera. Operationally, this may not be possible due to limitations within the aircraft environment, consequently the capability of the technology is compromised as the vector magnitude increases. Figure 4.12 illustrates the relationship between the camera and the GPS antenna, for a worst case example. This must then be addressed within the aerial triangulation adjustment.

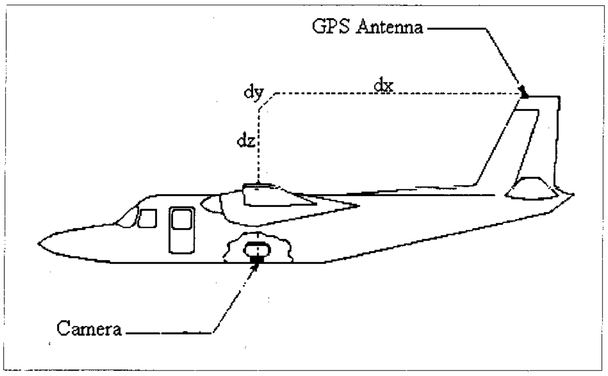


Figure 4.12 Worst case Antenna - Camera offset vector.

(c) Receiver - Camera Connection

Successful operation depends on transferring the derived antenna position to the camera reference point at the instant of full exposure. Obviously, some sort of correlation between the camera events and the GPS system events is required to achieve this.

There are two options available in establishing this connection:

1. At a particular GPS event a message is sent to the camera to expose. Aerial cameras, even today's models, are mechanical in their shutter operation. This mechanical process is subject to variations in operation of the shutter, therefore there is not a constant response. This lag between the GPS event and the shutter operation results in variable positioning for the camera, which is often difficult to model as an along track error. For an aircraft flying at 200kts (103m/sec), 1 millisecond (0.001 seconds) represents 0.1m in an along track movement.

   The mechanical operation of the camera shutter from the command to the exposure is not generally at this level of consistency. This results in poor position transfer.

2. Aerial cameras can be modified (or manufactured) to produce a pulse at the maximum exposure event. This pulse can be recorded very accurately (10^{-6} seconds) against a time standard. In most cases this standard is based on GPS time provided by the receiver but early testing used external clocks. This technique removes the uncertainty of the first option by recording the time of the event instead of initiating it.

"The aerial cameras had to provide a pulse at the midpoint of exposure, so that a very precise time could be associated with each photo. This capability already existed on the WDOT's Zeiss camera, but the TDHPT's RC-10 required a minor modification. A frequency counter was used to measure the time interval between the shutter pulse and the one pulse per second output from the TI-4100, and these time intervals were recorded on a Hewlett Packard desk top calculator" - description of event timing by Lucas & Mader (1989)

Van der Vegt (1989) - *"The pulse that can be generated with the Wild RC-10 camera proved to be too inaccurate for this purpose, fluctuations in the definition of the time of exposure at the 10-100 millisecond level were found. With a ground speed of 100m/s this would cause errors of 1-10 metres. To overcome this problem, a special photo sensor has been installed in the lens cone i.e. between the lens and focal plane. The sensor generates a pulse at the exact time-instant at which the shutter reaches its maximum aperture. With a pulse length of only 0.2 milliseconds, an accuracy of a few tenths of a millisecond was achieved. To relate this time instant to the GPS observations the pulse is then sent to the GPS receiver and timed in the receiver time frame, thus in the same time frame as the raw GPS observations."*

A limitation still remains in that the camera event takes place independently of the GPS epoch. The camera position is then generally derived by some form of interpolation. As a result, position quality is a function of the GPS update rate.

In the case of linear interpolation this assumes that the motion of the aircraft between epochs is linear! Table 4.3 illustrates the effect of the assumption of linear motion of an aircraft travelling approximately 100m/sec. This table is based on an arbitrary post processed GPS data set collected on day 034 of 1996. It is a comparison of interpolated 1 sec positions and 3 sec positions.

This table and the preceding comments highlight the limitations of the GPS technology for controlling aerotriangulation. Before aerotriangulation, the best estimate of camera position must consider the combined effect of these errors and the GPS position error itself.

Table 4.3 Comparison of 1 second and 3 second PNAV interpolation solutions to check linear motion of aircraft

Day 034_96 Exposure	Normal 1 Second Solutions			3 Second Solutions			Differences		
Time	Easting	Northing	Height	Easting	Northing	Height	Diff E	Diff N	Diff H
22:23:22.838975	280041.03	6261537.01	8054.15	280041.00	6261537.03	8054.14	0.033	-0.026	0.014
22:23:58.481613	281765.69	6265267.53	8050.09	281765.60	6265267.43	8050.43	0.091	0.094	**-0.339**
22:24:34.81961	283490.92	6269024.46	8053.84	283490.98	6269024.52	8053.95	-0.054	-0.062	-0.116
22:25:11.051817	285342.28	6272700.65	8055.78	285342.21	6272700.62	8055.40	0.070	0.037	**0.387**
22:25:47.806375	287189.51	6276401.75	8056.03	287189.52	6276401.63	8056.18	-0.015	0.114	-0.145
22:26:24.404092	288993.36	6280081.76	8057.05	288994.13	6280081.56	8056.99	**-0.777**	**0.198**	0.063
22:27:01.260795	290904.30	6283758.57	8059.80	290904.44	6283758.59	8059.80	-0.142	-0.012	-0.007
22:27:37.645288	292816.66	6287406.19	8061.99	292816.64	6287406.21	8061.95	0.019	-0.016	0.041
22:28:13.910516	294738.06	6291047.45	8058.96	294738.07	6291047.44	8058.97	-0.009	0.008	-0.010
22:28:50.459339	296679.30	6294718.68	8057.94	296679.26	6294718.64	8057.89	0.041	0.041	0.050
22:29:27.102348	298432.60	6298450.17	8060.21	298432.79	6298450.15	8060.10	-0.185	0.020	0.104
22:30:04.268498	300094.49	6302239.00	8059.89	300094.66	6302238.94	8060.06	-0.169	0.057	-0.176
22:30:40.962637	301850.64	6305958.24	8065.66	301851.12	6305958.13	8065.69	**-0.480**	**0.103**	-0.029
22:31:17.434617	303810.14	6309598.64	8069.78	303810.15	6309598.68	8069.38	-0.014	-0.037	**0.397**
22:31:53.497689	305747.56	6313208.69	8071.83	305747.67	6313208.63	8071.89	-0.108	0.061	-0.055
22:32:30.025254	307710.05	6316850.04	8069.44	307709.99	6316849.99	8069.40	0.057	0.050	0.032
22:33:06.581829	309649.74	6320481.29	8070.74	309649.63	6320481.37	8070.55	0.107	-0.079	0.190
22:33:43.613264	311409.84	6324207.96	8067.33	311409.95	6324208.04	8067.45	-0.105	-0.078	-0.113
22:34:20.775549	313159.77	6327955.82	8072.51	313159.93	6327955.72	8072.42	-0.161	0.099	0.081
22:34:57.844176	314961.42	6331682.25	8076.33	314961.48	6331682.20	8076.20	-0.054	0.047	0.136
22:35:34.137899	316843.27	6335328.38	8081.89	316843.29	6335328.49	8081.45	-0.018	-0.113	**0.440**
22:36:10.616878	318746.62	6338995.45	8076.67	318746.62	6338995.40	8076.35	-0.001	0.043	**0.322**
22:36:47.331601	320525.70	6342721.52	8075.15	320525.72	6342721.54	8075.32	-0.018	-0.021	-0.171
22:37:23.839997	322342.42	6346422.58	8071.43	322342.42	6346422.58	8071.69	0.000	0.006	**-0.259**
22:38:00.413614	324189.41	6350121.07	8078.65	324189.37	6350121.11	8078.61	0.038	-0.037	0.041
22:38:36.763723	326057.20	6353773.43	8075.91	326057.20	6353773.48	8075.84	0.007	-0.055	0.074
22:39:13.558310	327905.32	6357472.13	8080.16	327905.28	6357472.15	8080.05	0.042	-0.021	0.113
22:39:50.332331	329718.26	6361176.18	8082.34	329718.15	6361176.21	8082.24	0.113	-0.036	0.101
22:40:27.049445	331546.48	6364878.36	8082.88	331546.47	6364878.40	8082.88	0.005	-0.047	-0.002
22:41:03.644179	333395.18	6368561.51	8082.26	333395.16	6368561.52	8082.28	0.019	-0.007	-0.020
22:41:40.117677	335233.10	6372228.55	8088.92	335233.06	6372228.59	8088.62	0.040	-0.041	**0.302**
22:42:16.970215	337064.27	6375939.35	8082.88	337064.30	6375939.38	8082.96	-0.024	-0.035	-0.073
22:42:53.539131	338924.21	6379607.11	8080.21	338924.17	6379607.06	8080.38	0.044	0.049	-0.165
22:43:30.294111	340831.22	6383263.80	8091.64	340831.16	6383263.88	8091.40	0.055	-0.084	**0.236**
22:44:06.944627	342753.92	6386929.35	8081.94	342754.07	6386929.25	8082.08	-0.145	0.104	-0.142
22:44:43.537344	344661.47	6390582.44	8093.94	344661.36	6390582.44	8093.66	0.113	-0.004	**0.280**
22:45:20.055358	346521.91	6394247.20	8092.72	346521.94	6394247.25	8092.64	-0.033	-0.045	0.079
22:45:56.829577	348326.80	6397971.00	8088.13	348326.97	6397970.99	8088.17	-0.172	0.009	-0.036
22:46:33.241136	350095.70	6401689.92	8089.25	350095.79	6401689.80	8089.26	-0.092	0.126	-0.008
22:47:09.599908	351920.86	6405387.10	8089.69	351920.86	6405387.07	8089.64	0.006	0.023	0.051
22:47:45.959905	353780.28	6409073.45	8092.07	353780.18	6409073.49	8092.01	0.102	-0.041	0.061
22:48:22.364921	355625.88	6412765.88	8096.06	355625.90	6412765.88	8095.97	-0.019	-0.003	0.094

5. Operational Capture Standards for Aerial Triangulation

5.1 Tolerance of aerial triangulation to GPS navigation limitations

There are a number of aspects to consider when GPS is used for to the capture of aerial photography, and the adjustment of the observed photography data in the aerial triangulation process.

Apart from the technical and physical problems associated with the implementation of a data collection (and possible navigation display) system, a number of limitations of the actual use of GPS must be resolved.

A certain level of real-time navigation can be achieved using various proven techniques. Even so, high level navigation data which may include high update rates, does not guarantee that imagery is captured within the tolerances required for the aero-triangulation process. Photography capture requirements include specifications which are governed by the physical limitations of analytical and digital image observation and adjustment equipment/software. Some of these specifications are :

- Maximum heading change between successive photographs e.g $< 3^\circ$.
- Verticality of the photographic image.
- Overlap requirements maintained. In the case of rising or falling terrain the camera cycle time must be varied. This is a height function which must be monitored, scale requirements for the photographic coverage are also dependent on the mission flying height.

Commercial integrated camera navigation systems which interface to the aircraft's auto-pilot are not currently available. Even so, any such system is subject to a rigorous test program which is subject to the rules of governing Civil Aviation Authorities. As a result, GPS camera navigation systems in use today are manual operations, placing the onus on the pilot to keep the aircraft and the camera platform as close to the defined photographic line as possible. The tolerance for this is usually a function of the flying height and impacts on the required side overlap of subsequent runs. The pilot must also keep the aircraft as level as possible at the time of camera event to ensure verticality of the image. Today's modern cameras include options for gyro stabilised mounts which reduce the verticality problem to some extent.

Panel mounted aircraft specification GPS systems are now available which interface to the aircraft's auto-pilot but these are not practicable for camera navigation/control, mainly because of the coarseness of the display and the poor interface for the entry of the many way-points required for a photographic mission. They are specifically designed to provide an aviation navigation function.

A camera navigation system which is linked to a GPS receiver operating in single point mode will be subject to performance degradation due to Selective Availability, the higher specification receivers will also be affected by Anti-Spoofing. Hence 95% of the time it can be expected that better than 100m position accuracy is possible, given the pilot can fly exactly to a point.

This error will impact on the forward and side overlap requirements. For small scale photography, e.g. 1:50000, the impact of this error is of little consequence. For a 220mm format camera at a scale of 1:50000, 60% overlap is 6600m. An error of 100m equates to an error of about 1.5% in the overlap requirements, both side and forward. An error of 100m in height is about 1% error in scale.

However, for 1:5000 scale photography using the same lens a 100m error in position equates to an overlap error of 15% which is well outside specification (which is usually ±5% error for overlap). Similarly, a 100m error in height changes scale by 13%.

In both cases a combination of position and height error impacts on the planned photographic mission. As scale increases this aspect becomes mission critical. The worst case is in the event of being diametrically opposite for successive photographs when the total error could be of the order of 200m. The probability of this occurring is very small because as scale increases the cycle time of the camera decreases. The accuracy variations of single point positioning would not be apparent over a short time span, but the impact of the worst case error could occur on the adjoining strip either some time later, or on some subsequent flight. These implications cannot be overlooked when planning.

These errors can be reduced by using Real Time Differential GPS methods. Real time techniques reduce the position error magnitude to the 5m level, eliminating the majority of expected errors. As the scale of photography increases so do the demands on the pilot, but with real time differential data the reliability of his navigation information improves, decreasing the tendency of "chasing" the line that single point positions tend to encourage.

5.2 Errors associated with time

5.2.1 Hardware timing errors - camera to GPS

Mission critical position errors can result from timing errors that may arise from software, camera and GPS hardware. Timing errors will be evident as along track errors. Timing errors are characterised by a mismatch between position and epoch.

The obvious source of timing error for a photographic mission is the camera-GPS interface. These errors may be the result of software embedded in hardware firmware as used in the camera and GPS receiver. A positive or negative delay in the camera pulse will tag the camera exposure either before or after the camera event. These errors can be random or systematic. Random timing errors are those resulting from an inconsistent tagging system which cannot be modelled. Systematic timing errors are of the type where the time tag is incorrect, but consistently incorrect by a similar quantity. Systematic timing errors, and an estimate of their value, will be detectable at the aerial triangulation phase. These errors are real, as the author has observed the situation where the time tag of the camera event occurred ***before*** the actual camera exposure.

If the tag for the camera event is before or after it actually occurred and consistent for every camera event for a photographic run, then this will be apparent in the results of the aerial triangulation adjustment. If GPS drift is not an aerial triangulation adjustment parameter then the detection of the error may be more difficult, as the GPS positions to which the adjustment is constrained may out-weigh the image observations. This may suggest that the aerial triangulation is bad and lead to lengthy analysis.

If GPS drift is solved for using ground control, then an along track offset will be evident after aerial triangulation. If the timing error is consistent throughout a particular flight then, for photo flights in the reverse direction, the error will be of the same magnitude but reversed sign. These errors are then differentiated from position bias errors which, regardless of flight direction, are of the same sign and magnitude.

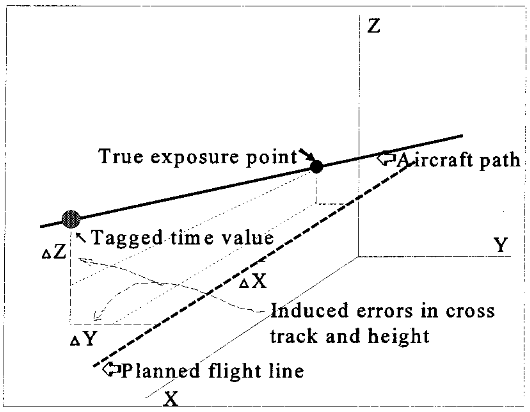


Figure 5.1 Induced timing errors. ΔX is the along track error, ΔY is the cross track error and ΔZ is the vertical error.

Errors associated with this problem are in all three components of position. Unfortunately an aircraft does not fly directly along the straight and level flight line. The aircraft will be flying at some incidence to it. A systematic timing error will include elements of induced cross track and height errors - see figure 5.1. The magnitude of the these errors can be reduced to some degree by using the along track error which is solved for in the aerial triangulation adjustment as a GPS drift parameter.

For a particular photographic run the aircraft will travel an average velocity. Using this velocity and the along track error (GPS drift parameter) then an estimate of time offset can be made. This can be applied to every camera time tag and the camera positions can be re-calculated using the corrected time tags. Although not rigorous, this procedure is suitable for small to medium scale triangulation. The corrected positions will also include biased GPS position errors.

5.2.2 Software timing errors - GPS to camera

When a real time navigation system is implemented that will include camera control, other errors have to be considered that will impact on product quality. Determining where the photo was taken is a little easier than taking the photo at a predefined location.

A real time navigation system will operate based on past information. There are a number of delays in a real time system. The camera control navigation system is based on preplanned exposure points and the real time position data that the GPS receiver can deliver. Camera control software must be designed so that a prediction can be made as to when the aircraft will arrive at the planned exposure point.

Delays exist throughout this process which make this prediction difficult:

- Delays exist within the firmware of the GPS receiver. The time tagged position data that is delivered to the communication port of the GPS receiver is already "old". This age may be a function of the age or the sophistication of the receiver. The number of satellites tracked, real time differential corrections, real time data logging are all subject to some sort of time slice sharing within the receiver, each attributing to some amount of data ageing at the communication port(s).

- The communication protocols will also effect the age of data. High data rates (115200 baud rate) will reduce age, but may be unreliable.

- The real time navigation software will poll its communication port and interpret the data as programmed. Again, depending on the sophistication of the software, some time sharing will be employed. By the time the software has determined its position the aircraft has moved on. It then has to determine whether or not it is before, at or past the planned exposure position.

- The shutter action of the camera is a mechanical sequence. It is expected that variations will exist in the time taken between when a command is received to execute an exposure and the actual tagging of the event by the GPS receiver.

These delays make the task of exposing at the exact preplanned position quite a challenge. In practice the exposure position is best defined as an along track distance and not as a point. This is because the pilot cannot maintain a cross track value of zero! Non-cardinal flight directions complicate this process.

One solution to this problem is to synchronise the computer clock driving the navigation software to GPS time. This can be done by using the one pulse per second signal that is available from many GPS receivers. Then reliable prediction can be employed to expose the camera at the preplanned point and time. This system is reliant on the accuracy of the clock synchronisation, noting that 1 second is equivalent to 100m along track in flight.

5.3 Other errors

Preplanned exposure positions which are controlled by a camera control navigation system will also be subject to errors which result from datum transformation parameter errors (if used). In NSW these errors should not exceed 2m in ϕ, λ and h.

5.4 Comments

Regardless of the problems associated with camera control/navigation systems, their performance in the main is far superior to the traditional manual methods of aerial photography. A system which incorporates real time differential corrections will deliver consistent positioning of an aircraft, reduce the workload, deliver a superior product and reduce costs in the photogrammetric process.

6. Operational Options

6.1 Status of a pre-GPS photographic mission

Before the introduction of on board navigation systems based on GPS the process of aerial image capture could be considered as more an art form than a science. The procedures were manually intensive and required a high work load for the entire crew within the aircraft environment.

6.1.1 Equipment

Paramount to quality image capture is the camera itself. Aerial photography was first used in the mid to late 1800s. Photographs at that time were taken from tethered balloons. Prior to World War 1 aerial photography produced mainly oblique images, however with the advent of war aerial photography became a planning and information tool, and continues to be part of today's national defence systems. In the 1920s, with the introduction of stereo coverage and vertical photographs, government agencies used aerial photography for compilation of maps.

Figure 6.1 Typical camera installation. *Photo: Leica*

The aerial camera has improved over the years. Figure 6.1 illustrates a typical camera installation (*Leica* RC20) in an aircraft. Some of its components are the lens cone, camera mount, drive unit, film cassettes and view finder/navigation sight. In support of this is the airframe itself which has to be modified to accept the camera and view finder/navigation sight. A pressurised aircraft requires a photographic quality flat glass plate below the lens cone so that the pressure hull of the aircraft can be maintained. Generally a camera door is required below the lens cone or glass plate to protect the lens of the camera or plate whilst the aircraft is operating on the ground. These expensive and somewhat specialised modifications must be compliant with aviation authority regulations and also be within the operational envelope of the aircraft.

The selection of a suitable airframe will be based on operational requirements. 1:50000 scale photography with a wide angle lens (152mm) demands a flying height above 23,000ft. This level of performance is at the high end of the general aviation market. Operations at this altitude require oxygen procedures or pressurisation, and an efficient heating system.

6.1.2 Execution

The traditional techniques of aerial photography are manual processes. The extent of a job or project is usually delineated on a map of suitable scale. Flight lines are ruled off on the map at intervals which are a function of the proposed photographic scale and the required side overlap. 1:50000 scale photography which has a side overlap of 20% will position each flight line 9.2kms apart. Aerial survey agencies usually have look-up tables for such planning purposes.

Projected cost for a particular project is then based on the estimated amount of film, the estimated aircraft flying time, labour, depreciation, and other costs. Flight plans are submitted to the appropriate air traffic control authorities for their information and for planning purposes.

Once airborne the navigator is responsible for positioning the aircraft and the pressure altitude calculations for the photographic run. He correlates his map indicating the plotted flight lines to features identified on the ground which he observes through the view finder/navigation sight. When positioned on line and at the correct altitude (mean sea level

+ terrain height) he would communicate to the camera operator the appropriate drift (yaw) to set on the camera and to begin the capture of images. The camera operator monitors through the camera view finder the "speed lines", or intervalometer lines, which move across the view finder at a speed which is a function of the lens focal length, the required overlap and the aircraft's velocity. This ensures that the correct photographic overlap is maintained. He also ensures that the camera is set in a vertical attitude for the flight run. At the navigator's instruction the camera operator switches the camera on to begin the image capture process, the camera automatically cycles according to the intervalometer setting. At the completion of the photo run the navigator will communicate to the camera operator to turn the camera off.

The navigator, based on his map and identified ground features, will guide the pilot to maintain the flight line. He also continues to monitor the drift settings for the camera operator. With the introduction of modern cameras such as illustrated in figure 6.1 the role of navigator and camera operator has been combined into a single function. The camera in this illustration is electrically connected to the view finder/drift sight. The verticality of the camera and its orientation is slaved to the drift sight which also provides the control function for the intervalometer. From the drift sight the camera can be remotely controlled.

The success of a photographic mission is very dependent on the skill of the navigator. It must be remembered that as the photographic scale increases the rate at which events occur and the error tolerance will create quite a heavy work load. Like almost any manually intensive operation there is no substitute for experience.

6.2 GPS controlled photography

The benefits and cost savings of high quality exterior orientation camera data have been demonstrated. In the case of using GPS to provide this data there are a number of ways in which this can be done. The simplest installation is to create a link between the camera event, i.e the instant of maximum aperture opening, and the GPS receiver (nominally on the GPS time scale as all GPS data is time tagged to this reference time). If the camera could be triggered on the GPS second or epoch then the associated interpolation problems of the reverse scenario would be avoided. Unfortunately the shutter action of the camera is a mechanical one and is not consistent enough in its operation to be used this way. This technique would also impact on the overlap sequence of the camera, particularly on large scale photography projects.

6.2.1 Equipment

The problem is how do you detect the instant of maximum aperture opening. Older cameras such as the RC10 cannot produce the necessary pulse, switch or high low status required to interface to a compliant GPS receiver. Van der Vegt (1988), Cortes & Heimes(1988) and Jacobsen (1991) made modifications to the camera using light sensitive diodes to detect maximum aperture opening, but this modification has to be rigorous throughout the camera shutter speed/aperture envelope. A critical part of the interface is that it must be consistent, as timing variations in the actual camera event create positional errors which are nonrecoverable.

"The first problem however was the determination of the exact time of exposure of a photograph. the pulse that can be generated with the Wild RC-10 camera proved to be too inaccurate for this purpose, fluctuations in the definition of the time of exposure at the 10-100 millisecond level were found. With a ground speed of 100m/s this would cause errors of 1-10metres. To overcome this problem, a special photo sensor has been installed in the lens cone i.e. between the lens and the focal plane. The sensor generates a pulse at the exact time-instant at which the shutter reaches its maximum aperture. With a pulse length

of only 0.2 milliseconds, an accuracy of a few tenths of a millisecond was achieved." Van der Vegt (1989)

Modern cameras such as the RC30 can produce this pulse within a tolerance of ±52μs of the time of actual centre of each exposure.

Having acquired or modified a suitable aerial camera the choice of GPS receiver or receiver systems has to be made. The choice will be based on a number of criteria depending on the accuracy requirements of the application.

For any positioning accuracies better than ±100m a camera/GPS interface will be required. Requirements outside this could be determined by manual means, either by a manually controlled event switch connected to the receiver, or by logging a stopwatch split-time that has been synchronised to GPS time. Data of this quality would be of little or no use beyond a rough estimation of the exposure position.

A single point position installation using a stand alone receiver would give camera position accuracy within 100m, 95% of the time. This installation can be improved to better than 5m positioning capability by addition of real time differential corrections, either from ground based or satellite borne transmission systems. Differential corrections can also be applied after the mission if GPS mission data is recorded on the aircraft (and simultaneously by a ground receiver).

For single point or differentially corrected positioning the displacement vector between the GPS antenna and the reference node of the camera is not an issue for typical general aviation type installations. The next stage of improvement is where the most benefits can be gained. Combining ground and airborne GPS carrier phase data improves positioning accuracy to the 0.1-0.2m level. This capability, which is highly desirable for photogrammetric applications, is subject to a number of conditions being met, particularly in receiver design and features. Dual frequency receivers have advantages over single frequency models. All sources of error are critical, e.g. the displacement vector is now a substantial source of error within the photogrammetric system, and timing is also a critical component.

To extract the most benefit from this equipment it may be desirable to not only be able to precisely determine where the photograph was taken, but to also position the aircraft using the real time position data from the GPS receiver itself. This would reduce the navigator's work load and lead to savings in other areas. The scope of the installation is only limited by the budget and to some extent, the imagination of those involved.

6.2.2 Execution with a GPS receiver

This installation is the simplest to contemplate but can deliver little in the area of cost reduction and related benefits if not utilised efficiently. A stand alone receiver will provide position information that is probably best suited for photographic indexing, given that it is only used for the singular purpose of providing camera event positions. Planning and execution of such a mission would require the same configuration as that required for that particular camera. The crew's workload would be increased with the addition of ensuring that the GPS receiver and its sub functions, e.g. data logging, are operating correctly.

It is possible to extend this scenario through to the carrier phase level of positioning. Although the precise relative positions of the camera stations have been determined, the navigator is still subject to the vagaries of his art. His workload in this simple installation has increased and there are few benefits in a photogrammetric sense. The great benefits from this installation result from the huge reduction in ground survey control requirements.

Today, the aviation community is very aware of the impact of GPS on their operations. Panel mounted aviation GPS receivers are common. Although not suitable for the photogrammetric application, they can provide navigation information which is valuable for steering to the project area, and limited information while flying a photographic strip. These systems are not user friendly for input of numerous way point data, and provide no means to check that entered data is correct. Such systems are never foolproof.

Utilising such an installation will immediately reduce the navigator's workload, and in some cases where a camera operator was required previously he can be dispensed with. The pilot then has his own source of steerage information which will assist in maintaining the flight line. The camera on/camera off sequence can also utilise this data but the intervalometer is still an operational requirement.

The modern survey grade GPS receiver is a versatile piece of equipment. Most are capable of multi-functioning and providing various formats of GPS data. This capability can be extended to providing navigation data to proprietary software packages which generate interactive graphical navigation information and camera control functions.

This level of operation moves the process of aerial image capture from the analogue to the digital realm. For this level of operation the traditional navigator's map becomes redundant. Flight plans become digital. Exposure stations, either easting/northing or latitude/longitude, are prepared in mission flight plans, and stored in special format digital files. These files are loaded into the flight computer onboard the aircraft.

Such systems usually provide a graphical display for the pilot, and control the camera exposures. The overlap is controlled by the digital flight plans. The navigator's role is only to monitor the operation of the hardware and software systems, correct the camera alignment for drift and verticality, and ensure, if fitted, that the intervalometer controlled Forward Motion Compensation (FMC) setting is correct.

It is claimed that the ASCOT system (*Leica*) can be operated successfully by just the pilot! The benefits of such systems do not end with the actual mission. The digital aspects of the operation ensure that data about the photography is in a form ready for database and Geographic Information System (GIS) application.

6.3 Comments

From the author's experience the impact of real time GPS-camera-navigation hardware and software is a revolutionary step forward in aerial photography operations - regardless of the application. The introduction of such systems do have their drawbacks of course. Becker (1993) identifies some of these:

- *Air crews operating T-FLIGHT*[3] *are quickly lulled into total dependence on, and blind confidence in GPS.*
- *One of the most frustrating contradictions since GPS's arrival in aerial photography is the amount of time wasted: in the hands of a trained aerial survey crew, T-FLIGHT can double or even triple their daily production. Yet, lack of preparation, a bad satellite window or a recalcitrant cable, can halt the operation even under a clear blue sky.*
- *The close tolerance required to optimise flight plans for GPS-controlled photo navigation are far above the possibilities of conventional visual navigation. With recently trained operators being either not capable, or not equipped, to navigate visually, a GPS hardware failure will bring the mission to a full stop.*

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[3] T-FLIGHT is a commercial photographic flight management system used with the RMK TOP camera system from Zeiss

7. Implementation Concepts

7.1 The Ideal System

What is required from the "ideal" integrated navigation - aerial camera system?

The photogrammetric solution to the tilted aerial photograph is the resolution of the perspective centre coordinates and three rotation elements ω ϕ κ. These measurements, in conjunction with the lens focal length and calibration data, enables a mathematical solution for extraction of planimetric information from the photographic image. Overlapping pairs of stereo photographs extend this to include vertical data.

If the rotation elements and perspective centre coordinates could be delivered to the photogrammetrist at the necessary accuracies then the requirements of aero-triangulation could be dispensed with. Image generation could be handled in a more refined process.

A system, then, is required that can deliver in any region:

- navigational data to support camera exposures at predetermined spatial positions and headings within specified accuracies,
- the precise spatial position, commensurate with the scale of photography, of the perspective centre of the photograph at the instant of maximum exposure,
- precise attitude data of the camera system at the instant of exposure, and
- precise spatial position to support the local datum. This eliminates the requirement for ground control.

To complement the above, the system has to be robust, reliable and be adaptable to the environment of the aircraft.

System operation should be as follows:

a. Preflight - preplanned project exposure points be transferred to the aircraft navigation photo system.

b. Navigation system guides the aircraft to the project area via an auto-pilot interface.

c. The navigator has the choice of a number of options regarding the project. The selected option guides the pilot (or the auto-pilot) to the exposure points.

d. At each exposure point the instantaneous precise position and attitude data is logged to the system. This information is also exposed on the photograph.

e. At the completion of the mission all logged information for image processing is ready. The amount of associated digital data should be kept to a minimum.

f. Data is format ready for photo index key diagram and data base generation.

Such a system has to be operationally simple to use. The work load in an aircraft can become quite high particularly

- during periods of excessive turbulence,
- in the vicinity of other aircraft, and
- during periods of high radio traffic.

Add to this the requirement to navigate the aircraft and monitor the camera operation.

Aircrew generally work as a team, although the pilot flies the aircraft the navigator provides heading, positional information, camera control and assistance to the pilot by maintaining a lookout and radio listening watch. The introduction of an integrated navigation - camera system should not increase this load, ideally some reductions should result.

A decrease in aircraft operation workload should lead to productivity and efficiency gains.

The navigator's role should be one of monitoring the system's performance, allowing for simple yes or no decisions regarding the operation of this system based on predetermined criteria. The more sophisticated the system operation the simpler these decisions become.

A general trend with technology is that as its sophistication increases so too does its reliability. The down side is it is not adaptive, either it works or it doesn't . Makeshift repairs of core system operations are not possible because of:

1. the complex nature of the system, and
2. the level of understanding of the operators.

The term "simple" to operate implies that decisions related to its operation are based on yes/no responses.

Reference to the Global Positioning System has not yet been made in this section. Predicting how such processes work in the future should not be based on current methods. Can the current technology deliver the ideal system?

The technology is available that can provide, in real time, centimetre level positioning accuracy over distances up to 20km (GPS equipment manufacturer's promotional material). It requires data links for the transmission of phase and code information from a receiver located at a known location, to a receiver at an unknown remote location.

GPS receivers are available that can determine attitude information, alternatively, inertial sensor data can determine relative changes in attitude. Navigation software to direct the pilot is accessible from a number of sources. This role can be filled in some cases by low-cost hand held GPS units but this is detrimental to the process of integrating a number of systems.

Some software will assist the pilot to navigate the aircraft on planned flight lines and will expose the camera at predetermined positions. However, the instantaneous position is always an interpolated one, although another option is to expose the camera at the instant of GPS position fix. An identified problem with this option is the inconsistent mechanical action of the camera when commanded to expose.

Some systems available today do satisfy some of the requirements listed above. Leica and Zeiss offer integrated photogrammetric flight management packages but are still subject to the limitations of data update rates, the mechanical nature of the camera, the shortfalls of data post-processing, the interpolated position between GPS fixes, and the spatial vector between the camera and the GPS antenna.

7.2 The Real System

Unfortunately, the “ideal” world is not the same as the real world, the two realms only approach one another as the amount of money, technology and innovation directed at the problem increases.

The Surveyor General’s Department (SGD) was charged with the task of providing digital capture accuracies of sub 5 metre quality, for the lowest possible budget, given all the technologies and methodologies available at the time. The Angledool Project evaluated the new methodology of photogrammetry supported by airborne kinematic GPS control and new generation Forward Motion Compensation aerial cameras to provide quality digital products from 1:50000 imagery. The ability to provide this quality standard without the extensive coverage of surveyed ground control resulted in significant cost savings over conventional techniques (Mitchell and Dickson, 1996; Dickson et al, 1998).

Based on the outcomes of the Angledool Pilot Project (Mitchell and Dickson, 1996) the SGD proceeded to "gear up" to the challenge of mapping the Western Division of NSW for the Legal Roads Project. This "gearing up" would lead to some resourceful initiatives. These initiatives would be based on past experience, both internal and external, and observation of current operations of our own agency and others.

The concept and mathematics of the photogrammetric adjustment model was well documented. The aerial triangulation adjustment software to realise this model, PATB-GPS, had been evaluated in the Angledool Project (Fraser, 1994), although within the SGD some aspects were not fully appreciated or understood.

Photogrammetry and Surveying have been two disciplines that, although inter-dependent, have tended not to overlap with each other. The photogrammetrist relied on the surveyor to identify object or ground points and attach coordinates or datum points to them. The surveyor would be guided by the photogrammetrist as to what areas the control would be required. The two disciplines work together to produce a specific representation of the real world - the photogrammetrist builds the representation of the world, the surveyor provides the foundations upon which to build it.

The introduction of airborne GPS and the direct observation of the coordinates of the camera exposure stations has brought the two disciplines closer. Now each needs to have a much greater understanding of the other's discipline. Airborne GPS control can be considered as a photogrammetric measurement more than a survey measurement as it is the observation of a previously derived point within the photogrammetric model. When the concept of GPS drift is considered the GPS observation is only a relative one within the photogrammetric model. In these cases the role of **ground control**, although much reduced, is still the same for the photogrammetrist, and within an aerial triangulation adjustment is treated as so. But the introduction of exposure station coordinates to the aerial triangulation adjustment is a new observation type. The exposure station coordinates are no longer indirectly derived.

A thorough understanding of both GPS principles and the mathematical modelling of the photogrammetric adjustment is needed to be proficient in providing a balanced and rigorous solution to the fusion of the model with real world observations.

This was an important aspect of the SGD's approach to implementing a process to deliver the project in hand. A number of facets had to be addressed. The major challenge was the acquisition of equipment that could be fitted to the SGD's aircraft, and the ancillary items needed to support the proposed operation. Before procuring this major plant some conceptual model had to be developed that described how the process would work on an operational basis.

The GPS drift models of Ackermann and Friess had proven to be workable mainly because, from the authors experience, the process of achieving reliable ambiguity free solutions from kinematic GPS data (implying no drift) was not a proven process in the real world, on a day to day basis. The project author had a wide experience with kinematic GPS and was aware of its limitations, but advances in GPS hardware since late 1994 (low noise, multi-channel, dual frequency P-Code receivers) and new kinematic software (initialisation on the fly, wide-lane processing), although expensive, offered the promise of workable solutions.

The contractor who supplied the photography and photo centre coordinates as part of the Angledool Project highlighted a number of pitfalls that the SGD should avoid. Some of these observations were:

- Single frequency receivers - implies limited range, sharp fall off in performance, no redundancy in the data.

- Data logging times not on full seconds - not a problem as long as third party data is not used, fall off in coverage (time tag matching).

- Reliability - the performance of the contractors equipment required a high maintenance overhead.

- Poor user interface with receiver.

- Limited receiver use - full capability of receiver not realised, this may have been only a developmental problem, there were no navigation or camera control "smarts".

- Little understanding of the post processing software.

- High overhead on base station monitoring in support of operation.

- Non-dedicated systems within aircraft - no modular installation.

- Non-standardised processes in data handling and management.

These were therefore problems that the SGD wished to avoid in its implementation program.

7.2.1 Operational concept

It was envisaged that this new operation within the SGD would be based on the following objectives:

- All base station data supporting the aircraft operations would be supplied by the SGD's existing base station operation. This would be a centralised system supporting aircraft operations throughout New South Wales.

- The migration of the computer and GPS technology into the aircraft was to be as modular and as simple as possible. Operation of all equipment to be as automated as possible to reduce work loads within the aircraft.

- It was expected that some form of GPS navigation system would be implemented as a result of this project. Addressing the effective operation of this system being a key factor in the implementation program. This also implied that guidelines within the office flight planning stages be established to support standard and project photographic coverage.

- A digital data flow process that would yield a number of process and product improvements.

- Ongoing process improvements that could be introduced over the longer term.

The success in addressing these objectives hinged significantly upon the performance of the hardware and software acquired during the tender acquisition process.

7.2.2 The tender process

The challenges of the Western Division Legal Road Network Project (Dickson et al, 1998) and the successful outcomes of the Angledool Pilot Project (Mitchell & Dickson, 1996) paved the way for the SGD to address the question of how it would implement the process of GPS supported aerial photography.

In April 1994, a business case for the preparation of a restricted tender was presented to the SGD management. Part of that document stated:

"The results of that pilot project met the ***required ±1m accuracy****. Considering the large saving (around 75%) in the amount of ground control needed for the exercise, this is a*

significant finding. The savings are not simply in terms of cost, but also in the time required to put the ground control into place. This has enormous positive effects on response times and throughput. It is thus confirmed that the addition of suitable GPS equipment to the SGD's existing aircraft will improve efficiency and increase productivity significantly."

A draft tender specification was prepared in May 1994, but the process was not finalised until September 1994. The following tender requirements are abstracted from that document:

- Supply and install into SGD's Cessna 421 an aircraft integrated camera/airborne global positioning system.

- Provide three dimensional coordinates of camera air stations.

- Differential post processing system must be included.

- Airborne GPS antenna must be optimised for use on aircraft, electrical phase centre uncertainty must be less than one centimetre.

- The system must be able to maintain and/or recover lock.

- The airborne antenna must have a low susceptibility to multipath interference, especially for low elevation satellites. The antenna must be capable of receiving signals from any direction above the antenna's horizontal reference plane without significant signal degradation.

- The airborne receiver must be capable of storing data continuously for at least six hours at it's maximum sampling rate.

- Details of any necessary field procedures to support block coverage of a 1:250000 map tile.

- Supply of any ground station equipment needed to support aerial GPS operations.
- Position data must be compatible with SGD's PATB-GPS triangulation adjustment software.
- The system must provide derived ground coordinates of any well defined photo point to sub-metre accuracy in all three axes.
- Operate at the specified accuracy up to a separation distance from the ground station of 350km.
- Details of previous experience in this field and results related to proposed system.
- Details of training of up to six staff.
- Both single and dual frequency systems will be considered.
- System should be capable of exporting RINEX, version 2 (Gurtner et al, 1989, Gurtner & Mader, 1990) format data
- Provide details of a camera flight management system capable of interfacing between the camera and the GPS system, and controlling the firing of the camera within 100 metres of the optimal point.
- Alternatively provide details of a yoke mounted aviation GPS receiver.

This is a very "low tech" tender specification but the document did specify that the system should be "turnkey" and that demonstrated results were to be available from an operating example. The document did leave out the fact that a substantial amount of ancillary support equipment was required.

This "turnkey" solution and proven experience with this technology considerably narrowed the field of contenders. The author was invited to participate in the evaluation of the tenders to supply. The evaluation process was reduced to two contenders. One system that was currently in use in Australia, and an overseas operation. The evaluation results were based on the facts that one system was next generation, could fit in with the planned, conceptual, operational model and could pay for itself in cost savings over its competition in less than two years. If it could be proven to work!

At the tender evaluation stage the ancillary equipment problem was obvious. An **affordable** off-the-shelf fully "turnkey" product was not in the market place. The difficulty ahead lay in assembling a number of bits and pieces into a workable, integrated and simple to operate airborne GPS camera navigation platform. This also included the development of the necessary ancillary ground support systems.

The outcome of the evaluation resulted in the purchase of Ashtech Z12 GPS receivers, antennas and static/kinematic post processing software. The camera navigation solution was supplied by the Swedish National Land Survey (or SWEDE Survey as their commercial arm is known) using their Computer Assisted Aerial Photography (CAAP) package. CAAP is based on two PC based programs, NAVPRO for navigation and camera control, and CR21 for flight planning.

8. System Construction

8.1 Hardware

8.1.1 Considerations

The tender process only supplied the hardware and software necessary to initiate an airborne GPS acquisition system. The equipment supplied provided a means to:

- Collect dual frequency GPS data
- Time tag camera events against the GPS time scale
- Control camera events based on pre-planned photographic flight-plans
- Display graphic navigation data to the pilot and camera operator/navigator.

This equipment, although sophisticated, was rudimentary and at that time had never been brought together in an aircraft environment in Australia. This system was described in the various documents supplied by the tenderer, but being basically a unique, “once off” product the operational installation within the SGD’s aircraft had to be addressed.

It was obvious that the installation of this equipment would not be viable or made operational without a concept of how the components could be made to work together.

The SGD’s aircraft has a pressurised hull and this presents problems not encountered with non-pressurised machines. Any modifications to the hull are subject to engineering plans and specifications and as a result such work is expensive. Therefore, any proposed modifications would be subject to evaluation based on projected cost. Similarly, modifications within the interior are also subject to engineering specifications. The installation of the GPS navigation and camera control system would have to satisfy not only the SGD’s requirements but those of the aviation authorities.

8.1.2 How would this system be realised?

The author had some experience with aircraft navigation systems during a staff exchange program between NORTECH Surveys Inc., Canada, and the SGD in 1987. The configuration of their system is illustrated in figure 8.1. Note the pilot's display mounted on the instrument glare shield. Figure 3.1 (chapter 3) is the same unit under development in the offices' of NORTECH. The approach was to combine all components into one manageable unit. Most mobile scientific platforms are generally designed around a rack mount system. This type of installation was considered the most appropriate for the SGD's requirements, as a number of components had been identified as part of the overall operational module.

Figure 8.1 NORTECH navigation rack in aircraft 1987.

Operator training had been recognised as a significant component of the tender. This training was to be provided by the Swedish National Land Survey (SNLS), who were suppliers of other components. Advice was sought from the SNLS on how their components were installed within their airframes. Figure 8.2 is of the interior of one of Swede Survey's Aero-Commander 690 aircraft. It can be seen that their operational installation is not a modular or permanent solution. This is due to the pattern of utilisation of the aircraft in Sweden. The

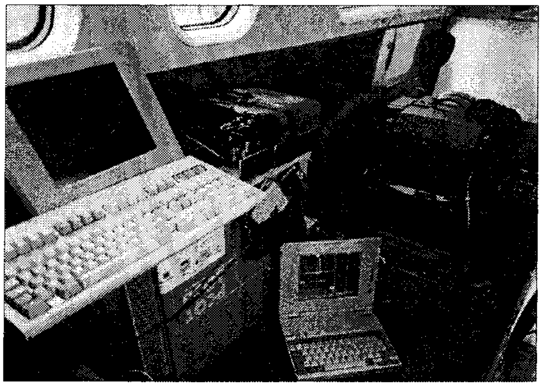
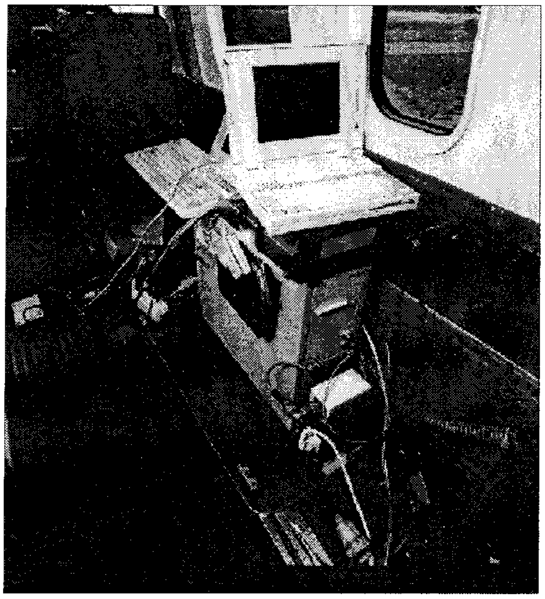


Figure 8.2 Above and below - GPS and Navigation system installation in Swedish aircraft.



photographic season in Sweden cannot support an aircraft operation that is dedicated to aerial photography only. Aircraft that are used for this process are multi-purpose so as to provide general aviation services during the longer winter months when aerial photography is not possible.

The following ancillary equipment had been identified:

- *The logging of raw GPS data would require a computer* - Early testing of this technology (Keel et al, 1988; Hein, 1989; Lucas & Mader, 1989) identified the advantages of high data collection rates. The Ashtech Z12 is capable of data rates of up to 10Hz. Evaluating the amount of raw GPS data that needed to be collected presented only two viable data-logging options:

    1. Purchase the GPS receiver with sufficient internal memory to record in excess of 3.5 hours of 1 second, dual frequency data.

    2. Provide a dedicated external personal computer to log the same data directly to hard disk.

    The latter option appeared to be the best for the following reasons:

    - receiver internal memory capable of retaining up to 15Mb of data was not easily available, if it were, it was extremely expensive. Furthermore, a 10Hz data collection rate, if adopted (the normal rate would be 1Hz), would increase the amount of data by a factor of 10!

    - transferring data from the GPS receiver to an external storage platform (PC) required connections to an external device, an extended period of time to transfer the data, and some means of sourcing power in an environment where power utilities are not readily available

- *The provision of camera control and navigation display would require a computer* - The essential element of the tender acquisition was the supply of equipment to provide 3 dimensional GPS coordinates of aerial photo centres. An option to this was some sort of navigation system that could improve the efficiency and reliability of the photographic procedures. The accepted tender was the Swedish CAAP (Computer Assisted Aerial Photography) system. CAAP is built around the camera control/navigation software NAVPRO, and the supplemental planning utility CR21.

The requirement was then for two dedicated computers to address the two independent functions of GPS data-logging and aircraft navigation.

The criteria for the modular rack design was then somewhat defined. The internal dimensions of the aircraft and a location which would not compromise safety also contributed to the rack design. A 600 x 600 x 600mm computer mounting rack was the most acceptable housing given the space available within the aircraft.

This unit is a standard office/industrial item. It could accommodate three standard components and included a small draw that could be used to house, for example, a pull out computer keyboard. The tenderers were able to offer a fascia, into which the GPS receiver could be mounted, that was rack mountable. This then filled the three available slots.

8.1.3 Computer considerations

Cost is always a consideration in the implementation of this technology. One guideline for the purchase of computers was to keep the costs to an acceptable level. Again off-the-shelf units were sought, being industrial design types that were rack mountable. These were 486DX/66 models, fitted with 500 megabyte hard disk drives (sourced from laptop PC designs), 3.5 inch floppy discs, 16550 UARTS for communication and Ethernet cards for networking.

The laptop disk drives were considered necessary as their design tolerated the high dynamic loads that might be experienced within the aircraft, the UARTS promised reliable communications and functionality over earlier designs, the Ethernet provided a local-area-network to ensure reliable data transfer and the floppy drive provided an initial means of moving data to and from the aircraft (this was soon found to be totally inadequate).

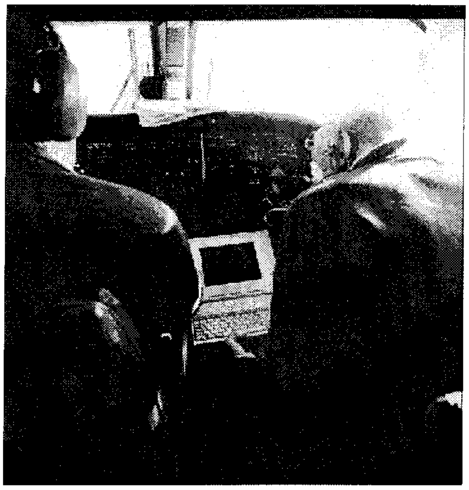


Figure 8.3 Navigating with laptop.

Still to be addressed was the challenge of providing a graphic display medium in the cockpit environment. Swede Survey were currently using a laptop PC on the pilot's lap, figure 8.3, to provide the navigation function. They had also experimented with a small LCD television to provide the display medium. They reported that neither system was ideal (personal communications). A problem in the cockpit is the amount of sunlight that enters, bearing in mind that photographic sorties are only flown when there are no clouds! This creates problems viewing displays and requires, in most cases, special modifications. Room within the cockpit, positioning and size all place limitations on the physical attributes of any auxiliary equipment.

The navigation function required a display of minimum dimensions that would be visible in direct sunlight and be VGA compatible. At the conceptual stage RGB to PAL to Video output was not considered a practical solution. A number of VGA LCD flat panel displays were available on the market in early 1995. The proposal was to purchase such a panel and mount it within the cockpit area. Unknown to the author at this time was the fact that these displays were, and still are, not "plug-and-play".

The SGD purchased a flat panel controller card that could also drive a standard VGA screen (RGB), a JED Microprocessors Pty Ltd AT350 VGA Flat Panel/CRT Controller. Being able to drive two displays from the one card provided redundancy for the navigation display function. It also provided an alternate means for the operator to monitor the behaviour of the navigation system. The SGD purchased a SHARP LM64K101 LCD for the pilot's monitor. This display required two small circuit boards to support its operation:

1. A J351C LCD and high brightness EL board to provide a bias voltage for adjusting contrast and viewing angle.

2. A J351F back-light invertor to provide a 1200V supply for artificial backlighting. This was to improve performance in extreme light conditions, both dark and bright.

The components that make up the pilot's display, the LCD screen, the contrast controller board and back-light board, are shown in figure 8.4.

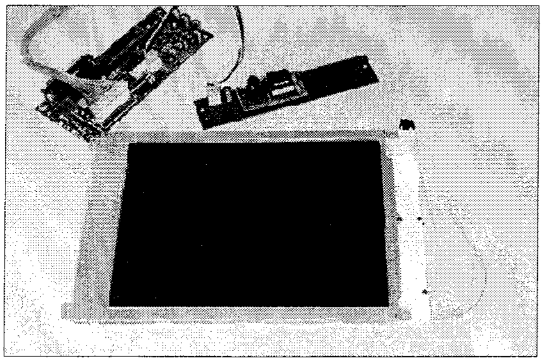


Figure 8.4 Components of pilot's display before assembly.

The external modular appearance of the rack was complete with the addition of two 9" monochrome monitors mounted on the top, a monitor for each computer.

The rack design was required to house two identical (apart from the flat panel driver card in one PC) 486/66DX computers, the GPS receiver, and mounted on top were two 9" VGA monitors. Figure 8.5 shows the rack under construction at the SGD (the door was soon to be removed).

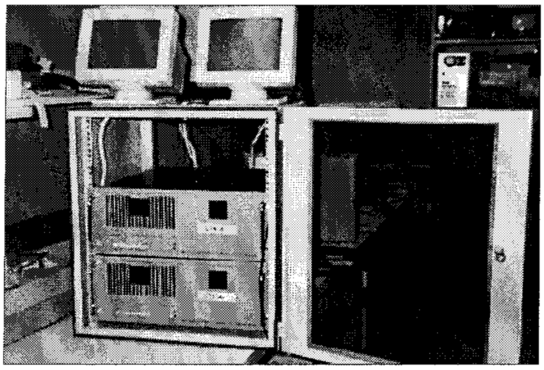


Figure 8.5 Computer rack being assembled in the SGD's offices.

8.1.4 Power

8.1.4.1 Power supply

A fundamental challenge of this installation was to reliably power this equipment. The SGD's aircraft is a nominal 28V direct current (DC) electrical system. It does not have any built in system for generating 240V AC which is the requirement most standard electrical appliances use. Aircraft such as the Air Ambulances have engine driven 240V AC alternators to provide power that medical equipment on board the aircraft may require. The provision of this type of power supply on board an aircraft is usually best arranged at the time of manufacture as "after market" modifications are very expensive.

The SGD was tied to some mechanism of providing 240V AC power, primarily through the demands of the two VGA monitors. Off-the-shelf 24V DC monitors were not an option given the budget given to work within. If 240V AC could be reliably produced then the computers could also be powered by this voltage!

The computers could have been purchased with 24V DC power supplies, but the 240V AC solution also had the advantage that the computers could be used in a normal office environment. This allowed for repairs and upgrades to be carried out and tested outside the aircraft. Using the 24V power of the aircraft required that the engines be started and ground run, as the aircraft battery does not have the capacity to power the system for extended periods, as may be needed for system testing and maintenance. Also, at this stage of development the SGD did not have a ground power unit to support the aircraft electrical system whilst on the ground.

The 240V AC power system had the advantage that the computers and screens could be run on the ground by just plugging the system into the normal hangar power using an extension lead.

The solution to the 240V AC requirement was a 24V DC to 240V AC invertor. Invertors are heavy and expensive, pricing is around $1 per WATT, and weight increases significantly with performance for typical invertor designs. The SGD purchased a POWERBOX UPG1500E, an electronic invertor whose non-typical specification was:

Input Voltage	24V
Input Current	71A
Output VAC	230V
Power cont.	1500W
Power surge	6000W
Weight	2.3kg

The weight of this invertor for its power output was an attractive feature given the weight restrictions that the aircraft operates under. It is also desirable not to have heavy components that can, if they become dislodged for any reason, become a projectile within the cabin area.

The demand on this invertor was to power the two computers and the two monitors. The overall load of these devices, two screens and two computers, was estimated at 540W Max. There was obviously plenty in reserve as far as the load capabilities of this device were concerned. Unfortunately, as development and testing proceeded, the design was found not to be up to expectation. Early testing proved problematic, but not having had experience with such devices beforehand, limitations were tolerated. The invertor was later to prove inadequate for the job, and was replaced by necessity when it expired with a frightening bang.

8.1.4.2 Receiver power

The Ashtech Z12 receiver is designed to accept DC voltages in the 10 to 32 V DC range which was compliant with the aircraft power system. The Z12 was mounted on it's own fascia panel. This panel, when mounted into the rack, prevented access to the receiver's power switch. To facilitate control over the receiver's operation a remote switch was installed on the fascia panel of the Z12 mounting frame.

8.1.5 Aircraft modifications

8.1.5.1 Navigation rack

The overall design of the installation had been determined. These model requirements were then communicated to the aircraft maintenance contractor for the physical installation, compliant with engineering specifications, of the rack into the aircraft. This required evaluating the power requirements, the structural integrity of the rack and fitting suitable mounting feet so that the rack could be fitted to the standard floor rails, ensuring the restraint of the unit in the event of high 'G' loading. The two screens were mounted on top of the rack in a position similar to that in figure 8.5. These screens were also restrained in an acceptable manner.

The positioning of the rack had been decided as being directly behind the pilot's seat. This location was the result of much debate. Originally, the aircraft had been configured for a three man crew and has a number of "holes" in the floor to accommodate the camera configuration. The primary drift-sight, which is slaved to the camera, i.e. the drift sight remotely controls the attitude aspects of the camera as well as its operational functionality, is mounted in the cockpit in front of the co-pilot's seat. To accommodate the drift-sight the co-pilot's control yoke has been removed and the glare shield has been modified so that the navigator can get his eye over the eye-piece without his head interfering with any hardware. Another drift-sight hole is located behind the pilot's seat.

Configurations using the various options were further constrained by the location of the emergency escape hatch on the port side and the requirements of weight and balance for aircraft performance. The most compliant location was then determined to be directly behind the pilot's seat. This allowed the operator, who would still occupy the co-pilot's seat, to monitor, by glancing over his left shoulder, the computer screens, camera and GPS operation. He could still operate the drift sight and assist the pilot by keeping a lookout for conflicting aircraft.

This position was also acceptable to the maintenance contractor.

The contractor elected to mount the invertor under the floor of the aircraft and the wiring was installed in such a way that three military specification outlets, 2 x 240V AC and 1 x 24V DC, were provided on the lower starboard side cabin wall trim. This is illustrated in figure 8.6.

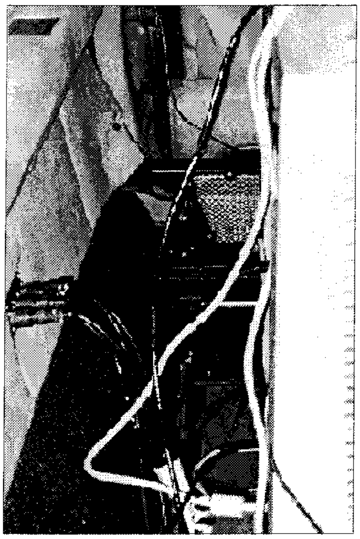


Figure 8.6 Original power outlets on cabin wall behind rack.

The whole electrical system for the rack installation was protected by a 10 Amp hour circuit breaker mounted on the cockpit fuse panel adjacent to the operator's right hand knee. In the event of an invertor overload the circuit breaker had to be cycled to reset the invertor. This, as it eventuated, was not an acceptable arrangement as cycling the circuit breaker also cycled all power to the equipment rack. Still, a reset of the invertor usually meant that power to the computers had been interrupted and consequently data-logging had been interrupted!

Most of the initial hardware requirements had been addressed. Although not critical to the operation, keyboards for the computers were still an issue. A standard 101AT keyboard was considered too cumbersome for the aircraft environment. Two German designed CHERRY keyboards were acquired for the task. These keyboards are very similar in size and functionality to laptop size units but provide the remote operation of the desk type 101 design via a coiled inter-connective cable. Unlike the 101 design, this keyboard can be easily stored in the rack drawer.

Within the rack, cabling for the 240V AC power was provided by modifying standard PC power leads to be acceptable to the military type wall outlets installed by the airframe contractor. Similar modifications were made to provide 24V DC by modifying the standard

Ashtech power cable.

At this stage of development the components within the rack were operational. Ancillary interfaces for networking, data-logging, navigation display, antenna and camera control remained to be addressed. These ancillary interfaces were considered to be software modules rather then hardware components, and would be addressed individually.

A final requirement of the contractor was to test the electromagnetic radiation generated by the operation of the electrical components. This was to ensure that aircraft avionics are unaffected by any electrical radiation. At the time of testing, and to this day, the operation of the system has had no effect on the avionic systems of the aircraft.

It was expected that the installation of this system would result in improvements in operational efficiency. The anticipated gains in aircraft endurance through the removal of one crew member would be measurable but as the navigation rack approached the operational stage any gains in this area were quickly eroded. It's weight at this stage was around 60kg! Laptop computers had been considered, particularly from a weight and size perspective. Unfortunately they were not really suited to applications of this type as in the event of a failure they generally have to be returned to the manufacturer, their expansion capability is limited and they are somewhat fragile. They can also become obsolete very quickly.

8.1.5.2 Antenna position

Ideally the GPS antenna should be positioned as close as possible vertically above the camera axis, whilst the aircraft reference system is in its typical operational attitude. This location would provide the smallest camera-GPS offset vector, minimising a known source of error. The antenna should also be positioned so that any signal shading is avoided. On most aircraft the greatest source of shading results from the vertical fin, but this effect is minimal if the antenna is positioned co-linear with the fin centre-line. Aircraft with twin vertical tails or V-tails only increase the chance of signal shading and should be avoided.

High wing aircraft are also more prone to signal shading by the aircraft's propellers.

On low wing aircraft the shading effect of the wings is minimised because the antenna on top of the fuselage is above the roll centre of the aircraft, the effect of the wings is not apparent until steep bank angles are encountered. On high wing machines the wing shading is more immediate because the antenna is located on the roll centre. The top of the fin provides the most un-interrupted satellite views, but its remote location greatly increases errors in the camera to antenna vector offset model.

Signal loss will be experienced any time the aircraft roll angle or bank exceeds the minimum elevation tracking angle away from a low elevation satellite. This will result from the shading effect of the fuselage as the antenna rolls away from the horizontal.

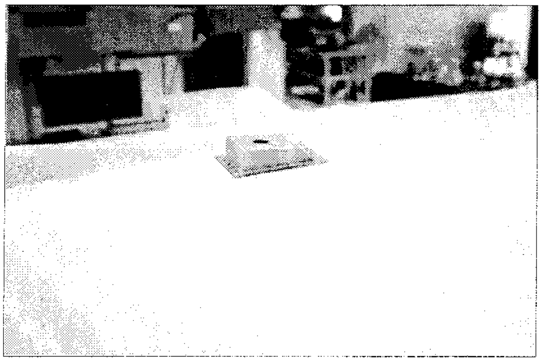


Figure 8.7 View of antenna base fairing adjacent to fin spine on VH-NSW.

Hawker Pacific, the SGD's aircraft maintenance contractor, was requested to position the Micro Strip dual frequency antenna as close to perpendicular above the camera as possible. Figure 8.7 illustrates the flared antenna mounting box during the installation process. The antenna is adjacent to the aircraft centre-line just near the fin extension fairing. The GPS antenna location and the aerial camera position were then surveyed within the aircraft reference system. The aircraft reference system has the primary axis defined as the aircraft centre line from nose to tail. The relationship between the antenna and the camera is then determined within this frame. The aerial triangulation adjustment software, PATB-GPS, uses this orientation for establishing the offset vectors between the camera and antenna.

The offsets were determined using a Wild T2 theodolite, a string line, a straight edge, plumb bob and pocket tape. A simple process of projected straight lines was used to locate the antenna and the camera within the aircraft reference frame.

The aircraft was positioned on jacks on the concrete floor within the Hawker Pacific hangar. The centre line of the aircraft was defined by projecting the nose and tail points to the floor using the plumb bob. Connecting these two points realised the aircraft centre line on the hangar floor. The theodolite was then positioned so that the extremities of the antenna (both sides) could be clearly sighted. Each side of the antenna was then observed. The vertical arc was projected to the floor and a straight line was drawn based on the position of the vertical cross hair. This produced two slightly divergent lines on the floor of the hangar. The theodolite was then positioned at a location which was approximately 90° to the first pair of lines and the same observation process carried out. The position of the antenna was then projected to the hangar floor. This determination was quite easy as the antenna position was easily visible from points around the starboard side of the aircraft. The fin fairing obscured the antenna from the port side!

The same technique was used for determining the camera location but was more difficult as sight lines could only be made through the aircraft access door and the windows. The projected arcs were positioned on the fiducial marks of the camera plane. Problems were encountered when locating another viable observing point other than the access door. The only option was to use a plumb bob and observe the string through one of the observation windows. Because the aircraft is pressurised, the windows are convex by design. The effect of this was to refract the plumb bob string. To minimise this the observation points were made at the extremities or perimeter of the window porthole. Figure 8.8 illustrates the theodolite and the open access door.

The vertical offset was made using the pocket tape. This was simply the vertical measure from the camera image plane to the base of the antenna mount.

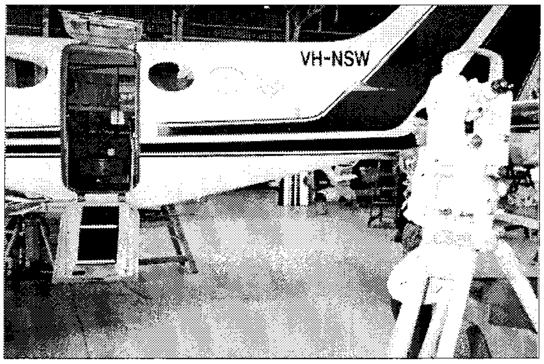


Figure 8.8 Determining the camera - antenna offset in the Hawker Pacific hangar.

There are other means to determine the antenna-camera relationship. An alternative would be to use an electronic tacheometer to determine the aircraft reference axis by directions and distances. This would require some calculations but would have used less set up points and not been subject to the refraction of the window!

The determined offsets were: X: -0.010m Y: 0.080m Z: 1.081m

The focal length of the lens in use is added to the Z measurement.

The expected measurement error of the offset vector is estimated to be < 1cm.

8.1.5.3 Antenna installation considerations

The antenna installation has already been addressed but it is important that it is installed correctly! Quite common today are pre-amplifiers that are part of the GPS antenna body or incorporated as an in-line module in the antenna cabling. The latter can be a problem if not connected with the right polarity, i.e. the right way round. The author is aware of one GPS installation that delayed a contract delivery of an aircraft because the in-line antenna pre-amplifier was installed the wrong way around! The problem still existed after returning all the components to the United States for checking. The lesson learned from this episode is to engage people who are conversant with the technology when installing such equipment.

A simple reversing of the pre-amplifier changed a "dead" GPS receiver into a fully operational airborne GPS platform!

8.1.5.4 Pilot's display

The pilot's display proved to be a challenging aspect of this project. What was actually desired and what was available, and to this day what is available, is far from ideal. From the author's viewpoint, what was needed was a display that would:

- be visible in bright sunlight,
- be VGA compatible,
- be very thin,
- be the minimum size in length and breadth (suitable for the cockpit area) but still be clear to read, and
- be an acceptable operational component to all involved parties.

Having used the navigation software in the office environment on a 14" display, it was obvious that there was a minimum screen size below which data would be unreadable.

The display purchased was described elsewhere (section 8.1.3) and is illustrated in figure 8.4. According to the documentation, the PC controller card was capable of driving the screen over distances up to 5m via a standard 25 pin printer cable. This ensured that the screen and the rack could be accommodated within the planned system.

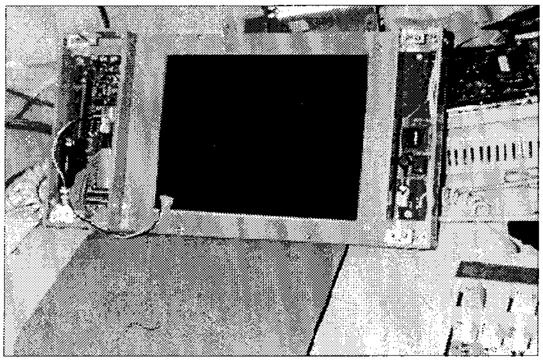


Figure 8.9 First attempt at pilot's display, overall width is too great.

The length of the cabling provided with the two small circuit boards necessitated that the screen and the circuit boards be in very close proximity, basically mounted on the same platform. The author designed and built the first prototype illustrated in figure 8.9. This version was not acceptable to Hawker Pacific's engineers because of its size, particularly its width. A second version was produced that was reduced to the width of the screen, the circuit boards being mounted on the back of the screen. A 10,000 Ohm linear potentiometer is used so that the contrast can be suitably adjusted and a small switch is provided to turn the back-light on and off as needed. This version has been in service for almost four years without a problem.

A temporary mounting which utilised an omni-directional arm ensured that the screen could be configured for any reading angle. The trans-flective nature of the screen presents particular problems for users wearing Polaroid glasses. In this case the screen must be rotated 90° to view screen data, or the screen appears opaque.

Having assembled the main hardware components of the system a test flight was conducted to see if the process of logging GPS data to the onboard computers would actually work. **The successful flight was conducted 20th February 1995, 8 weeks after delivery of the first components!**

The implementation procedure then focussed on the training aspect of the program.

8.1.5.5 Training

Training was offered in two components:

- GPS operation and processing, and
- CAAPS - Computer Assisted Aerial Photography System.

Having had extensive experience in the use and processing of GPS data this training option was not activated. CAAPS training proceeded as this was a new operational development for aircraft procedures. This involved bringing a trainer from Swede National Land Survey to the SGD. Aspects of the training included flight planning procedures and use of the NAVPRO software.

Using the aircraft for the camera control and navigation software training was out the question as it was expensive and inefficient. It was inefficient as the aircraft would only be able to accommodate one operator and the trainer for each flight. It also required that the equipment installation within the aircraft and its operation be reliable enough to support a training environment. Also considered problematic with using the aircraft were the consequences of unfavourable weather. The budget only accommodated the Swedish technical officer for a limited time period.

This problem was overcome by using a dynamic, ground-based training system. An eight seater van was fitted with a GPS antenna, the Ashtech receiver was connected to a 12V battery and a laptop computer was loaded with the software. The flight planning software was used to generate "flight lines" across a large recreation reserve situated on the flood plain of the Macquarie River in Bathurst. Although the setup was rather crude, and the full camera functionality was not realised, the ground simulation was sufficient to train the involved aircrew in the operation of the NAVPRO software.

The van driver (the pilot) was able to navigate along the "flight lines" using the NAVPRO's graphical display. The operator was able to travel through various screens and functions just as he would in a typical photo mission. The camera interface was the only component missing from the simulation.

Before the sign-off of tender compliance could be made the full operation of the camera control/navigation system had to be demonstrated. This flight was successfully conducted over Bathurst on 1st March 1995. The full functionality of NAVPRO was demonstrated and the performance of the hardware components were proven. However, this flight, and subsequent operational flights, revealed many bugs and weaknesses that were to be addressed as the project matured.

8.1.6 System overview

The physical design of the aircraft data capture and control sub-system is illustrated in figure 8.10. This is the configuration as it is today.

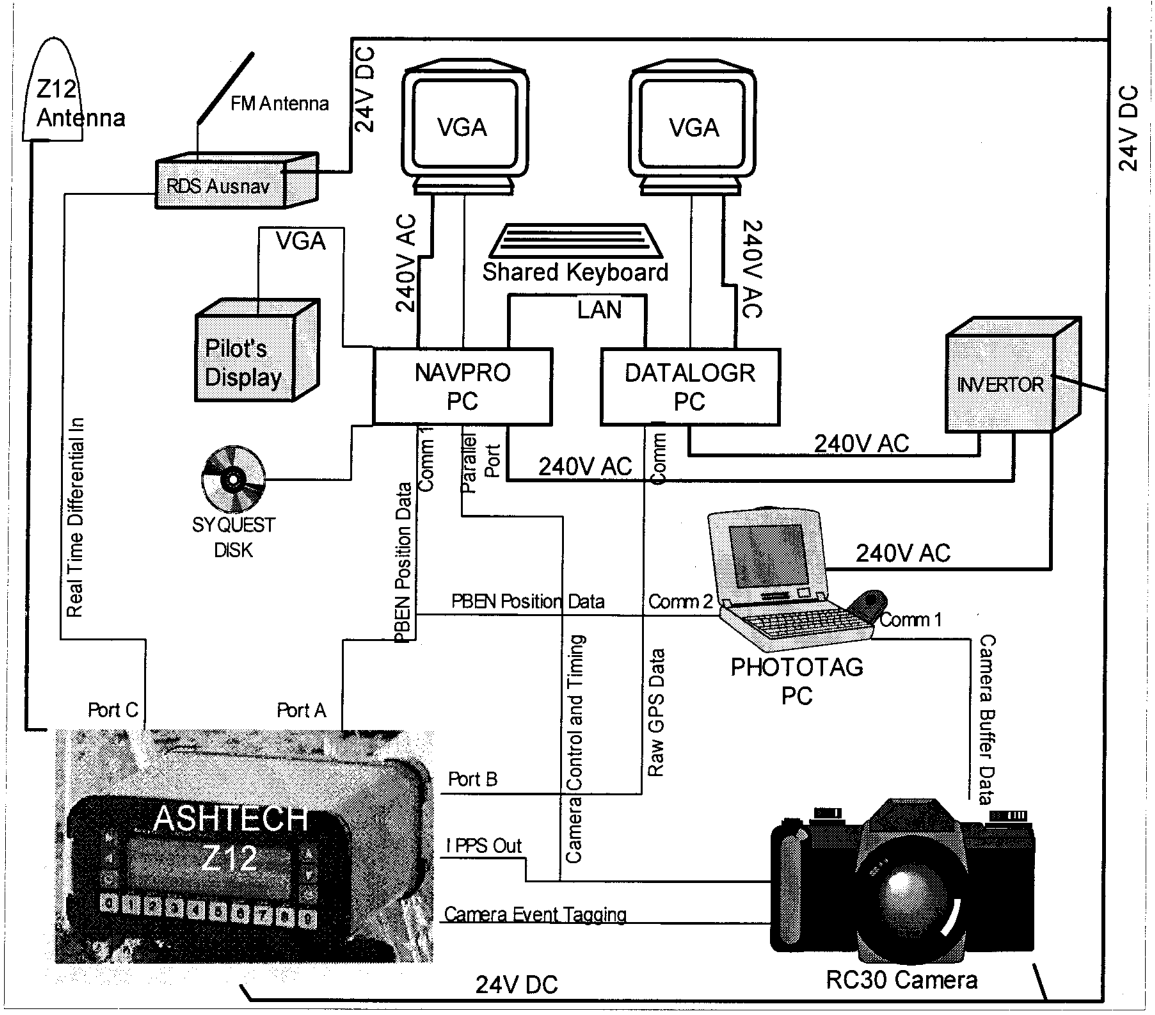


Figure 8.10 Connectivity diagram for aircraft navigation, data-logging and camera control sub-systems.

The following figures 8.11 to 8.13 are photos of the computer installation in the aircraft.

Figure 8.11 Rack mount behind pilot's seat. Not visible here the Phototag laptop is mounted on the rack between the pilot's seat and the rack.

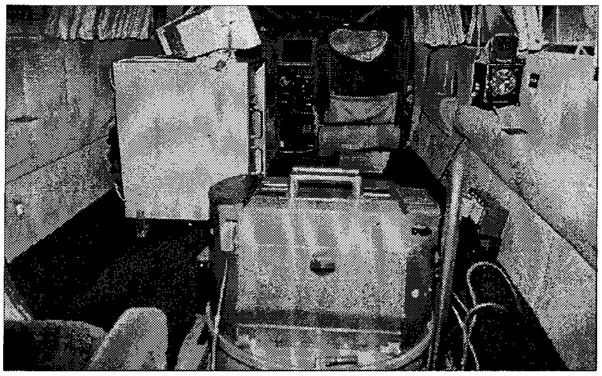


Figure 8.12 Inside aircraft looking forward over camera. Note the pilot's screen between seats.

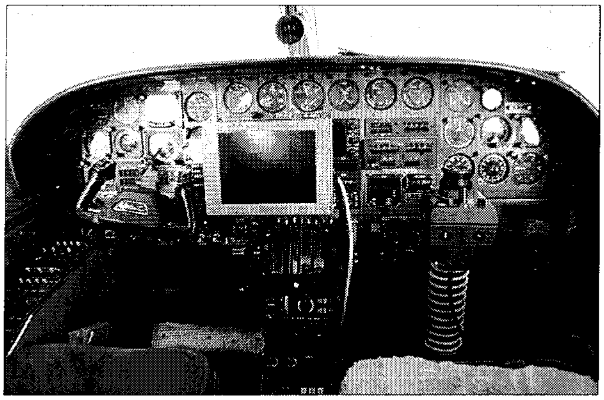


Figure 8.13 Cockpit showing pilot's screen.

8.2 Software

The dedicated nature of the computer processes, and the platform that the software was designed to run on, demanded that the operating system be DOS-based. Multi-tasking platforms were considered in the planning stage whilst evaluating the tender package. A multi-tasking platform such as LINUX would have eliminated one computer, and the subsequent extra screen, resulting in reductions in equipment weight. A multi-tasking platform was also expected to enhance computer reliability and performance standards.

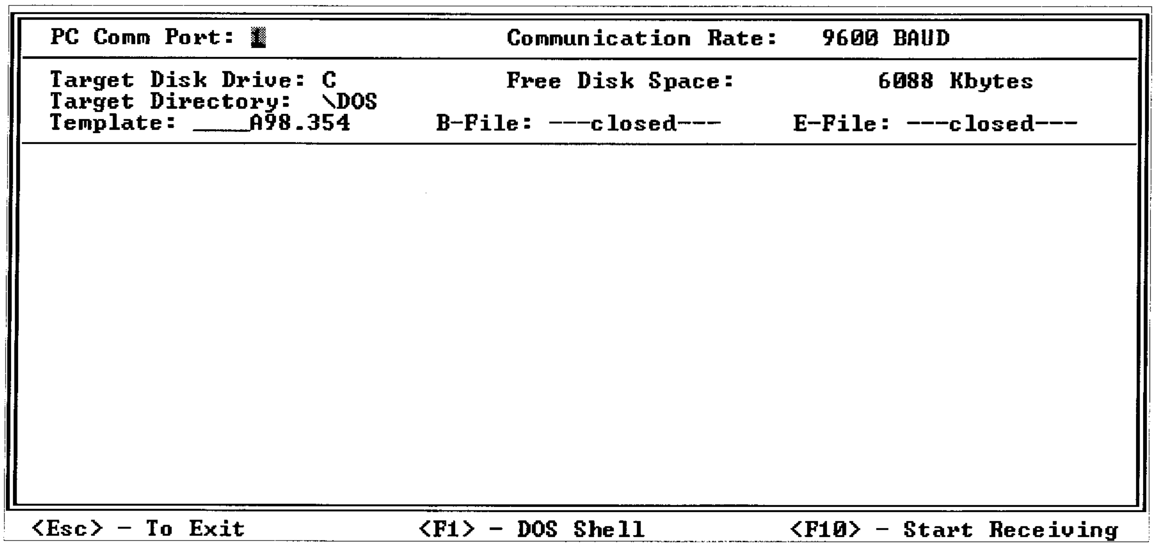
Against the use of such platforms was the lack of suitable software to perform the desired functions. Such platforms would have required the writing of source code to do the jobs that were already possible in the DOS environment.

Both DATALOGR, the Ashtech data-logging software, and NAVPRO are interface software which provide functionality through the RS-232 and the parallel ports of the PC.

8.2.1 DATALOGR

DATALOGR is a proprietary DOS-based software supplied with Ashtech GPS receivers. It has been designed to function with a range of Ashtech receivers. When in operation it directs raw GPS data, Ashtech MBEN (measurement) and EBEN (ephemeris) data, to a PC hard disk via one of the nominated RS-232 receiver ports of the PC. The software is initiated via a command line entry at the DOS prompt. In its usual mode it is keyboard interactive and requires that a number of parameters be entered before the logging process can begin. Figure 8.14 is an example of the data logging screen before logging has begun. An input checking routine ensures that each prompt needs to be addressed before the program will progress to the logging stage.

For this operation 38400 baud rate was selected using communication port 1 on the PC. Although higher transfer rates are possible, the author had concerns about the reliability of higher data transfer rates. This configuration has proven to be adequate for situations where as many as 12 satellites are logged simultaneously at one second data rates. The



```
PC Comm Port: 1                   Communication Rate:   9600 BAUD

Target Disk Drive: C              Free Disk Space:          6088 Kbytes
Target Directory:  \DOS
Template: ____A98.354     B-File: ---closed---      E-File: ---closed---

<Esc> - To Exit           <F1> - DOS Shell          <F10> - Start Receiving
```

Figure 8.14 DATALOGR configuration screen.

GPS data is transferred to the current default computer drive and directory, unless otherwise nominated under `Target Directory`. File naming of data files is based on the naming convention provided in the template field, a 4 character identifier. The template adopted for the aircraft data is ***NSW1***. This is based on the aircraft's call-sign or registration identification, VH-NSW. The number ***1*** denotes the sequence file number for the day, for situations where more than one file is generated for a day's work. The remainder of the template is based on the last two digits of the current year and the local Julian day. This information is generated from the PC system time.

When the templates are correctly filled in then the F10 key can be pressed to initiate the data- logging sequence. The program will also detect duplicate file names, which avoids the problem of over-writing valid data files.

The data-logging sequence is terminated by pressing the ESC key. This will end the data-logging function and close down the RS-232 port of the GPS receiver and the PC, leaving the receiver correctly configured for the next logging mission. The effect of this action was identified very early in the implementation phase. To avoid an inadvertent termination of the data-logging function, the keyboard was disconnected from the computer. The use of one keyboard for both computers ensured that the logging function could not be terminated whilst camera navigation was in progress.

The necessary data-logging action was now operational although in a rather rudimentary form. The GPS receiver was providing raw dual frequency GPS data at a 1Hz data rate via receiver port B. The satellite elevation tracking angle had been set to a minimum of 5° above the horizon, ensuring that tracking was maintained for as long as possible. This also provided more leeway for aircraft manoeuvring. The receiver antenna was operational, the cable being routed across the cabin floor and up the cabin wall, hidden by the trim of the aircraft interior and the power for the receiver being supplied directly off the aircraft's 24V system.

8.2.2 NAVPRO

The installation and operation of NAVPRO in comparison to DATALOGR is a little more complex. Primarily, NAVPRO requires an aerial camera which has an electronic interface. The Leica RC30 used in the SGD's aircraft is such a camera, designed with computer interface capability.

Apart from a suitable camera, NAVPRO's operation requires a number of inputs. Firstly, it is essential that it have navigation information. The software can be configured for a number of GPS receiver types. In some cases it will interpret receiver dependent message strings. The configuration of NAVPRO with an Ashtech Z12 receiver requires that the PBEN message string is available from the receiver. This string must be configured as binary format and output every second. The structure of this string is shown in table 8.1

The receiver should also be configured to output a TTT NMEA message string which time tags any event that the receiver has recorded. The format of this string is ASCII and is a standard NMEA message. For the software to operate successfully the PC system time must be aligned as close as possible to GPS time. This is achieved by reading the 1 Pulse Per Second (1PPS) available from the GPS receiver and identifying the time tag of each pulse, and setting the system time to it. The purpose of this feature is to maintain camera control through short periods of dead reckoning when GPS data is unavailable, for whatever reason.

Table 8.1 Binary structure of PBEN data.

```
struct pben
  {
  $PASHR,PBN,              /* 11 bytes */
  long  pbentime;          /* 4 bytes */
  char sitename[4];        /* 4 bytes */
  double navx;             /* 8 bytes */
  double navy;             /* 8 bytes */
  double navz;             /* 8 bytes */
  float navt;              /* 4 bytes */
  float navxdot;           /* 4 bytes */
  float navydot;           /* 4 bytes */
  float navzdot;           /* 4 bytes */
  float navtdot;           /* 4 bytes */
  unsigned short pdop;     /* 2 bytes */
  char;                    /* 1 byte */
  char;                    /* 1 byte */
  };
```

The third requirement is the interface to initiate each programmed camera exposure. The software will interpret the aircraft's spatial position in relation to the photographic flight plan. If the aircraft is at the desired location then the camera will be instructed to expose a frame. The fourth interface is the provision of an event logging capability. This is provided via the event input terminal on the rear of the receiver. For the Ashtech Z12 receiver this option will record up to 3600 "events" internally within the receiver's memory. This event functionality is linked to the previously mentioned TTT message. When an event is logged a message is generated at the receiver RS-232 port.

NAVPRO provides these four interfaces via the following:

1. PBEN and TTT data is provided by receiver port A and is delivered to PC COMM port 1 at a baud rate of 38400.

2. 1 Pulse Per Second is provided by the receiver 1PPS output terminal. This is delivered to an interface box mounted on the camera Electronic Data Interface (EDI) terminal. The 1PPS is then transferred to the NAVPRO computer via the parallel output port (printer) of the PC.

3. The command function to expose the camera is provided via the parallel port of the NAVPRO computer. At the appropriate moment a pulse is sent from the computer to the same interface box on the camera EDI. This pulse results in the camera cycling through an exposure event.

4. The occurrence of a camera exposure, within 52μsec of maximum time of exposure (Leica RC30 Operational Manual), is captured at the camera event terminal on the rear of the Ashtech receiver. This precise timing capability is one of the critical issues for successfully managing this technology.

This design provides a closed loop operation that is robust and consistent, essential characteristics for a successful and reliable camera control and navigation system.

8.2.3 Flight planning

The introduction of camera control navigation software required that guidelines be developed for the process of image acquisition, for all facets of aerial photography.

The SGD is primarily responsible for maintaining an aerial photo library of the State of NSW. The Department runs a rolling program of aerial photography flown at a scale of 1:50000. This program systematically covers the State with aerial photography over a period of approximately four years. To the layman this program appears disjointed and inefficient but it is based on the capabilities of the aerial survey unit, the seasonal variations of solar altitude and the seasonal weather patterns throughout the State. As a result, the aircraft operates in pre-determined areas of the State depending on the time of the year.

A drawback with this program is the patchwork matching of photography along project boundaries which results from the seasonal and annual changes in the environment. It should be pointed out that edge matching problems aren't restricted to seasonal and annual photography. Problems can arise from adjoining runs flown at different times of the day. The appearance of the environment can change in a matter of days as a result of recent rains, the ravages of flood or bushfire, etc. Even the use of a different brand of film can change the appearance of the landscape in a photographic image.

The SGD will, from time to time, undertake larger scale photography, generally 1:25000, 1:16000, 1:10000 and on special project work for other agencies, as large as 1:500. All photography needs to be indexed in some manner. This indexing has been a manual process that is quite involved, inaccurate and labourious.

Photographic indexing, or creating a "key diagram", begins with a suitable copy of an appropriate topographic map. The key diagram system is based on the national 1:100000 topographic map index. Upon this map is placed the interpreted position of every second photograph along a photographic run. The interpreted position of the photograph is made by identifying the principal point of the image on the topographic map. Obviously, the accuracy of this procedure is dependent on a person's interpretation, and is also influenced by the type of landscape being photographed. In the western areas of NSW this identification process can be very unreliable because of the featureless characteristics of this region!

The topographic map is then annotated with a suitable legend which depicts such information as run number, dates flown, film numbers, lens type, job number etc. This map is then photographed and transferred onto clear film as a black and white image positive. This then becomes the master key diagram for that photographic map coverage, which can be reproduced as a dyeline copy for supply to any customer or agency. The major deficiencies in this whole process is the manual process, and the hard copy storage and recovery system of photographic image data. The data retained and its breakdown is sound, but this photographic data could be better accessed if it could be migrated to a digital data base system.

What is apparent from studying any of these key diagrams is firstly the inaccurate track that the aircraft follows along the photo run, and secondly the random displacement of photographic centres from one run to the next. The reasons for these variations are apparent after consulting the aircrew. The changes in cross-track along the line results from the various heading changes due to the manual map reading navigation that is employed. The offset in adjacent photo centres from one run to the next results from the "camera on" position at the start of the run, the intervalometer of the camera maintains the consistent forward overlap controlled by the "spiral lines" in the camera drift sight. Once lined up on the photographic run the camera is turned on, and the camera then cycles consistently as defined by the intervalometer setting, any adjacent alignment of photo centres between adjacent runs under this operational procedure is purely coincidental.

Although photography is quoted at a given height, implying a particular scale, the actual height flown can be quite different from that specified. Manual navigation requires a calculation on an airman's computer to determine the correct altitude for photography, based on the current area air pressure and outside air temperature. This is only a model of the atmospheric profile and can be quite incorrect in reality. This leads to scale changes in runs of photography which can make the task of building quality photographic mosaics quite difficult.

A navigational system with camera control could lead to improvements and efficiencies in a mapping program through:

1. guaranteeing side overlap specifications by providing real time information about the aircraft's position in relation to the projected line of the photographic run (cross-track),

2. providing far superior and more consistent height information,

3. reducing the amount of required photographs to a minimum, and

4. reducing the amount of photogrammetric observations of tie points which result from the alignment of adjacent photo centres.

An aerial photography project begins its life as a particular coverage depicted on a map or photograph. The SGD requirement was addressing the needs of the Western Lands Legal Road Project. It necessitated the 1:50000 photographic coverage of 22 1:250000 map tiles. Under current procedures the aerial survey branch would annotate suitable topographic maps with the various flight lines as required. Their general procedures were to fly two adjoining 1:100000 map blocks at a time.

Adopting this procedure for the Western Lands project would have necessitated extra ground control and more photography than required as a result of the ratio of tie runs to blocks flown, and the amount of duplicated exposures which would occur along block boundaries. (The previous statement is based on the minimum requirements of GPS controlled photography, where tie runs and four ground control points in the corners of the mapping block are necessary.)

It had been accepted that the accuracy of the aerial triangulation adjustment block supported by airborne GPS does not degrade as block size increases, and that it had been shown that it may be to advantage (Friess, 1986a; Friess, 1986b). Again, efficiencies were identified in capturing a 1:250000 map as one coverage block. There was some debate within the aerial survey unit about this, but mainly questioning whether it was possible to consistently fly 150km without breaking a run. This would require more operational changes for the air survey operations.

Having weighed up the various options the decision was made to proceed with photographic coverage based on the 1:250000 map tile. It was also decided that the photographic coverage for each tile would be flown in such a way that the top and bottom runs and the two edge tie runs of the tile would be centred along the tile boundary. This meant that these runs would be incorporated into the adjoining tile when it came to be aerial triangulated. Figure 8.15 illustrates this situation.

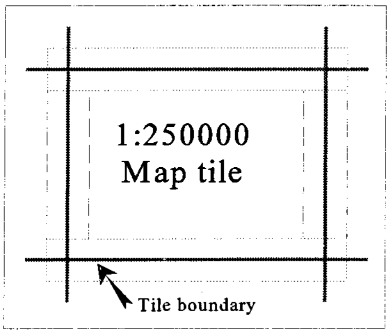
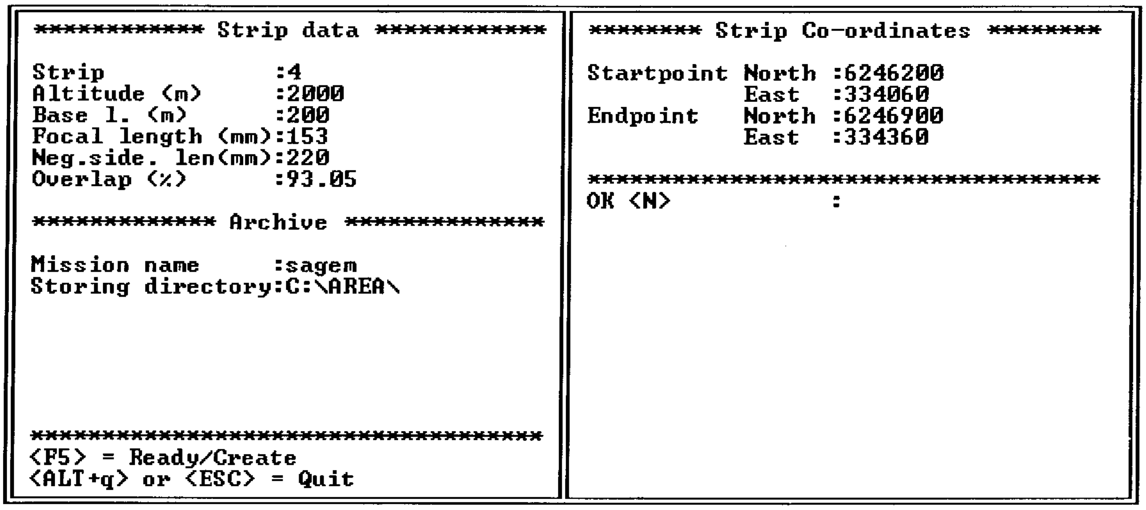


Figure 8.15 Edge photo coverage.

The navigation software for the aircraft promised to deliver "pinpoint" photography exceeding anything that the SGD had been able to attain before. How could this capability be addressed in the flight planning stage?

The flight planning utility, CR21, delivered with the CAAP package, can produce NAVPRO compliant flight plans based on a number of user entered parameters. An example of the input screen is shown in figure 8.16



```
************ Strip data ************      ******** Strip Co-ordinates ********

Strip            :4                       Startpoint North :6246200
Altitude (m)     :2000                               East  :334060
Base l. (m)      :200                     Endpoint   North :6246900
Focal length (mm):153                                East  :334360
Neg.side. len(mm):220
Overlap (%)      :93.05                   ************************************
                                          OK <N>             :
************* Archive **************

Mission name     :sagem
Storing directory:C:\AREA\




************************************
<F5> = Ready/Create
<ALT+q> or <ESC> = Quit
```

Figure 8.16 Input screen for CR21 (sample only).

The critical input values in this program are the start and endpoint coordinates shown in the upper right-hand window. If these are incorrect then the generated photo-centre coordinates which will go into the aircraft navigation flight plan will be incorrect.

The first option suggested to generate start and endpoint coordinates was the same routine used for manual flight planning, i.e. draw the planned runs on the topographic map and transfer the start and endpoint coordinates from the map into CR21. This was not a rigorous solution to the problem as sources of error still exist. Not only could a typo error occur but the map coordinate could be incorrectly read!

The SGD is a major GIS agency and retains many map tile databases. It was decided to utilise the 1:250000 map tile database as it provided a source of reliable consistent map boundary coordinates. Based on the edge coverage plan illustrated in figure 8.15 it was determined that for a 1:250000 tile, 14 east-west runs would be required. This provided an edge overlap of 25%, comfortably more than the required minimum of 15%, but the pattern would not have been possible without the side overlap concession.

A GENAMAP[4] script was developed that would output the zone dependent endpoint AMG

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[4] GENAMAP is a GIS software package used extensively by the SGD

coordinates of each of the 14 east-west runs and north-south tie runs of any 1:250000 map tile within NSW, taking into account terrain effect. This script was based on a coverage model where only one photograph fell outside the coverage area on the lead into the run and on exit. This also applied to the tie runs.

This photography plan ensured that stereo imagery was available for the complete map tile. Based on this plan it was then known that any standard Western Division map tile would be made up of 14 east-west runs of 35 exposures and 2 north-south runs of 29 exposures. A complete triangulation block then consisted of 548 exposures. This then delivered the promise of reducing film usage to a minimum!

The coordinate output file is then manually transferred to the CR21 program. This still remains a weak-link in flight planning process but external checking mechanisms have been put into place before a flight plan is accepted for insertion into the aircraft navigation system.

The NAVPRO navigation system operates on map grid coordinates, in NSW this is the Australian Map Grid, a Transverse Mercator system. Map grid coordinates in this case are zone dependent. In creating flight plans, care has to be taken to ensure that the correct zone is nominated both in generating the initial endpoints and when using these coordinates within NAVPRO.

After the flight plans have been generated by CR21 two checks can be performed on the data to ensure that the plans are correct. The first is to read the photo centre coordinates back into GENAMAP and actually plot them out. Blunders are evident immediately but smaller errors can be detected by zooming the image. The tie runs are planned in such a manner that every second exposure occurs on an east-west exposure point. Figure 8.17 illustrates this condition.

Small windows like figure 8.17 are used to detect errors in the flight plan. Figure 8.17 is acceptable as the planning process is not exact but large errors are obvious.

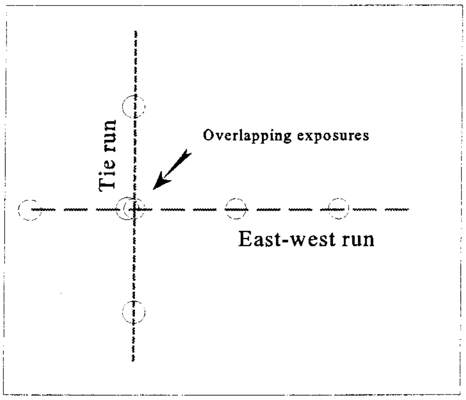


Figure 8.17 Relationship between tie runs and cross runs.

A secondary blunder detection procedure is to use NAVPRO to display the actual flight plan. This ensures that not only is the overall plan correct but the data files are NAVPRO compliant and do not contain any corrupt data. NAVPRO will display error messages if flight plan files are non-compliant.

It was now possible to generate digital information about planned photography. The next innovation was to combine these planned exposure stations with a satellite image of the map tile. Again this was met with trepidation from the flight crews, but it has proven to be a valuable asset in providing a redundant system to cross check the navigation system and maintain a situational awareness that the aviation authorities demand at all times. Aircrew have since acknowledged that the satellite image provides a better navigational tool than a topographic map. Figure 8.18 is a portion of a satellite image map with a flight plan overlaid.

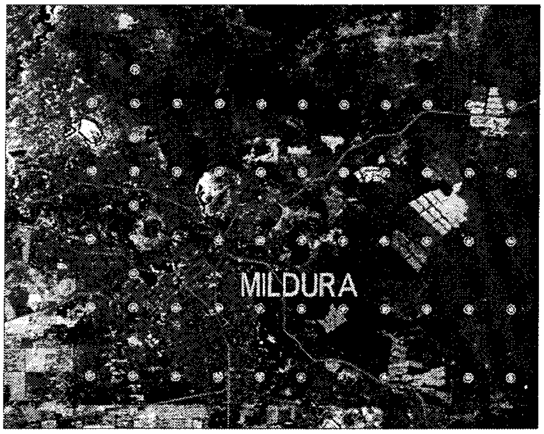


Figure 8.18 Portion of satellite image map with photography flight plan overlay.

The format of the flight plans is quite simple, and they can be generated by any method, as they are in ASCII format. In the sample screen figure in 8.16, the *mission name* in this case is SAGEM, the *storing directory* is C:\AREA\. From this information CR21 will create a directory C:\AREA\SAGEM\STRIP. In this directory CR21 will create a strip file, in the case of the sample, called 4.dat. This file will contain exposure point coordinate data based on the endpoint, the overlap requirement and altitude data entered by the user for photo run four (see table 8.2).

Table 8.2 Contents of file 4.dat.

```
Altitude  8000 60
/
4*POE*1   6246200   334060
4*POE*2   6246383   334138
4*POE*3   6246567   334217
4*POE*4   6246751   334296
4*POE*5   6246935   334375
/
```

The format of 4.dat in table 8.2 is:

Line 1	Altitude (key word)	Flying height above G.L.	average ground elevation
Line 2	Forward slash data delimiter		
Line 3	Exposure identifier	AMG Northing	AMG Easting
....			
Line 8	Forward slash data delimiter		

Table 8.3 is a sample of an operational flight plan from the Cobar 1:250000 flight plan. This flight-strip file is of run 6. Note the exposure identifier, SH551406, this is run 06 of map SH55/14, POP is **PhOto Planned**, and the last number is the exposure number of the run which is non-directional. Also note how the northings change due to the projection. In practice the aircraft flies the rhumb line and not the circle of latitude. The displacement at the midpoint of a standard 150km strip is 270m, which is less than 2.5% of the format for 1:50000 photography.

Table 8.3 Sample strip file for run 6 from the Cobar 1:250000 map flight plan - SH551406.DAT.

```
Altitude  7650  300
/
SH551406*POP*1   6526726   352913
SH551406*POP*2   6526756   357369
SH551406*POP*3   6526787   361826
SH551406*POP*4   6526818   366283
SH551406*POP*5   6526849   370740
SH551406*POP*6   6526880   375197
SH551406*POP*7   6526911   379654
SH551406*POP*8   6526942   384111
SH551406*POP*9   6526972   388568
SH551406*POP*10  6527003   393025
SH551406*POP*11  6527034   397481
SH551406*POP*12  6527065   401938
SH551406*POP*13  6527096   406395
SH551406*POP*14  6527127   410852
SH551406*POP*15  6527158   415309
SH551406*POP*16  6527188   419766
SH551406*POP*17  6527219   424223
SH551406*POP*18  6527250   428680
SH551406*POP*19  6527281   433137
SH551406*POP*20  6527312   437593
SH551406*POP*21  6527343   442050
SH551406*POP*22  6527374   446507
SH551406*POP*23  6527405   450964
SH551406*POP*24  6527435   455421
SH551406*POP*25  6527466   459878
SH551406*POP*26  6527497   464335
SH551406*POP*27  6527528   468792
SH551406*POP*28  6527559   473249
SH551406*POP*29  6527590   477706
SH551406*POP*30  6527621   482162
SH551406*POP*31  6527651   486619
SH551406*POP*32  6527682   491076
/
```

CR21 also creates a control file in the same strip directory with the extension .AEA. This file is actually an include file which NAVPRO uses to set up a project.

Table 8.4 is a sample of the Cobar .AEA file. The configuration of the project can be changed by removing or adding other strip files names to the .AEA file. Note the file name SI55201.dat, this is run 1 of the Nymagee map tile which adjoins the Cobar tile immediately below it.

This rigorous naming convention was required to maintain a uniqueness about the individual facets of each map tile down to each individual exposure.

Table 8.4 Sample of .AEA file for Cobar.

```
/
SH551402.dat
SH551401.dat
SH551403.dat
SH551404.dat
SH551405.dat
SH551406.dat
SH551407.dat
SH551408.dat
SH551409.dat
SH551410.dat
SH551411.dat
SH551412.dat
SH551413.dat
SI550201.dat
SH5514WK.dat
SH5514EK.dat
```

Variations on this methodology have also been utilised for non-standard mapping applications, but there are limitations. These limitations could not be addressed by developing the database themes outlined here as this technique is not focussed on the unique photograph. The author has developed another software package to overcome these limitations, and this will be discussed later in this report.

At this stage the flight planning component is complete, a rigorous process has been used to determine endpoint coordinates for each map tile, the transfer of these coordinates is checked through the functions of a GIS and also through pre-flight testing in NAVPRO. These simple ASCII files are then transferred to a floppy disk, the transport medium between the office and the aircraft.

9. Base Station

9.1 Background

In mid 1992 the Surveyor General's Department purchased and installed its GPS base station. This acquisition was based on projected income flows that would result from the expected "explosion" in the use of GPS products throughout the community. This assumption of expansion was founded on the growth in embedded positioning devices used by a diverse cross-section of users.

The concept of the base station was to provide, at a nominal cost, a seamless GPS data set of the highest quality, via an electronic delivery system which could be automated as much as possible. This data could be used as either:

- Differential **range** data in after-market and proprietary software packages to improve a user's single point positioning results.
- Differential **position** data, again, in after-market and proprietary software packages to improve a user's single point positioning results.
- Differential/Double difference phase data to improve position for those users operating at the higher end surveying and positioning community.

As real time differential delivery services were still in their infancy, the base station was perceived to meet the needs of those uses who were using low-cost GPS receivers. These receivers would have some data-logging mechanism that would facilitate the option of post-processing the results in conjunction with reference station data.

Part of the SGD's hardware acquisition at the time included Magellan Mark V handheld GPS receivers. These receivers were purchased with the new release phase data tracking and logging system. The emergence of this technology in a receiver of this type and cost supported the base station concept: that a number of low-cost high-performance GPS receivers would be available to take advantage of quality reference station data. What was lacking was simply the education of the user community and the necessary promotion.

For this concept to be economically viable, the cost of producing and providing the reference station data had to be as cheap as possible. It would also have to meet customers needs, as well as meet the needs of the SGD.

9.2 Purchase

The acquisition of GPS hardware at the time was divided into three categories:

- High precision survey-based hardware and software.
- Low precision handheld positioning systems.
- High precision base station hardware and software.

The requirements for the base station were:

- Dual frequency capability
- Versatile communication capability (multi-port)
- Capable of 1 second or higher data logging rate
- Internal data storage capability
- Full control over receiver functionality
- Base station capability

A number of GPS receivers were evaluated for this role but the receiver at the time that promised the most was the Ashtech MXII. This was a dual frequency receiver which used a squaring technique to recover the L2 frequency signal. At the time this receiver fulfilled all the requirements required of it.

9.3 Base station development

The challenge came in automating this receiver as a dedicated base station. The greatest problem with base station operations is how to get the data from the receiver to some storage medium and onto a distribution centre. In 1993 the general options were to either log the data directly to a dedicated computer or store the data within the receiver's own memory and at some point in time transfer the data to an external computer. Note that both these options require the receiver to be taken off satellite tracking status or stop logging data so that the external computer can download the data.

These limitations are a legacy of the DOS operating system which is incapable of performing two functions at once. If transferring data directly from the receiver's memory then the receiver will no longer be capturing data. This was the case with all receivers available at the time. If logging data on line then the computer can only perform the logging function, nothing can be done with the data unless the computer stops logging. This was the case with the Ashtech MDXII. There were two options available with the receiver to transfer data from the receiver. The first utility is the HOSE software. HOSE provides access to the receiver's onboard memory but once communications are established, all logging functions cease. The HOSE utility reads the memory data from the receiver and converts it to B, E and S file formats. These formats are the standard file formats for data that is ready for post processing.

The second utility provided by Ashtech is the DATALOGR software. It has been described elsewhere, but this software must be terminated if the data must be transferred elsewhere. The SGD wanted to create a system where there would be seamless data collected. If the data was available in small pieces then it could be concatenated into larger sets. These files would then be seamless. The involvement of the SGD in the IGS programs at the time made collection of this type of data desirable.

Ashtech provided one other utility that could access the receiver's memory. This utility is the REMOTE software. This was designed so that the receiver could be located at a remote site and still be controlled by modem from a computer located elsewhere. Unlike the other utilities mentioned this program allows the user to control the receiver on a different level. A clever aspect of it is the memory management function. It allows the user to close active files and then transfer the contents of that closed file via the modem line to the user's computer. The file that is transferred is not in the standard Ashtech format of B, E and S files but in an "image" format of the receiver's memory. The standard Ashtech format files can be recovered from the "image" file using a variation of the HOSE utility. This is fine if the operator is using a modem, but Ashtech have also configured the software to operate as if a modem line was being used.

The most powerful aspect of the REMOTE software is that while the contents of the closed file in the receiver memory are being transfer to the attached computer the receiver continues to log and store data. It continues to do this indefinitely whilst the receiver memory is emptied. The concept allows for the memory to be considered as a closed loop, and data can be stored continuously on that loop whilst there is space available.

The REMOTE software offered the means to deliver seamless data sets. This ability is the core of the SGD's base station operation, for without it seamless data would not have been possible on a DOS based operating system. The system could be duplicated on a NT or UNIX platform but this would have required software development beyond the budget of the SGD.

Having the ability to produce seamless data was one thing, making it happen automatically was another. The receiver was purchased with its standard memory configuration of 1Mb. This was enough memory to hold just over one hour's worth of data collected at a one second data rate for satellites 5° above the horizon. Testing had shown that transferring the contents of a full receiver memory to a PC using REMOTE could take more than 20 minutes depending on transfer settings. The planning then, of data transfers, had to ensure that enough memory remained after a file was closed, that the data logging could continue while the transfer and deletion of the inactive data from memory was taking place. These aspects of the operation had to be addressed so that data could be delivered to the user end.

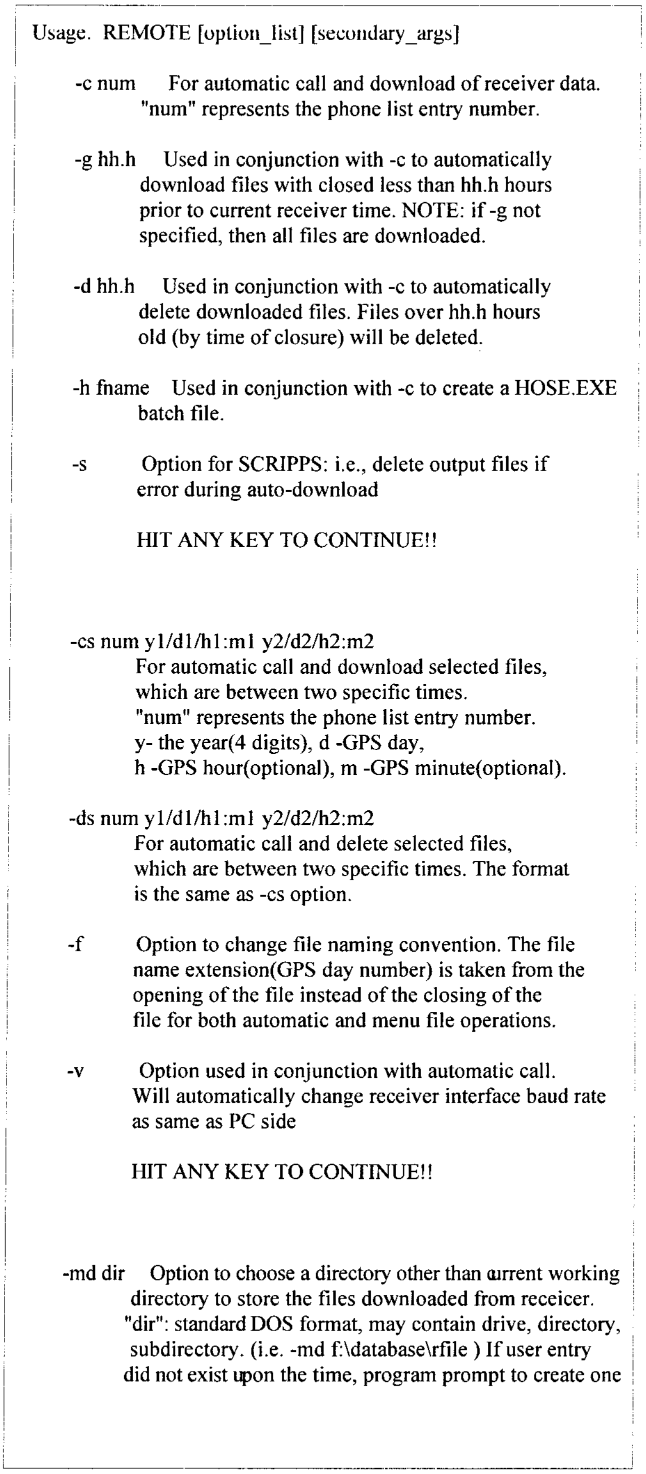
All GPS receiver manufacturers use their own proprietary formats for data management. To overcome this and to provide some standardisation of GPS data formats the RINEX (Receiver INdependent EXchange) format was introduced and widely adopted. It was acknowledged that not all the user community was going to be interested in Ashtech data. The most generic option, and the most acceptable, would be to provide RINEX base station data. Software was available that was capable of producing RINEX standard data from Ashtech raw data. Ashtech provided its own utility as part of its suite of tools. The University of Bern also had a version that was available to the SGD and the wider community. The SGD adopted the Bern version as it offered a more flexible operation in that it could be uniquely configured and could be included in a batch process while maintaining its full functionality.

The size of the RINEX files dictated what would be an acceptable data period. A RINEX file of one second, dual frequency data of ½ hour duration when compressed was around 0.2 to 0.3Mb. A size that appeared acceptable to transfer by modem. In 1993 such transfers took 20 minutes or more!

It had been established that the REMOTE software could be used to effect the data transfer. The REMOTE software could be used in a batch process as a number of command line options are available. Figure 9.1 lists these options. The only command line options used are the -c and the -d. The -c 0 option defaults the program past the telephone number directory and dial-up. The -d 00.00 ensures that the inactive file, which has been closed longer that zero hours and minutes, is deleted after a successful data transfer.

Having decided on creating ½ hour zipped RINEX data files a means of automatically creating them was needed. The DOS utilities available made it possible to design and build an endless batch process.

The first stage of this batch process is a FORTRAN program, CHEKCLK, written by the author. This program interrogates the PC's system time and determines the next file transfer time based on times held in a control file. The control file contains the times when data was to be transferred from the receiver memory. The times could be set for transferring the data every ½ hour for 24 hours or could be set for just a subset of the day depending on demand or requirement. The configuration of transfer times is very flexible.



```
Usage. REMOTE [option_list] [secondary_args]

   -c num     For automatic call and download of receiver data.
              "num" represents the phone list entry number.

   -g hh.h    Used in conjunction with -c to automatically
              download files with closed less than hh.h hours
              prior to current receiver time. NOTE: if -g not
              specified, then all files are downloaded.

   -d hh.h    Used in conjunction with -c to automatically
              delete downloaded files. Files over hh.h hours
              old (by time of closure) will be deleted.

   -h fname   Used in conjunction with -c to create a HOSE.EXE
              batch file.

   -s         Option for SCRIPPS: i.e., delete output files if
              error during auto-download

              HIT ANY KEY TO CONTINUE!!


   -cs num y1/d1/h1:m1 y2/d2/h2:m2
              For automatic call and download selected files,
              which are between two specific times.
              "num" represents the phone list entry number.
              y- the year(4 digits), d -GPS day,
              h -GPS hour(optional), m -GPS minute(optional).

   -ds num y1/d1/h1:m1 y2/d2/h2:m2
              For automatic call and delete selected files,
              which are between two specific times. The format
              is the same as -cs option.

   -f         Option to change file naming convention. The file
              name extension(GPS day number) is taken from the
              opening of the file instead of the closing of the
              file for both automatic and menu file operations.

   -v         Option used in conjunction with automatic call.
              Will automatically change receiver interface baud rate
              as same as PC side

              HIT ANY KEY TO CONTINUE!!


   -md dir    Option to choose a directory other than current working
              directory to store the files downloaded from receicer.
              "dir": standard DOS format, may contain drive, directory,
              subdirectory. (i.e. -md f:\database\rfile ) If user entry
              did not exist upon the time, program prompt to create one
```

Figure 9.1 REMOTE software command line options.

The CHEKCLK program determines which time in the control file is the closest in the future and makes allowances for day rollovers where seconds of the day reset. When the system time reaches this future time the program terminates.

The REMOTE software will only transfer receiver files that are inactive. To create an inactive file within the receiver requires sending a command string "$PASHS,FIL,C". To batch this operation, which wasn't available under the REMOTE command line, a script was written using the TELIX SLT language. Using the TELIX command line with the script extension provided a means to instruct the receiver to close the active file and immediately open another. Another utility was written that would then provide a specified delay period to ensure that the communication protocols of the receiver and the PC are both correctly reset before the next instruction.

The next command in the batch process is the REMOTE function. As described earlier it transfers the contents of any closed receiver file to a specific directory on the PC. If the data is successfully transferred then the inactive file is deleted from the receiver, instantly freeing memory to continue the current data-logging.

If an error occurs during this process a trap will attempt to repeat the transfer process. The trap is a simple utility, WARNING2, that scans the output of the log file created by the REMOTE program. If an error string is detected within the log file then a warning flag is set. The batch process will repeat the REMOTE program if this warning flag exists.

The batch process is designed to manipulate all file copying and renaming functions within a generic directory. The file that is created by the REMOTE file is always prefixed with “RMLY1". The next letter is the file sequence identifier which for normal operations is always “A”, the following two letters are the last two digits of the current year. The last three letters of the file name are the current Julian day. A typical file name for a receiver image file is RMLY1A99.018 for a file collected on day 18 of 1999. Unfortunately, all files that are transferred in this process are created with the same name until the day changes.

Another utility, CHEKSUM4, writes the current receiver image file name to the clock control file so that the next phase of the process can generate the correct file naming sequence.

The next utility BLDBTCH5 creates a unique batch file, ARCHIVE.BAT, to control the next phase of the batch process. The ARCHIVE.BAT routine calls the HOSE program which is used to explode the receiver image file out into the standard Ashtech B, E and S files. The process then passes these files to the RINEX conversion routines. At the completion of this stage, another routine, SAVRNX, opens the RINEX observation file and reads the time of the first observation. This time is used to uniquely rename the RINEX files and the original receiver image files. These are the only data files retained for archive. A typical name for a RINEX file or an R file would be L0112023.99o which is created from the UT date and starting time of the data within the file. The 'L' is for LIC (Land Information Centre), '01' is the month, '12' is the day of the month, '02' is the hour of the day, the '3' is the 10 minutes past the hour that the data set begins, the '99' is the year and the 'o' is for observation file. The convention is the same for navigation files with the extension 'n'. Receiver image files use the same convention but begin with an 'R' prefix and have no extension after the year.

A secondary function is performed on the day rollover. This function is the creation of an Ashtech almanac file. After each file down load a copy of the ephemeris file is moved to a temporary storage area. When a day rollover occurs the almanac creation process is initialised. This ensures that an up-to-date almanac file, compatible with the Ashtech MISSION PLANNING software is always available.

The final stage of the base station process is the movement of the current files to the SGD computer network. This phase is handled by the IM&TS Branch. Its basic operation is an automatic log-in to the network and transfer the current data to a file server. Once the data is on the network it is handled and sorted by UNIX CRONs. In the event of a failure to log-in to the network, the current data is moved to a temporary storage location on the computer's hard disk. This data resides there until a successful log-in occurs, at which point it is moved to the network along with other files with the same status. The backup, maintenance and accessibility of this data is then the responsibility of the IM&TS Branch.

The batching process is finally complete and the process loops back to the beginning where the clock routine takes over and awaits the next download time. Figures 9.2 and 9.3 are flowcharts of the base station operation.

This process has been in operation in this form, or under development, since 1993. Before the network was available data was stored on tapes which were continually overwritten. This system meant that data over 6 months old was eventually lost. Now the networking arrangements have ensured that data which is more than 12 months old can be recovered, if ever the need were to arise.

The proven reliability of the base station data recording system supported the concept of basing all aircraft kinematic positioning on the receiver located in Bathurst. Although not a proven concept the author believed that, given the quality of data in the new generation instruments, the new algorithms using wide laning, the PNAV software and the approach to aerial triangulation used by Ackermann and others, the standard of positioning required for the Western Lands Legal Road Network Project could be delivered from a centralised base station.

The current system, although proven to be very reliable, was inadequate to support the aerial survey program. The base station operation was developed to provide both an internal and external service to customers. Once a vendor travels down the path of promoting the availability of this data and the standards to which it is captured, then there is an obligation on the vendor to maintain this service as advertised. For this service to support the aerial survey program the base station would have to be capable of running fault free on a continuous basis.

Even though an uninterruptible power supply was part of the hardware associated with system, it was difficult to accept that this complex operation could function unsupervised or unchecked over public holidays and weekends. There was no alternative system running to offer redundant data.

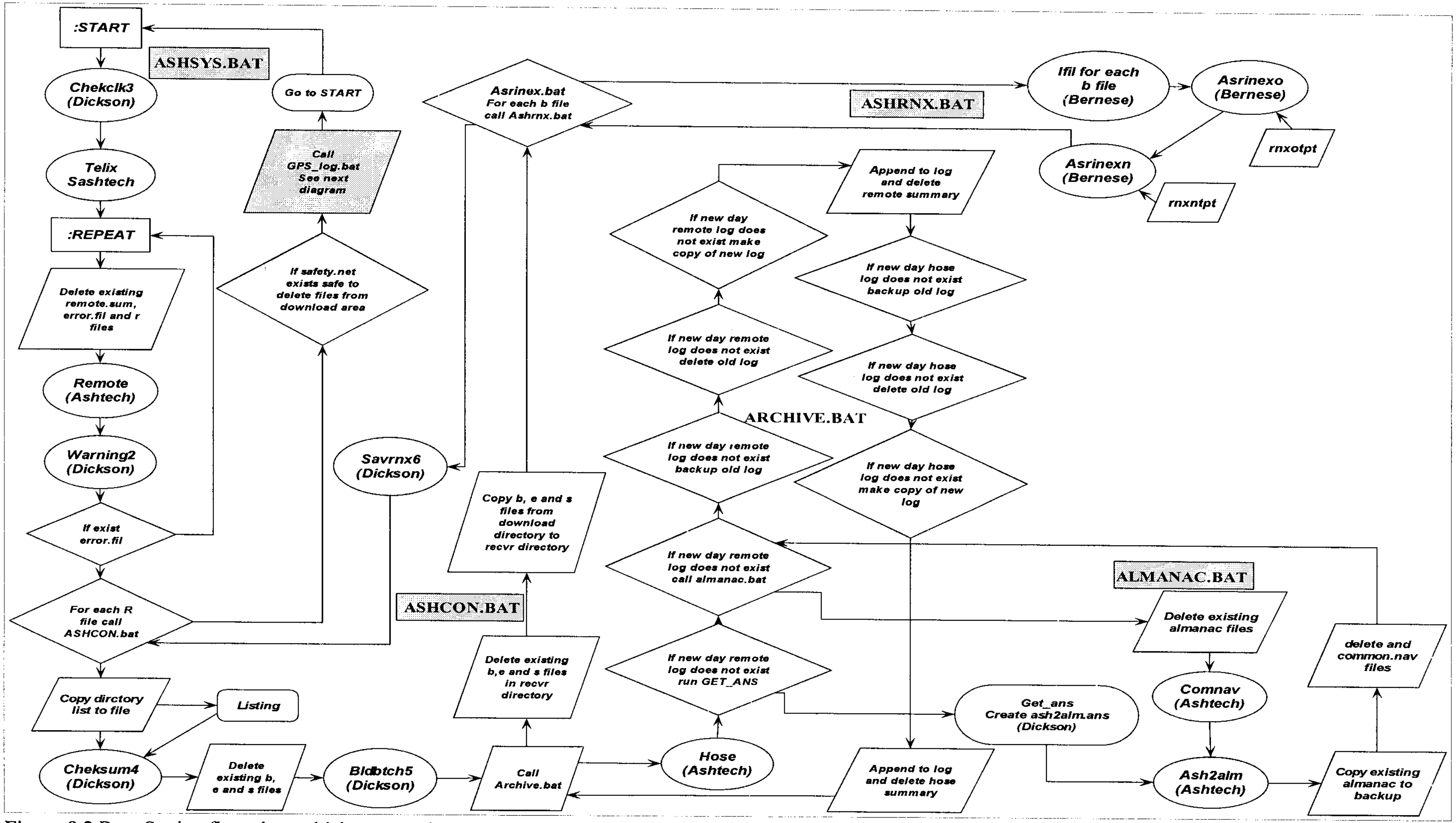


Figure 9.2 Base Station flow chart which runs on the PC. Network process is shown in figure 9.3.

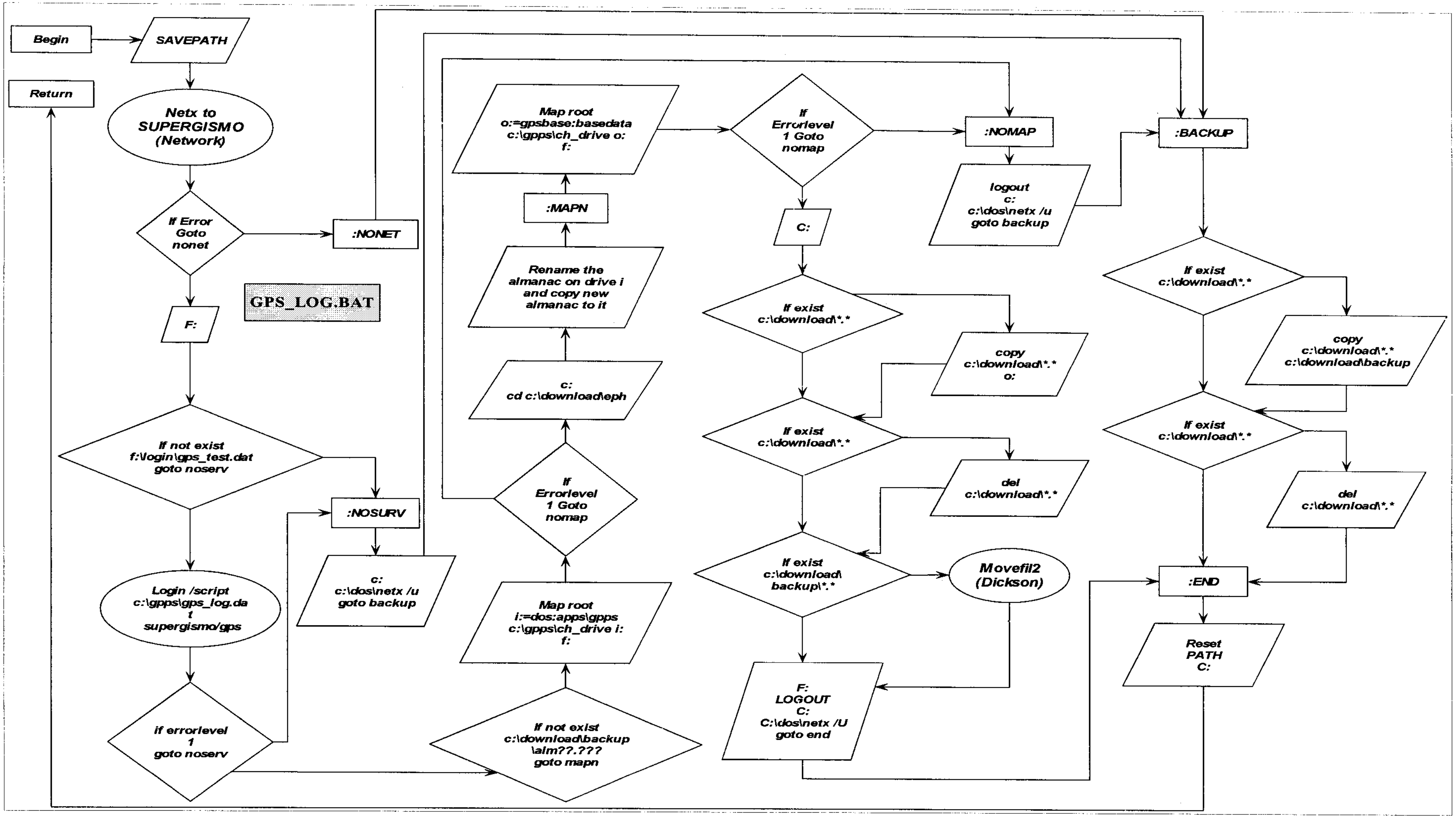


Figure 9.3 Flow diagram of network login and recovery processes.

The concept of operating an aerial photography platform supported by GPS virtually anywhere within NSW was highly dependent on the performance of the new Ashtech Z12 receiver. The effectiveness of the software relies on the quality of the GPS data. To achieve the level of positioning desired necessitated the upgrading of the Ashtech MDXII base station receiver to a Z12 standard. In effect, Ashtech replaced the MDXII with a new Z12 receiver as part of the aircraft GPS tender.

The new Z12 receiver simply replaced the old MDXII receiver. Not all was well, for all of a sudden the reliability of the base station system deteriorated. Problems were occurring with the transfer of data from the receiver to the computer. The local agent was contacted and he advised that the latest version of the REMOTE software should be used. This was obtained and installed, but it also necessitated the re-writing of routines as a result of format changes in output files and built in error trapping in the upgraded versions of the software.

Failures were still occurring and it was not until Ashtech engineers suggested checking the UARTS in the computers that the problem may have been solved. The new design of the Z12 is built around new high speed chips. The Z12 could not tolerate the old INS8250 UARTS which were incompatible with the switching rates of the Z12. Even though the parity and baud rates were correct the data could not be reliably transmitted or received. The purchase and installation of INS16550 UARTS in the base station computer fixed the problem instantly. Solving this problem took 12 weeks, but fortunately aircraft operations with the GPS receiver on board had not commenced. Failures are still occurring today with the base station operation, but these stem from ongoing changes in computer hardware and operating systems.

The base station computers are still the original 486DX2/66 units. As stand alone units they perform the base stations functions without problem. Incompatibility arises when connecting these 16-bit based machines to network servers that have moved on to 32-bit architecture. The only solution to this appears to be in migrating the base station functions to 32-bit machines and hope that none of the functionality and reliability of the current DOS programs is lost. Machines like these when networked have to be configured correctly. Simple things like "network broadcast messages" which require user input to clear, can bring the whole base station operation to a standstill if the network configuration for the computer is not setup correctly.

From the aerial survey and data processing perspective, base station data that is only available in ½ hour chunks is an inefficient way to handle the data. It also means that the data must be handled many times before it is process-ready. Extracting the data requires information about mission start and end times, and also requires the services of IM&TS if the data is not active on the network - data has to be recovered from back-up tapes. Assembling the data is a slow and exacting process. This process could be avoided in a redundant data collection system, designed to support the aerial survey program.

When the base station program was initially setup two identical PCS were purchased and configured for the task. One machine was to perform the base station management task and the second was only there in a backup role, in the event that the other had failed. The option now was to use the backup machine to provide the redundant data collection system.

The data collection system required to support the aircraft operation has different design criteria to the base station function:

- The data does not need to be available less than an hour after the mission so the data can be managed at a later stage, either when disk storage space is limited or data processing is to begin.

- Preference is for data to be collected in one continuous file each day regardless of the aircraft operational status.

- The data management process be simple and operate off-line from the network. Manual processes can be used to manage data on the PC and across the network as data processing is not time critical.

Where the DATALOGR software was unsuitable for the base station data transfer function, it could be utilised to collect the data to support the aircraft operations. Another batch process was designed to collect this data on a daily basis. This batch program, MLYSTART.BAT, is listed in figure 9.4. It makes use of a similar clock function as the base station. The program CHEKCLK2 reads the start time from the control file, when that time is reached the program stops and the program LOGMLY1 creates the batch file SETPARM.BAT based on information in the control file and the current date. SETPARM.BAT is listed in figure 9.5.

```
@echo off
:start

cd\
c:\gpps\chekclk2
c:\gpps\logmly1
call c:\gpps\setparm.bat

goto :start
```

Figure 9.4 MLYSTART batch file.

An initial limitation in the operation of this process was that to stop the DATALOGR program required someone to press the ESC key to terminate the operation. This was OK during the week but this requirement meant that sufficient free disk space be available over the weekend. In the early stages of the implementation, weekend sorties were prohibited because the base station data could not be guaranteed.

```
@echo off
cd\
cd data
echo.
if not exist 324_95 md 324_95 > nul
echo.
cd 324_95
echo.
echo.
C:\DATALOGR\DATALOGR -b 38400 -Y HOB1A95.324  -l   40000
```

Figure 9.5 Sample of batch file SETPARM.BAT.

If the DATALOGR source code could be acquired from Ashtech then it may be a simple task modify the code so that it could stop logging data after a particular time. Ashtech were forthcoming in offering the code on the understanding that:

1. There will be absolutely no distribution of this software code to any party outside of SGD.

2. Ashtech will not be obligated to provide technical support to SGD on any issue concerning the DATALOGR source code.

Accepting these conditions the author was able to edit the code to include an epoch counter. The base station receiver is set to record data at a one second rate, this is 3600 epochs per hour, so counting epochs is a technique to indirectly keep track of time. A command line argument was added to the DATALOGR option list, "-L n Number (n) of epochs to log.". Entering a number for 'n' defines the number of epochs counted before the logging process terminates. Of course, if the data logging rate is lower than the 1Hz currently in use, then the number of epochs to count will have to be adjusted accordingly. The modified REMOTE command line options created by the author are highlighted in bold in figure 8.1, section (8.1.3).

With this option in the DATALOGR software, it was now possible to start the data-logging process at a particular time and terminate it after a certain period of time. The data could then be collected automatically to coincide with the aircraft's operating window. Fortunately, the operation of DATALOGR does not interfere with the operation of the REMOTE software, but the reverse is not true. It was discovered that if the base station computer was communicating with the Z12 via the REMOTE software, then the DATALOGR could not be initialised. But if DATALOGR was already logging data, then the REMOTE software would still operate.

To ensure that the automatic functions operating on both PCS would not interfere with one another, the DATALOGR function is started during periods that the REMOTE software is not in use. These periods are generally 20-29 minutes past the hour and 20-29 minutes past the ½ hour. Generally DATALOGR is programmed to start 5 minutes before the REMOTE start time. The ongoing success of this function is maintained by ensuring that the times on both computers are the same. This situation is achieved by regularly logging the DATALOGR computer onto the network - the base station computer logs onto the network every ½ hour. Logging onto the computer network transfers the current network system time to the PC.

Timing is an important element of the overall function of data collection. From time to time when the network fails the network system time has to be reset. For the base station data management system to function correctly, particularly the UNIX CRONs used to shuffle the base station data files into their respective locations, the network system time should be set to be some time after GPS time. The minimum time after should be no less than 10 seconds and no greater than 9 minutes otherwise the time of first observation in the RINEX file will be outside the definitions prescribed in the management processes. The author proposes to write a C utility that will ensure that the times of both PCS will be set to 10 to 15 seconds after GPS time regardless of the current network time. This will avoid the critical nature of network timing.

Having identified the timing problems associated with running the two data collection functions in parallel and the automated capabilities of DATALOGR, the all clear was given for flight operations over weekends and public holidays. A redundant data set was available in the event that one of the data collection functions failed. A complete loss of data would have to be related to a receiver failure, which from experience was rare. The SGD's budget could not be extended to provide a second Z12 receiver in the event of a failure. Based on the performance of the current unit, which has been re-initialised less than five times in the last three years, the purchase of a second unit could not be justified.

Not only does the Z12 receiver provide the two data logging functions but it services the external needs of a space-based, real-time differential correction supplier.

Although the base station development dates back to before the implementation of the GPS in the aircraft it is an important aspect of the project. It provides the basis and support for the concept of operating from a centralised location. Other projects have been undertaken by the SGD using this concept and have, given the limited quality of the MDXII data, demonstrated its potential (Dickson, 1993).

The operational costs of the alternative, setting up a base station within the temporary operational area of the aircraft, incurred too many overheads. Some of these are:

- Communication with the aircraft in the event of a base station failure. Whether located at a centralised location or at a remote site, communication can only be established by:

    1. radio; if the base station is within radio range and the aircraft is listening on a specific frequency for that purpose. With today's airspace rules there are too many frequencies to monitor. If a hand held radio is used, the background noise level within the aircraft is generally too high to acknowledge a transmission.

    2. Mobile telephone; if the crew can hear the call over the aircraft background noise. Both the base station and the aircraft must be positioned within a mobile telephone cell.

- Relocating the aircraft. The base station must be moved to the same location as the aircraft. For operations that are diverse this creates a number of problems:

    1. Ground power and maintaining it; in its simplest form a base station will require a receiver, antenna and power, usually a battery, data can be stored on board the receiver. The option of moving this equipment efficiently is to put it in the aircraft. This requires gel cell batteries as liquid based batteries are prohibited on aircraft, how do you maintain these batteries? The aircraft always has to return to the location of the base station to pick up the equipment. Alternatively, if a motor vehicle is used then the travel takes three times as long to relocate.

    2. Supervision; do you leave the base station unattended and un-supervised? This requires a certain amount of confidence in the equipment, particularly the batteries. Is the site safe? Can you be sure that it will all be there when you get back. Alternatively, provide an operator to ensure the ongoing operation. This is extra cost to be avoided.

- Survey Control. Locating a suitable site to locate the base station, this impacts on how the survey is run and whether or not an operator is available, and whether or not he has the ability to survey in a point.

The provision of base station data appears to be simple in the first instance but it is for reasons such as those listed above that the SGD implemented the concept of using a centralised, automated base station to support the acquisition of airborne GPS controlled photography.

10. Flight Operations - Early Experiences

Having satisfied the requirements of the tender contracts the SGD then proceeded to implement operational procedures. From the start of the project a major consideration was the capabilities of the aircrew to adapt to computerisation within the aircraft. The only computer technology used on the aircraft at that time was a rather awkward software package that would enter an off-line prepared text string into the RC30 camera character buffer.

Up until the implementation of this program aircraft operations had required a three man crew: pilot, navigator and camera operator. Not all staff were at the same level of "hands-on" computer proficiency. It was intended that this new technology would reduce crew requirements to two, the pilot and operator. For this to be successful the operation of the new technology had to be as simple as possible so that all members of the aerial survey group could function at the same level of proficiency.

In some cases this meant training staff in the basic functions of a DOS operating system. In the very early stages the aim was to ensure that, regardless of the operators limitations at the time, that data would be successfully logged and that the navigation system was correctly loaded with flight plans. For the crews this was not an easy process as they only felt confident with the new system as their experience with it grew, remembering that the operator was also responsible for the functionality of the camera. The fact that the early missions were indeed so productive reflects the effectiveness of the early planning.

10.1 Getting off the ground

It was mentioned earlier that the costs of operating the SGD's aircraft makes test flights a luxury. Test flights if undertaken were generally a single proving flight to ensure that all aspects of the aircraft's airborne GPS camera control and support functions were operating correctly.

Even though the tender contract was signed off, having satisfied the conditions of the tender, the SGD was aware of a number of system problems. The NAVPRO software on some occasions would fail to time synchronise the PC clock. The time synchronisation function was used to set the PC time to GPS time so that some form of dead reckoning could be achieved for the camera sequencing if position data was unavailable. This problem was evident even when the technician from Sweden was present. However he was unable to offer any explanation to the source of this problem. A more serious problem was the performance of the power invertor.

10.1.1 The invertor

Many hours of ground running the engines were lost due to the failure of the invertor to handle the power load of the two PCS and the two monitors. Although on paper (chapter 8.1.4.1) the invertor was more than capable of handling the load, time and again the unit would drop out on overload. This was a source of continual frustration as a reset required a cool down period which was dependent on the current ambient temperature. On hotter days, if the computers and monitors were not up and running on the first attempt, then a mission would have to be cancelled due to the unserviceability of the invertor.

On some occasions the cabin temperature was so high from ground running and exposure to the sun, that the aircraft took off in the hope that the system could be booted as a result of the cooling effects of the aircraft's air-conditioning system. Although against the initial operational policy for the system, this option to take-off was generally rewarded with success. One redeeming feature of the invertor was that if it did get everything going then it usually kept going!

Initially the problems with the invertor were attributed to the aircraft's power system. It was thought that the voltage level within the aircraft's electrical system was too low. This conclusion was based on observations made during test work where common automobile lead acid batteries were used as a portable power source. It was found that the invertor's performance fell off quickly as the batteries' voltage level waned.

To overcome this limitation a strict start-up procedure was adopted:

1. First, try to keep the interior of the cabin as cool as possible. As the ambient temperature increases so do the problems associated with the invertor.

2. Before engine start ensure that the camera is off, the GPS circuit breaker is off and all the modules of the rack are off.

3. After both engines are started and the pilot is satisfied all is ready to go, the engines are set to a fast idle to ensure that the charging system is producing it optimum voltage of 28 volts.

4. When the pilot gives the OK, turn on the GPS circuit breaker.

5. Ensure that the keyboard is connected to the navigation computer and turn that computer on. Monitor the indicator lights on the computer's front panel and listen to the indicator beeps. A correct computer start-up sequence should see the green LED light up solid, the red LED will flash on and off as the hard disc activity takes place. If the green LED stays on for more than one minute then all is OK.

6. Remove the keyboard from the navigation computer and connect it to the data logging computer. Turn the data logging computer on and monitor the LED behaviour as in step 5. If the green lights on both computers suddenly fade then the invertor has overloaded and will require a cool down period and a reset.

7. If the green LEDs of both computers stay on then the two 9" monitors can be turned on one at a time. This is generally an uneventful procedure. At this point there are no further demands on the invertor.

8. The GPS receiver and the camera (which are 24V DC powered) can then be turned on one at a time.

9. In the event that the computer boot-up sequence has hung up then **do not** attempt a cold restart (i.e. do not turn the power switch off!). If necessary, press the reset button on the front panel and monitor until up and running.

This procedure usually resulted in a successful start up, but there were still other problems to contend with.

10.1.2 The GPS receiver

The Ashtech Z12 receiver is a versatile electronic device. Apart from its satellite tracking abilities it has certain functionality which lends itself favourably to applications such as airborne positioning. The instrument can be configured for a certain survey application and then all parameters associated with that configuration can be saved. For the SGD's aircrew this is an asset that saves time and prevents unnecessary mistakes. This feature means that when the unit is switched on it is already in the correct survey mode and the communications ports are correctly configured.

The receiver was configured as follows:

- Epoch logging interval set at 1 second.
- Satellite elevation cutoff set at 5° above the horizon.
- Log dual frequency data **on**.
- Port A settings, REAL TIME ON, PBEN data on, format BINARY, baud rate 38400, NMEA on, TTT output on.
- Port B baud rate set at 38400.
- Display units set to nautical miles (knots) and feet.

- Other settings such as 1PPS and EVENT logging are on by default.

These settings would be the startup configuration when the receiver was turned on. If the settings of the *communication ports* were changed during a mission then they would become the defaults at the next start up. This was a source of many problems particularly with the operation of the DATALOGR software. On occasion the DATALOGR software may have had an abnormal shutdown. In these cases certain reset commands, that are essential for the correct communication protocols for the receiver, were not set. The DATALOGR shutdown commands, to receiver port B, would turn the transmission of measurement data off and reset the output format of the port B to ASCII. This was, and still is, an essential part of the data-logging process so that for the next data-logging session the receiver is correctly configured.

The DATALOGR software uses the initial ASCII string format, transmitted from the receiver, to determine the receiver communication baud rate even though DATALOGR has been configured via its own interface window, see figure 8.14. If communications cannot be established the software will cycle through the available communication baud rates. When this occurred on board the aircraft the aircrew were bewildered by what was happening, the subsequent mission usually resulting in an abort on the ground. The original requirement that all functions must be operating before the aircraft left the ground was fully justified when problems such as this occurred.

Like most other problems such as this it took some time to analyse and rectify them. Remedial action today, if this situation occurs, is a simple process.

10.1.3 Logging data

The DATALOGR software is a DOS based command line computer program. The program has a number of command line start up options which are listed in figure 10.1.

The aircraft operation utilises two of these options, that of the *-Y tn* option for the file naming template and the *-b* for the communication baud rate.

The following is an extract from the operator's original instructions in how to get the DATALOGR program up and running after the computers are booted up and are functioning correctly:

1. Connect keyboard to DATA LOGGER (should be displaying C:\DATA) - *autoexec.bat file was configured to this location at startup.*

2. TYPE "MD (Julian Day)_(Year)" (↵) (MD = Make Directory)

3. TYPE "DATE" (↵) (Might need updating) Month-Day-year (↵)

4. TYPE "TIME" (↵) (Might need updating)

   Hours:Minutes:Seconds Local Time (↵)

5. TYPE "CD (Julian Day)_(Year)" (↵) Change to this directory

6. TYPE "LOG" (↵) This will initialise software DATALOGR

7. TAB ⇨ TEMPLATE ⇨ TYPE "NSW1" (↵) For first flight of day

   DATALOGR is now ready, initialised awaiting the F10 command to begin data collection.

“LOG” is a simple batch file that ensures that the correct communication baud rate is used to initialise DATALOGR. The batch file only consists of the command line string “C:\GPPS\DATALOGR -b 38400". This makes use of one of the command functions given in figure 10.1.

The requirement for data logging to begin was generally 20 minutes before the camera was to be switched on. There was no reason to log GPS kinematic data any longer than necessary. The 20 minute requirement was to allow sufficient time during the post processing stage for the Kalman filter and the positioning algorithms to converge, before the first camera exposure was taken. A similar buffer time was requested after the camera was turned off. (These operational procedures were based on post processing requirements that will be discussed later.)

```
Incorrect command line parameters.

USAGE:

 DATALOGR                    -> Initializes on COM1 at 9600.

 DATALOGR -[c][b] [PORT] [BAUD] -> Specifies the initialization port
                        and communication rate. Examples:

                 1) -b 38400 <CR>

                    Initializes on COM1 at 38400.

                 2) -c 2 <CR>

                    Initializes on COM2 at 9600.

                 3) -cb 2 19200 <CR>  or
                    -bc 19200 2 <CR>

                    Initializes on COM2 at 19200.

Presss any key for more ...      -F t  Update FAT of b,e file at t(seconds)
interval.
     -I   Implies ignore RS-232 status lines.
     -L n  Number (n) of epochs to log.
     -P   Implies logging position data only.
     -S   Do not set real-time setup commands.
     -T   Implies logging attitude data only.
     -N p  Do not poll COMM speed. This command requires
          that the receiver port (p = A or B) be specified.
     -Y tn Direct mode. 'tn' is the template name which will
          be used to name the B- & E-files. When this command
          is issued the logging will start automatically.
          This command may be used with the Emulation Mode for
          for batch downloading.
     -Z fn Emulation mode. 'fn' is the file name which contains
          the captured RID and realtime data stream out from
          the receiver COM port.
```

Figure 10.1 Command line arguments for DATALOGR.

The data-logging process initiated by pressing the F10 key is terminated by pressing the ESC key. Using one keyboard between two computers, i.e. only one computer can be controlled at a time, ensured that the data-logging function could not be accidentally terminated by a simple brush of the keyboard.

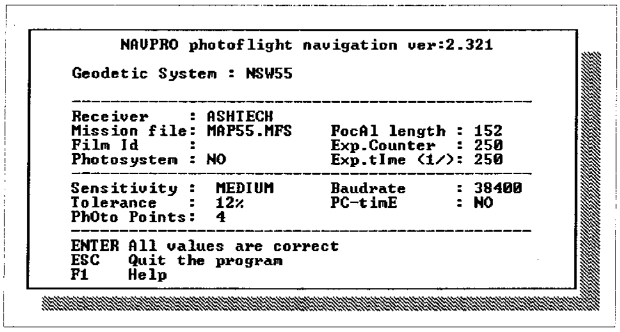
The crew's operational procedure was to initiate data logging by pressing the F10 key, monitor its performance for correct operation, then remove the keyboard plug from the socket. At the completion of the mission, insert the keyboard plug back into its socket and press the ESC key, confirming this at the next prompt. This sequence would ensure that the data port of the GPS receiver will be shut down correctly.

10.1.4 Navigation

The navigation and camera control function, which is handled by the NAVPRO software, was a little easier to setup for operation than the data-logging function, mainly because NAVPRO uses a configuration file. The program runs in its own directory and sources its flight plan files from a file directory structure given in the NAVPRO.CFG file.

Once configured correctly NAVPRO is a relatively user friendly package. Transferring and enabling new flight plans has been the major hurdle to overcome for the operators in coming to terms with this software. For those operators who have had little exposure to PCS and DOS, the transfer of the flight plan files to the navigation computer has been one of the main sources of problems. These type of problems are more of a training issue than technical one, but for NAVPRO to operate correctly, flight plan files must be placed in their correct directory structure, the correct AMG zone selected and the appropriate mission file edited to include the new project.

The opening configuration screen is illustrated in figure 10.2. The operator can set a number of variables and configurations in this screen. At this point of the program the screen display mode is still in 80 x 25 characters.



```
        NAVPRO photoflight navigation ver:2.321

    Geodetic System : NSW55

    ----------------------------------------------------
    Receiver     : ASHTECH
    Mission file: MAP55.MFS    FocAl length : 152
    Film Id      :              Exp.Counter  : 250
    Photosystem : NO            Exp.tIme (1/): 250
    ----------------------------------------------------
    Sensitivity :  MEDIUM       Baudrate      : 38400
    Tolerance    :  12%          PC-timE       : NO
    PhOto Points:  4
    ----------------------------------------------------
    ENTER All values are correct
    ESC   Quit the program
    F1    Help
```

Figure 10.2 Opening NAVPRO configuration screen.

As previously mentioned, NAVPRO depends on an incoming position data stream, in this particular installation Ashtech PBEN binary data. It also utilises the 1PPS output signal, the NMEA TTT message and communication with the camera exposure control interface. Important options for the SGD operations are the selections under Receiver and PC-time.

The Receiver option is set to Ashtech /S. This synchronises the PC clock to the incoming 1PPS signal. From the author's experience this is not an exact process as a time synchronisation better than 0.1 seconds has not been witnessed. The time synchronisation process limits the dead reckoning error that may occur when GPS data is unavailable. It ensures that the next predicted exposure uses the current cycle time for the camera (a 1 second error in time is equivalent to 100 metres for the SGD aircraft). This is of little consequence at photographic scales of 1:50000, but at larger scales, say 1:2000 where maintaining a rigorous coverage pattern may be critical to the client, special attention is paid to this synchronisation process so that the time difference is as little as possible. The PC-Time option is always "yes". This option will record the PC time of the exposure, though this is only used as a backup in the event that all other time tagging data is lost. These particular operational options are all part of procedures that are put in place to ensure that redundancy is built into the system.

An explanation of the other options on this screen are:

Geodetic System:	This option defines the parameters to be used to convert the incoming WGS84 position data to the local datum, in this case *NSW55* which implies AGD66-AMG zone 55 coordinates.
Mission file:	This option defines the mission file, MAP55 for zone 55, which exists in the MFS directory containing the valid information about active projects and the map parameters.
Focal Length:	This is the focal length of the lens in use, it is used within the software to calculate the amount of image movement, FMC, which is displayed in another window.

Film Id:	This is an option which is not used. It is purely a reference number.
Exp.Counter:	This is the exposure frame counter that is used by NAVPRO internally, it is not linked electronically to the camera frame counter.
Photosystem:	This identifies the camera type in use for NAVPRO.
Exp.time (1/):	This is the exposure time setting used to calculate the image movement value, FMC. This is not electronically linked to the camera and will only give an estimate of FMC, as the camera may be in auto mode and use a varying exposure time.
Sensitivity:	This setting controls the sensitivity of the track deviation indicator which is on the on-strip screen.
Baudrate:	This is data transmission rate adopted for communication between the PC and the GPS receiver. NAVPRO uses by default COMM 1.
Tolerance:	This setting defines the working navigation boundaries or cross-track as a percentage of the flying height.
Photo Points:	This is the number of exposure points displayed at any one time on the on-strip screen.

Once satisfied with the settings the operator presses the ENTER key. The program will then validate the navigation plans in the nominated mission files. At this point the program will proceed to the next stage, or it will display a number of error messages, or it will stall.

Error messages are usually related to incorrectly loaded or configured flight plans, a stalled condition is related to the non-availability of incoming GPS position data.

The next stage is the time synchronisation. This is either accepted or repeated by using either the F6 key or the ALT F6 key. When satisfied with the synchronisation the screen mode becomes graphic and control of NAVPRO is then interactive via the various function keys.

Figures 10.3 through 10.5 are the main screens and the sequence the operator will traverse as the aircraft is navigated. Figure 10.3 is the *Ferry flight* screen that the operator is able to select a valid project. The top of this screen displays dynamic GPS information about the current movement of the aircraft. The project name is in the bottom left hand corner above the function key window. The project is selected by the keyboard arrow keys. The F7 key then takes the operator to the *Confirm mission* screen.

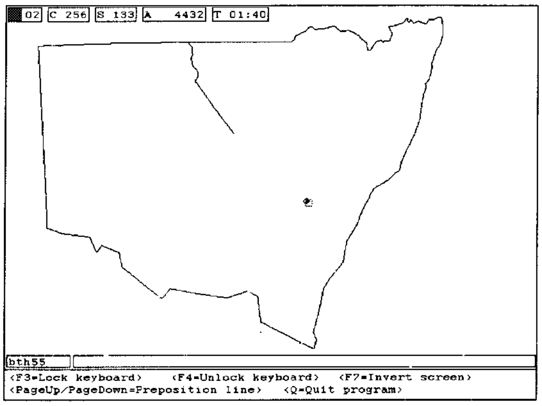


Figure 10.3 Main project selection screen - *ferry flight.*

Figure 10.4 is the Confirm mission screen. Again this screen displays the flight plan of the selected mission or project. An icon, representing the aircraft, moves across the screen with a pointer indicative of the aircraft's trajectory. This graphic image is used by the operator to select the appropriate photo strip, again using the arrow keys. The same image is used by the pilot to align himself with the selected photo strip and provide strip lead in information. Text information about the mission and the selected photo strip is displayed across the bottom of the window.

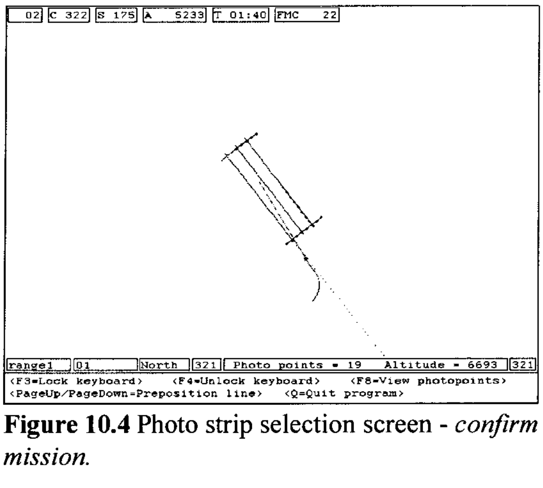


Figure 10.4 Photo strip selection screen - *confirm mission.*

Other key functions are given in the lower window. The F10 key then takes the operator to the *Strip* window.

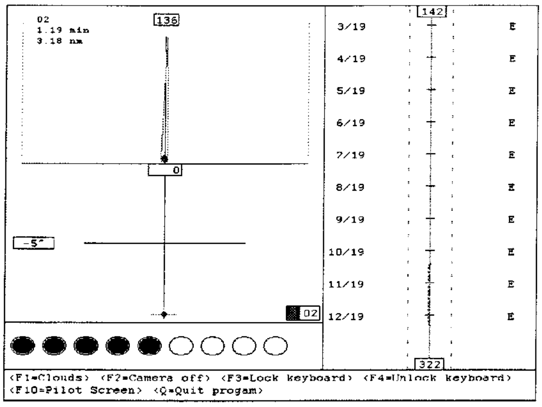


Figure 10.5 On-strip screen - *on strip.*

Figure 10.5 is the *On strip* window. At this stage of the program the control of the camera is active. Key functions are given in the lowest window. This screen is primarily for the pilot. The task is to keep the aircraft icon on the cross-hairs, both laterally and vertically. Unlike the traditional technique of flying to a pre-calculated pressure altitude, the aircraft can be flown to a GPS height. This height includes single point positioning errors further degraded by Selective Availability, and the error associated with the geoid-ellipsoid separation model. A heading deviation indicator in the top left window assists in course changes down the strip, the circles across the bottom are a count down to an exposure event and the window on the right provides information about progress down the strip.

10.1.5 Execution

With all this new technology come new procedures. For the operator he still has to monitor the drift angles for the camera, set the intervalometer and maintain his log. He also has to check the behaviour of the navigation system, evaluating its performance against other information

A new aspect of this operation is that the aircraft is bringing back with it, not only photography but, raw GPS data for a surveyor to process, it is his role to locate the position of the aerial camera at the instant of exposure. From the experienced GPS surveyor's view point he needs as much information about that survey as can be mustered. Occurrences such as when the run started, what was the epoch count, what was the *pics*[5] number, what

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[5] *pics* is the Ashtech term for the photo events stored within the receiver.

was the PDOP and number of satellites tracked is information which may assist in post-processing.

The following is an extract from the operator's early notes of his procedures:

In Flight:

1. Before start ensure camera door open and heater on (Check)
2. Put on blanks
3. Set and record drift value
4. Check frame numbers tally (Camera frame number and NAVPRO)
5. Enter first run tag (existing software on laptop)
6. Record pics and data logger epoch numbers
7. Make sure confirm mission screen has correct run
8. Make sure ground speed lines are set correct (intervalometer)

During run:

1. Record time, direction, etc
2. Monitor drift and flight lines
3. Prepare next run tag

4. Monitor pics and epoch numbers, PDOP

5. Monitor ground speed lines (for FMC)

* (for emergency stop camera e.g cloud when in strip mode press ALT F10. ALT F8 will keep dots there)

After run:

1. Record frame, pics and data logger numbers

2. Enter next run tag

3. Blanks

4. Change drift

5. Make sure confirm mission screen, F7, has correct starting end of strip!

* When changing film take usual steps, just ensure that <u>frame numbers on F7 screen tallies with the camera!</u>

10.1.6 Comments

For the aircrew, the introduction of this technology to the photographic task was a daunting prospect. Given all the processes and functions described here it is to their credit that the first sorties were flown successfully. This report has described the basic operations required to get the operational system into the air. If successful in starting up the invertor, ensuring that the GPS receiver was collecting data, the DATALOGR software was communicating with the receiver and functioning correctly, NAVPRO was happily showing the position of the aircraft on the *Ferry flight* screen, and the camera was on and operating, then the operator could proceed to take-off and hopefully complete a successful flight. As previously stated, if the system had reached this point then it would generally keep going. The whole process from engine start to an up and running system takes approximately 3 minutes, less time than the pilot requires before he can depart, but a problem in this sequence would create frustration and concerns for those involved, as each was well aware of the costs associated with wasted resources and lost opportunity.

Loss of 240 V AC power in flight would be critical as all PC functioning would terminate. On the other hand software lockups could be recovered from by warm computer re-boots. Instruction was to not turn off either of the computers or monitors unless completely necessary, always re-boot via the reset button. Problems with the GPS receiver in some cases were not recoverable in the air due to the complexity of the receiver's operation and the lack of understanding by the air crew. In many cases the mobile phone has played a significant role in supporting this operation, particularly in the air.

The early flights revealed many technical and operational facets that needed to be addressed, not to make the system ideal but just to tame it!

10.2 Landing

Having successfully completed a mission the shut down procedures at the end of a flight needed to accommodate the data backup and transfer requirements. As a general guideline the DATALOGR software was terminated approximately 15 to 20 minutes after camera switch off. This requirement was necessary for certain aspects of the post-processing software PNAV. Excess data at the start and end of a mission fitted PNAV's capability of processing kinematic data both forward and backward. The excess data ensured that sufficient lead in time was available for the convergence of the Kalman filtering.

Redundancy is an important factor in data handling. The two computers on the aircraft are connected via a local area network. Each can see the other's hard disk. At the completion of a flight only one copy of the raw GPS data exists but two copies of the NAVPRO result data files are retained, but in different parts of the directory structure of the NAVPRO computer. One file is retained in the AREA directory under the job name and another is kept in another location.

For data retention purposes the raw GPS data is backed up by the operator from the data-logging computer to the navigation computer. Before this procedure actually takes place exposure time tags must be down loaded from the GPS receiver. The Ashtech program HOSE is used to communicate with the receiver and retrieve the exposure time tags into the generically named PHOTO.DAT file. To avoid confusion with other camera exposure tag files this file is immediately copied to another file which follows the DATALOGR template format but is prefixed with the letter P for photo, e.g. PNSW1A98.150. A check is made of the active data directory to ensure that the appropriate raw data files exist, if they do not then there is cause for concern. In the event that the operator has incorrectly configured the DATALOGR software the data may still reside elsewhere on the hard disk.

A mirror copy of the raw GPS data directory structure exists on the navigation computer. Under this directory structure the operator creates the same directory for the current day's raw data. The raw data for the flight is then transferred, via the LAN, to the navigation computer as a backup. The task of moving the raw data from the aircraft to the office is still to follow. This was initially handled by copying the raw data to 3.5" floppy disks in the format of .ZIP files, configured to span a number of disks.

The operator's early notes for this procedure were:

After landing:

1. Both computers should still be operating

2. Connect keyboard to data logger, Press ESC, ESC to terminate DATALOGR

3. Display should show current directory C:\DATA\(Julian day)_(year)>

4. Type “DIR” (↵) (To make sure that data is there)
Should show a B & E file

5. Type “HOSE” (↵) (To down load data)

6. Type “F” (↵) (from menu) (i.e. read the photo tag data)

7. Press ESC, ESC to exit from HOSE program and return to DOS prompt

8. Type “DIR” (to see raw data files and PHOTO.DAT file)

9. Type “COPYΔ PHOTO.DATΔ PNSW1A95.150" (↵)
(sample command to make backup of PHOTO.DAT)

10. Type “DIR” (to ensure that copy has worked)

11. Type “COPYΔ *.*Δ D:\DATA\(Julian day)_(Year)
(This command backs up the data)

In the early configuration of the local area network both computers saw each other’s hard disk as drive D:.

At this point in time the mission was complete apart from the task of transferring the raw GPS data to the office. It should be pointed out here that a successful flight of approximately 3.5 hours would gather around 12 to 13Mb of dual frequency, single second GPS data.

11. Initial Problems

Without considering aspects of data processing, and subsequently the aerial triangulation procedure, the main issue at hand was the reliable operation of the aircraft data acquisition and navigation system.

It has already been mentioned that problems existed in the supply of a reliable power source for the computers and that some bugs existed within the NAVPRO software. There were also operational problems associated with the various aircrews that were used.

At the time of implementing the system five staff had been identified for aircraft operations. These five staff were to operate on a rolling roster associated with the aircraft movements. This continual changing of operators necessitated that the system operation be reduced to a common denominator ensuring that extra special skills were not a requirement to be proficient at the task of aerial survey. Those systems functions that could be automated were subject to continuous monitoring and ongoing development.

Other issues identified were:

1. Data transfer from the aircraft to the office environment.
2. The pilot's display screen - viewing, mounting, size.
3. Inconsistent behaviour of the GPS receiver.
4. PC BIOS problems.
5. GPS receiver firmware.
6. AUSNAV - initialisation problems.

11.1 The invertor

The invertor is a critical component in the chain of hardware. Others have commented on the importance of a reliable power supply to ensure success for an airborne GPS mission (Lucas & Mader, 1989; Hothem et al, 1994). The SGD's Aerial Survey Branch was using a laptop computer for its photo tagging system well before this project was implemented. The Branch was well aware of not being properly prepared with sufficient power in the form of charged NICAD battery packs to power the laptop. This function was not critical to the process of aerial photography, but it reflects on the quality of products when inconsistencies such as incorrect tags or missing tags appear on the photographs.

In the early stages of development the project implementation was somewhat saved from the inadequacies of the invertor because operations were gearing up over the approaching winter months. The cold early morning starts provided favourable conditions for the invertor, which made its performance appear acceptable.

Any further spending on development was subject to budget constraints, the thought of writing-off a new $1500 component was not an acceptable option. Operations had commenced in late May, with the only other previous full flights being some test flights at various scales over the Bathurst area and some project photography in the Sydney area. The behaviour of the invertor appeared to be reliable enough when powering one computer, and it could still handle the two monitors as well, but bringing the second PC on line was always a fine line between success and failure.

The Industrial Computer Source PCS in use on the aircraft can be configured and optioned for specific applications. One of the available options is a 24V DC power supply. Using this option would bypass the invertor, reducing the load demand on it, and power the PC directly off the aircraft power supply, as in the case of the camera and the GPS receiver. A disadvantage of this configuration was that any work or maintenance needed on this PC would require, if the PC was not in the aircraft, a 24V power supply. If the maintenance was required whilst the computer was still installed in the aircraft, then either the engines would need to be running, or for quick fixes the aircraft battery could be used.

Using the aircraft battery had not proven to be an acceptable alternative since experience had shown that the installed system would flatten the aircraft battery sufficiently, to a level where starting the engines was not possible, in 15 minutes or less.

Given the drawbacks of using a 24V system to power a PC, the advantage would be that some reliability would result in energising the various components. A 24V power supply was purchased and installed in June 1995, this led to an immediate improvement in operations in the area of mission power up. Both PCS could be booted up with a high degree of confidence.

What followed, however, was a false sense of security, and being mislead by external factors that were not related to the problem. The PC powered by 240V AC began to have boot up problems, messages about the BIOS and failure to detect hard disk drives. This situation was creating another source of bewilderment to the operator, and to the author whose task it was to solve these problems, on a number of occasions, over the phone, whilst the aircraft was at some desolate airfield in Western NSW.

The PC supplier was contacted and informed of the problems and promptly forwarded a new motherboard to the SGD. This board was then taken to the aircraft's temporary field base and retro-fitted into the troublesome PC. This has been the only time in the project's history that such field servicing has been necessary.

Unlike a desktop PC, which in most cases is subject to everyday use, and in some cases may not even be turned off overnight, the aircraft computers can be turned off for extended periods of time; periods of weeks between use is not uncommon. When the PC is not powered, BIOS (Basic Input/Output System) and real time clock information is retained via power supplied through the backup batteries, which are mounted, in this case, on the computer motherboard. When in general day to day use the demand on these batteries is low. The circuitry within the PC is such that when the PC is powered from an external source the backup batteries are bypassed and they are no longer under load. When the PC is turned off then the backup batteries provide the maintenance power resource once more.

The aircraft computers had been idle for quite extended periods, particularly during the time that operational processes and flight planning procedures were being rationalised. As a result the backup batteries on the motherboard were discharged quicker than normal. What initially appeared as hardware problems was in fact the slow failure of the backup batteries. The real time clock was running progressively slower, which was difficult to explain given that the clock was set to GPS time each time NAVPRO was used. The operators couldn't understand why the clock could loose as much as a 24 hours in a couple of days. Another questionable aspect of the motherboard batteries was their mounting, this was not a suitable arrangement given the dynamic loads the equipment was subjected to.

As it eventuated the change of motherboard was unnecessary, simply replacing the discharged batteries would have sufficed.

Lessons are learned in situations such as this. Losing the PC BIOS brings with it other problems as well, particularly when information such as hard disk drive configuration data is lost. In this case operational status was only restored because the BIOS of both computers on the aircraft are identical, the settings of the functioning PC were used to recover the non-functioning unit. If this had not been the case then the in-field service may have been a disaster. As a result of this experience, a copy of all BIOS settings is carried onboard the aircraft at all times.

A comment on servicing the PCs in this particular installation is that the process of dismantling and assembling the components is an arduous one, as the location within the aircraft is very restrictive. Access to the rear of the computers, where the inter-connectivity exists, can only be made by dismantling each component in a certain sequence. To service the data-logging computer requires first, the removal of the GPS receiver in its mounting facia and the dis-connecting of all cabling, then the navigation computer and its associated cabling and finally removing the data-logging computer and its cabling. A labourious task for the sake of two small button batteries. Assembly is the reverse procedure.

Operations proceeded with some normality but problems still existed with the reliability of the invertor. As a result of modifications by Hawker Pacific the invertor was relocated from its position under the floor to a vacant space inside the rack behind the GPS receiver. In this location it was possible to utilise the reset switch option available on the invertor unit. A small switch was installed on the back of the rack that was wired into the power bus of the invertor. Using this switch it was possible to turn the invertor on and off, providing a reset function. The power to the rack was re-wired, the three power outlets available on the cabin wall were replaced by one 24V DC outlet. In this configuration all power delivery and inversion functions are provided within the rack itself, creating a self-contained unit.

The fitting of this switch provided a means to cycle the invertor in the event of an overload. This was previously achieved by cycling the main GPS circuit breaker located in the cockpit. This reset switch did not guarantee any better performance from the invertor but at least the receiver could be left powered up, reducing the chance of further failure.

As the summer months approached the vulnerability of the power supply again began to become evident. What else could be done to reduce the susceptibility of the invertor to failure? The suppliers were approached about the problems associated with this unit but unfortunately an acceptable solution was not forthcoming. After approaches to a number of companies specialising in this type of power delivery, in-rush current appeared as the source of the problem, particularly in the case of this electronic invertor design. UPS a power supply company, provided a simple circuit diagram for an in-rush current limiter. This diagram and associated text is illustrated in figure 11.2 Based on this circuit a small unit was constructed to provide the current limiting that was required. This device is illustrated in figure 11.1.

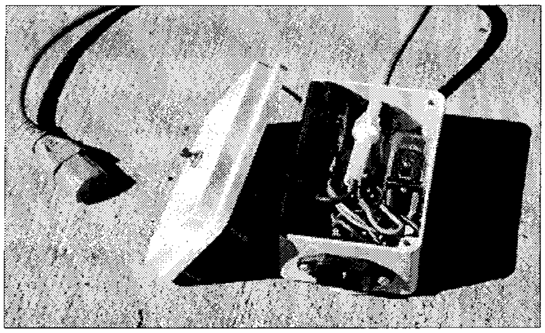

Figure 11.1 Device constructed to limit in-rush current.

The cause of the invertor failures was its inability to carry the instantaneous current encountered when a computer was turned on. It is suspected that a very sensitive thermal overload detector was tripping due to the initial current experienced for one or two cycles of the AC supply. The current limiting device bypasses this instantaneous current through the power resistor R1, which reduces the load to a minimum. The in-rush current drops off very quickly after the initial cycles.

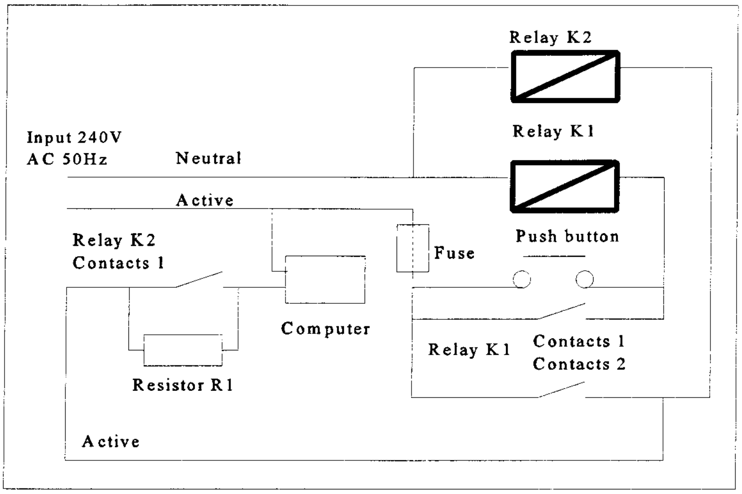

Figure 11.2 Circuit to limit In-Rush current.
Operation - When load is switched on at the power point nothing happens until the push button is pressed and momentarily held. The push button enables the relay K1. Enabling K1 closes contacts 1. Contact 1 keeps relay operating after the push button has been released.
Relay K1 contacts 2, upon closing power the load via the resistor R1 and at the same time Relay K2 is supplied.
Resistor R1 limits in-rush current. It will take approximately 20ms for the relay K2 to operate, shorting resistor R1 allowing full power to be available.

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The current limiter was built as an in-line device that has a male plug and a female socket, similar to most household utilities. A small interrupt switch on top of the box activates the circuit as described in figure 11.2. This device operated with some success, but its use was short lived as the invertor eventually expired. The bang and smell associated with its demise was not appreciated by the aircrew as they were preparing to depart on a mission.

This event necessitated the quick acquisition of a replacement invertor. Again, budget restricted the options but a purchase would only be made if the new unit could be demonstrated to continually and reliably start and restart two desktop PCS and their monitors. As a result of a satisfactory demonstration the SGD purchased a 750W CSA Sine Wave Invertor.

This unit is of the traditional design, not depending on electronic high speed switching. Its drawbacks being its weight/watt increase over the previous unit and its lower capacity, but this is of little consequence as this unit has never failed to operate the system and is now providing back-up power to a laptop as well!

Operations were going well but as is usually the case, one thing leads to another. The behaviour of the data-logging computer was becoming erratic. Ongoing problems were occurring at boot-up, particularly with the disk controller function. This time it was not the onboard backup battery, as problems with these had been addressed by wiring into the motherboards easily accessible external battery packs which are mounted behind the front access door of the computer facia. These external packs should power the motherboards far beyond their useful life. This new computer problem was related to the slow deterioration of the 24V power supply. The output of this power supply was failing, particularly the 5V supply to the disk drives. It was with some confidence that the original 240V power supply was re-installed into this computer, knowing that the new invertor would be up to the job.

But was it? A new phenomenon was occurring, why was the aircraft's GPS circuit breaker tripping all of a sudden, what was different now that would cause the circuit breaker to react? Tripping circuit breakers are not appreciated on an aircraft as they indicate a short circuit or an overload condition which could lead to a fire. Hawker Pacific had requested the original load requirements for the new navigation installation when the hardware installation was contracted. The highest load estimate was around 600W maximum according to specifications supplied with the various hardware, this would require a 25 Amp circuit breaker or fuse. This was a fairly large demand within the aircraft and Hawker's considered lower rating protection. The SGD was under the impression that a 15 Amp circuit breaker had been installed which would have provided protection beyond the 360W load that one PC and two monitors would draw.

The only thing that was different now was the new invertor, it wasn't overloading, but the system was. The answer lay in the new invertor, its operation in comparison to the previous unit was less efficient. To produce the power outputs required needed a higher level of input. There was nothing wrong with the installation, there were no short circuits, but the new invertor used more power to produce the same output as the previous unit. The overload was very marginal as the circuit breaker would not trip immediately, but after a period of time. This was actually a poorer scenario than having no power at all.

Previously, once everything was going, given its shortfalls, things would tend to keep going. Now the system could fail at any time.

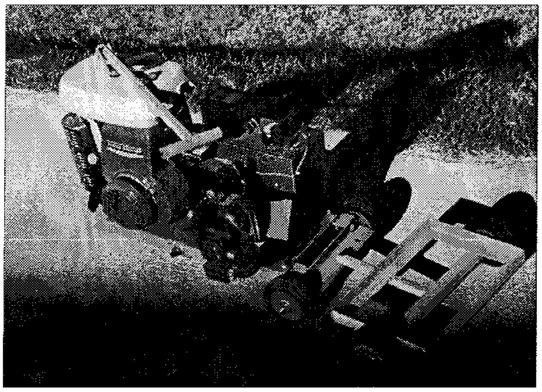


Figure 11.3 24 Volt generator shown without batteries. This unit will ground power the aircraft for hours.

A request was made to Hawker Pacific to replace the existing circuit breaker with a higher rated unit, a 20 Amp. In the mean time the 9" monitor associated with NAVPRO was not used. This reduced the power demand of the system enabling operations to continue using only the pilot's display for navigation. When Hawker Pacific replaced the circuit breaker it was discovered that the original was a 10 Amp unit. A 15 Amp breaker is used today to protect the aircraft power system from faults. In hindsight, the original installation was operating on a very small overload margin, but this was not the source of all the other previous problems. But operating in this way was able to identify just how much power that the system required.

Unlike the reports of Lucas & Mader (1989) who resorted to using 12V gel cells to power their equipment, there has been no problems with power variability from the aircraft system. The current power supply system has been operating faultlessly since late 1996. It has been augmented by a ground power unit which uses an upright HONDA engine to power a 24V generator, see figure 11.3. The power from this generator is regulated by two 12 volt batteries connected in series. This power unit can operate all the airborne GPS and camera functions via the Cessna ground power coupling provided in the rear of the left hand engine nacelle. The airborne equipment can be operated for extended periods to test all functionality without putting any demands on the aircraft's own power supply system or battery. The requirement of ground running the engines for equipment testing purposes is no longer necessary.

Many of the power supply problems outlined in this narrative may appear to be trivial but in a day to day operation they are issues that incur substantial costs in lost time and opportunity. They are also representative of the variety of unlikely challenges that can arise on a project such as this.

11.2 NAVPRO

Australia's isolation from the rest of the world has a number of problems associated with it when assumptions that are totally valid for other localities are applied to situations in this country. Two of these assumptions which impact on the SGD's airborne GPS and photography platform are time zones and the mathematics of the southern hemisphere.

From experience, software quality can be readily assessed when the internal calculations fail to account for the fact that latitude values can have negative signs. NAVPRO, fortunately, does not suffer from this syndrome, but the time zone difference between Europe and Australia has created a few problems, some of which have been solved and some that have not. Only those considered serious have been corrected by the supplier.

Initially, the time synchronisation method used by NAVPRO to set the PC clock to GPS time was not a reliable process. On some days the synchronisation process would work flawlessly, on others it would never work, often delaying the departure of the aircraft. On these occasions the only option would be to depart without a clock synchronisation and hope that dead reckoning would not be required.

It was by chance that the author was able to solve this mystery. The aircraft was preparing for departure, the engines were running, computers and other equipment were on but the clock could not be synchronised, the display not giving any indication to the source of the problem. Over and over the cabling was checked, i.e. the receiver was removed from the rack, the cables were checked and the receiver replaced, all was checked and considered correct, but still no success.

A time synchronisation cannot be performed unless the receiver had determined its position, but again this was not the problem. Then, as if magically, a synchronisation was possible. On another occasion during testing, synchronisation was possible but then it stopped.

Analysing this behaviour, it appeared that these problems were occurring between 10:00am and 11:00am. Nothing special about these times in NSW, for our projects they are typical operational periods for a mission, but in Europe they equate to UT0hr and UT1hr, periods of the day when photography is not taken. They are also unique time strings in any message data that may be generated from a GPS receiver.

It was deduced from the behaviour of the NAVPRO software that a bug existed within the program that was related to reading the time pulse and message strings emanating from the GPS receiver. The logic could not correctly interpret strings between these two times. Swedish National Land Survey was informed of the problem and they proceeded to fix it. In the interim the SGD was still able to function efficiently planning operations around this time period until a bug fix version was available.

Another problem with UT0hr also affected the performance of NAVPRO. NAVPRO uses a file creation function which is based on the current PC date and time. The clock in the navigation computer operates on GPS time as a result of the synchronisation process. As part of its functionality NAVPRO opens result files which contain position and time information about camera exposures. These files are opened and named based on the current date and time. Data about an exposure taken at 9:00am on the 12/08/98 (local) would be recorded in a file named 980811.DAT. Exposures taken after 10:00am would be recorded in 980812.DAT. This process works fine if the day rollover does not occur at 10:00 in the morning. The program logic continually checks the time to determine whether or not a new file has to be opened. This process is complicated when a planned exposure occurs very close to 10:00am.

NAVPRO invariably freezes if an exposure is planned to occur within a few seconds after 10:00am. The SGD requested a fix to this problem from the SNLS. A simple solution would have been the inclusion of a time zone option in the configuration screen. At this stage a fix is not yet forthcoming.

Some steps have been taken to reduce the impact of this problem. Information about the time of next exposure is provided through another software package. Procedures have been developed for use with NAVPRO, so that in the event of a lockup a manual exposure is fired by using the camera control on the operators drift sight. NAVPRO is then cycled back to the Photo Strip Selection screen and back to Strip Mode. This generally results in a new file being opened for the new GPS day. In this case continuous data about a strip needs to be concatenated and edited. The primary purpose of this procedure is to ensure that all planned photographs are taken, otherwise a re-fly may be necessary.

Preparation of flight plans is also worthy of mention. NAVPRO is not tolerant of NULL characters within the flight plan files. This was discovered when NAVPRO would not read some flight plans. It happened to be the result of a certain way that one of the aircrew edited the strip files. It is now standard procedure to use a shareware utility, FILEMOD, to remove all nulls from the strip files.

11.3 Data transfer

The initial data transfer proposal necessitated the purchase of 200 3.5" floppy disks. These would be used to transfer the raw GPS data from the aircraft to the office for processing. Once the data was processed and stored, the disks could be recycled. In the early stages of the project implementation, the data transfer function was performed whenever the aircraft was returned to its base. This time delay between data capture and processing was tolerable owing to the lag between photography and aerial triangulation. From a surveyor's point of view it ensured that the data was handled correctly and not corrupted or lost. The time taken to transfer data to floppy disk was substantial but this was not of consequence when the computers could be connected to the hangar power via an extension lead. One of the limitations of using floppies was the time needed to move data, and this was unacceptable when the aircraft was based away from Bathurst.

Raw GPS data on the aircraft is stored on both computers. Either computer can be used to copy the data to floppy disk but generally it is more convenient to use the navigation computer because it also contains result file data which is relevant to office processing.

Raw data files larger then 1.44Mb meant that some technique would be needed to bridge the data across multiple disks. The widely accepted utility, PKZIP, could compress the raw data and copy it to floppy disks in a proprietary format so that the reverse sequence, PKUNZIP, could be used to recover the data onto another computer hard disk or, in this case, a particular drive of the SGD computer network. Although this methodology worked, the process was extremely cumbersome as:

1. Large raw data files used as many as 8 floppy disks for a flight.

2. The medium was not reliable as on occasion a floppy disk would fail or be unreadable at the PKUNZIP stage. This required organising to copy another set of disks which would be subject to the aircraft's current location and explaining to the operator what was necessary to obtain them. Even so, the round trip from the SGD office to the Bathurst airport, copy the files and return could take 2 hours.

3. The transfer of this data to the SGD computer network was provided by another branch within the organisation, Information Management and Technical Services (IM&TS). The policy within the department is that operational PCS not be fitted with floppy disk drives. This requirement is based on the virus protection policy adopted by the SGD. From the data migration aspect this policy introduces unnecessary complication to an in-house process.

Once the operators were instructed in the use of PKZIP the data transfer to floppy disk was completed at the end of each flight with the engines running on the ground. The number of failures occurring in the transferring of the data, and the extended engine time to provide power for data backup after a mission, was not a satisfactory arrangement.

It was suggested that a tape backup utility might be a better solution. A Central Point tape backup system was purchased, which could be mounted into the navigation computer. This brand was compatible with existing units within the SGD at the time and fitting it in the navigation computer ensured that external 240V power could be used during the tape backup process. At this stage the data-logging computer was operating on 24V DC and was not a suitable option for data transfer applications.

The tape drive system was installed with its DOS based software package but unfortunately it could not be configured to append each flight's data to the tape in a batch process. The backup function could only be configured manually, a process that was, in the author's opinion, too difficult for the aircrew to manage, given the workload that they were currently handling.

Tape units, although appearing attractive for their data storage capacity, are not designed for real time interactive operation. To append data to a tape, the tape must be transported through to the end of the current data block. As the existing data block grows the search time to reach the end of the data block grows, and with it the transfer time. Added to this a verify function and the time required for the data transfer function is doubled.

Another drawback, although it can be said to apply to all media, is the data storage format. This is generally proprietary, with each manufacturer using its own format for data storage. Even though the media is the same, the data cannot be read by another vendor's software. Tape backups also use special directory structure storage techniques and invariably require the same directory structure to exist when restoring data to a disk drive. Within the SGD a similar requirement exists for data brought into the organisation on tape. The retrieval process from a tape to the SDG computer network is handled by IM&TS, as a tape drive unit was not allowed in the Aerial Survey Branch.

The strict operation of the tape backup media does not, in the SGD's case, provide the flexibility and simplicity to operate in a manner acceptable to the aircraft operation. This was disappointing because the process of capturing the raw data, backing it up across the aircraft LAN, and copying the data to a transfer media, could not be implemented satisfactorily. Again, the data transfer process was very convoluted, required specialised skills and was inefficient.

The data transfer process used today on the aircraft is via a SYQUEST 270Mb removable floppy disk. The tape drive unit was removed from the navigation computer and replaced by the SYQUEST unit. A similar drive unit is installed in one of the PCS in the Aerial Survey Branch's office area. This was allowed as this unit was not a standard media within the Department, and did not contravene any standing IM&TS policy. The SYQUEST is the ideal solution because its operation is simple and it behaves in exactly the same manner as a hard disk drive. This behaviour allows it to be included in normal batch processes, it only has to be correctly addressed. The LAN on the aircraft is set up so that both computers can "see" the other's hard disk drive. The LAN was modified with the addition of the SYQUEST unit so that both computers accessed the SYQUEST as drive D:. The two computers then both see each other's hard disk as drive E:.

This arrangement provides a safe data storage environment and a flexible, efficient method to move bulky data from the aircraft to the office. This data movement is extremely important, not only in providing a robust methodology to the storage, backup and transfer of GPS data but, it also ensures that the data is there and is available in an identified data storage structure.

This whole operation has been supported by ongoing development of batch files and utility software written in C. These utilities support the start, data capture, transfer and shutdown of computer operations for every flight. The initial DATALOGR batch outlined in chapter 10.1.3 has been extended with each new development to reduce the operator's workload and to ensure that a rigorous process is followed for every flight.

The current software used on the aircraft is a batch driven routine which is created by a C program. The program is quite simple in that it executes a batch file immediately after the C program creates it. The C program also creates a back-up batch file called FAILSAFE.BAT. This batch file provides a back-up routine in the event that some computer element has failed or been unavailable during the data transfer and back-up functions. If for some reason there is a failure during this process then the operator only has to restore normal operations, maybe a system re-boot, and type the command

FAILSAFE and this will ensure that the data of the current day will be backed up and transferred to the removable disk drive as planned.

Batch files are used for this purpose as embedding other executable code within programs via system calls can lead to memory limitation problems within the DOS operating system. Batch files provide a simple means of achieving a result without the complication and "hard wired" nature of an executable.

The batch file START.BAT, listed in figure 11.4, initialises the data-logging routine. The commands are shown in bold. If the time and date are incorrect then the operator has the option to correct or reset them. The time and date should be set to the *LOCAL* time and date. The command C:\pnav\logstart calls the C routine which creates the batch file KICKOFF.BAT. After LOGSTART creates the batch file KICKOFF.BAT the START batch file calls KICKOFF.BAT. The contents of this file is listed in figure 11.5.

```
@echo off
:begin
cls
echo.
echo.
time
echo.
echo.
date
echo.
choice /c:yn Is the time and date
the correct ←[1;5mLOCAL←[0m
time
if errorlevel 2 goto begin
c:\pnav\logstart
call c:\pnav\kickoff.bat
```

Figure 11.4 Batch file START.BAT.

The LOGSTART program creates all the commands and options that the operator would have to know to operate DATALOGR, manage the backup and transfer of the raw GPS data, down load the photo tag data and rename it to the adopted convention. The sample listed is for day 018, 1999. Various messages are given to validate the data movement and the successful copy and storage of the data. In the event of a failure in the data storage and back-up procedure the command, FAILSAFE, will perform the required functions. Figure 11.6 lists the contents of this batch file.

```
@echo off
cd\
cd airgps
if not exist 018_99 md 018_99 > nul
cd 018_99
echo.
echo   This is flight 1 of 018_99
echo.
echo  ←[1;5mIMPORTANT:←[0m DO NOT TURN OFF NAV COMPUTER BEFORE LOGGING COMPUTER
echo.
choice /c:yn Start DATALOGR
if errorlevel 2 goto stop
DATALOGR -b 38400 -Y NSW1A99.018
DIR
echo.

choice /c:yn Do you wish to keep this data
if errorlevel 2 goto stop
if not exist d:\nul goto mesage1
if not exist e:\nul goto mesage2

d:
cd\
cd airgps
if not exist 018_99 md 018_99 > nul

e:
cd\
if not exist 018_99 md 018_99 > nul

c:
HOSE
copy photo.dat PNSW1A99.018
copy *.* d:\airgps\018_99
copy *.* e:\018_99
xcopy d:\area\results\*.res e:\018_99 /d:17/01/99 /Y
echo.
echo   Data backup complete
echo.
goto stop

:mesage1
echo.
echo   The nav computer has not been detected.  Establish network and type
echo   ←[1mFAILSAFE←[0m at the DOS prompt.  This will back up your data automatically
echo.
goto stop

:mesage2
echo.
echo   The SyQuest drive has not been detected.  Check the disk and type
echo   ←[1mFAILSAFE←[0m at the DOS prompt.  This will back up your data automatically
echo.
:stop
```

Figure 11.5 Sample of batch file KICKOFF.BAT generated by the C program LOGSTART.EXE.

```
@ccho off
cd\
cd airgps
cd 018_99
if not exist d:\nul goto mesage1
if not exist e:\nul goto mesage2

d:
cd\
cd airgps
if not exist 018_99 md 018_99 > nul

e:
cd\
if not exist 018_99 md 018_99 > nul

c:
copy *.* d:\airgps\018_99
copy *.* e:\018_99
xcopy d:\area\results\*.res e:\018_99 /d:17/01/99 /Y
echo.
echo.
echo   Data backup complete
echo.
echo.
goto stop

:mesage1
echo.
echo.
echo   The nav computer has not been detected.  Establish network and type
echo   ←[1mFAILSAFE←[0m at the DOS prompt.  This will back up your data automatically
echo.
echo.
goto stop

:mesage2
echo.
echo.
echo   The SyQuest drive has not been detected.  Check the disk and type
echo   ←[1mFAILSAFE←[0m at the DOS prompt   This will back up your data automatically
echo.
echo.
:stop
```

Figure 11.6 Sample of batch file FAILSAFE.BAT.

This system has been in operation for more than two years and simplifies the movement and safety of data within the aircraft environment. The FAILSAFE command, which has been used many times, ensures that data can still be managed in the event that some component within the system should temporarily fail. At the end of the day there are three copies of the original raw data including the photo tag information. This may seem a bit of an overkill but disk storage is comparatively cheap, and from an overall quality control viewpoint, ensuring that the data is there and stored in a rigorous fashion is essential to delivering an acceptable product. The operator doesn't need to know every command to move the data, his time and energy can be better focussed on the more critical aspects of guaranteeing quality photography, in the right place and with the right data.

11.4 If its not broke don't fix it!

The airborne GPS, camera navigation and control system is a complex integration of sophisticated equipment. The assumption that "latest means the greatest" is not always the true. In late 1995 the navigation board in the aircraft Ashtech Z12 failed. Fortunately this occurred during some testing whilst the aircraft was in the hangar. The failure being evident by the inability to boot the receiver when switched on. The problem was immediately addressed by the local agent.

From the initial implementation the receiver had been fitted with 1E00 firmware. The firmware had functioned satisfactorily and was completely compatible with the NAVPRO software. The only real limitation of this version was the limited input/output options available on the Ashtech receiver. Although four I/O ports were available, only ports A and B provided full functionality. Ports C and D only offered limited data options for some real time differential applications. Some bugs existed within the 1E00 version, these were mainly related to cosmetic items and display errors such as switching the velocity components on page 2 of screen 2, but data output as far as the SGD was concerned was sound. This presumption was supported by NAVPRO's operation and the post-processing of kinematic GPS data.

As part of the repair to the navigation board the agent upgraded the receiver firmware to version 1F00. This later firmware provided a number of bug fixes and extended user interface. The capability of the receiver I/O was extended to full functionality on all four receiver ports, correcting the velocity outputs on screen 2, additional NMEA message strings, modified display for screen 0, and various other small fixes. New firmware could only be a step forward in providing a more refined system as part of process improvement.

The repaired and upgraded receiver was re-installed into the aircraft. On its first flight out of Bathurst the operator telephoned from the aircraft that he was having trouble with the heading indicator on the NAVPRO on-strip screen, but all other indicators were fine. Another dilemma, what was happening to cause the software to behave in this fashion? Upon reflection the only change to the system had been the navigation board repair and the new firmware. Obviously the data coming out of the receiver was somehow erroneous, but only parts of it.

Again the agent was contacted but they could shed no light on the problem. The only way to duplicate the problem was on a dynamic platform and using NAVPRO. The manufacturer continued to deny that any problem existed in the data format and suggested that the problem lay in the NAVPRO software. The author suspected that the small fix-up to correct the velocity components on screen two of the receiver had somehow corrupted the velocity data embedded in the PBEN string. SNLS was contacted regarding this problem and in reply to the question about the operation of NAVPRO and the PBEN data stated:

> "About the firmware 1F00, we haven't used it together with NAVPRO, but there has been a problem on the reference stations.
> The current version of NAVPRO does not take any format error into account, and doesn't compensate anything in the PBEN data.
> If the velocity PBEN data is reversed in the latest firmware, ONE of the effects is just as you discovered, severe heading correction to the right or left"

The solution lay in returning the receiver to its original configuration. The local agent supplied a copy of the "Flash" software so that the SGD could correct the software in-house. Unfortunately this process was un-successful as the receiver died mid-way through the re-programming procedure. Again the receiver was returned to the local agent, who replaced the firmware on the spot. Two and a half weeks after the initial navigation board failure operations were back to normal.

From this experience a policy has been implemented where no new upgrades or software changes are implemented until they are thoroughly tested. Migrating the aircraft receiver to the current 1G10 Beta firmware required the following process.

First, in order to convince the local agent that there was a problem with the 1F00 firmware the author configured a test data flight plan that was actually around the streets of Waterloo near the agent's offices. This required a vehicle, two Ashtech Z12 receivers, one configured with 1E00 and another configured with 1F00 firmware, a laptop computer and a roof mounted antenna. It was demonstrated using NAVPRO that something was wrong with the PBEN data stream when the trajectory indicators using 1E00 were correct, but were incorrect when using 1F00 over the same course.

The local agent then acknowledged that something was wrong with the later version firmware, but this did not carry much weight with the parent company. In mid 1997 the agent offered a new firmware version 1G10 Beta which "fixes the velocity component problem". Obviously the problem was finally acknowledged by Ashtech. This new firmware, which offered all the features of 1F00 only more, was not installed until the author had performed the same tests around the streets of Waterloo. Although it is only a beta version it has performed satisfactorily, but it has revealed some weaknesses in the Z12's operational capacity.

The aircraft is currently utilising three computers. All of which are supported by GPS data of one type or another. There is also a real time differential correction component as well. The attraction of 1F00 or 1G10 was the enabling of four full I/O ports. Unfortunately the ability of the receiver to service all four ports at a 1 second update rate has revealed some limitations. When configured in this manner the receiver locked up a number of times, impacting on the mission performance. The configuration has reverted to the original output on ports A and B, real time differential data comes in on port C. The servicing of these components is now achieved by splitting the communications output through cable splitters.

The SGD is also in receipt of updated versions of NAVPRO but the testing required to implement it, and the changes required to procedures cannot be justified under the current conditions - the change isn't worth the trouble!

11.5 Other small problems

11.5.1 The pilot's displays

Previously mentioned were the construction and installation problems concerning the pilot's navigation screen. Even though in appearance this unit looks to be very fragile it has been in fact a very robust mission effective component. It has always been an item of contention in the cockpit area because of its size and the shielding effect it has on a number of instruments on the panel, particularly in the radio area. Although it has been in use for over four years the unit has only ever been tolerated in the cockpit.

This part of the implementation has been the most difficult to address as satisfying the needs of aircrew and the safety authorities is a difficult balancing act. Having acknowledged the size of the LM64K101 screen, 205mm x 141mm, was its greatest weakness, a smaller VGA compatible LCD screen, a LM64K11 was purchased in early 1996. This screen's overall size of 167mm x 116mm, was considered to be a more suitable design than the existing unit. It was purchased with the same controller card and back-light board. Also supplied was a small interface ribbon cable approximately 15cm long.

The success of this new screen would lay in how small the final dimensions of the screen in its mounting surround would be. It was thought that if the dimensions could be kept to an absolute minimum in length, breadth and depth then it may be possible to mount it on the back of the pilots sun-visor.

This installation would require that the back-light power board and the controller card be situated at a location remote from the screen. A number of challenges existed with this design. The first problem being the cable that connected the screen to the controller card. The 16 pin connector provided on the back of the screen is designed for a flat ribbon cable that is 0.5mm pitch and whose contact portion is 0.3mm thick. The cable pictured in figure

11.7 is approximately 1cm across and the conductors are like alfoil. The problem faced was how to terminate the other end of the cable that had to go to the controller card. The screen end was designed for this cable type so it was OK. Further to this the cable was only about 15cm long, not long enough to remotely locate the controller and back-light circuit boards.

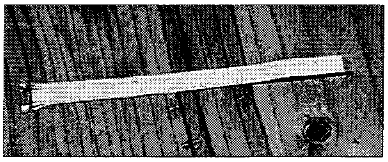
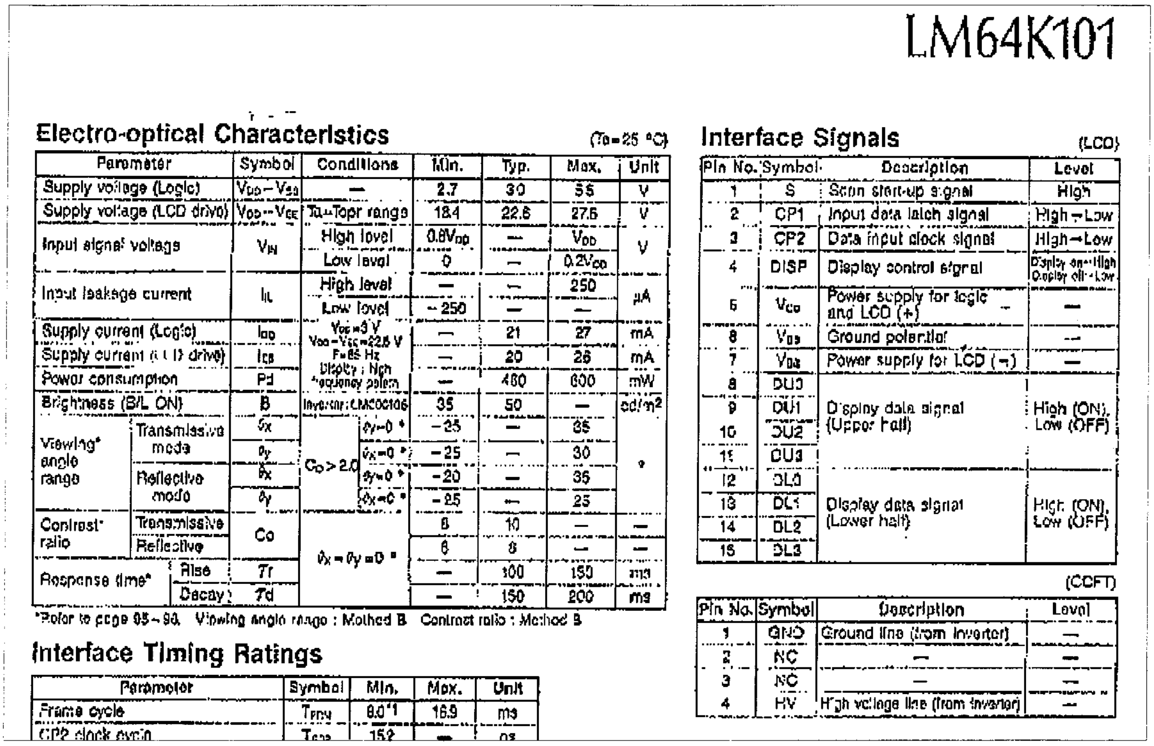


Figure 11.7 Flat ribbon cable.

Somehow the delicate flat ribbon cable had to be joined to a more robust ribbon cable that could be then connected to the remote circuit boards some 600mm away! This was achieved by drilling 2 parallel rows of 16 0.7mm holes very close together in a piece of laminex. Laminex seemed the best option as it was light , thin, strong and an excellent insulator. This piece of laminex became a termination board by using 0.4mm copper strand wire through each hole. The alfoil-like ribbon was soldered to each strand that stuck through each hole in the laminex. Care had to be taken that the connections were sound and that none of the cables were touching each other causing a possible short. The soldering was executed using a table light stand incorporating a magnifying glass.

The other end of the copper strand wire mounted in the laminex was soldered to a standard computer type flat ribbon cable. All went well until it was apparent that the number of conductors for this screen was different to the number of conductors for the larger screen. This necessitated studying the specification sheets for both screens. These specifications are shown in figures 11.8 and 11.9. To overcome the pin number difference it was possible to loop pin numbers 6 and 12 as these are both ground potential.

To make this connection ruggedised the laminex board and cables were covered in epoxy so that no load could be placed on the soldered terminals. Special low loss silicone insulated cables capable of carrying 1200V were connected between the screen and the back-light circuit board. A small perspex surround was made that was no larger than the



LM64K101

Electro-optical Characteristics (Ta=25 °C)

Parameter		Symbol	Conditions		Min.	Typ.	Max.	Unit
Supply voltage (Logic)		$V_{DD}-V_{SS}$	—		2.7	3.0	5.5	V
Supply voltage (LCD drive)		$V_{DD}-V_{EE}$	Ta=Topr range		18.4	22.6	27.6	V
Input signal voltage		V_{IN}	High level		$0.8V_{DD}$	—	V_{DD}	V
			Low level		0	—	$0.2V_{DD}$	
Input leakage current		I_{IL}	High level		—	—	250	µA
			Low level		−250	—	—	
Supply current (Logic)		I_{DD}	V_{DD}=3 V $V_{DD}-V_{EE}$=22.6 V F=85 Hz Display : high frequency pattern		—	21	27	mA
Supply current (LCD drive)		I_{EE}			—	20	26	mA
Power consumption		Pd			—	480	600	mW
Brightness (B/L ON)		B	Inverter : LMC00106		35	50	—	cd/m²
Viewing* angle range	Transmissive mode	θ_x	$C_O>2.0$	$\theta_y=0$ °	−25	—	35	°
		θ_y		$\theta_x=0$ °	−25	—	30	
	Reflective mode	θ_x		$\theta_y=0$ °	−20	—	35	
		θ_y		$\theta_x=0$ °	−25	—	25	
Contrast* ratio	Transmissive	C_O	$\theta_x=\theta_y=0$ °		8	10	—	—
	Reflective				6	8	—	—
Response time*	Rise	T_r			—	100	150	ms
	Decay	T_d			—	150	200	ms

*Refer to page 95~96. Viewing angle range : Method B Contrast ratio : Method B

Interface Timing Ratings

Parameter	Symbol	Min.	Max.	Unit
Frame cycle	T_{FRM}	8.0*1	16.9	ms
CP2 clock cycle	T_{CP2}	152	—	ns

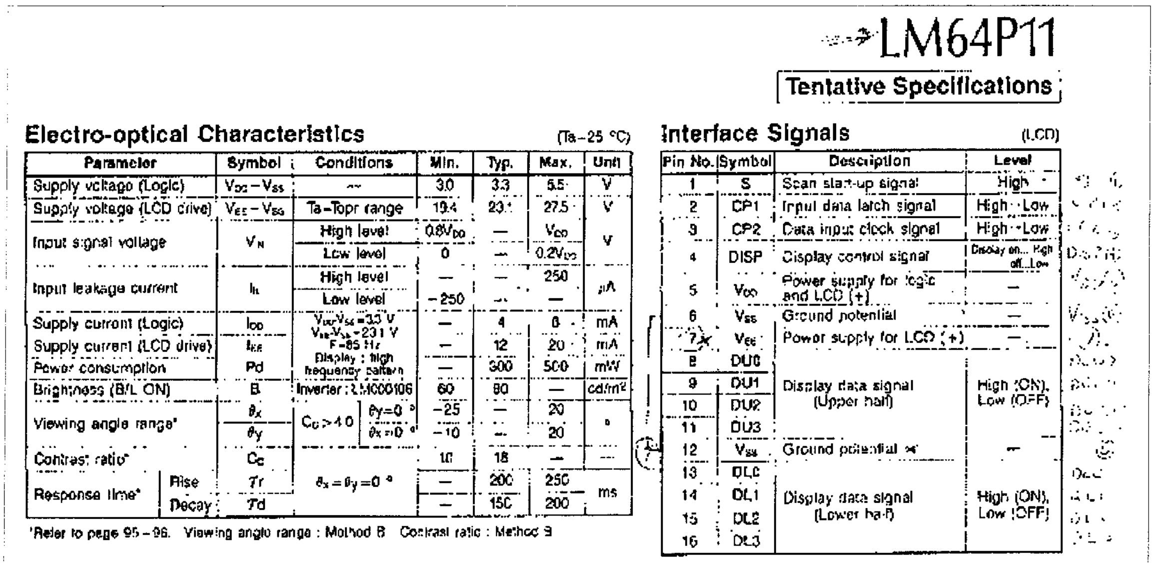
Interface Signals (LCD)

Pin No.	Symbol	Description	Level
1	S	Scan start-up signal	High
2	CP1	Input data latch signal	High→Low
3	CP2	Data input clock signal	High→Low
4	DISP	Display control signal	Display on→High Display off→Low
5	V_{DD}	Power supply for logic and LCD (+)	—
6	V_{SS}	Ground potential	—
7	V_{EE}	Power supply for LCD (−)	—
8	DU0	Display data signal (Upper half)	High (ON), Low (OFF)
9	DU1		
10	DU2		
11	DU3		
12	DL0	Display data signal (Lower half)	High (ON), Low (OFF)
13	DL1		
14	DL2		
15	DL3		

(CCFT)

Pin No.	Symbol	Description	Level
1	GND	Ground line (from inverter)	—
2	NC	—	—
3	NC	—	—
4	HV	High voltage line (from inverter)	—

Figure 11.8 Specifications for LM64K101.



LM64P11

Tentative Specifications

Electro-optical Characteristics (Ta=25 °C)

Parameter		Symbol	Conditions		Min.	Typ.	Max.	Unit
Supply voltage (Logic)		$V_{DD}-V_{SS}$	—		3.0	3.3	5.5	V
Supply voltage (LCD drive)		$V_{EE}-V_{SS}$	Ta=Topr range		19.4	23.1	27.5	V
Input signal voltage		V_{IN}	High level		$0.8V_{DD}$	—	V_{DD}	V
			Low level		0	—	$0.2V_{DD}$	
Input leakage current		I_{IL}	High level		—	—	250	µA
			Low level		−250	—	—	
Supply current (Logic)		I_{DD}	$V_{DD}-V_{SS}$=3.3 V $V_{EE}-V_{SS}$=23.1 V F=85 Hz Display : high frequency pattern		—	4	8	mA
Supply current (LCD drive)		I_{EE}			—	12	20	mA
Power consumption		Pd			—	300	500	mW
Brightness (B/L ON)		B	Inverter : LMC00106		60	80	—	cd/m²
Viewing angle range*		θ_x	$C_O>4.0$	$\theta_y=0$ °	−25	—	20	°
		θ_y		$\theta_x=0$ °	−10	—	20	
Contrast ratio*		C_O			10	18	—	—
Response time*	Rise	T_r	$\theta_x=\theta_y=0$ °		—	200	250	ms
	Decay	T_d			—	150	200	

*Refer to page 95–96. Viewing angle range : Method B Contrast ratio : Method B

Interface Signals (LCD)

Pin No.	Symbol	Description	Level
1	S	Scan start-up signal	High
2	CP1	Input data latch signal	High→Low
3	CP2	Data input clock signal	High→Low
4	DISP	Display control signal	Display on...High off...Low
5	V_{DD}	Power supply for logic and LCD (+)	—
6	V_{SS}	Ground potential	—
7	V_{EE}	Power supply for LCD (+)	—
8	DU0	Display data signal (Upper half)	High (ON), Low (OFF)
9	DU1		
10	DU2		
11	DU3		
12	V_{SS}	Ground potential	—
13	DL0	Display data signal (Lower half)	High (ON), Low (OFF)
14	DL1		
15	DL2		
16	DL3		

Figure 11.9 Specifications for LM64P11. These specifications are the same as the LM64K11 model.

overall screen dimensions. The back perspex panel was routed out so the that the ribbon cable terminator board and the back-light connector terminal could be accommodated on the back of the screen and also ensure that the delicate connectivity components would be protected.

At the other end of the ribbon cable a small component box was modified to accommodate the back-light board and the controller panel. A similar rheostat and switch was fitted to control the contrast and the back-light. This unit is illustrated in figure 11.10. Note the two heavy cables for the back-light, the flat ribbon cable, the rheostat and the switch.

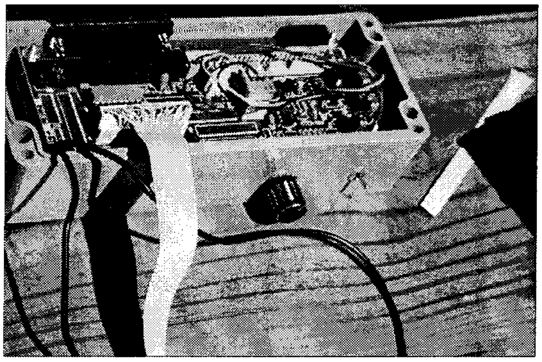


Figure 11.10 Screen controller box, note the flat 16 ribbon cable on right.

Having assembled all this it was time to test. This could only be done in the aircraft because the only flat screen controller available is mounted in the navigation computer. Unlike the existing screen which worked at the very first attempt it was disappointing when the screen was blank, there were indicators that something was happening but it wasn't going to work. Again, it was back to the drawing board. The first thing checked was the connectivity, was a connection broken? This was not the case.

The author was assured when the new screen was purchased that the controller and the back-light cards were 100% compatible. Studying the specifications again, figures 11.8 and 11.9 a discrepancy existed between the polarity of pin 7. The pin 7 polarity, V_{EE} for the LM64K101 is negative, which was the reverse case for the LM64K11. This was explained to the supplier who recommended that JED Microprocessors be contacted. The controller board needed to be modified, something that the author could not undertake. After discussions with JED they offered to modify the controller card to provide the correct polarity.

This modification resulted in a fully operational screen. Unfortunately the screen was broken not long after it was test flown mounted on the pilots sun-visor. The screen performed satisfactorily but the sun-visor mount has not been a good location, mainly because of the eye accommodation problems in continually changing focal length. The sun-visor is just a little too close to the pilot's face to be comfortable.

At this stage negotiations are continuing about where the ideal place to mount the screen will be. There are problems today associated with flight safety and the new airspace regulations that make it difficult to incorporate what can be see as distractions within the cockpit environment. The trend today for pilots is to "look out and be aware", this cannot be done if distracted by the needs of a navigation system. It may be that the operator will again tell the pilot which way to turn or correct his heading, but this appears to be a retrograde step.

11.5.2 Differential corrections

Operations such as this can be susceptible to many problems. The best way to combat any possible failure is to build in redundancy. Redundancy exists in the data storage and data flow procedures already described. These are suitable if the data-logging function works faultlessly. What can be done to minimise the impact of a data-logging failure? If it were to happen mid photo-strip then it may not be detected until the end of the strip, if the operator is not alert, or is simply pre-occupied.

In this case, some evaluation has to be made whether or not it is totally necessary to re-fly the strip. This decision can only be made based on the quality of redundant data. Redundant position data is available through the result files created by NAVPRO. The single point position data provided through the PBEN data stream is interpolated for every planned exposure and stored with that exposure ID and time tag. The quality of this data could be enhanced if differential corrections were provided to the receiver.

A number of options were available regarding suppliers but budget would dictate the selection of a provider. Those in the market included AUSNAV with its ground-based system provided on the side band of the 2JJJ FM signal, and the space based carriers, RACAL and OMNISTAR. The decision to go with AUSNAV was the lower cost of its service in comparison with the other carriers, and its ease of installation in the aircraft. The aircraft installation was also influenced by budget considerations. The cost of installing another satellite antenna on the top of the pressure hull was prohibitive in comparison to the cost of mounting a FM antenna on the bottom rear of the fuselage. In 1995 AUSNAV's rates were also far cheaper than the competition, given the 24 hour, 7 days a week coverage that the SGD required.

An aircraft FM antenna was sourced for less than $800. Hawker Pacific fitted this unit and installed the antenna lead so that it would exit from the cabin wall adjacent to the existing power outlet. A RDS3000 receiver was purchased and subscribed at the "premium rate". (AUSNAV quotes the premium rate as "1m (2drms) accuracy with high quality GPS receivers - Best suited to positioning, mapping and data gathering".) The RDS3000 was fitted in the back of the Ashtech Z12 mounting frame.

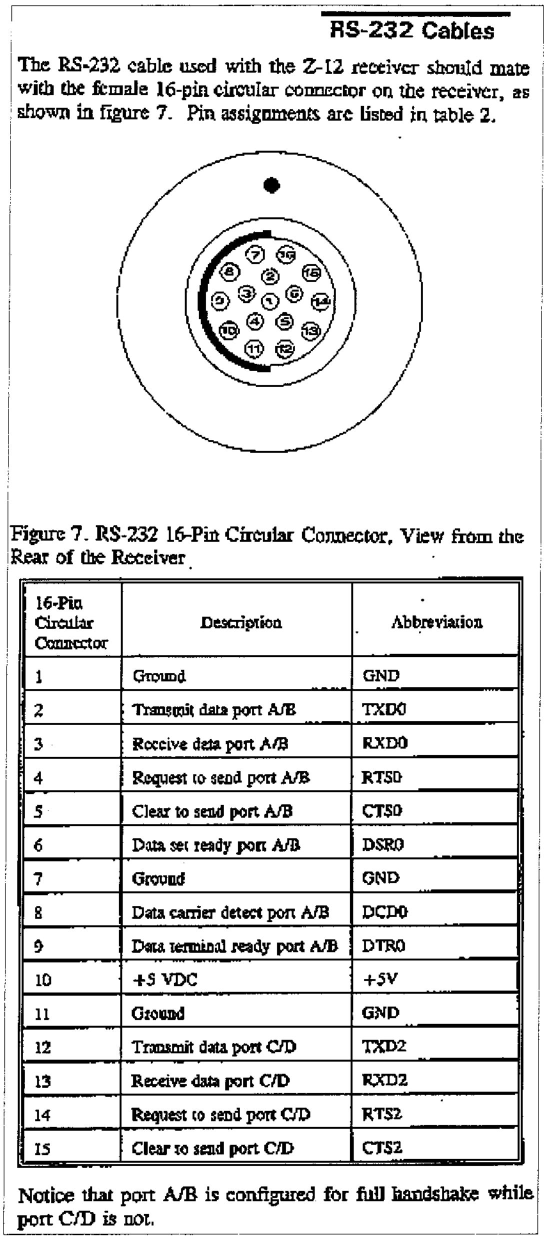
This installation necessitated the use of a third port on the GPS receiver. Up until September 1995 only ports A and B had been used. The Z12 receiver, even with the 1E00 firmware, was Real Time Differential Correction capable. This could be input on port C or D.

Although the Z12 has four I/O ports there are only two physical sockets on the rear of the receiver. The 16 pin sockets are configured so that ports A and C share an outlet and similarly for ports B and D. This arrangement requires a communication cable that is split. The receivers are supplied with a standard single port configuration cable. A split unit can be purchased form Ashtech, but this cable is very expensive.

The author was able to purchase the appropriate Fischer plug and make a split cable based on the information provided in the Z12 Operator's Manual. Figure 11.11 is an extract of the pin outs for the Z12. Making the cable in-house also offered the opportunity to piggy back the AUSNAV output terminal with another cable. The extra cable would allow the monitoring of the RDS receiver using the RDS software provided with the unit. This has been a useful option particular when the receiver subscription has come up for renewal. With this software the RDS receiver can be interrogated as to its system status.

Having differentially corrected position data not only adds to the quality of the redundant position information stored in NAVPRO's result files, but also provides smoother navigation information which is free of the effects of Selective Availability. Unfortunately, nowhere within the NAVPRO version in use, or the PBEN data stream, is there a flag available to tag the data as differentially corrected. This issue has been addressed in another software package recently introduced for aircraft operation.

Tables 11.1 and 11.2 demonstrate the capability of differential GPS positioning in an aircraft application. The positions that are compared are derived in two totally different methods. The PNAV positions are determined by interpolation between successive post-processed positions. Precise time tags recorded by the GPS receiver determine the camera exposure point between successive GPS epochs. The differential positions, referred to as AUSNAV, are determined on the fly by NAVPRO. Some comments on this are provided in chapter 13.3.2. The suitability of this data type is subject to testing in chapter 13.



RS-232 Cables

The RS-232 cable used with the Z-12 receiver should mate with the female 16-pin circular connector on the receiver, as shown in figure 7. Pin assignments are listed in table 2.

Figure 7. RS-232 16-Pin Circular Connector, View from the Rear of the Receiver

16-Pin Circular Connector	Description	Abbreviation
1	Ground	GND
2	Transmit data port A/B	TXD0
3	Receive data port A/B	RXD0
4	Request to send port A/B	RTS0
5	Clear to send port A/B	CTS0
6	Data set ready port A/B	DSR0
7	Ground	GND
8	Data carrier detect port A/B	DCD0
9	Data terminal ready port A/B	DTR0
10	+5 VDC	+5V
11	Ground	GND
12	Transmit data port C/D	TXD2
13	Receive data port C/D	RXD2
14	Request to send port C/D	RTS2
15	Clear to send port C/D	CTS2

Notice that port A/B is configured for full handshake while port C/D is not.

Figure 11.11 Communication configuration for Ashtech Z12 I/O sockets.

Even though the results are extremely impressive this data type is not correlated to successive observations in the same way that phase data is. The use of drift to address differential data in the aerial triangulation adjustment is more of a tool to minimise unrelated positional errors than a rigorous solution to predictable data behaviour.

Table 11.1 Comparison of post processed positions by PNAV and differential positions through AUSNAV over Narrabri, NSW.

Comparison between PNAV post processed positions
and Real Time AUSNAV positions for Narrabri Run 4 day 191/98

Planned Exposure Point	PNAV East	PNAV North	PNAV Up	AUSNAV East	AUSNAV North	AUSNAV Up	Diff East	Diff North	Diff Up
M213204*POP*1	793161.0	6651792.0	7935.3	793160.2	6651792.5	7932.0	0.76	-0.47	3.32
M213204*POP*2	788648.0	6651874.0	7926.6	788647.4	6651873.9	7923.0	0.60	0.07	3.62
M213204*POP*3	784154.0	6652049.5	7931.1	784153.2	6652049.6	7927.0	0.86	-0.13	4.09
M213204*POP*4	779630.4	6652155.5	7935.3	779629.5	6652155.4	7931.0	0.99	0.05	4.28
M213204*POP*5	775134.7	6652229.0	7940.1	775133.4	6652228.4	7936.0	1.23	0.59	4.13
M213204*POP*6	770626.9	6652317.6	7935.5	770625.6	6652317.7	7931.0	1.26	-0.11	4.47
M213204*POP*7	766086.7	6652281.2	7934.6	766086.1	6652282.4	7930.0	0.67	-1.18	4.61
M213204*POP*8	761589.7	6652255.8	7936.7	761589.9	6652256.9	7933.0	-0.17	-1.11	3.68
M213204*POP*9	757076.8	6652404.0	7936.2	757076.4	6652404.7	7932.0	0.40	-0.70	4.22
M213204*POP*10	752563.0	6652729.5	7935.0	752562.2	6652730.8	7930.0	0.79	-1.30	5.00
M213204*POP*11	748075.2	6652940.2	7937.9	748073.2	6652941.0	7934.0	1.95	-0.82	3.94
M213204*POP*12	743555.0	6652991.8	7936.9	743554.9	6652992.7	7933.0	0.10	-0.87	3.93
M213204*POP*13	739042.1	6652723.8	7936.2	739042.2	6652724.1	7934.0	-0.11	-0.30	2.20

Table 11.2 Comparison of post processed positions by PNAV and differential positions through AUSNAV over Cobar, NSW.

Difference between PNAV Post Processed Position
and Real Time AUSNAV positions COBAR Run 11 day 312/95

Planned exposure Point	PNAV East	PNAV North	AUSNAV East	AUSNAV North	Diff East	Diff North
SH551411*POP*1	353640.5	6484069.9	353639.5	6484070.0	1.0	-0.1
SH551411*POP*2	358078.7	6484054.4	358078.4	6484054.5	0.3	-0.1
SH551411*POP*3	362525.3	6484045.6	362524.8	6484045.8	0.5	-0.2
SH551411*POP*4	366967.1	6483977.5	366966.7	6483977.8	0.4	-0.3
SH551411*POP*5	371405.8	6484025.6	371405.6	6484025.5	0.2	0.1
SH551411*POP*6	375848.0	6484087.9	375847.6	6484087.7	0.4	0.2
SH551411*POP*7	380274.7	6484100.5	380274.3	6484100.4	0.4	0.1
SH551411*POP*8	384720.5	6484091.1	384719.9	6484090.8	0.6	0.3
SH551411*POP*9	389162.6	6484066.6	389162.1	6484066.5	0.5	0.1
SH551411*POP*10	393592.1	6484051.7	393591.9	6484051.6	0.2	0.1
SH551411*POP*11	398039.3	6484184.1	398039.0	6484183.5	0.3	0.6
SH551411*POP*12	402477.4	6484364.7	402477.6	6484364.3	-0.2	0.4
SH551411*POP*13	406918.3	6484526.2	406918.3	6484525.9	0.0	0.3
SH551411*POP*14	411354.9	6484694.5	411354.4	6484694.9	0.5	-0.4
SH551411*POP*15	415791.5	6484860.9	415790.0	6484859.7	1.5	1.2
SH551411*POP*16	420225.7	6484823.6	420224.3	6484822.3	1.4	1.3
SH551411*POP*17	424661.7	6484722.5	424660.4	6484720.9	1.3	1.6
SH551411*POP*18	429111.2	6484619.7	429110.0	6484618.0	1.2	1.7
SH551411*POP*19	433558.9	6484523.6	433557.4	6484522.3	1.5	1.3
SH551411*POP*20	437992.6	6484434.1	437991.3	6484432.5	1.3	1.6
SH551411*POP*21	442437.9	6484454.9	442436.3	6484453.6	1.6	1.3
SH551411*POP*22	446875.5	6484546.3	446873.9	6484544.8	1.6	1.5
SH551411*POP*23	451308.4	6484648.6	451306.9	6484647.8	1.5	0.8
SH551411*POP*24	455737.8	6484753.5	455736.7	6484752.6	1.1	0.9
SH551411*POP*25	460185.4	6484781.8	460184.4	6484781.1	1.0	0.7
SH551411*POP*26	464629.1	6484788.9	464627.8	6484788.3	1.3	0.6
SH551411*POP*27	469072.1	6484866.4	469071.1	6484865.6	1.0	0.8
SH551411*POP*28	473501.8	6484952.9	473500.8	6484952.0	1.0	0.9
SH551411*POP*29	477934.8	6485030.9	477933.9	6485030.1	0.9	0.8
SH551411*POP*30	482368.3	6485117.1	482367.4	6485116.1	0.9	1.0
SH551411*POP*31	486819.4	6485185.4	486818.9	6485184.5	0.5	0.9
SH551411*POP*32	491264.9	6485216.1	491264.3	6485215.1	0.6	1.0
SH551411*POP*33	495694.9	6485248.5	495694.6	6485247.4	0.3	1.1
SH551411*POP*34	500146.5	6485303.6	500146.3	6485302.2	0.2	1.4
SH551411*POP*35	504576.4	6485383.5	504576.0	6485382.2	0.4	1.3

12. Post Processing

Post-processing the raw GPS kinematic data is one of the easier aspects of the overall process of airborne GPS controlled photography. In any GPS survey the processing of data is always uncomplicated when the data is complete and clean. Ensuring that this will always be the case requires that rigorous procedures are followed.

The data management procedures ensure that data sets are correctly named, complete and stored in pre-defined directory structure, either on the network or on the aircraft. Post-processing isn't just limited to bringing two data sets together and producing a trajectory of the aircraft, and deriving the subsequent photo centres. It also includes the management of the data before the post-processing begins, the archiving and the finalisation of the survey product.

This aspect of the project has always been a surveyor's role. The surveyor derives the positional information about the camera at the instant of exposure. The data needed for post-processing is:

1. Raw GPS data recorded on the aircraft.

2. Raw GPS data recorded at a base station.

3. Precise time tags of the camera events.

4. Coordinates of the base station in WGS84 datum values.

5. Information about the aircraft operation pertaining to the data, primarily, where and when it was operating.

To support the post-processing a number of tools are required:

1. Suitable hardware, particularly memory and disk space.

2. Binary data manipulation tools.

3. ASCII editor.

4. Plotting/printing capability.

5. Recovery options when premium data is not available.

Figure 12.1 is an illustration of data movement from the point of capture to the end products of key diagrams, data bases, archived data and aerial triangulation. The data transfer process supporting the whole airborne GPS function within the SGD is quite

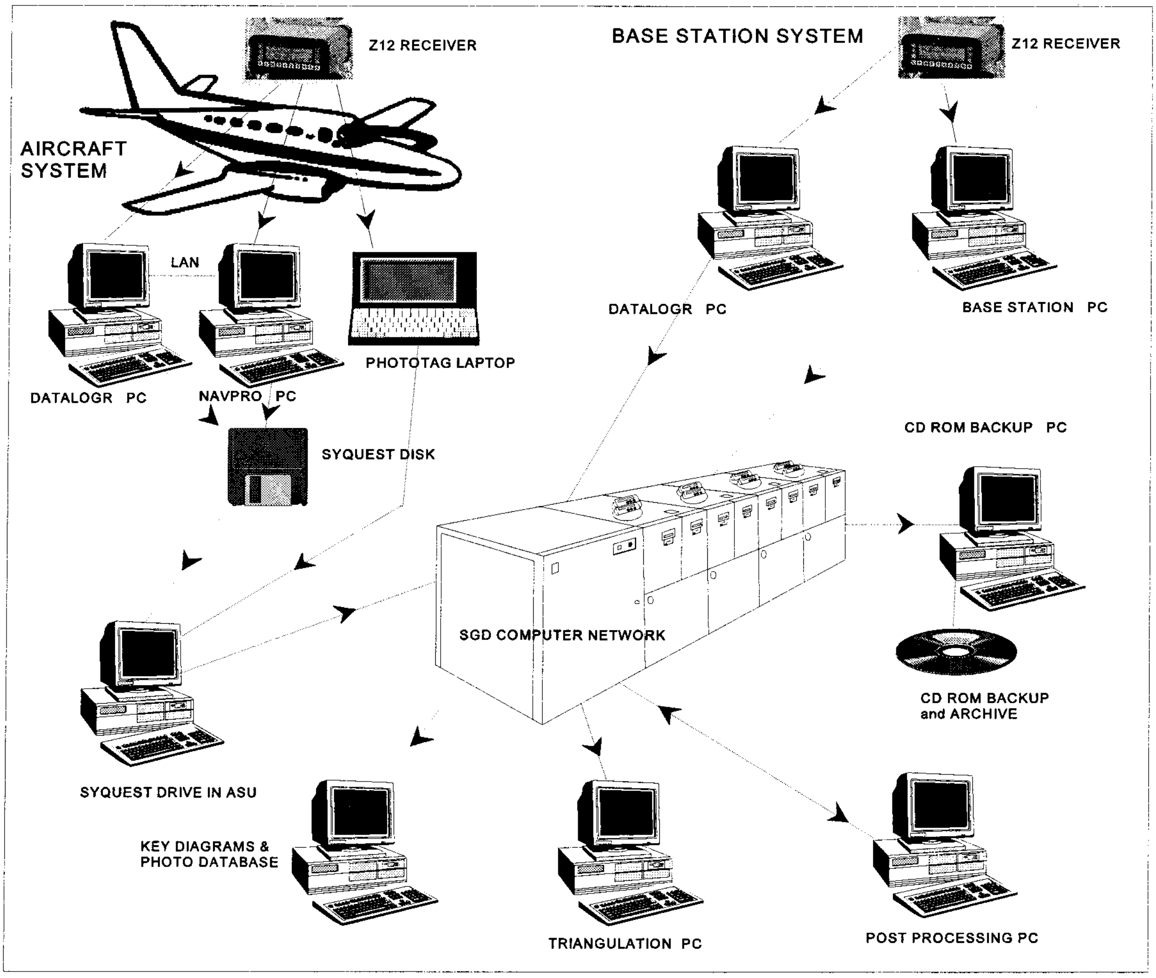


Figure 12.1 Schematic of data flow supporting the GPS post processing function.

complex. The diagram reflects the built in redundancy and automation that has evolved since the initial concept was developed.

The systems to collect the data and store it in pre-determined locations have already been described. The data that is held is discussed below.

12.1 Aircraft data

The data-logging system is designed so that each flight will produce data files which are consistently named and are unique to each flight.

DATALOGR will produce a raw GPS data file in binary format, commonly known as a B-file, and its naming convention is BNSWxAyy.zzz. The letter ‘x’ being a number representing the flight number for that day, generally a number between 1 and 9, the ‘yy’ being the last two digits of the current year and ‘zzz’ being the current local Julian day. DATALOGR also produces an E-file. This is an ephemeris file whose file naming convention follows that of the B-file except that the file is prefixed with an E, e.g. ENSWxAyy.zzz.

In the event of a system failure the operator only has to restart DATALOGR with a new flight number, this will ensure that no data is over written and that unnecessary system prompts and error trapping will be avoided. The system has successfully handled more than 9 restarts, although the template model is no longer valid.

The batch process also extracts the PHOTO.DAT file from the receiver’s memory. This file is sequentially appended with each camera event. The limit of this file is 3600 events. When this number is approached then the receiver event file is deleted. This procedure only occurs on the project surveyor’s instruction. As part of the batch process, the PHOTO.DAT file is copied to a backup file named using the same template as the raw data and ephemeris files, e.g. PNSWxAyy.zzz, the ‘P’ denoting Photo. The PHOTO.DAT file is backed up in this way because in the event of a second flight, or a data transfer problem, the original file is overwritten. In this way the photo data can be delineated between successive flights and different days.

This file naming convention ensures that **all** data is uniquely named, making the process of assembly for post-processing an easy one. The batch process used to transfer and backup the data onboard the aircraft also captures any active global result files created by the NAVPRO software less than 1 day old. NAVPRO creates a global result file for any day a mission is flown. The term 'global' is used to describe the file that is created in a generic directory on the NAVPRO computer. These files make no distinction between the various job or project names, whereas other result files are made under specific job directories. The global files are representative of all photographs taken that day.

NAVPRO continues to append data to the result file until the day rollover, which occurs at 10 or 11am depending on the status of daylight saving. When the day rollover occurs a new file is opened. This accounts for the requirement to transfer files at least 1 day old. This copy function switch is used in the sample in figure 9.5, section (9.3).

After any sortie there should be a minimum of five files transferred to the SYQUEST disk, a B-file, an E-file, a P-file, a PHOTO.DAT file and at least one .RES file. If for example two sorties are flown on the one day then the minimum amount of files for that day would be 8, two B-files, two E-files, two P-files, a PHOTO.DAT file and a .RES file. The batching process takes care of any variations. It will always transfer more data than is needed.

The size of these files varies with flight time, the PHOTO.DAT, *.RES and the P-files are small ASCII files. The B-files can be up to 13Mb, depending on the length of the flight and the length of time that DATALOGR was active. The transfer time for this amount of data is very short, the movement of files across the LAN is as fast as the disk drives can read and write the data, the SYQUEST is of similar performance. This aspect of the mission is of little consequence because of its speed and efficiency.

The aircraft raw data is brought to the office on the removable SYQUEST disk. The disk can hold up to 270Mb of data. Given that no file has exceeded 13Mb then it is estimated that the SYQUEST media can accommodate up to 20 full sorties. The data is then moved from the SYQUEST disk to a dedicated location on the SGD's computer network. Some of this data is on its third move, the raw data has been moved twice.

12.2 Base station data

Every day both GPS collection systems gather raw data, they will be referred to here as the aircraft base station and the master base station. Depending on the status of missions on various days the data collected by the modified DATALOGR system, i.e. the aircraft base station, is either retained or discarded. Data collected by the master base station is always retained. The operation is now a mutual support system. In the event of lost master base station data, which still occasionally occurs over weekends, this void is filled to some extent by the data collected by the aircraft base station. When the reverse occurs the master base station data is used to support the aircraft operation. This is a little more involved as will be outlined later.

12.2.1 Aircraft base station

It has already been described how the master base station observes and retains data collected in 30 minute blocks. This is a totally automated process. The aircraft base station also collects data in an automated process but the files are one large continuous set which span from a predetermined time in the morning until a shutdown time in the afternoon. The times of operation are dictated by the solar altitude window applicable to the area the aircraft is operating in. The general settings are to start at 07:20am and switch off at least 10 hours later.

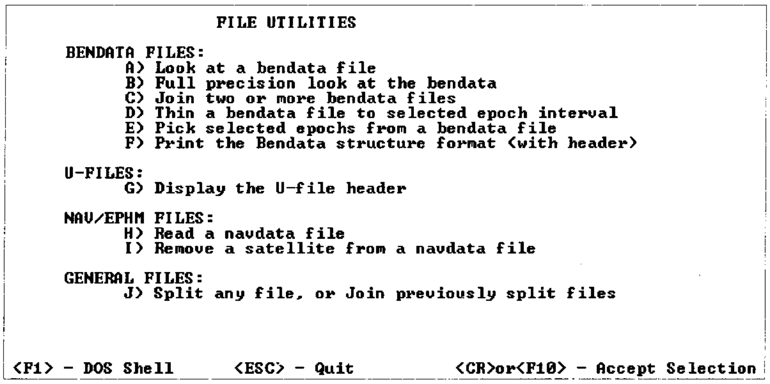
This operational period creates data files which are 35Mb or more. Depending on the status of post-processing, or the current disk space available on the aircraft base station, the data is from time to time transferred to the SGD computer network and stored in the same directory location as its corresponding aircraft data. Once data is located on the network, the security and permanency of that data is then the concern of the IM&TS branch. It is their responsibility to ensure the ongoing availability of the data. The movement of the aircraft base station data has to be carefully monitored as there are no backups of this data apart from what exists in the master base station ½ hour data sets. Aircraft base data has been lost through the inadvertent deletion of valid files. In some cases, as a result of network problems, this data has not been available from the master base station system either.

Data handling is a process that must be carefully monitored. The directive for this project is that no data files of any kind can be deleted without the knowledge and approval of the project surveyor. Unfortunately, things can go wrong, for these reasons redundant data sets such as differential positions are retained, evaluating their quality may possibly avoid a mission repeat. Due to the delays between photography and post-processing, re-flies may not be a viable option, the aircraft may have moved out of the region or seasonal changes prevent any further photography. These situations endorse the amount of redundancy that has been built in.

Once the data files are collected into their appropriate network location this data is then copied to another PC where the post-processing will take place. All the files for the particular day are copied to a directory identified by the day and year. To successfully process typical SGD GPS data using PNAV software requires that at least 80Mb of free space exists on the PC before any processing begins, the maximum amount of DOS 640Kb memory is available and for expediency, the fastest PC available is utilised. PNAV is not a Windows or NT product so once the calculation phase is begun the PC cannot be multi-tasked.

Upon a typical examination of the raw data files presented for processing, it is immediately evident that there is an excess of base station data. A typical base data file is 35Mb unless the DATALOGR process was terminated early after the aircrew had reported in that operations were finished for the day. Even so, the data file sizes from the aircraft and the base station are still not matched. If the data was matched so that the start and end times of the base station data matched the start and end time of the aircraft data then the manipulation of the data files would be easier. The processing would be quicker as PNAV would not have to search through the data files to find matching starting and ending epochs and the storage of raw data would be minimal. There is no point in storing data which has no useful purpose.

Ashtech provide a utility program named FILETOOL. This program allows the user to look into the binary data files, join files, cut pieces out of files etc. Figure 12.2 gives the capabilities of the utility. This utility could be used to cut out pieces of base station data that was time matched to the aircraft data. The procedure to do this is:



```
                    FILE UTILITIES

     BENDATA FILES:
           A> Look at a bendata file
           B> Full precision look at the bendata
           C> Join two or more bendata files
           D> Thin a bendata file to selected epoch interval
           E> Pick selected epochs from a bendata file
           F> Print the Bendata structure format <with header>

     U-FILES:
           G> Display the U-file header

     NAV/EPHM FILES:
           H> Read a navdata file
           I> Remove a satellite from a navdata file

     GENERAL FILES:
           J> Split any file, or Join previously split files



<F1> - DOS Shell     <ESC> - Quit          <CR>or<F10> - Accept Selection
```

Figure 12.2 Options available using FILETOOL.

1. Run the program FILETOOL.

2. Select option A) Look at a bendata file.

3. Select the aircraft data file, e.g. BNSW1A98.294. The program will interrogate the file for its integrity and its records.

4. Record the number of epochs in the file, the seconds of the week of the first epoch and the seconds of the week of the last epoch.

5. Repeat the process for the base data information and record the same information.

6. From this information determine how many epochs into the base data file that the time of the first aircraft epoch occurs. For example BNSW1A98.325 contains 9572 epochs starting at 506516 seconds of the week and ends at 516087 seconds of the week. BMLY1A98.325 contains 32400 epochs, starts at 505218 and ends at 537617 seconds of the week. The difference between the two start times is **1298** epochs, the end epoch number is 1298 + 9572, **10870**.

7. Still in FILETOOL, select the option F) Pick selected epochs from a bendata file. Select the base file and enter the start epoch number and the end epoch number and hit the enter or F10 keys. A new file will be created with the same name and the original will be renamed with the extension .BAK.

Both the data files are matched and are of a manageable size. They no longer slow the post-processing which result from excessive epoch searches. But this is a slow process which adds considerably to the processing preparation time and it is prone to simple add and subtraction errors. Unfortunately the data sets created by the SGD exceed the capability of FILETOOL to cut out the matching data. The sample data set in step 6 above cannot be handled by FILETOOL because the number of epochs, 10870, exceeds the valid number range imposed by the program.

This situation was likely to occur frequently as the size of the file was not the issue, it was where the aircraft data and the base data overlapped that was the problem. Aircraft data collected early in the day could be cut out if the number of epochs counted were less than 10000. Flights late in the day could not be matched because the epoch count number would roll over 10000.

The author wrote a C program to overcome the limitations of this utility. This program avoids the time taken to read through the whole files and count the epochs as FILETOOL does. A simple command line statement will complete the process automatically. The command is MATCHUP <Aircraft file name> <Base file name>.

E.g. MATCHUP BNSW1A98.325 BMLY1A98.325.

The program first renames the base file with the extension .BAK. The process then opens the aircraft raw binary GPS file and records the time in seconds of the week of the first record and then counts the number of epochs in the file. The aircraft file is closed, a new file is opened with the original base file name but with a matching flight number. If for example BNSW4 was being matched with BMLY1 then the new matched base file would be created as BMLY4.

The original base data file is scanned until the matching time tag record of the aircraft data is found. A message is displayed on the screen "Common start time found ....". The program then counts through the base data the corresponding number of epochs writing the data to the matched file. Another message is displayed "Last common time at........".

This program is far quicker then the Ashtech utility, it has no limit on file size and accommodates seconds of the week rollover. After this process both sets of data are PNAV ready.

12.2.2 Master base station

If for some reason data is not available from the aircraft base station system then data can be retrieved from the master base station. Data from the master base station is kept active on the SGD network for three weeks. Any data older than this is only retrievable from backup tapes through IM&TS.

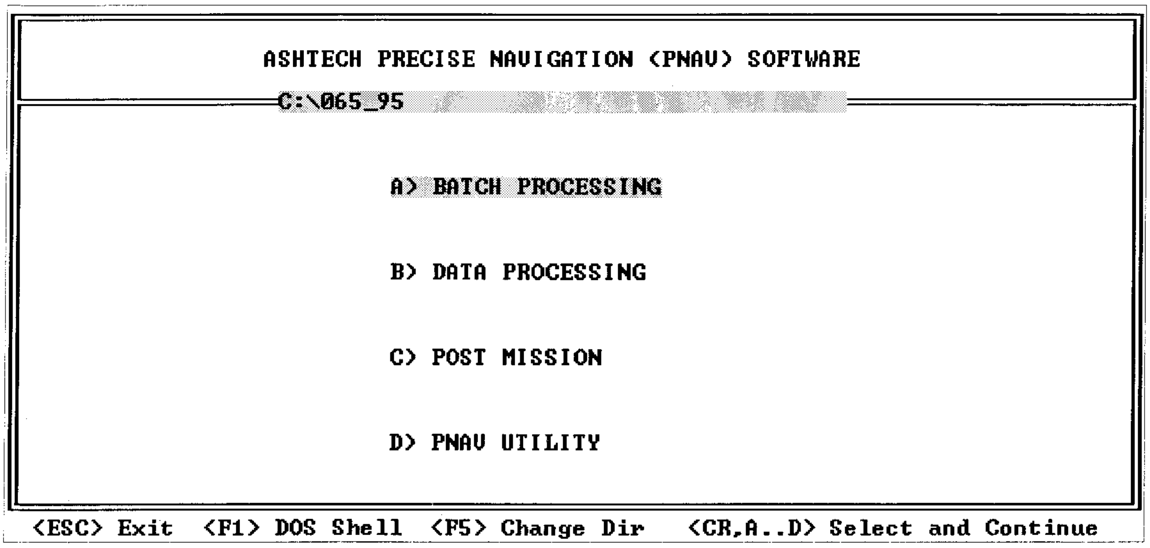
The process of retrieving this data is an involved one and begins with the determination of the operation time period of the aircraft GPS data. This is resolved using the FILETOOL utility, using the subfunction to look at a bendata file. The utility returns the time of first and last observation in GPS seconds of the week and the number of epochs. The seconds of the week of the start and finish times are converted to day, hours, minutes and seconds of the week.

These times are used to recover the original ½ hour period receiver image "R" files. The R files are recovered in preference to the RINEX files as the R files contain information not found in the RINEX files that is beneficial to the PNAV post-processing. The process to recover the raw data from the R file is the same as the master base station process. The HOSE software is used to recover the B and E files from the R file. Care has to be taken in the order that R files are recovered using the HOSE utility. The procedure is to start with the latest file and work backwards to the first. This procedure is necessary as the B and E files embedded in the R file have the same file name. The technique is to recover the latest file and rename it. Then recover the next and rename it. This process continues until all files are recovered. The recovered files are then concatenated using the FILETOOL software. When finished this process, a compliant B file containing all the concatenated data will exist, there will also be a number of E files, each corresponding to a particular ½ hour of GPS tracking. To tidy up the data all that is left is to use the MATCHUP utility to ensure that excess data is discarded.

12.3 PNAV

After using either of the two processes described above, the raw GPS data is PNAV ready. Using the DOS "PATH" command the PC is configured to execute the PNAV software from any directory location. To ensure the consistent operation of the software a small batch file begins the program. This batch file always copies the base station position information file containing the WGS84 latitude, longitude and ellipsoid height to the active data directory.

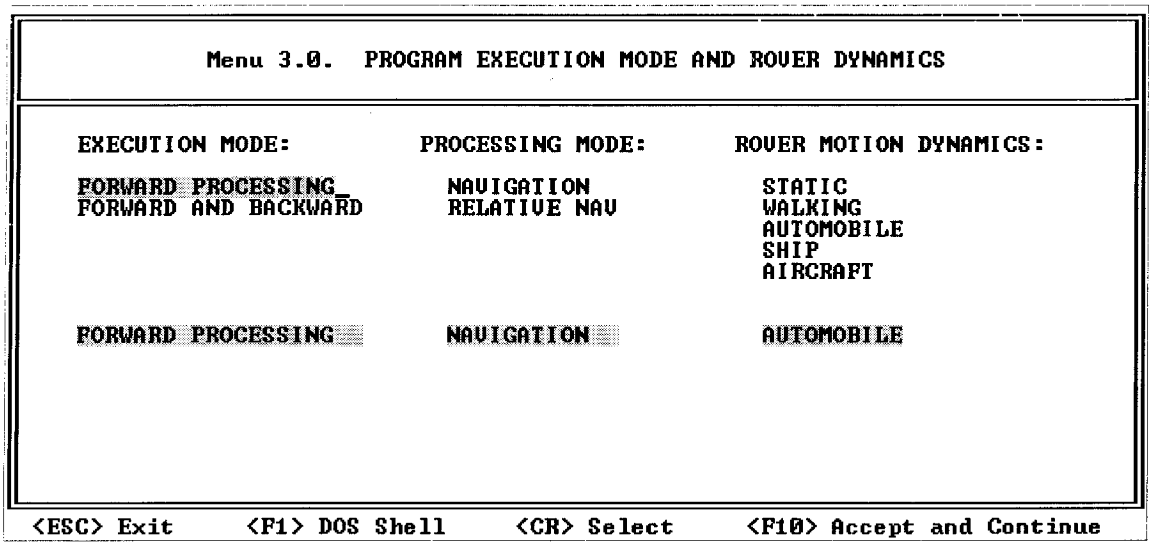
The opening PNAV screen displays the software version number. The version currently used by the SGD is 2.4.00D dated October 1997. This is a special version which has the capability to process RINEX data and is not flagged to abort processing of baseline lengths beyond 1000km. Even though it is a later version it still retains a number of "bugs".The opening screen to PNAV is given in figure 12.3. Although batch processing is the first option the selection here is **B) DATA PROCESSING** to provide as much control over the processing as possible. The option of **POST MISSION** is used after the processing phase



```
                 ASHTECH PRECISE NAVIGATION <PNAV> SOFTWARE
                 C:\065_95

                           A> BATCH PROCESSING

                           B> DATA PROCESSING

                           C> POST MISSION

                           D> PNAV UTILITY

 <ESC> Exit  <F1> DOS Shell  <F5> Change Dir   <CR,A..D> Select and Continue
```

Figure 12.3 Opening PNAV screen.

is acceptable and complete, PNAV UTILITY is a selection of tools to recover some basic positional information from individual B files.



```
           Menu 3.0.  PROGRAM EXECUTION MODE AND ROVER DYNAMICS

  EXECUTION MODE:          PROCESSING MODE:       ROVER MOTION DYNAMICS:

  FORWARD PROCESSING_        NAVIGATION             STATIC
  FORWARD AND BACKWARD       RELATIVE NAV           WALKING
                                                    AUTOMOBILE
                                                    SHIP
                                                    AIRCRAFT

  FORWARD PROCESSING         NAVIGATION             AUTOMOBILE

 <ESC> Exit      <F1> DOS Shell      <CR> Select      <F10> Accept and Continue
```

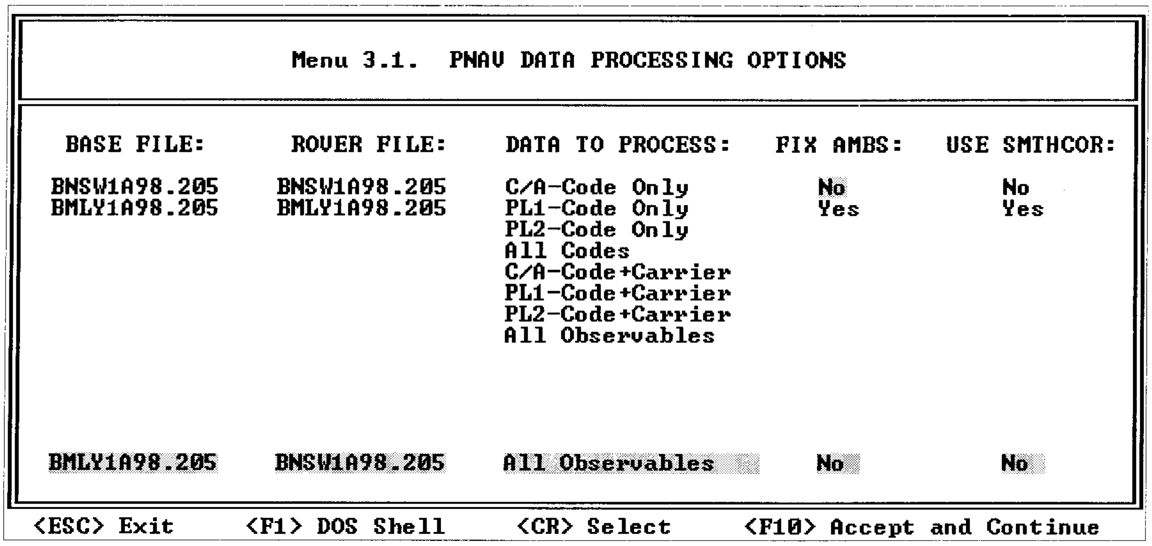
Figure 12.4 Execution Mode screen.

The next screen, shown in figure 12.4, sets up some basic controls about the processing. The selection here is always, except in special difficult circumstances, EXECUTION MODE - FORWARD AND BACKWARD, PROCESSING MODE - NAVIGATION and PROCESSING PARAMETERS - AIRCRAFT.

The forward and backward option is a means to check the quality of the processing algorithms and the strength of the positioning. Ideally, the same trajectory should result from both directions but a number of factors influence this. Settings within the program flag the quality of the two solutions. The final solution to the trajectory is a combination of both solutions. The PNAV User's Manual states:

> "However, the results from FORWARD PROCESSING alone will contain one or more "holes" (periods when the solution accuracy is metre-level due to unresolved ambiguities). FORWARD AND BACKWARD processing will help to fill these holes in the results by solving for the ambiguities in both directions, maximizing the number of data points with resolved ambiguities and good solutions."

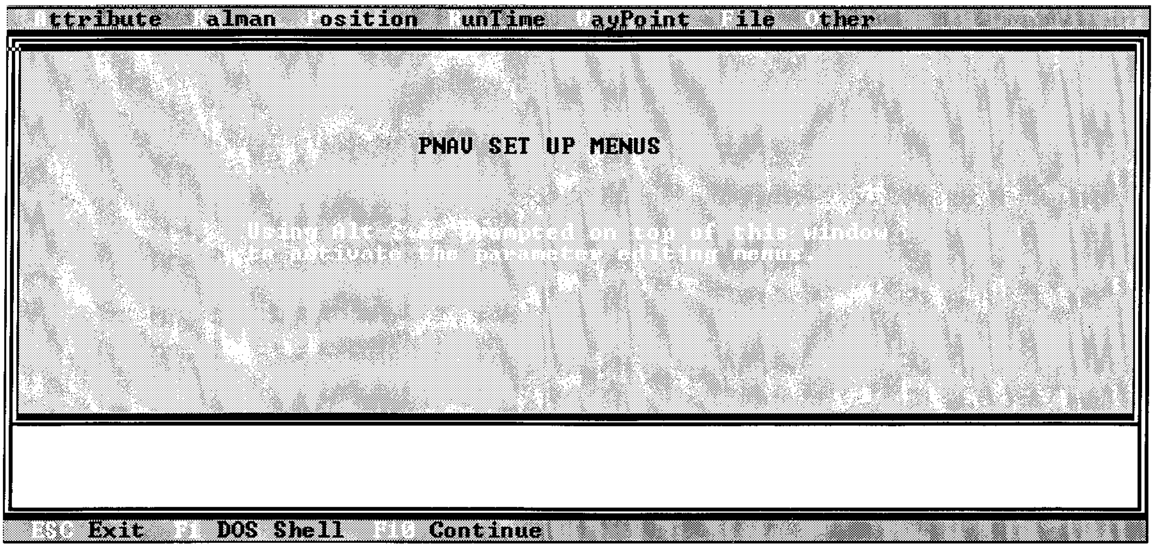
ROVER MOTION DYNAMICS allows the user to select the Kalman filter parameters indicative of the rover's motion, in the SGD's case, an AIRCRAFT.



```
                    Menu 3.1.  PNAV DATA PROCESSING OPTIONS

 BASE FILE:      ROVER FILE:     DATA TO PROCESS:    FIX AMBS:    USE SMTHCOR:

BNSW1A98.205    BNSW1A98.205    C/A-Code Only         No             No
BMLY1A98.205    BMLY1A98.205    PL1-Code Only         Yes            Yes
                                PL2-Code Only
                                All Codes
                                C/A-Code+Carrier
                                PL1-Code+Carrier
                                PL2-Code+Carrier
                                All Observables



BMLY1A98.205    BNSW1A98.205    All Observables       No             No

 <ESC> Exit     <F1> DOS Shell     <CR> Select     <F10> Accept and Continue
```

Figure 12.5 Data Processing Options screen.

The next screen, shown in figure 12.5, selects the actual base station and aircraft files to be processed. This is where the adopted file naming convention and the matching of files is appreciated. The default, All Observables and USE SMTHCOR - No is always adopted.



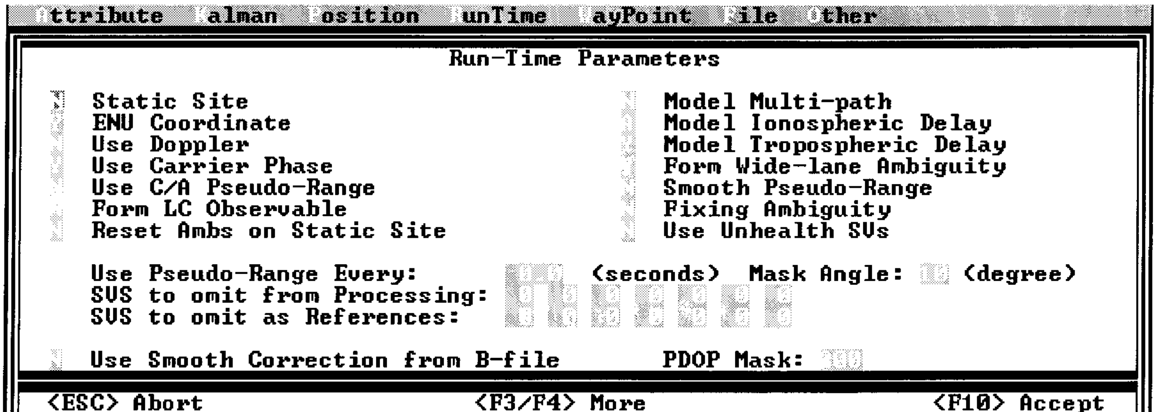
```
 ttribute  alman  osition  unTime  ayPoint  ile  ther

                      PNAV SET UP MENUS

       Using Alt-Keys prompted on top of this window
        to activate the parameter editing menus.

     Exit     DOS Shell     Continue
```

Figure 12.6 PNAV SET UP MENU screen.

For all general processing, **FIX AMBS**: is set to No. In those cases where precise results are required and the proximity of the aircraft to the base station is acceptable, this option can be set to Yes.

Figure 12.6 is the PNAV SETUP MENU screen. A number of options are presented across the top of the window.

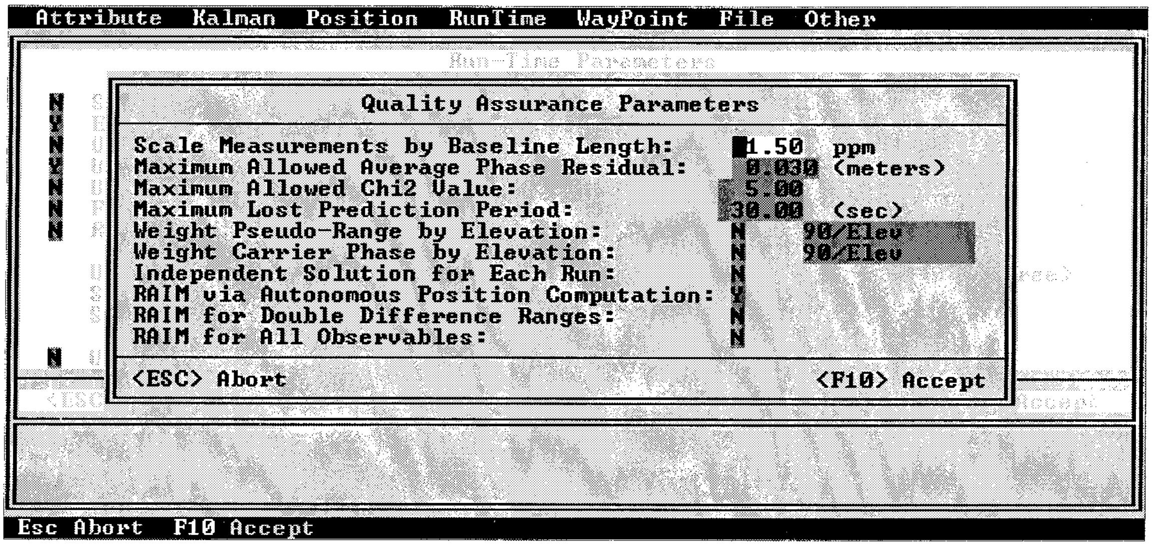
The most common option is the **Runtime** option. The runtime screen is shown in figure 12.7. The most useful options used on this screen are the Mask Angle, SVs to omit from



```
 ttribute  alman  osition  unTime  ayPoint  ile  ther
                          Run-Time Parameters

    Static Site                             Model Multi-path
    ENU Coordinate                          Model Ionospheric Delay
    Use Doppler                             Model Tropospheric Delay
    Use Carrier Phase                       Form Wide-lane Ambiguity
    Use C/A Pseudo-Range                    Smooth Pseudo-Range
    Form LC Observable                      Fixing Ambiguity
    Reset Ambs on Static Site               Use Unhealth SVs

    Use Pseudo-Range Every:           (seconds)  Mask Angle:    (degree)
    SVS to omit from Processing:
    SVS to omit as References:

    Use Smooth Correction from B-file       PDOP Mask:
 <ESC> Abort                      <F3/F4> More                    <F10> Accept
```

Figure 12.7 Runtime options screen.

processing and SV to omit as reference satellite. Mask angle is usually entered at 8° for baselines up to 250-300km. As distances increase the mask is dropped to the maximum value of the data collected, which is 5°. Omitting satellites from the processing or as reference satellite is only used on subsequent processing runs when an error has occurred. There are further processing options embedded under the F3/F4 key. The F4 key contains one option which has turned out to be somewhat of a problem in particular instances. The options under this hot key are given in figure 12.8.



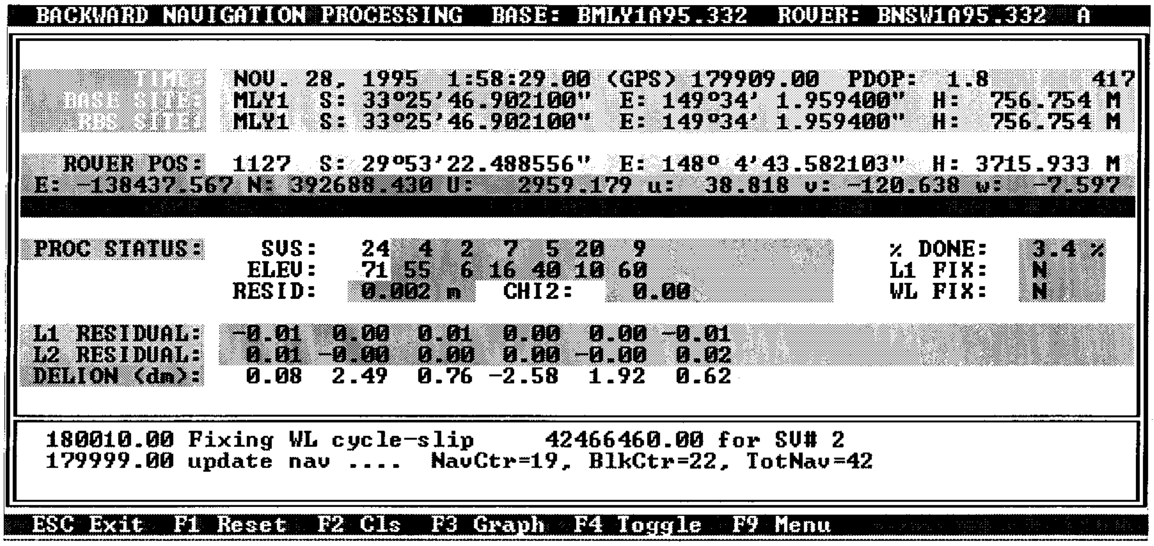
```
Quality Assurance Parameters

Scale Measurements by Baseline Length:          1.50   ppm
Maximum Allowed Average Phase Residual:         0.030  <meters>
Maximum Allowed Chi2 Value:                     5.00
Maximum Lost Prediction Period:                30.00   <sec>
Weight Pseudo-Range by Elevation:               N      90/Elev
Weight Carrier Phase by Elevation:              N      90/Elev
Independent Solution for Each Run:              N
RAIM via Autonomous Position Computation:       Y
RAIM for Double Difference Ranges:              N
RAIM for All Observables:                       N
```

Figure 12.8 Options given under the F4 key, note the RAIM options.

Of particular concern is the RAIM via Autonomous Position Computation: Y, this option is set to No. The reason for this is that PNAV will by-pass epochs where RAIM (**R**eceiver **A**utonomous **I**ntegrity **M**onitoring) fails. Phase data that is in fact quite valid will be ignored when RAIM fails. Setting this option to No ensures that the processing of all data will occur even if the positioning quality of that data may be inferior for some reason.

Having set the options, accepting them will return the operator to the PNAV MENU SETUP screen, see figure 12.6. On this screen the option Other is sometimes used when problems occur with the data. This option may have to be used to section out slices of data, but this is the exception and not the rule. The other options are of little consequence, the author has not experimented with the Kalman filter options as there has not been a need to do so. The aim of the post-processing is to produce the smoothest trajectory possible, one which holds as many parameters constant for the longest acceptable period.

Having set up the menus as required the post-processing is commenced. The typical screen for post-processing is shown in figure 12.9. The process is basically set to run its course, both forward and backward. The display is monitored from time to time, such items as the residuals and the CHI2 values, the most important window being the bottom one, displaying what events are happening at particular epochs.



```
 BACKWARD NAVIGATION PROCESSING  BASE: BMLY1A95.332  ROVER: BNSW1A95.332  A

        TIME:  NOV. 28, 1995  1:58:29.00 (GPS) 179909.00  PDOP:  1.8       417
   BASE SITE:  MLY1  S: 33°25'46.902100"  E: 149°34' 1.959400"  H:  756.754 M
    RBS SITE:  MLY1  S: 33°25'46.902100"  E: 149°34' 1.959400"  H:  756.754 M

   ROVER POS:  1127  S: 29°53'22.488556"  E: 148° 4'43.582103"  H: 3715.933 M
 E: -138437.567 N: 392688.430 U:   2959.179 u:  38.818 v: -120.638 w:  -7.597

 PROC STATUS:    SVS:   24  4  2  7  5 20  9                  % DONE:   3.4 %
                ELEV:   71 55  6 16 40 10 60                  L1 FIX:   N
               RESID:  0.002 m   CHI2:    0.00                WL FIX:   N

 L1 RESIDUAL:  -0.01  0.00  0.01  0.00  0.00 -0.01
 L2 RESIDUAL:   0.01 -0.00  0.00  0.00 -0.00  0.02
 DELION (dm):   0.08  2.49  0.76 -2.58  1.92  0.62

   180010.00 Fixing WL cycle-slip     42466460.00 for SV# 2
   179999.00 update nav ....  NavCtr=19, BlkCtr=22, TotNav=42

 ESC Exit  F1 Reset  F2 Cls  F3 Graph  F4 Toggle  F9 Menu
```

Figure 12.9 Sample of PNAV processing screen.

12.3.1 Tell tale indicators

It wasn't until the post-processing phase of the implemented project had begun that some more data capture problems were to arise. The bottom display window is a very helpful processing aid. Mostly, the window will display messages like those in figure 12.9:

180010.00 Fixing WL cycle-slip 42466460.00 for SV# 2

These are very common messages but this message tells the operator that SV 2 has either just risen and been locked on to, or has lost lock for a period of time and is being tracked again. Other similar messages may say a cycle slip of 1 or 0, this is a processing correction within PNAV that adjusts the position solution by a cycle. The time between corrections is important, and it is preferable to see minimal cycle slip messages as the aircraft is actually flying a photo strip. This is generally the case, as it is these periods when the satellite tracking is the most stable and signal lock is maintained.

A disturbing feature of the data, that was not expected early in the project, and is still a by-product of the whole master base station process, produces messages like:

```
454205.00  Missing epoch in the BASE receiver.
454205.00  No good reference SV has been found.
454206.00  Missing epoch in the BASE receiver.
```

Why was base data missing? The aircraft base station system recorded a continuous file of data, but this message was occurring on a regular basis. Another message that is regarded as an indicator of processing problems is a message with the following format (sample output):

```
175169.00 DIFF 8 25 8 04 -4913058.95   19.04
```

Unfortunately the PNAV user manual doesn't explain the meaning of this message.

Through some personal communication the author was able to determine that this message is an alarm that the trajectory solution for the forward problem is significantly different from the backward result. There is reference to offending satellites but the message is obscure. This message only occurs in the forward solution, as the comparison between forward and back can only be made after the backward solution is known. The user doesn't know where the fault lies, in the backward or forward solution. This message always requires re-processing the data until the message is eliminated. Quality management dictates that this message will only be tolerated in the data set if it occurs outside of on-strip data.

12.3.2 The log file

The software supports the post-processing routines by producing a log file of all messages presented in the lower window. A portion of a log file is given in figure 12.10. Various samples of processing messages are given but the sample is not complete. Noticeable are the messages referring to fixing cycle slips, examples are given of large and small corrections.

Notice also the reference to missing data in the base receiver. Upon analysis of this type of occurrence in base station data it was evident that data was missing every ½ hour. It was found that part of the REMOTE software process caused this loss of one or two epochs. Even though the receiver displayed the ability to transfer data whilst at the same time capturing it, the final step performed by REMOTE, the deletion of the inactive file, causes the receiver to miss the capture of a number of epochs. This incident occurs approximately 11 minutes after the hour and ½ hour, so was traceable to the REMOTE transfer function which takes approximately that amount of time to transfer the data. The tracking characteristics of the receiver

```
Ashtech, Inc.   Program: PNAV    Version: 2.4.00T
---------------------------------------------------------------------------
Tue Sep 23 17:40:06 1997
 BASE FILE: BHOB3A95.068
ROVER FILE: BNSW_A95.068

  365893.00 update nav ....  NavCtr=0, BlkCtr=7, TotNav=8
  365893.00 Initializing the reference site position
  365893.00 Initializing Kalman Filter.
  365893.00 Fixing L1 cycle-slip    -4855563.00 for SV#21
  365893.00 Fixing WL cycle-slip     3746655.00 for SV#21
  365893.00 Fixing L1 cycle-slip   -32557163.00 for SV#28
  365893.00 Fixing WL cycle-slip    25328182.00 for SV#28
  365893.00 Fixing L1 cycle-slip      824509.00 for SV#31
  365893.00 Fixing WL cycle-slip     -666297.00 for SV#31
  365893.00 Reforming the Kalman filter ...
Updated week number of 791 at  365893.00
  365885.00 Add SV#15 at an elevation of 18 27.
  365885.00 Fixing L1 cycle-slip   -22038024.00 for SV#15
  365853.00 Add SV#23 at an elevation of 19 19.
  365853.00 Fixing L1 cycle-slip   -36116554.00 for SV#23
  365844.00 Add SV#25 at an elevation of 24 14.
  365843.00 Fixing L1 cycle-slip   -25956802.00 for SV#25
  365843.00 Fixing WL cycle-slip    20230988.00 for SV#25
  365820.00 Eliminating SV#15 at an elevation of 18 27.
  365777.00 Add SV#15 at an elevation of 18 26.
  365777.00 Fixing L1 cycle-slip   -21450620.00 for SV#15
  365755.00 Total number of SVS is less than 3.
  365745.00 Eliminating SV#28 at an elevation of 31 24.
  365745.00 Eliminating SV#23 at an elevation of 19 19.
  365742.00 Total number of SVS is less than 3.
No measurement for     31 seconds.
  365730.00 Have to reset Kalman Filter
  365729.00 Initializing the reference site position
  365729.00 Initializing Kalman Filter.
  365702.00 Reforming the Kalman filter ...
  365700.00 Fixing L1 cycle-slip    -3853933.00 for SV#21
  365700.00 Fixing WL cycle-slip     2966165.00 for SV#21
  365700.00 Fixing L1 cycle-slip      947049.00 for SV#31
  365700.00 Fixing WL cycle-slip     -761784.00 for SV#31
  365700.00 Fixing L1 cycle-slip   -15106335.00 for SV#15
  365700.00 Fixing WL cycle-slip    11754164.00 for SV#15
  365679.00 Add SV#28 at an elevation of 31 24.
  365679.00 Add SV#25 at an elevation of 23 12.
  365678.00 Fixing L1 cycle-slip    -2401100.00 for SV#25
  365678.00 Fixing WL cycle-slip     1863313.00 for SV#25
  365677.00 Fixing L1 cycle-slip     2234313.00 for SV#28
  365677.00 Fixing WL cycle-slip    -1759770.00 for SV#28
  365674.00 Add SV#23 at an elevation of 19 20.
  365673.00 Fixing L1 cycle-slip   -20479136.00 for SV#23
  365673.00 Fixing WL cycle-slip    15923439.00 for SV#23
  365673.00 Detected small cycle-slip in L1 channels.
  365673.00 Detected small cycle-slip in L2 channels.
  365673.00 Increase the ambiguity process noise
  365663.00 Reduce the L1 ambiguity process noise.
  365663.00 Reduce the WL ambiguity process noise.
  365626.00 Fixing WL cycle-slip          -1.00 for SV#15
  365622.00 Fixing WL cycle-slip          -0.00 for SV#15
  365594.00 Fixing L1 cycle-slip          3.00 for SV#15
  365594.00 Fixing WL cycle-slip          -2.00 for SV#15
  365402.00 Fixing WL cycle-slip           2.00 for SV#23
  365355.00 Eliminating SV#15 at an elevation of 15 23.
  365332.00 Missing epoch in the BASE receiver
  365332.00 No good reference SV has been found.
  365331.00 Missing epoch in the BASE receiver
  365330.00 Missing epoch in the BASE receiver
```

Figure 12.10 Sample portion of a processing log file.

remain unchanged as no cycle slips occur in the data.

As a result of this attribute of the data some dead reckoning occurs in the data set, which may be as many as 3 epochs every ½ hour. This is considered to be tolerable but there is a chance, about 1 in 600, that the camera will expose at one of these lost epochs. In these cases the data is flagged at the aerial triangulation phase as “could be questionable”. A sample of this lost epoch is shown in figure 12.11

Resolving the DIFF problem when it occurs is more complicated. The problem is determining the cause, which is difficult as the message is obscure. Some study of the log file may point to a change over in reference satellite or a satellite may be cutting into or out of the solution. Options to the user are to omit reference satellites, omit satellites, raise or lower the satellite elevation cutoff, reset the Kalman filter at specific times or reduce the processing time interval. This is a lengthy process as the whole data set has to be run through both ways before the problem can be considered to be solved. This may take a number of re-runs in various configurations.

The author has spent as long as three days resolving this type of problem. It may not be of any consequence but determining all trajectory solutions to the same standard of accuracy is part of the on-going quality control of this process.

A characteristic of this type of problem is that it tends to occur on flights where the aircraft is in that “grey zone” where the ability to determine fixed ambiguities starts to degrade. Although the solutions calculated in this process are basically wide lane the internal algorithms tend to become “confused” when the trajectory moves from “near solution “ to “far solution” and visa versa, which is exactly what happens when processing backwards and forwards.

Having processed the data and scanned through the log file for critical messages a quick study of the two trajectory files, the C and J files, is made to determine if the PDOP (geometry of the solution) and the RMS is satisfactory and typical of the process.

```
RECORD = 1376  RECEIVE TIME = 85153.000000
SV CH  WN G TXMTTIME  CDPHASE     DOPPL     CARRIER_PH   EL  AZ S/N  DTYPE
23  1   2 24 0.9252  22427263   7888341  -45265570.491 36 124 237   L1
       32 22 0.9252  22427262   7888330  -45265570.484        186   L1P
       32 22 0.9252  22427266   6146742  -35241624.646        185   L2P
17  3   2 24 0.9215  23521803  10437719  -47128363.555 26  62 231   L1
       32 22 0.9215  23521803  10437714  -47128363.548        180   L1P
       32 22 0.9215  23521809   8133279  -36704460.230        180   L2P
 9  4   2 24 0.9187  24366458  -9447111  -19031106.935 16 120 222   L1
       32 22 0.9187  24366458  -9447133  -19031106.930        157   L1P
       32 22 0.9187  24366462  -7361386  -14817785.382        157   L2P
21  5   2 24 0.9299  21028249  -7266027  -41815777.001 62 174 244   L1
       32 22 0.9299  21028249  -7266023  -41815776.992        207   L1P
       32 22 0.9299  21028253  -5661836  -32563973.368        207   L2P
 1  6   2 24 0.9313  20607705 -26269777  -41948604.937 73 348 248   L1
       32 22 0.9313  20607705 -26269779  -41948604.929        218   L1P
       32 22 0.9313  20607710 -20469956  -32650498.846        218   L2P
28  8   2 24 0.9273  21795315  -1133916  -31035796.344 48 292 243   L1
        0 22 0.9273  21795315  -1133920  -31035796.340        228   L1P
        0 22 0.9273  21795318   -883571  -24156858.140        220   L2P
31 12   2 24 0.9229  23127695 -29921593  -21166885.460 29 236 230   L1
       32 22 0.9229  23127695 -29921599  -21166885.458        175   L1P
       32 22 0.9229  23127699 -23315504  -16470331.574        175   L2P
SITE          NAVX              NAVY              NAVZ               NAVT
MLY1  -4594799.835974    2699286.920424    -3494312.582463     243199.562500
PDOP       NAVXDOT           NAVYDOT           NAVZDOT            NAVTDOT
  2         -0.177            -0.020             0.003           -271.860168
RECORD = 1377  RECEIVE TIME = 85154.000000
SV CH  WN G TXMTTIME  CDPHASE     DOPPL     CARRIER_PH   EL  AZ S/N  DTYPE
23  1   2 24 0.9252  22427413   7891606  -45264781.669 36 124 237   L1
       32 22 0.9252  22427412   7891617  -45264781.662        186   L1P
       32 22 0.9252  22427416   6149296  -35241009.981        185   L2P
17  3   2 24 0.9215  23522001  10442893  -47127319.684 26  62 230   L1
       32 22 0.9215  23522001  10442887  -47127319.677        180   L1P
       32 22 0.9215  23522007   8137311  -36703646.825        180   L2P
 9  4   2 24 0.9187  24366278  -9439986  -19032051.424 16 120 220   L1
       32 22 0.9187  24366278  -9439954  -19032051.420        157   L1P
       32 22 0.9187  24366283  -7355862  -14818521.348        157   L2P
21  5   2 24 0.9299  21028111  -7262211  -41816503.578 62 174 245   L1
       32 22 0.9299  21028110  -7262204  -41816503.569        207   L1P
       32 22 0.9299  21028115  -5658870  -32564539.531        207   L2P
 1  6   2 24 0.9313  20607205 -26262708  -41951231.775 73 348 248   L1
       32 22 0.9313  20607205 -26262705  -41951231.767        218   L1P
       32 22 0.9313  20607210 -20464439  -32652545.732        218   L2P
28  8   2 24 0.9273  21795294  -1126433  -31035909.528 48 292 243   L1
        0 22 0.9273  21795293  -1126426  -31035909.523        229   L1P
        0 22 0.9273  21795297   -877734  -24156946.335        220   L2P
31 12   2 24 0.9229  23127126 -29913782  -21169877.363 29 236 231   L1
       32 22 0.9229  23127126 -29913760  -21169877.359        175   L1P
       32 22 0.9229  23127129 -23309418  -16472662.927        175   L2P
SITE          NAVX              NAVY              NAVZ               NAVT
MLY1  -4594800.011694    2699286.905699    -3494312.567050     242927.687500
PDOP       NAVXDOT           NAVYDOT           NAVZDOT            NAVTDOT
  2         -0.193            -0.008            -0.005           -271.811951
RECORD = 1378  RECEIVE TIME = 85157.000000
SV CH  WN G TXMTTIME  CDPHASE     DOPPL     CARRIER_PH   EL  AZ S/N  DTYPE
23  1   2 24 0.9252  22427864   7902007  -45262415.508 36 124 237   L1
       32 22 0.9252  22427862   7902007  -45262415.500        186   L1P
       32 22 0.9252  22427867   6157405  -35239166.220        185   L2P
17  3   2 24 0.9215  23522597  10455283  -47124187.461 26  62 230   L1
       32 22 0.9215  23522597  10455283  -47124187.455        180   L1P
       32 22 0.9215  23522603   8146887  -36701206.137        180   L2P
 9  4   2 24 0.9187  24365739  -9413917  -19034882.600 16 120 220   L1
       32 22 0.9187  24365739  -9413917  -19034882.598        157   L1P
       32 22 0.9187  24365744  -7335513  -14820727.461        157   L2P
21  5   2 24 0.9299  21027696  -7246312  -41818682.845 62 174 244   L1
       32 22 0.9299  21027696  -7246312  -41818682.836        207   L1P
```

Figure 12.11 Sample of base station data illustrating the lost data at receive times 85155 and 85156. Note that the record count is continuous.

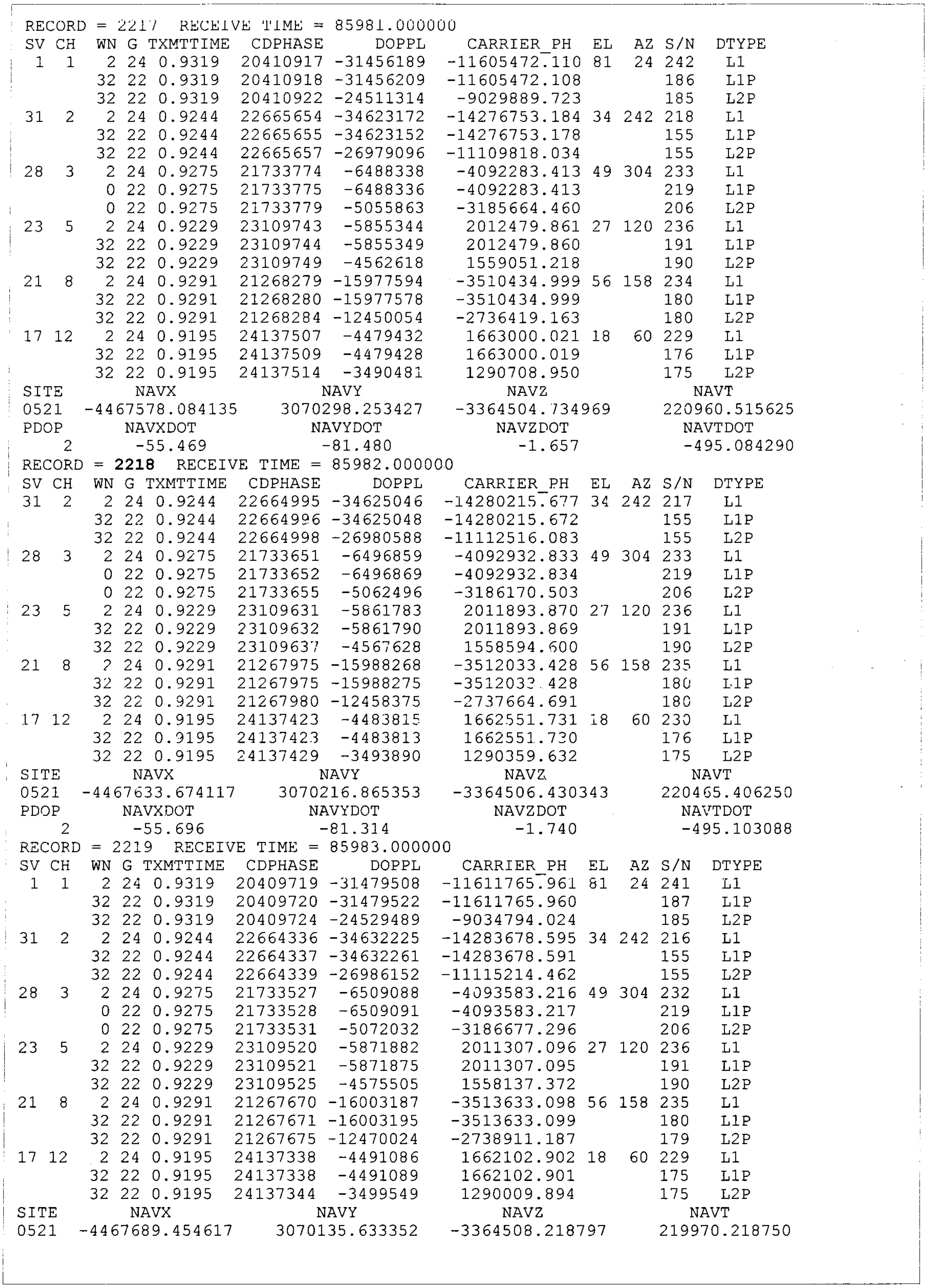
Generally the RMS of each epoch is below 0.4m, this value is a combination of the RMS of the three local coordinates E, N and U. The U component is typically greater than E and N by a factor of 2

Early in the implementation period another problem was detected with the receiver data. The aircraft receiver firmware was somehow corrupted which made the receiver fail to log a satellite when the camera event occurred. If the receiver was tracking 7 satellites every second and a camera event occurred, then that event would cause the receiver to momentarily stop logging one satellite for 1 or 2 epochs. For that event only 6 satellites would be used in the solution. This was not of consequence for the 1:50000 photography being flown, but for long range work the amount of common satellites drops remarkably, creating a situation where 5 satellites could drop to 4 or worse, 4 could drop to **3**!

Figure 12.12 is part of a raw data file which illustrates the lost satellite data after a camera event, figure 12.13 is part of a trajectory file or C file which illustrates the effect of lost data on solutions - note the RMS changes.

This problem disappeared when the navigation board was replaced late in 1995. The fault actually vanished two flights before the navigation board failure after the receiver required a total memory reset to boot the receiver. Unfortunately the receiver was unserviceable shortly afterwards.

The PNAV process creates many output files as a consequence of its calculations. The main working files from which all trajectory information is extracted are identified as C files and J files. These files are created for the forward, backward and combined solutions. The C files are a record of the aircraft's GPS antenna position in latitude, longitude and height for every GPS data point.



```
RECORD = 2217  RECEIVE TIME = 85981.000000
SV CH   WN G TXMTTIME  CDPHASE      DOPPL    CARRIER_PH  EL   AZ S/N  DTYPE
 1  1    2 24 0.9319  20410917 -31456189  -11605472.110 81   24 242   L1
        32 22 0.9319  20410918 -31456209  -11605472.108         186   L1P
        32 22 0.9319  20410922 -24511314   -9029889.723         185   L2P
31  2    2 24 0.9244  22665654 -34623172  -14276753.184 34  242 218   L1
        32 22 0.9244  22665655 -34623152  -14276753.178         155   L1P
        32 22 0.9244  22665657 -26979096  -11109818.034         155   L2P
28  3    2 24 0.9275  21733774  -6488338   -4092283.413 49  304 233   L1
         0 22 0.9275  21733775  -6488336   -4092283.413         219   L1P
         0 22 0.9275  21733779  -5055863   -3185664.460         206   L2P
23  5    2 24 0.9229  23109743  -5855344    2012479.861 27  120 236   L1
        32 22 0.9229  23109744  -5855349    2012479.860         191   L1P
        32 22 0.9229  23109749  -4562618    1559051.218         190   L2P
21  8    2 24 0.9291  21268279 -15977594   -3510434.999 56  158 234   L1
        32 22 0.9291  21268280 -15977578   -3510434.999         180   L1P
        32 22 0.9291  21268284 -12450054   -2736419.163         180   L2P
17 12    2 24 0.9195  24137507  -4479432    1663000.021 18   60 229   L1
        32 22 0.9195  24137509  -4479428    1663000.019         176   L1P
        32 22 0.9195  24137514  -3490481    1290708.950         175   L2P
SITE       NAVX              NAVY              NAVZ              NAVT
0521  -4467578.084135    3070298.253427   -3364504.734969     220960.515625
PDOP       NAVXDOT             NAVYDOT           NAVZDOT           NAVTDOT
  2        -55.469             -81.480            -1.657          -495.084290
RECORD = 2218  RECEIVE TIME = 85982.000000
SV CH   WN G TXMTTIME  CDPHASE      DOPPL    CARRIER_PH  EL   AZ S/N  DTYPE
31  2    2 24 0.9244  22664995 -34625046  -14280215.677 34  242 217   L1
        32 22 0.9244  22664996 -34625048  -14280215.672         155   L1P
        32 22 0.9244  22664998 -26980588  -11112516.083         155   L2P
28  3    2 24 0.9275  21733651  -6496859   -4092932.833 49  304 233   L1
         0 22 0.9275  21733652  -6496869   -4092932.834         219   L1P
         0 22 0.9275  21733655  -5062496   -3186170.503         206   L2P
23  5    2 24 0.9229  23109631  -5861783    2011893.870 27  120 236   L1
        32 22 0.9229  23109632  -5861790    2011893.869         191   L1P
        32 22 0.9229  23109637  -4567628    1558594.600         190   L2P
21  8    2 24 0.9291  21267975 -15988268   -3512033.428 56  158 235   L1
        32 22 0.9291  21267975 -15988275   -3512033.428         180   L1P
        32 22 0.9291  21267980 -12458375   -2737664.691         180   L2P
17 12    2 24 0.9195  24137423  -4483815    1662551.731 18   60 230   L1
        32 22 0.9195  24137423  -4483813    1662551.730         176   L1P
        32 22 0.9195  24137429  -3493890    1290359.632         175   L2P
SITE       NAVX              NAVY              NAVZ              NAVT
0521  -4467633.674117    3070216.865353   -3364506.430343     220465.406250
PDOP       NAVXDOT             NAVYDOT           NAVZDOT           NAVTDOT
  2        -55.696             -81.314            -1.740          -495.103088
RECORD = 2219  RECEIVE TIME = 85983.000000
SV CH   WN G TXMTTIME  CDPHASE      DOPPL    CARRIER_PH  EL   AZ S/N  DTYPE
 1  1    2 24 0.9319  20409719 -31479508  -11611765.961 81   24 241   L1
        32 22 0.9319  20409720 -31479522  -11611765.960         187   L1P
        32 22 0.9319  20409724 -24529489   -9034794.024         185   L2P
31  2    2 24 0.9244  22664336 -34632225  -14283678.595 34  242 216   L1
        32 22 0.9244  22664337 -34632261  -14283678.591         155   L1P
        32 22 0.9244  22664339 -26986152  -11115214.462         155   L2P
28  3    2 24 0.9275  21733527  -6509088   -4093583.216 49  304 232   L1
         0 22 0.9275  21733528  -6509091   -4093583.217         219   L1P
         0 22 0.9275  21733531  -5072032   -3186677.296         206   L2P
23  5    2 24 0.9229  23109520  -5871882    2011307.096 27  120 236   L1
        32 22 0.9229  23109521  -5871875    2011307.095         191   L1P
        32 22 0.9229  23109525  -4575505    1558137.372         190   L2P
21  8    2 24 0.9291  21267670 -16003187   -3513633.098 56  158 235   L1
        32 22 0.9291  21267671 -16003195   -3513633.099         180   L1P
        32 22 0.9291  21267675 -12470024   -2738911.187         179   L2P
17 12    2 24 0.9195  24137338  -4491086    1662102.902 18   60 229   L1
        32 22 0.9195  24137338  -4491089    1662102.901         175   L1P
        32 22 0.9195  24137344  -3499549    1290009.894         175   L2P
SITE       NAVX              NAVY              NAVZ              NAVT
0521  -4467689.454617    3070135.633352   -3364508.218797     219970.218750
```

Figure 12.12 Extract of aircraft data illustrating lost tracking data to one satellite. Notice that record 2218 at receive time 89582 SV1 on channel one is not recorded, but no cycle slip is evident in the data in the next record.

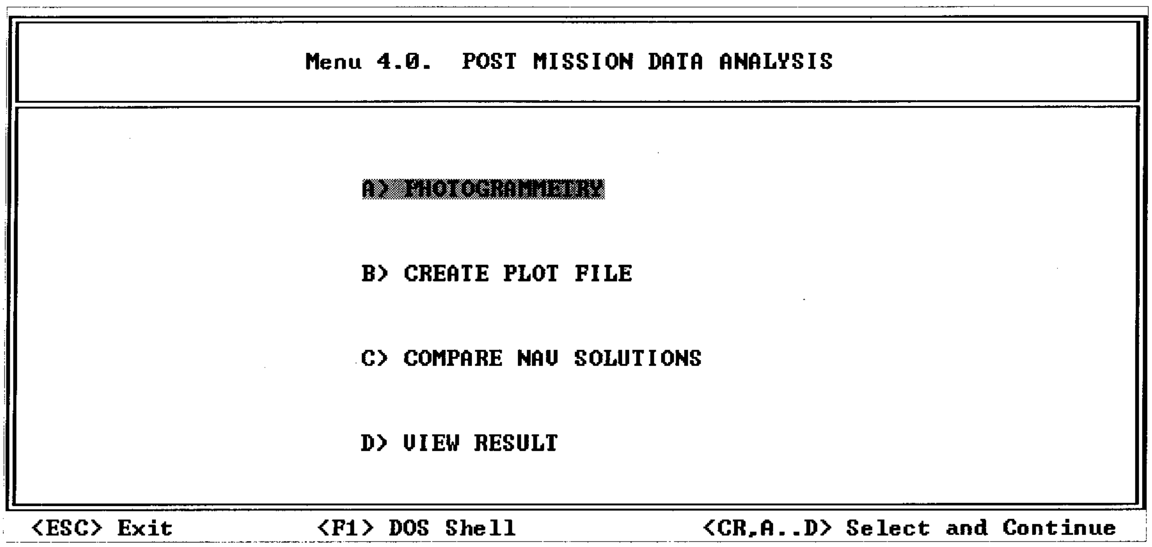
```
                                No SVs                                      RMS

0521 05/21/95 23:52:07.000000  6  1.7  S 31.99815801  E 145.44480605  7938.8435   0.319  1   99.272   1.435   0.035
0521 05/21/95 23:52:08.000000  6  1.7  S 31.99814564  E 145.44585528  7938.7749   0.320  1   99.270   1.305  -0.163
0521 05/21/95 23:52:09.000000  6  1.7  S 31.99813425  E 145.44690459  7938.5756   0.320  1   99.292   1.257  -0.187
0521 05/21/95 23:52:10.000000  6  1.7  S 31.99812271  E 145.44795421  7938.4291   0.320  1   99.320   1.304  -0.127
0521 05/21/95 23:52:11.000000  6  1.7  S 31.99811086  E 145.44900409  7938.2925   0.320  1   99.347   1.317  -0.156
0521 05/21/95 23:52:12.000000  6  1.7  S 31.99809902  E 145.45005433  7938.1163   0.321  1   99.387   1.315  -0.189
0521 05/21/95 23:52:13.000000  6  1.7  S 31.99808704  E 145.45110502  7937.9042   0.322  1   99.431   1.357  -0.254
0521 05/21/95 23:52:14.000000  6  1.7  S 31.99807456  E 145.45215621  7937.5823   0.323  1   99.482   1.407  -0.395
0521 05/21/95 23:52:15.000000  6  1.7  S 31.99806180  E 145.45320798  7937.1208   0.324  1   99.541   1.422  -0.514
0521 05/21/95 23:52:16.000000  6  1.7  S 31.99804907  E 145.45426037  7936.5892   0.322  1   99.593   1.395  -0.526
0521 05/21/95 23:52:17.000000  6  1.7  S 31.99803851  E 145.45531158  7936.2241   0.447  1   99.605   1.599  -0.844
0521 05/21/95 23:52:18.000000  5  2.5  S 31.99802368  E 145.45636650  7935.5767   0.429  1   99.669   1.466  -0.511
0521 05/21/95 23:52:19.000000  6  2.0  S 31.99800984  E 145.45742028  7935.1238   0.325  1   99.739   1.659  -0.541
0521 05/21/95 23:52:20.000000  6  1.7  S 31.99799479  E 145.45847471  7934.5112   0.323  1   99.783   1.609  -0.650
0521 05/21/95 23:52:21.000000  6  1.7  S 31.99798184  E 145.45952950  7933.8890   0.325  1   99.801   1.229  -0.566
0521 05/21/95 23:52:22.000000  6  1.7  S 31.99797313  E 145.46058426  7933.4357   0.323  1   99.781   0.688  -0.312
0521 05/21/95 23:52:23.000000  6  1.7  S 31.99796990  E 145.46163860  7933.2649   0.322  1   99.720  -0.007  -0.057
0521 05/21/95 23:52:24.000000  6  1.7  S 31.99797355  E 145.46269211  7933.3129   0.320  1   99.625  -0.803   0.172
0521 05/21/95 23:52:25.000000  6  1.7  S 31.99798411  E 145.46374446  7933.6221   0.319  1   99.503  -1.514   0.439
0521 05/21/95 23:52:26.000000  6  1.7  S 31.99800004  E 145.46479549  7934.1813   0.319  1   99.381  -1.962   0.678
0521 05/21/95 23:52:27.000000  6  1.7  S 31.99801817  E 145.46584538  7934.9265   0.318  1   99.293  -1.978   0.763
0521 05/21/95 23:52:28.000000  6  1.7  S 31.99803439  E 145.46689464  7935.6508   0.318  1   99.267  -1.567   0.680
0521 05/21/95 23:52:29.000000  6  1.7  S 31.99804651  E 145.46794381  7936.2325   0.318  1   99.256  -1.195   0.435


0521 05/22/95 00:09:37.000000  5  2.2  S 31.99992720  E 146.54439428  7965.3236   0.319  1   99.031   1.648   0.571
0521 05/22/95 00:09:38.000000  5  2.2  S 31.99991280  E 146.54544064  7965.9521   0.319  1   98.963   1.540   0.654
0521 05/22/95 00:09:39.000000  5  2.2  S 31.99989933  E 146.54648620  7966.6238   0.319  1   98.886   1.487   0.698
0521 05/22/95 00:09:40.000000  5  2.2  S 31.99988593  E 146.54753100  7967.3715   0.319  1   98.814   1.472   0.797
0521 05/22/95 00:09:41.000000  5  2.2  S 31.99987310  E 146.54857505  7968.1931   0.319  1   98.752   1.370   0.807
0521 05/22/95 00:09:42.000000  5  2.2  S 31.99986142  E 146.54961867  7968.8123   0.319  1   98.741   1.223   0.280
0521 05/22/95 00:09:43.000000  5  2.2  S 31.99985087  E 146.55066254  7968.7522   0.320  1   98.793   1.156  -0.267
0521 05/22/95 00:09:44.000000  5  2.2  S 31.99984028  E 146.55170714  7968.4329   0.322  1   98.872   1.206  -0.365
0521 05/22/95 00:09:45.000000  5  2.2  S 31.99982948  E 146.55275259  7967.9939   0.326  1   98.954   1.155  -0.562
0521 05/22/95 00:09:46.000000  5  2.2  S 31.99981896  E 146.55379827  7967.6160   0.444  1   99.039   1.037  -0.796
0521 05/22/95 00:09:47.000000  0  0.0  S 31.99980976  E 146.55484552  7966.7189   3.460  1   99.129   1.023  -0.984
0521 05/22/95 00:09:48.000000  0  0.0  S 31.99980022  E 146.55589387  7965.6769   3.457  1   99.247   1.114  -1.086
0521 05/22/95 00:09:49.000000  5  2.2  S 31.99979022  E 146.55694462  7964.7510   0.334  1   99.397   1.311  -1.048
0521 05/22/95 00:09:50.000000  5  2.2  S 31.99977757  E 146.55799591  7963.5982   0.326  1   99.532   1.475  -1.284
0521 05/22/95 00:09:51.000000  5  2.2  S 31.99976371  E 146.55904864  7962.2045   0.322  1   99.676   1.632  -1.474
0521 05/22/95 00:09:52.000000  5  2.2  S 31.99974792  E 146.56010295  7960.7187   0.319  1   99.823   1.883  -1.475
0521 05/22/95 00:09:53.000000  5  2.2  S 31.99972962  E 146.56115872  7959.3313   0.318  1   99.955   2.204  -1.260
0521 05/22/95 00:09:54.000000  5  2.2  S 31.99970843  E 146.56221582  7958.2302   0.318  1  100.069   2.468  -0.965
0521 05/22/95 00:09:55.000000  5  2.2  S 31.99968547  E 146.56327399  7957.3635   0.317  1  100.163   2.645  -0.800
0521 05/22/95 00:09:56.000000  5  2.2  S 31.99966106  E 146.56433325  7956.4838   0.317  1  100.288   2.744  -1.089
0521 05/22/95 00:09:57.000000  5  2.2  S 31.99963650  E 146.56539412  7955.1069   0.317  1  100.460   2.700  -1.628
0521 05/22/95 00:09:58.000000  5  2.2  S 31.99961242  E 146.56645692  7953.3813   0.317  1  100.653   2.670  -1.721
0521 05/22/95 00:09:59.000000  5  2.2  S 31.99958812  E 146.56752187  7951.7821   0.317  1  100.866   2.746  -1.476
```

Figure 12.13 The top sample data illustrates the effect on the trajectory solution when the data of one satellite is not available, the second sample illustrates the estimates of the dead reckoning solution when base station data is not available.

The J files are a record of the displacement vectors from the base station to the aircraft for every GPS data point. The J files also contain the statistical information from which the trajectory plot files are derived.

12.3.3 Camera event positions

PNAV is designed to support photogrammetric operations. Option C) POST MISSION on the main screen in figure 12.3 takes the user to the utilities available after post-processing is completed. The POST MISSION screen is illustrated in figure 12.14. The photogrammetry option takes the user to the photogrammetry menu. This stage offers the user the selection of a number of P files, usually the options will be PHOTO.DAT and any other photo tag files with the convention PNSWxAyy.zzz. Before this step the user deletes any data from the specific photo tag files which is not specific to the particular data set.



Menu 4.0. POST MISSION DATA ANALYSIS

A> PHOTOGRAMMETRY

B> CREATE PLOT FILE

C> COMPARE NAV SOLUTIONS

D> VIEW RESULT

<ESC> Exit <F1> DOS Shell <CR,A..D> Select and Continue

Figure 12.14 Post Mission screen.

The photogrammetry option interpolates the C and J trajectory files based on the time tags within the P files, creating the data sets that form the basis of the camera centres appropriate for photogrammetry. New interpolated C and J files are created. The new files are named after the standard file naming templates with the addition of an @ symbol.

The interpolation process is an area where software bugs are present. The software is incapable of interpolating data sets that span across a week rollover. Missions that are flown on a Sunday have to be treated differently to other weekdays. The trajectory data produced by PNAV must be divided into data sets that fall before and after the week roll-over. The interpolation process is then conducted on the separate sets without incident.

The limitation lies in the camera event that falls between 23:59:59 and 0:00:00. In this case, the solution will be a manual calculation.

Unfortunately this is another legacy of the time zone problem in this part of the world. It is disappointing that sophisticated software like PNAV is supported by utilities that do not account for situations such as this.

The next step is to create hard copy results of the trajectory and the statistical results. This is the last checking function in the post-processing phase. Plots are created using the option B) CREATE PLOT FILE. This option will create a number of plots based on the information embedded in the J files, data from the interpolated camera positions, if available, is also used in plot creation process. Figures 12.15 through 12.22 are samples of plot files created by the post mission utilities.

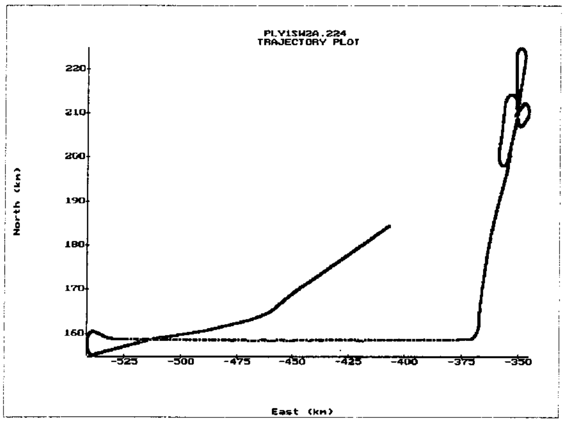


Figure 12.15 Ashtech software utility, PLOT, aircraft trajectory.

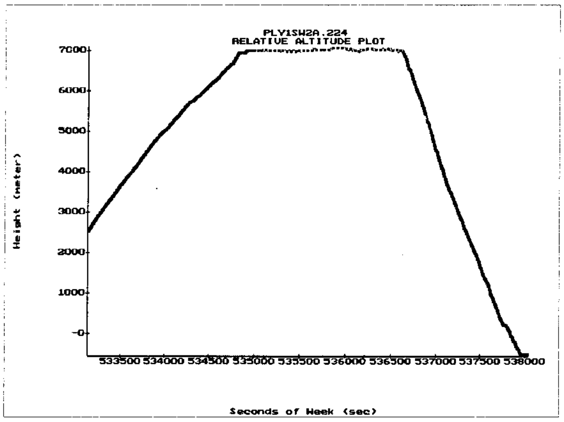


Figure 12.16 Aircraft vertical trajectory.

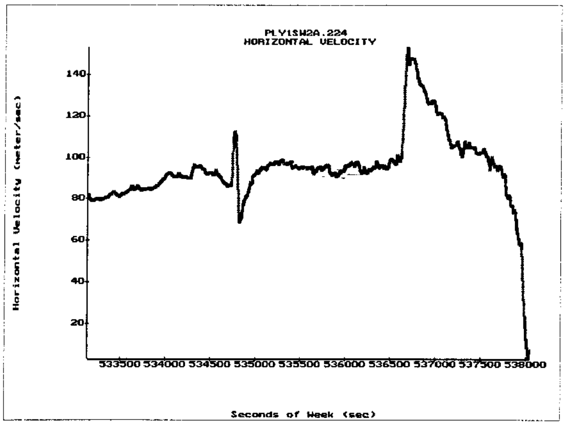


Figure 12.17 Aircraft horizontal velocity.

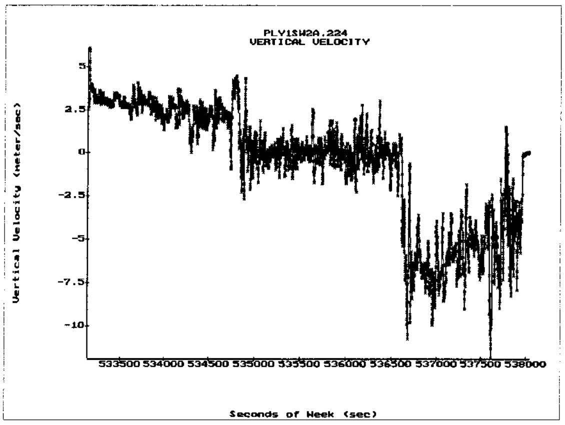


Figure 12.18 Aircraft vertical velocity.

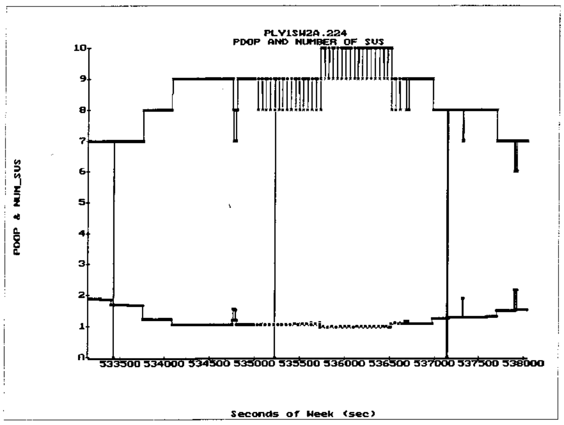


Figure 12.19 Plot of PDOP and number of satellites in the solution.

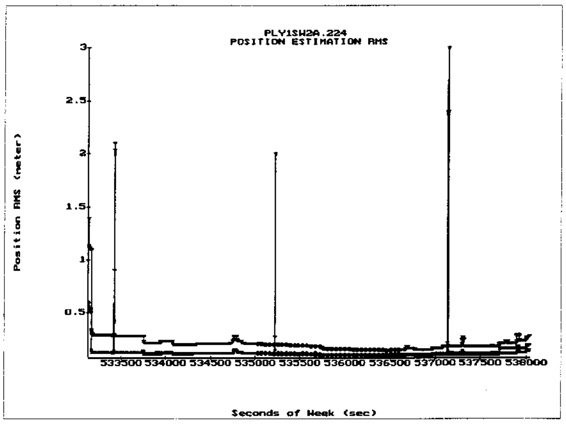


Figure 12.20 Plot of position RMS for lat, long and height.

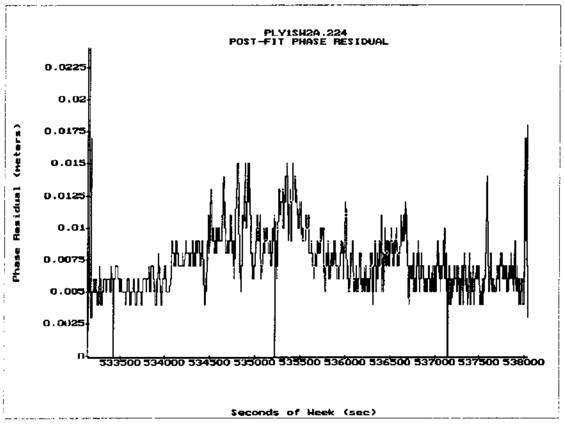


Figure 12.21 Plot of phase residuals for each solution.

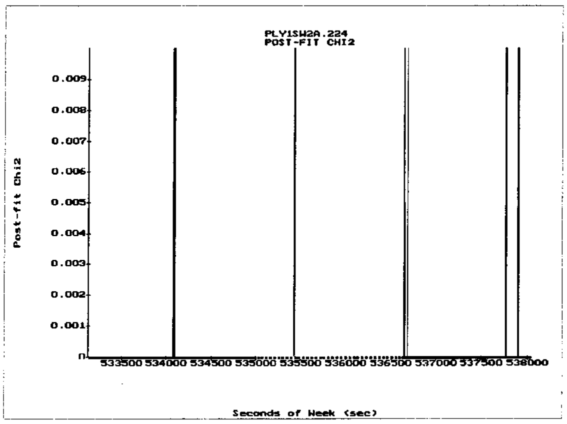


Figure 12.22 Plot of Chi^2 fit of solution.

Processing today is a set and forget process, the user is not required to sit there and monitor the whole process. A 13Mb data file takes approximately 1.5 hours to process on a Pentium 90 machine, so it is a waste of resource and a boring pastime to watch numbers continually changing on a computer screen. The processing skill lies in the analysis of the results and the evaluation of the information available in the processing log file.

12.3.4 Data collation

Although the processing is complete, there still remains the tasks of collating the data, archiving and forwarding the data for the purposes of aerial triangulation and photographic indexing. These are not overly technical processes but aspects of this data management and photographic indexing have resulted in further improvements in image collection and data tagging techniques used on the aircraft.

The system described so far only addresses the needs of the photogrammetric process. It does deliver some of the requirements of a photography archive and indexing system. Photography information is currently retained by film number and exposure number. The NAVPRO version in use provides some rudimentary data to support this system but it is by no means foolproof and cannot provide any information about film and job numbers or other data unique to each photograph.

The trajectory files produced by PNAV contain no information about photography apart from the derived 3 dimensional position of the aircraft antenna at a specific time. The NAVPRO result files contain time tagged positions of each exposure, an exposure number and an exposure identifier. The exposure number can be in error if the operator has incorrectly keyed it in, so this is not a reliable means to tie the actual exposure to a position, neither does the negative image contain any precise time tag information anywhere on it apart from an image of the camera clock face in the edge margin of the exposure. The clock used in the RC30 is powered by a spring and escapement system. $0.75 M camera with a 1960 watch design!

The .RES file and the trajectory file can be merged together via the precise time tags within the two data sets. This is a manual process using a simple editor. One aspect that does make the process simpler is that flight planning only accounts for a certain number of photographs, so it is very rare that more time tags appear in one file than the other. Not all photography is collated in this manner. Only photography destined for photogrammetry is subject to this collation process. Standard coverage non-mapping photography is only subject to post-processing and archiving.

The collation is a precise and time consuming process, for enough information has to be brought together to correctly and uniquely identify each exposure. The prepared file for photogrammetry contains the exposure identifier, exposure number, film number and WGS84 latitude, longitude and ellipsoid height. This process can be complicated when there have been re-flies of particular runs. In these cases it is important that unambiguous information is available which is specific in its identification of the correct photo run.

All data, whether standard coverage or mapping is eventually archived on CD-ROM. The raw data, the appropriate result files and the NAVPRO result files are retained so that at any time the data can be re-processed or re-evaluated.

Although this system is far in advance of traditional photographic procedures used at the SGD the digital data it provides is very rudimentary. For photography indexing and tracking this process only provides a small part of what is required. This has recently been addressed by new software, PHOTOTAG, which provides real time, camera interactive, exposure tracking. This software will be described in a later chapter.

12.3.5 Comments

It must be stressed that the methodology of the SGD in its photogrammetric process is based on the concepts of GPS drift. This concept requires the use of ground control to support the aerial triangulation model when drift is an unknown.

Having adopted this methodology, then a different approach can be used for the post-processing problem. The strength of the trajectory solution in this new case lies in how well the relative positions of successive photographs can be determined. Absolute position is of little consequence, what is important is the stability of the solution for the duration of the photo run. The processing log provides indicators for this, the previous plots also provide information about solution quality. Studies of the many log files that are now available from post-processing since the inception of the project, reveal that the trajectory is always very stable when flying the photographic strip. Very few cycle slips are detected when the aircraft is in a stable condition, on the turn-arounds the data becomes noisy as expected, but recovers in time for the next strip.

The processing selection for PNAV is NO to ambiguity resolution. The PNAV algorithms generally resolve the wide lane solution and it tends to remains so. This assures that the adopted wide lane values are stable. Ambiguity searches, if requested, may result in the adopted solutions continually changing in the relentless search for the correct integer ambiguities. In most of the SGD's operations the chances of determining ambiguities over the operational distances of the aircraft, are low. The expected searching would be detrimental to the stable situation that is being pursued.

Using current technology, the value of fixed ambiguity solutions is somewhat defeated given the error budgets associated with the camera offset vector, interpolation and datum errors.

13. GPS Drift and Long-Range Kinematic Tests

The principles of GPS-controlled photography supporting photogrammetric adjustment processes have been defined and demonstrated by many investigators - Ackermann (1992, 1994a, 1994b), Friess (1988, 1991), Lucas & Mader (1989). There are aspects of the technology which still make it a relatively new application to explore. The basis of this new methodology is the integration of kinematic GPS data into the aerial triangulation model.

There is no doubt that ambiguity-fixed, double-differenced carrier phase solutions obtained using commercial survey type GPS receivers are capable of baseline determinations to 1 to 2 cm accuracy. This has been demonstrated time and again for static survey applications. Aspects of static surveying have been adapted for kinematic applications, but unlike static surveys the nature of kinematic surveying provides little in the way of redundancy to check the quality of the results.

GPS-controlled photogrammetry using redundant ground control provides a means to determine the performance of kinematic hardware and software. Most research to date has concentrated on short-range kinematic GPS where reliable ambiguity resolution is generally realised. In those aerotriangulation adjustments, where GPS drift is considered not to exist, the only way of testing kinematic GPS performance is to fully populate the adjustment with ground control so that the coordinates of the camera stations can be reliably determined. These values can then be compared to the kinematic GPS camera station solutions.

The task of resolving ambiguities becomes more difficult as distance from the base station increases. The costs of supporting an aerial survey operation by establishing a ground base station within the confines of a project is high. Han & Wong (1996) has proposed the "GPS traverse technique" which is independent of baseline length but is dependent on maintaining lock during the period of the survey. The technique yields high relative accuracy between stations, absolute position is based on beginning and ending the survey on a known point. This technique is not unlike that proposed by Ackermann (1992,1994a,1994b), where he addresses the absolute position error as offset and drift but acknowledges the high relative positioning that results from continuous phase tracking. Resolving drift is dependent on the aerial triangulation block configuration and the incorporation of some minimal ground control.

Can this high relative accuracy be repeated over very long baselines? This project was dependent on the premise that long-range kinematic GPS, using the base station data collected at the SGD building in Bathurst, could provide image point accuracies to support the SGD's digital capture programs anywhere within NSW. All points in NSW are located within a radius of about 1000km of the Bathurst GPS base station.

Unlike traditional mapping processes, where the accuracy of the hard copy product is a direct result of the sum of the error budgets associated with each phase of the production process, the SGD expects to capture digital data from its 1:50000 photography at accuracies better than 5m in ground units. Already, aerial triangulation results from this scale photography have reached 2m accuracy after adjustment. This quality of digital data can support the production of 1:10000 mapping products.

The photogrammetric adjustment process adopted by the SGD is based on the GPS drift model. It is accepted that kinematic GPS data and commercial processing software cannot reliably deliver an absolute position solution of sufficient accuracy to support aerial triangulation without ground control.

Questions to be addressed regarding GPS drift are:

- Is it as expected, can it be modelled as linear behaviour?
- Accepting that drift can be modelled, what range can be achieved without compromising results?

These are appropriate questions for the SGD to ask as its whole operational process is based on using a centralised base station.

To answer these questions, a number of test flights have been conducted.

13.1 Drift

The standard of data quality collected by the modern GPS receiver has seen major improvements which have contributed to significant progress in ambiguity resolution techniques. These changes have been notable, particularly in kinematic applications where static initialisation has been eliminated. Many vendors now provide software with Ambiguity Resolution On The Fly (AROF).

The PNAV software package from Ashtech has this capability when using Ashtech Z12 dual frequency data. There are limitations to this but, given the right conditions (some of these being suitable PDOP, sufficient satellites tracked, proximity to the base station and the availability of clean data), then there is a good chance that ambiguities can be resolved on-the-fly.

Based on this presumption, test flights have been flown in two areas of NSW: over Bathurst and in the proximity of Lightning Ridge in northern NSW.

13.2 Bathurst test

13.2.1 Method

The Bathurst test flights were to examine the behaviour of long-range kinematic GPS. A test network was established based on a number of base stations located at various distances from the project test area. The site of the project test area was located in the immediate airspace over Bathurst. Ashtech Z12 dual frequency receivers were located at Bathurst (SGD), Sydney (SAGEM offices, Alexandria) and Hobart (Department of Environment and Land Management). These base stations were used to produce three different trajectory solutions for the flight path of the aircraft. The proximity of the aircraft to the Bathurst base station was to encourage fixed-ambiguity solutions. If this could be achieved, then the trajectory of the aircraft could be very precisely defined and could be regarded as a "control set", or as the benchmark solution.

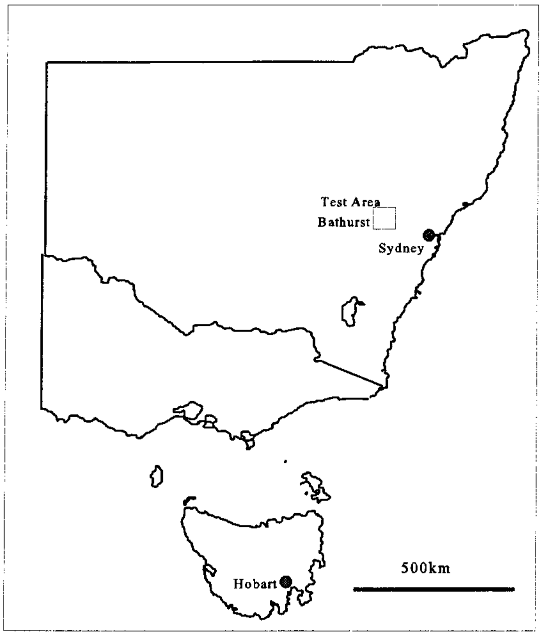


Figure 13.1 Location of base stations for test conducted over Bathurst.

The approximate distance of the project area from Sydney was 160km and from Hobart, 1080km. The location of the base stations is illustrated in figure 13.1.

The methodology was to collect single second dual frequency data at all sites, as would be the case in normal operations, and then to process this data using the Ashtech PNAV software. Standard processing options were used in the data post-processing, the same as proposed to be used in day-to-day production. The major processing difference between the solutions was the ambiguity YES option for baselines linked to Bathurst and the ambiguity NO option for those linked to the Sydney and Hobart stations. It was expected that the data processed between the Bathurst base station and the aircraft would provide ambiguity-fixed solutions for the majority of the flight and therefore be the **benchmark** data set of the flight profile. It would also provide some level of evaluation of the PNAV software and whether or not processing data below satellite elevations of 10° would impact on the results.

All test solutions were based on the combined result of the backward and forward solutions. This is particularly useful for the fixed-ambiguity solution as it generally contributes to a larger percentage of fixed-ambiguity epochs. The profiles produced based on the Sydney and Hobart base station data would be differenced from the benchmark data, providing a degree of evaluation of performance, both in a relative and absolute sense.

A successful outcome would suggest that long-range operations were viable, but further testing on a proven aerial triangulation adjustment area would have to follow.

13.2.2 Data collection

Test data was collected over the period 1st to 9th March 1995 (060_95 to 068_95). Static data to establish the relative positions of the base stations was collected as follows:

29/2/95	060/95	Bathurst to Sydney	22:30 - 01:30UT	159546.979m
6/3/95	065/95	Bathurst to Hobart	05:00 - 06:00UT	1066424.145m
6/3/95	065/95	Bathurst to Hobart	07:00 - 08:00UT	1066423.693m
7/3/95	066/95	Bathurst to Hobart	06:00 - 07:00UT	1066423.699m

Considering the observation times of the baselines to Hobart the results are reasonable and serve their purpose.

Kinematic data was collected on a test flight conducted on 9/3/95 (068/95). Three hours of single second GPS data was collected during the flight. Single second data was also collected at the three base stations. A setback to the processing of this data was the misunderstanding that occurred with the staff at the Hobart station. Although the data was collected with a Z12 receiver, the raw data was converted to RINEX format before dispatch and the original format data deleted. The post-processing software GPPS could handle RINEX format for the static baseline processing but the kinematic processor PNAV could not. It was not until a beta version 2.4 of PNAV was made available that the data for Hobart could be usefully recovered.

Although the aircraft was flown for three hours the only base station to record a full simultaneous data set was the SGD's Bathurst base. Sydney and Hobart both recorded subsets. The Hobart data was only 1 hour in duration.

Aerial photography was incorporated in the test flight. This produced time tag data for the camera event. This data also defines the periods when the aircraft is stabilised on a photo run, the periods when satellite tracking is not subject to the effects of aircraft manoeuvring.

13.2.3 Processing

The benchmark data set, Bathurst base to the aircraft, was processed for the entire flight. The complete trajectory is illustrated in figure 13.2. From this plot it can be seen that the aircraft was never more than 40km from the base station and that aircraft manoeuvring was quite substantial.

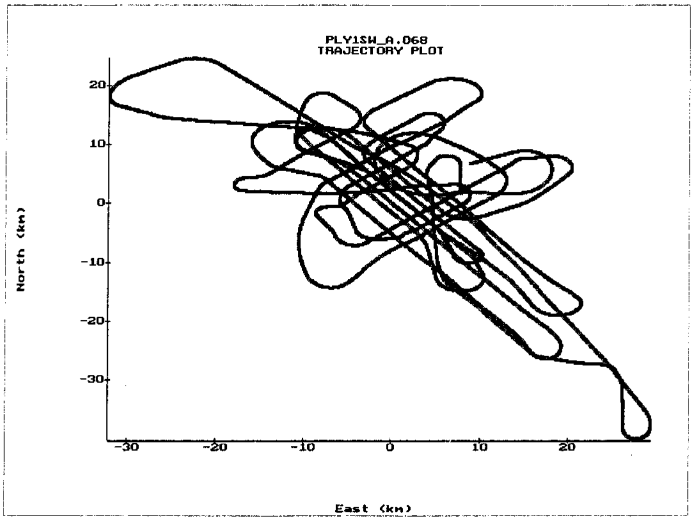


Figure 13.2 Trajectory plot of test flight.

Figure 13.3 is a plot of the aircraft's vertical profile for the flight. Notice the steps in the altitude required for the different photo scales. Figure 13.4 is a plot of the aircraft's velocity. The changes in velocity result from the exposure of the aircraft to headwinds, crosswinds and tail-winds.

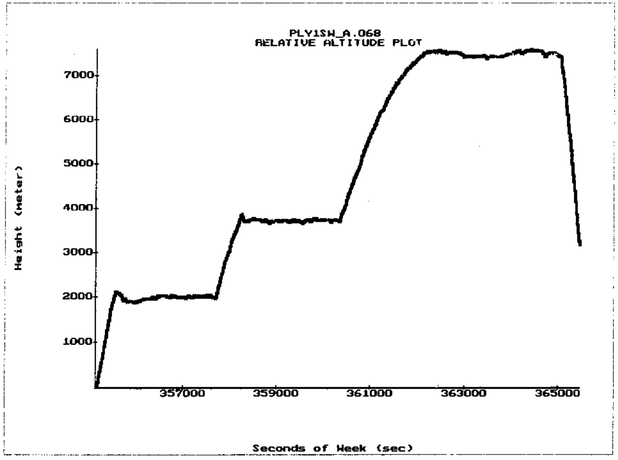


Figure 13.3 Vertical profile of test flight.

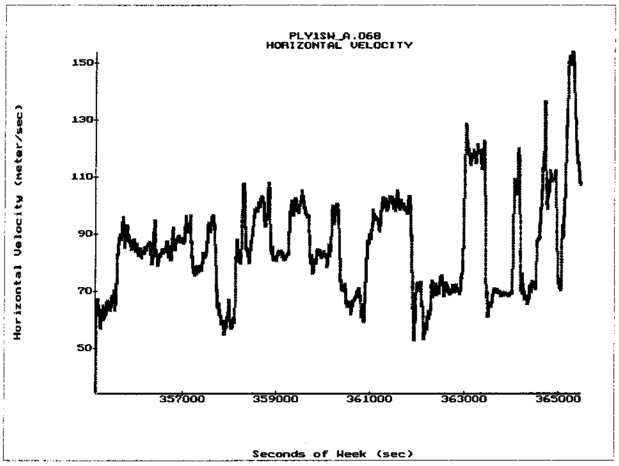


Figure 13.4 Horizontal velocities of test flight.

A feature of the PNAV software is the ability to process the data both forwards and backwards. This option is (to some degree) an independent determination. If selected as a processing option the reverse solution is calculated first.

Elements of the solution are retained in a temporary file and compared to the results of the forward solution. Any internal discrepancies are highlighted in the processing log file and displayed on the processing screen.

The independence of solution results from the initialisation that occurs at the beginning of either directional process. Even though the data is the same the algorithms used have to initialise and converge to similar results for both directions. There are different elements to consider when this takes place, e.g. the forward solution may initialise very close to the base station achieving a strong solution very quickly and with high confidence levels for the resolution of the ambiguities. The reverse solution could initialise well away from the base station, or during a period of manoeuvring and poor satellite geometry. The ability of the software to resolve the same solution using different initialisation elements can be considered to be an indicator of the reliability of the solutions.

The solutions adopted here are based on the mean weighted solutions of the reverse and forward results. Another benefit of processing the data in both directions is that the effects of cycle slips, and the "blow-outs" that occur in the RMS of each epoch, are minimised by the combination of solutions. The reverse solution converges with time, similar to rapid static and phase smoothing techniques. When losses of lock occur the Kalman filter "opens up" and the convergence process begins again. The result is a saw tooth pattern of high RMSs which track the convergence of the solution ambiguity resolution and reset when cycle slips occur. Figure 13.5 illustrates the effect of taking the mean of forward and backward solutions to achieve ambiguity- fixed solutions for a greater amount of the data set. The combination will give almost a flat line (Figure 13.5 fine grey solid bottom line) if losses of lock are infrequent.

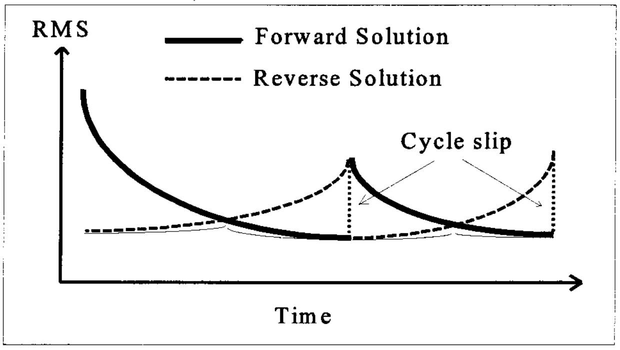


Figure 13.5 Average of forward and back solutions.

The solution settings for the kinematic processing of Sydney and Hobart data was not to fix ambiguities and to use a satellite cutoff angle of 5 °. This solution is still sensitive to cycle slips in the data, but tends to be a “smoothed solution”. The low satellite elevation cutoff angle is required to achieve an acceptable common satellite coverage.

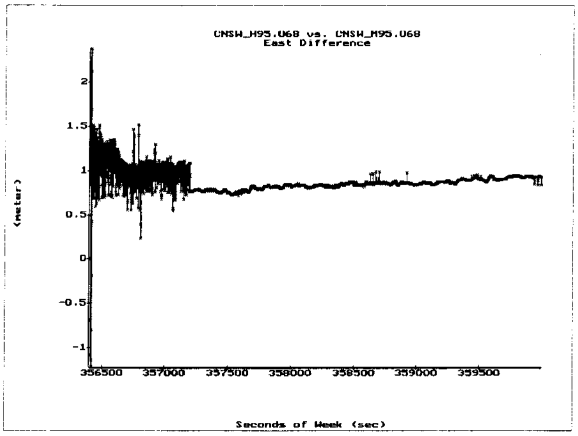


Figure 13.6 East difference between Hobart and Bathurst trajectories highlighting poor Hobart data for first 14 minutes.

The Sydney data set processed without concern but some problems existed with the Hobart data. The Hobart data contained a series of “drop outs” in the first 14 minutes of the one hour data set. The reasons for these drop outs is not known, but after examining the raw data files it appeared that whole epochs are missing. The effect on the results is evident in figures 13.6, 13.7 and 13.8.

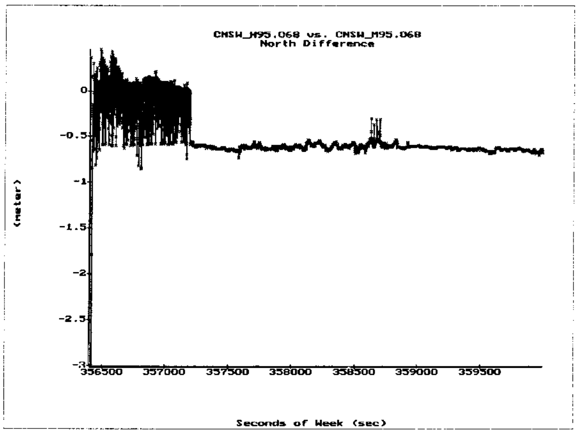


Figure 13.7 North difference between Hobart and Bathurst trajectories highlighting poor Hobart data for first 14 minutes.

This may be the result of transforming from the Ashtech raw data format to the RINEX format, and then back to the Ashtech format. There is insufficient data to make an analysis.

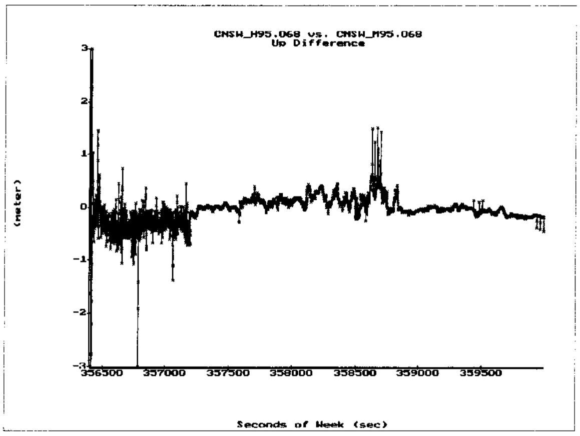


Figure 13.8 Up difference between Hobart and Bathurst trajectories highlighting poor Hobart data for first 14 minutes.

13.2.4 Some results

For the purpose of comparing the trajectories each was reduced to a common 1 hour data set that was defined by the Hobart observation period. The period of comparison spans the period 03:00:00UT (356400 sec of week) - 03:59:59 UT (359999 sec of week). A subset of this data set, a period when the aircraft is flying photographic lines and is at a relatively stable attitude, is 03:14:00UT - 03:22:00UT.

A number of plots are shown here. These plots are generated by the PNAV suite of software. A post mission option is to compare the results of two trajectory files by differencing the positions with common time tags. This will produce a plot file that contains the differences in east, north and up, plus the differences in the velocity vectors for the same three components.

The purpose of this process is to detect the behaviour of the "remote" trajectory against the "near" trajectory, which in this case is considered to be the benchmark trajectory. This assumption is based on the processing results for the near trajectory which are basically ambiguity-fixed for most of the flight. Some unfixed solutions are evident during manoeuvring periods when phase lock has been lost. These occurrences are outside the testing window.

For GPS to be a suitable technology for aerial triangulation the characteristics of the difference graphs should, ideally, be a horizontal straight line with a mean value of zero. Considering these data sets, such a result would suggest that regardless of the distance from the base station the solution is error free! If it is not, then the displacement from zero has to be modelled within the aerial triangulation adjustment. This displacement could be parameterised and determined as a constant if minimum ground control was used to detect the shift. If the plot is a straight horizontal line for the entire flight then the constant can be considered valid for all aspects of the flight. This implies that only one constant parameter needs to be determined, for each cardinal axis.

If the plot of the differences approximates a sloping straight line then there is a constant and a tilt coefficient, i.e. the equation of a straight line. Again, only one constant and one slope coefficient needs to be determined, for each cardinal axis. These constant and slope parameters are commonly referred to as "drift" in photogrammetric terms.

If the plots are "noisy" then a study must be made of periods of linear motion of the aircraft where the difference data approximates a straight line and whether those short periods coincided with intervals when the aircraft was taking photographs and satellite tracking was "locked". Unfortunately, the periods of linear motion in these data sets are very short, approximately 2 minutes in length. If the data approximates linearity for these periods, then drift parameters can be resolved within the bundle adjustment for **each** photographic run (if correctly configured with minimum ground control and suitable cross tie strips).

Figures 13.6, 13.7 and 13.8 result from differencing the Hobart-based trajectory and the Bathurst-based trajectory for the one hour data set. Figures 13.9, 13.10 and 13.11 result from difference between the Sydney-based trajectory and the Bathurst-based trajectory for the one hour data set.

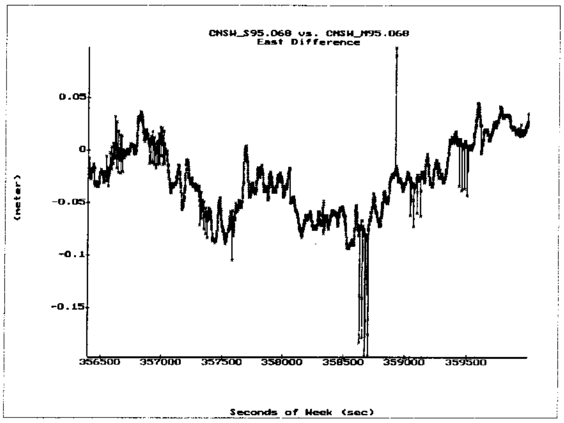


Figure 13.9 East difference between Sydney-based and Bathurst-based trajectories.

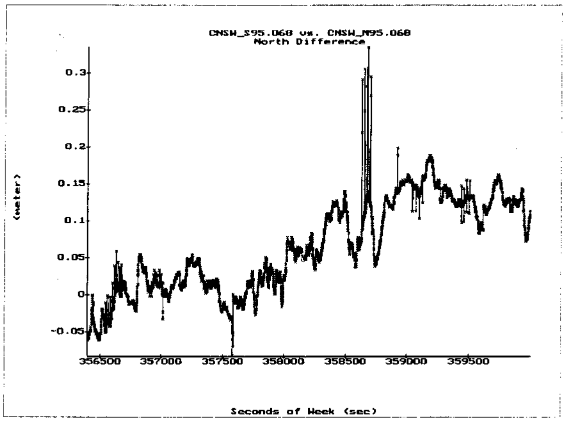


Figure 13.10 North difference between Sydney-based and Bathurst-based trajectories.

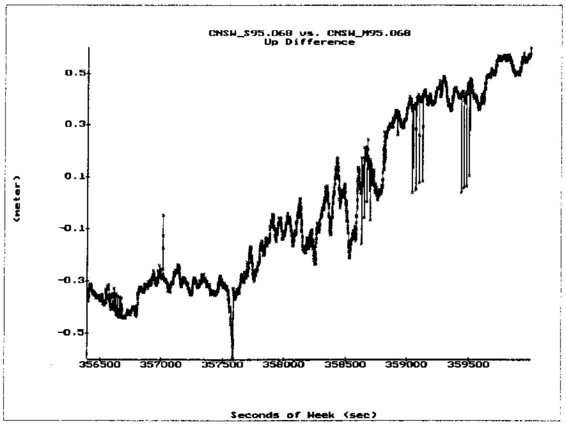


Figure 13.11 Up difference between Sydney-based and Bathurst-based trajectories.

The most noticeable characteristic of the difference plots is that the Hobart - Bathurst set appears to be more stable than the Sydney - Bathurst set. However, taking into account the vertical scales this is not the case.

For the purposes of aerial triangulation, when drift is recognised as being in existence, the behaviour of the data should approximate linearity. Each of the 1 hour data difference sets have been entered into EXCEL spreadsheets. The differences between east, north and up have been modelled as a straight line: $y = mx + b$

The coefficient m is the slope, the constant b is the y intercept, x is the time and y is the model value. Once m and b are determined then values for y are derived for each epoch of the data set. The modelled data is subtracted from the real data generating residuals, and the standard deviation of the residuals is determined. The results are given in Table 13.1.

Table 13.1 Linear modelling of trajectory differences.

		East(m)	North(m)	Up(m)
Sydney - Bathurst 3600 epochs	Std Dev	**0.033**	**0.032**	**0.101**
	Max Err	0.171	0.245	0.408
Hobart - Bathurst 2801 epochs[1]	Std Dev	**0.019**	**0.029**	**0.148**
	Max Err	0.138	0.315	1.485
Sydney - Bathurst 236 epochs[2]	Std Dev	**0.010**	**0.009**	**0.020**
	Max Err	0.036	0.022	0.020
Hobart - Bathurst 236 epochs[2]	Std Dev	**0.011**	**0.008**	**0.036**
	Max Err	0.026	0.023	0.154
Sydney - Bathurst 244 epochs[2]	Std Dev	**0.016**	**0.012**	**0.065**
	Max Err	0.047	0.066	0.260
Hobart - Bathurst 244 epochs[2]	Std Dev	**0.019**	**0.019**	**0.071**
	Max Err	0.054	0.108	0.338

[1] The data set is reduced as a result of unresolved data dropouts

[2] Data subset when aircraft is flying photographic run

The above results are based on double-differenced solutions. The shortened data sets (236 and 244 epochs) are periods when the aircraft was online taking photographs. These periods, although short, are intervals when satellite tracking is stable. Based on these subset results the long-range kinematic trajectories, after the removal of the systematic drift components, are highly correlated with the benchmark fixed-ambiguity trajectory. These results are well within the accuracy requirements defined for the largest of photo scales (Table 1.2), but they can only be confirmed by aerotriangulation testing.

As a matter of interest another processing package, Hydrostar Post Mission (HPM), was used which has phase smoothing capability, as discussed in chapter 3.2.2. This has single frequency capability only, and is a fairly old package (1990 vintage). The raw aircraft data was processed with HPM and compared with the benchmark double-difference trajectory.

The full data set was processed but only the one hour data subset in question was analysed. This procedure was followed so that the solution could reach some level of convergence. Unlike PNAV, reverse processing is not available in HPM. The comparison is made in Table 13.2.

Table 13.2 Linear modelling of phase smoothed trajectory differences.

		East (m)	North (m)	Up (m)
Phase S - Bathurst 3600 epochs	Std Dev	**16.49**	**27.41**	**85.90**
	Max Err	64.5	65.08	231.67
Phase S - Bathurst 236 epochs	Std Dev	**4.395**	**2.476**	**11.568**
	Max Err	39.981	22.582	35.023

13.2.5 Comments regarding the Bathurst results

13.2.5.1 Double-differencing using PNAV

The results were very encouraging as far as aerial triangulation is concerned. The overall standard deviations for the extended data sets, 3600 and 2801 epochs, demonstrate that the worst case error, based on a least squares linear regression, is less than 2 metres. In all cases the largest errors occur in the height component, except for the Sydney - Bathurst results for the 236 epoch data set.

The standard deviations could be further reduced if outliers were removed from the data sets. The identification of outliers in kinematic results is difficult. From an analysis of the short data sets, 236 and 244 epochs during photo runs, outliers in these data sets can be related to events which are evident in the processing log files. Data spikes tend to occur when the processor encounters a control limitation or detects a change in the raw data.

The crucial element of the data is the continuous tracking of satellites. This needs to be established before the camera begins to cycle. Based on the these results a conservative period would be between 1 and 2 minutes lead in and lead out of photo strips to guarantee clean continuous tracking needed for acceptable post-processing.

13.2.5.2 Phase smoothing

The results of the phase smoothed processing are disappointing, however this could also be the result of receiver hardware problems and the unpredictable manoeuvring of the aircraft. The continual loss of lock is very bad for phase smoothing processes. The technique also suffers from the limitations of a single receiver processing, which doesn't benefit from the elimination of systematic errors due to double-differencing. The author has not been able to determine to what extent the pseudo-range data has been de-weighted, for although the processing parameter file is set to "100% phase" the solution approaches but never reaches "100%". It is suspected that the seemingly cyclic variations evident in the results reflect the influence of Selective Availability.

Table 13.3 Behaviour of phase smoothed east coordinates compared to benchmark results.

Epoch	HPM East	PNAV East	Diff	y=mx+b	Diff
357314	738717.370	738704.624	-12.746	-12.742	-0.004
357315	738655.050	738642.209	-12.841	-12.821	-0.020
357316	738592.580	738579.629	-12.951	-12.901	-0.050
357317	738529.700	738516.815	-12.885	-12.981	0.096
357318	738467.090	738454.029	-13.061	-13.060	-0.001
357319	738404.280	738391.177	-13.103	-13.140	0.037
357320	738341.430	738328.202	-13.228	-13.220	-0.008
357321	738278.560	738265.220	-13.340	-13.300	-0.040
357322	738215.560	738202.234	-13.326	-13.379	0.053
357323	738152.830	738139.320	-13.510	-13.459	-0.051
357324	738089.990	738076.473	-13.517	-13.539	0.022
357325	738027.350	738013.675	-13.675	-13.619	-0.056
357326	737964.920	737951.148	-13.772	-13.698	-0.074
357327	737902.600	737888.869	-13.731	-13.778	0.047
357328	737840.410	737826.601	-13.809	-13.858	0.049
		m	-7.97E-02	Sum	0.000
		b	2.85E+04	StdDev	0.049
				Max	0.096
				Min	-0.074

Table 13.4 Behaviour of phase smoothed north coordinates compared to benchmark results.

Epoch	HPM North	PNAV North	Diff	y=mx+b	Diff
357314	6304879.75	6304877.409	-2.341	-2.316	-0.025
357315	6304833.04	6304830.576	-2.464	-2.444	-0.020
357316	6304786.56	6304783.976	-2.584	-2.572	-0.012
357317	6304740.34	6304737.711	-2.629	-2.700	0.071
357318	6304694.29	6304691.466	-2.824	-2.829	0.005
357319	6304648.37	6304645.466	-2.904	-2.957	0.053
357320	6304602.96	6304599.857	-3.103	-3.085	-0.018
357321	6304557.78	6304554.523	-3.257	-3.213	-0.044
357322	6304512.82	6304509.491	-3.329	-3.341	0.012
357323	6304468.13	6304464.646	-3.484	-3.469	-0.015
357324	6304423.56	6304419.945	-3.615	-3.597	-0.018
357325	6304379.12	6304375.387	-3.733	-3.725	-0.008
357326	6304334.50	6304330.636	-3.864	-3.853	-0.011
357327	6304289.59	6304285.626	-3.964	-3.982	0.018
357328	6304244.62	6304240.522	-4.098	-4.110	0.012
		m	-1.28E-01	Sum	0.000
		b	4.58E+04	StdDev	0.030
				Max	0.071
				Min	-0.044

Despite these limitations the phase smoothed results do show some linearity, but only for very short periods of time. Table 13.3 illustrates the behaviour of the phase smoothed easting component results against the benchmark results. This data falls between two consecutive photographs so it is "clean". It is an extremely good result, the same is evident for the northings (table 13.4) and height components (table 13.5).

Table 13.5 Behaviour of phase smoothed heights compared to benchmark results.

Epoch	HPM Up	PNAV Up	Diff	y=mx+b	Diff
357314	2821.280	2781.742	-39.538	-39.523	-0.015
357315	2821.310	2781.763	-39.547	-39.542	-0.005
357316	2821.350	2781.786	-39.564	-39.561	-0.003
357317	2820.970	2781.422	-39.548	-39.580	0.032
357318	2820.940	2781.405	-39.535	-39.599	0.064
357319	2821.540	2781.980	-39.560	-39.618	0.058
357320	2822.430	2782.713	-39.717	-39.637	-0.080
357321	2823.190	2783.484	-39.706	-39.656	-0.050
357322	2824.170	2784.532	-39.638	-39.675	0.037
357323	2825.380	2785.603	-39.777	-39.694	-0.083
357324	2826.080	2786.378	-39.702	-39.713	0.011
357325	2826.740	2787.000	-39.740	-39.732	-0.008
357326	2827.350	2787.586	-39.764	-39.751	-0.013
357327	2827.360	2787.595	-39.765	-39.770	0.005
357328	2826.120	2786.384	-39.736	-39.789	0.053
		m	-1.90E-02	Sum	0.000
		b	6.75E+03	StdDev	0.046
				Max	0.064
				Min	-0.083

If this type of behaviour were typical of "clean" data over extended periods of time (no longer than 10 minutes for large scale applications) then the requirement of a base station can be dispensed with. Long-range processing would no longer be an issue! The phase smoothed results, if typical, could be extended to large scale mapping projects using minimal ground control and the inclusion of drift parameters in the aerial triangulation adjustment.

This is not the case as figure 13.12, which is the difference between the benchmark trajectory and the phase smoothed trajectory for a one hour data set, does not display any behaviour that can be modelled linearly. The height differences exaggerate this problem.

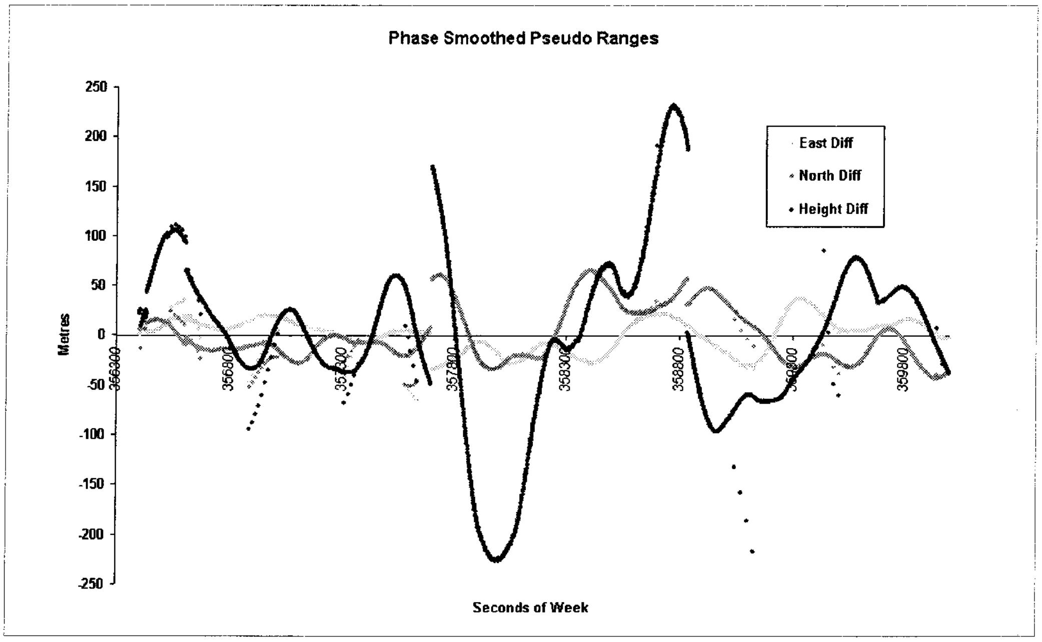


Figure 13.12 Phase smoothed pseudo-range based point position solution behaviour showing East, North and Up differences.

Figure 13.12 also illustrates the overall variability inherent in an uncorrected single point smoothed position.

From these results it was reasoned that it was not a worthwhile exercise to pursue phase smoothed pseudo-range solutions to support aerial triangulation.

13.3 Lightning Ridge test

The second test, conducted in the Lightning Ridge area of NSW, was similar to the Bathurst test but utilised four base stations, with the longest baseline being 1500km. The test was also designed to incorporate long-range kinematic data into the aerial triangulation adjustment. The evaluation of GPS drift follows the same methodology as the Bathurst test. The configuration of the base stations used, Lightning Ridge, Bathurst, the University of NSW and Hobart is illustrated in figure 13.13.

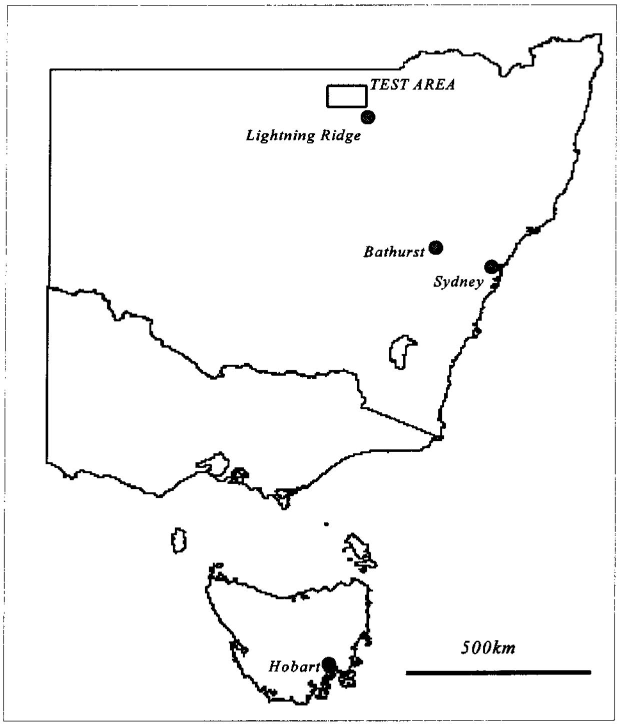


Figure 13.13 Base station configuration for test of GPS drift and the effect on photogrammetry.

The test was to re-photograph three of the runs of the original Angledool test. Due to a number of problems on the day only one run was captured, run 6. It was not a complete run but covered the two western 1:100000 map sheets of the original Angledool map coverage. This was of no concern as the Angledool test range was well controlled with tie runs and ground control. Having a run of photography that covered at least ½ of the original run 6 it was decided to extract a subset of the original photogrammetric adjustment observations and control. The layout of the extracted data subset is illustrated in figure 13.14.

The subset adjustment block was extracted and aerotriangulated using the PATB-GPS adjustment software. This process established a stable block configuration upon which further configuration testing could be carried out. This subset adjustment block was then modified by substituting the new image observations and the various GPS-derived trajectories for run 6.

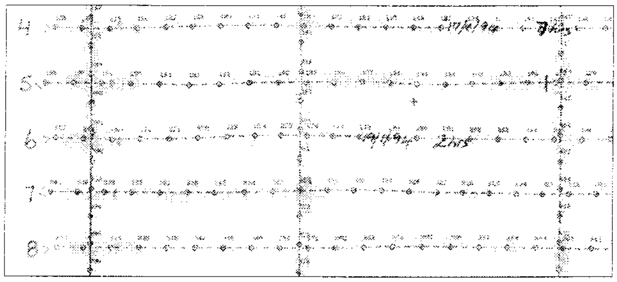


Figure 13.14 A section of the original Angledool observation plan showing the five east-west runs and the three north-south runs.

The substitution of new photography into this block suffers from some limitations:

- Two different aircraft camera combinations have been used. PATB-GPS can only accommodate one set of camera-antenna offsets, although the small difference in this case is negligible. Some of the error is absorbed into the drift components.
- The new photography is two years younger than the original.
- Pugging and observation of points can introduce differences up to a few metres between the old and new adjustment.
- The location of the Lightning Ridge base station was chosen to encourage fixed-ambiguity solutions and create the benchmark data set for the aircraft trajectory. Fortunately this was the case, and the ambiguities were resolved. Although the complete trajectory was calculated based on each base station, the GPS results that were studied have been reduced to coincide with the photography interval of run 6. This data set spans from UT 00:56:00 through to 01:22:00 on the 28/1/95, 26 minutes in all.

Unlike the short two minute data sets in the Bathurst test, this data set is representative of a typical photographic run. It was flown from east to west so the aircraft flew a little slower than in the opposite direction, which is nearly always quicker due to the prevailing jet stream. A complete 1:250000 map sheet spans over 150km. On average this takes 30 minutes to traverse.

The trajectory solution adopted as the benchmark is the Lightning Ridge forward result. This solution is considered superior to the combined solution as the periods of fixed-ambiguity results are greater. This was partly due to the fact that the processor was initialised within the proximity of the Lightning Ridge base station. The base station was set up close to the airport, at a geodetic station located there.

To give some idea of the quality and value in processing the trajectory both ways the Lightning Ridge trajectory solution was differenced with itself. Although the utilities within PNAV make it possible to difference various solutions the sequence of the files being differenced must be in the same time order. To difference a forward solution with a backward solution requires that the order of the backward file be reversed. This was managed on a UNIX terminal using an AWK routine. Similar functionality is available in EXCEL. The results of this differencing are displayed in figures 13.15 to 13.17.

The processor was able to resolve ambiguities on-the-fly and it was able to maintain them to the western edge of the Angledool map sheet. Once the aircraft manoeuvred for the

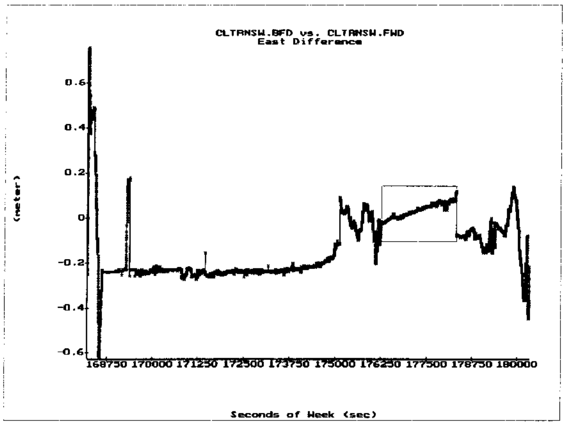


Figure 13.15 Easting difference between forward and backward solution for aircraft trajectory using Lightning Ridge base station.

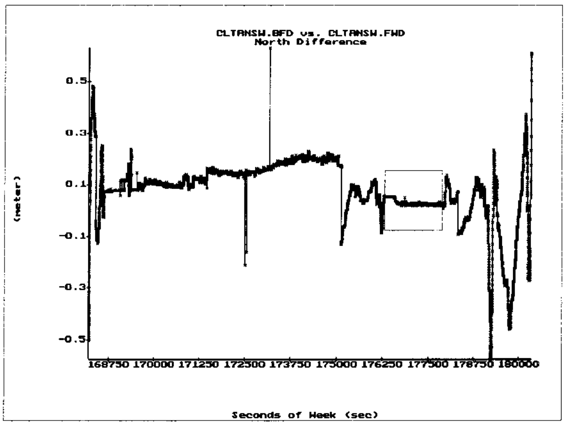


Figure 13.16 Northing difference between forward and backward solution for aircraft trajectory using Lightning Ridge base station.

return direction the ambiguities were "lost", but were "picked up" again as the aircraft neared the base station. A portion of the processing log for this data set is given in Appendix A. Notice that the ambiguities were fixed at 176042.00 with a ratio test value of 2.61477. In other words, this combination was 2.6 times better than the next best ambiguity combination. Fixing ambiguities occurred about 140 seconds before the first exposure. At 176296.00 a new combination of ambiguities resulted in a ratio test value of 2.86722e+10. This was 16 seconds after the first photograph and the ambiguities were retained for the remainder of the run.

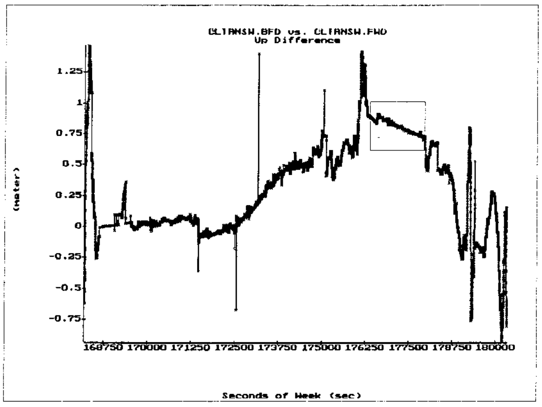


Figure 13.17 Up difference between forward and backward solution for aircraft trajectory using Lightning Ridge base station.

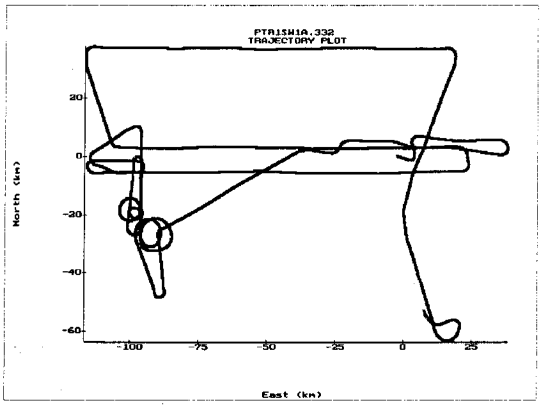


Figure 13.18 Trajectory of aircraft for the Angledool test.

The trends in these plots are interesting. The photography occurred between 176160 and 177730 seconds of the week, and these intervals are outlined by the boxes in the plots. The differences between the forward and backward east, north and up component solutions do not map as straight lines but they do have very low noise. The height solution is the worst, as usual, whereas the east and north values are close to zero.

A great deal of the noise evident in these plots can be attributed to the ground receiver. Manoeuvring of the aircraft contributed the remainder. On the day of the test the outside temperature was in excess of 40 ° Celsius. The Ashtech Z12 receiver used at the Lightning Ridge base station was an early model, high power unit. Although it was shaded throughout the survey the unit became too hot to touch. The logging was direct to a portable computer that was also struggling with the conditions. The liquid crystal display was so hot it was black and unreadable.

Despite all this the data was complete and the results are acceptable as a benchmark trajectory. Unlike the Bathurst test, this investigation also included the opportunity to use aerial triangulation to test the capability of kinematic GPS. Figure 13.18 illustrates the trajectory of the test flight. The axes indicate how far the aircraft was from the Lightning Ridge base station.

13.3.1 Linear behaviour

The forward trajectory result based on the Lightning Ridge base station has been adopted as "truth". The results are ambiguity-fixed for the duration of the photographic run. The interpolated photo events are entered into PATB-GPS along with the photogrammetric measurements for the new photography.

How do the trajectories derived from the other three base stations compare? The relationships between the four base stations was determined using a combination of existing and new GPS data. The inclusion of the Mather Pillar at the University of NSW was possible by using subsets of other data available to the author. The relationship between these stations is only important in as far as it would guarantee a suitable position to pin the kinematic trajectory on. Over these distances the datum effect and propagation errors are significant, hence absolute values are difficult to achieve.

Using these derived base station coordinates, the three aircraft trajectories were calculated. Each of these was for the complete aircraft data set, which is in excess of four hours of single second data. In each case the combined solutions were adopted as the best results, as this is in line with current SGD practice. No special control settings were used in the post-processing, apart from the fact that the version of PNAV used was a Beta version, which was not flagged to terminate kinematic baseline calculations beyond 1000km.

The three derived trajectories from Bathurst, UNSW and Hobart data were then sectioned out to match the interval of the photography. These trajectories were then differenced against the Lightning Ridge benchmark trajectory. The difference between the Hobart-based trajectory and the Lightning Ridge-based trajectory is illustrated in figures 13.19, 13.20 and 13.21.

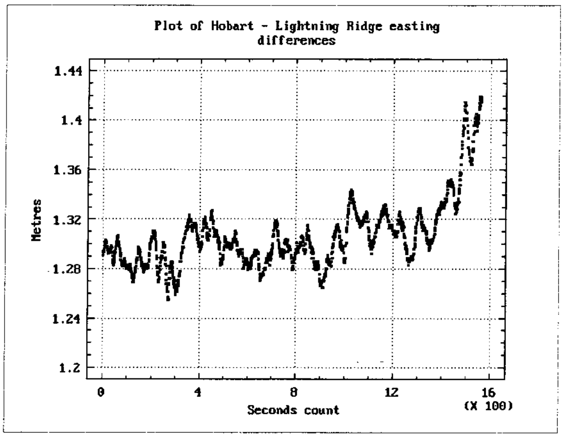


Figure 13.19 Easting trajectory differences from Hobart base station data

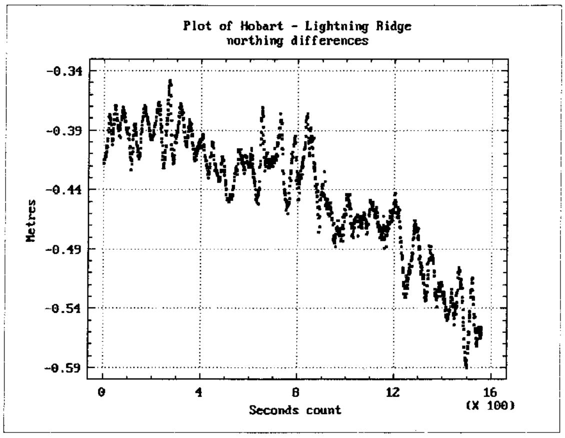


Figure 13.20 Northing trajectory differences from Hobart base station data

Apart from the initial offset the difference between the two trajectories is very small, which is surprising considering the distance between the receivers, and that no special processing procedures were used. It is also evident that some linear modelling could be applied to these results. The test was designed to follow as close to operational procedures as possible.

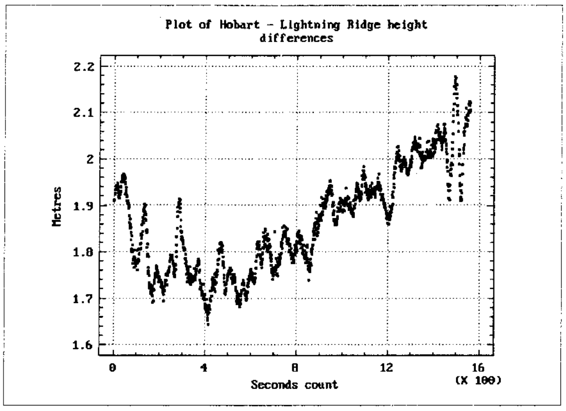


Figure 13.21 Height trajectory differences from Hobart base station data.

The Bathurst differences are illustrated in figures 13.22 to 13.24 and the UNSW differences illustrated in figures 13.25 to 13.27. The behaviour of the data is very different for the various samples. It is best to examine the results in their east, north and up components. The Hobart result is the cleanest and there is not a great deal to comment on, apart from the fact that the data does tend to fit a linear pattern.

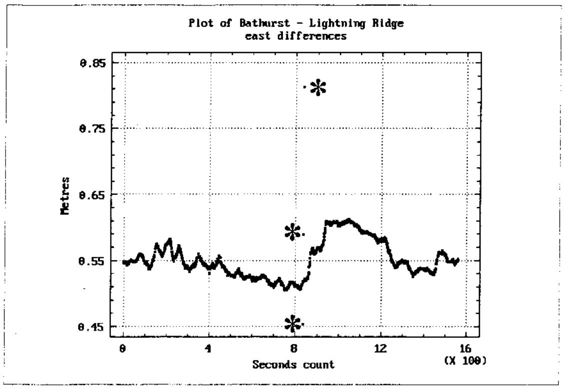


Figure 13.22 Easting trajectory differences from Bathurst base station data.

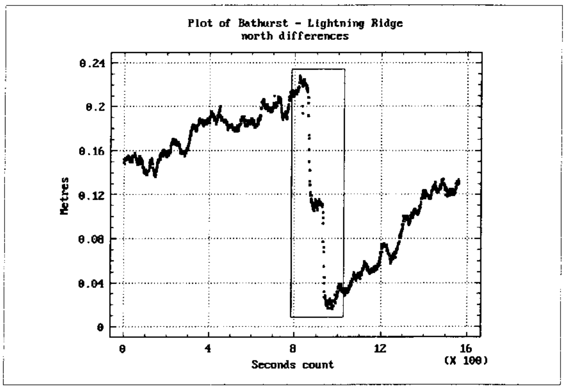


Figure 13.23 North trajectory differences from Bathurst base station data.

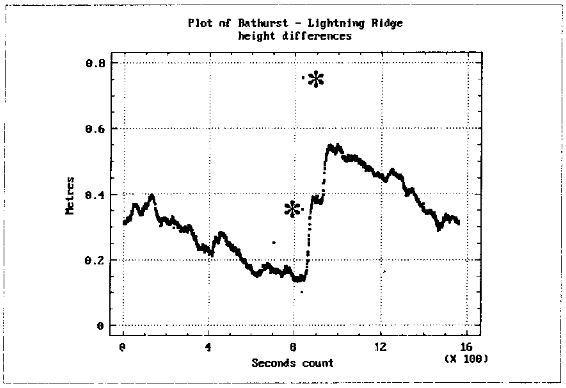


Figure 13.24 Height trajectory differences from Bathurst base station data.

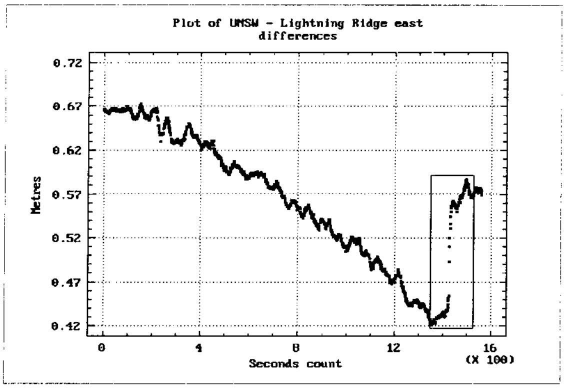


Figure 13.25 Easting trajectory differences from UNSW base station data.

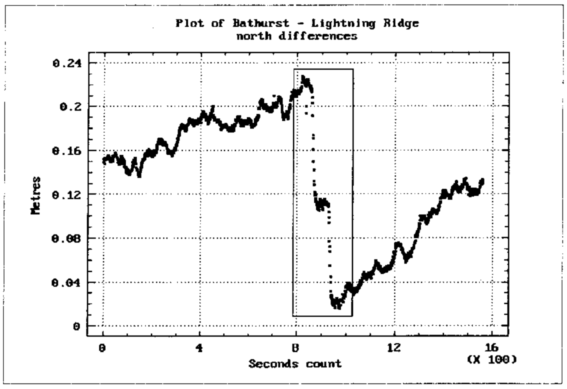


Figure 13.26 Northing trajectory differences from UNSW base station data.

The problems that occur in the Bathurst data set around the 800 epoch mark, highlighted by the asterisks, is a direct result of missing base station data. It is suspected that the reason for the change in the trend is due to the influence of the Kalman filter after the period of missing data.It must also be remembered that this is a combined solution of the forward and backward trajectories.

These solutions have been studied and there is no reason for this behaviour. EXCEL was used to compare the forward and reverse solutions. Figures 13.28 to 13.30 are plots of the

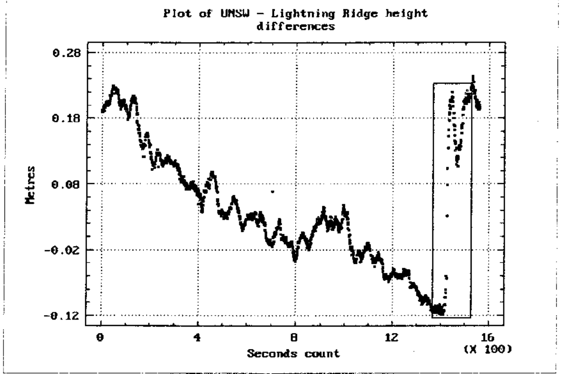


Figure 13.27 Height trajectory differences from UNSW base station data.

differences over the photographic interval. These plots do not give any hint as to the cause of the steps in the Bathurst - Lightning Ridge data sets (figures 13.22 to 13.24). It is possible that the two lost epochs has a greater effect on the solution than the statistics imply. Even so, the difference in the easting is approximately 0.1m, for the northing is 0.2m and the up is 0.4m. After some linear modelling this can be reduced by half.

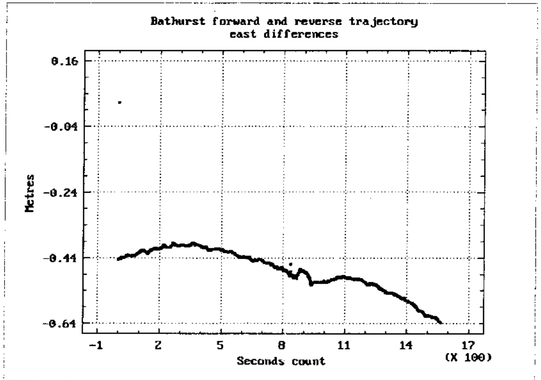


Figure 13.28 Easting difference between forward and reverse solution for Bathurst trajectory.

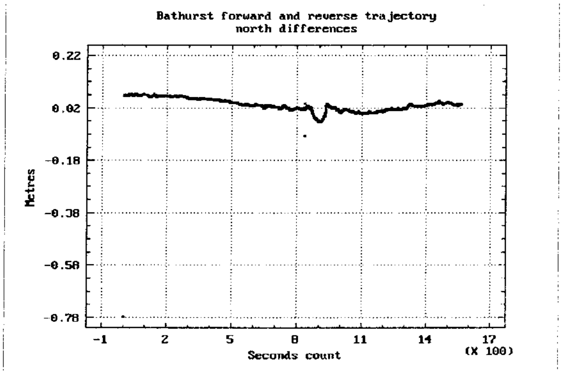


Figure 13.29 Northing difference between forward and reverse solution for Bathurst trajectory.

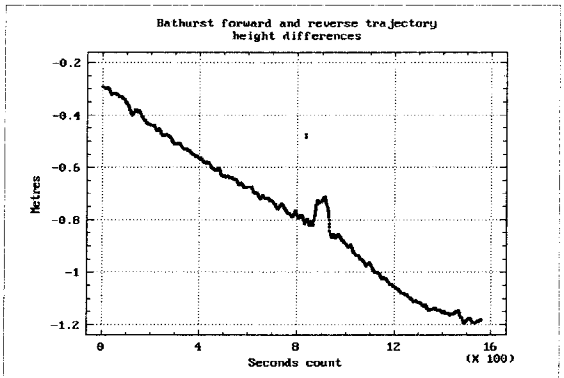


Figure 13.30 Height difference between forward and reverse solution for Bathurst trajectory

The UNSW plots, figure 13.25 to 13.27, are a cleaner data set, though the tail end of the interval deteriorates. A study of the processing output indicates that the change is attributable to the change in the satellite constellation. Seven satellites with a PDOP of 1.4 dropped to six satellites with a PDOP of 1.7. The base data at both Hobart and UNSW were free of data "drop outs", so these sets were not subject to the same phenomenon that the Bathurst data displays.

Linear modelling has been applied to these data sets following the same principles that were used in the Bathurst test, and table 13.6 indicates the results. The difference here is that the data set is representative of a typical 1:50000 photographic run.

Table 13.6 Analysis of residuals after linear modelling the differences between the three trajectory solutions and the benchmark solution.

		East(m)	North(m)	Up(m)
Bathurst - Lightning Ridge 1561 epochs	Std Dev	**0.028**	**0.048**	**0.107**
	Max Err	0.261[1]	0.106	0.420[1]
UNSW - Lightning Ridge 1561 epochs	Std Dev	**0.037**	**0.044**	**0.081**
	Max Err	0.121	0.145	0.275
Hobart - Lightning Ridge 1561 epochs	Std Dev	**0.021**	**0.023**	**0.074**
	Max Err	0.083	0.074	0.239

[1] Maximum error is an outlier due to the missing epoch in the base station

The results are similar to the Bathurst test, and given the presences of outliers, the standard deviation of the overall data set would be of the order of 0.1m. All three examples having the same overall magnitude. The important components of each of the trajectories are the interpolated camera station coordinates. These have been extracted from the four trajectory solutions. There are 21 valid camera stations in this data set. The following figures, 13.31 to 13.33, are scatter plots based on the linear regression fit of the camera station differences for each of the trajectories adopting Lightning Ridge-based camera station coordinates as the reference. They highlight the linear nature of the trajectories, compared to the Lightning Ridge benchmark, after fitting to a straight line.

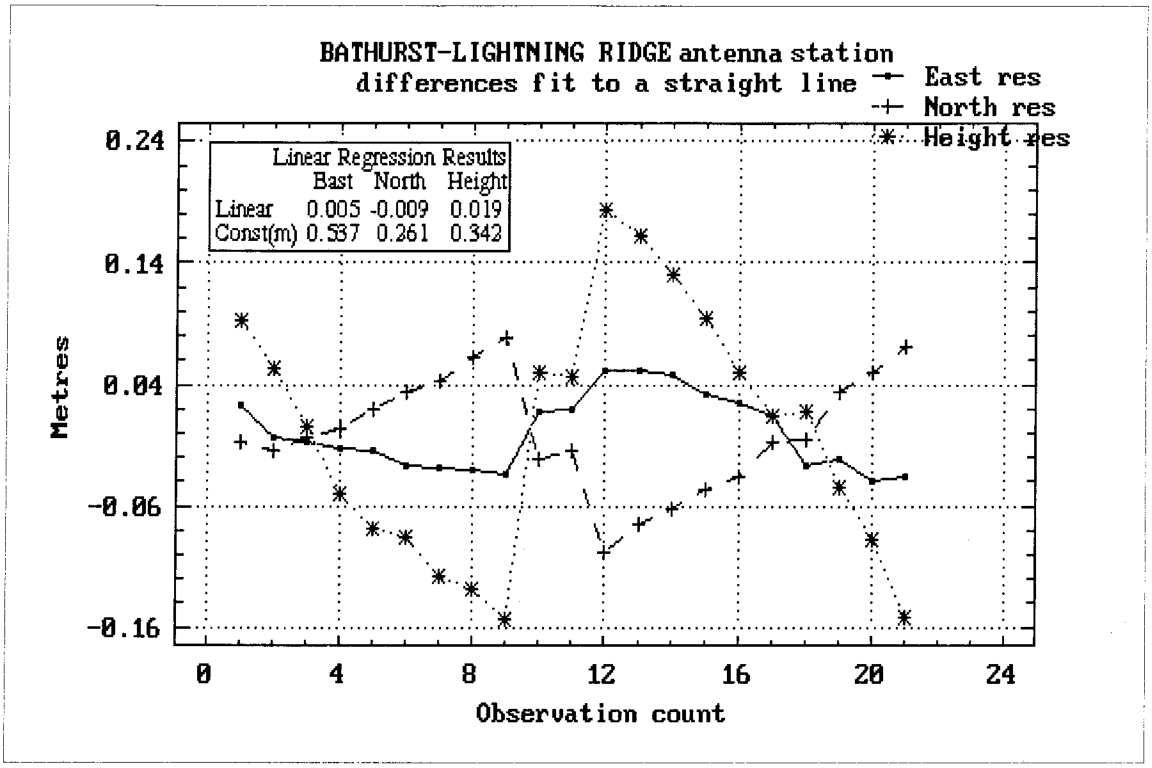


Figure 13.31 Linear regression of Bathurst trajectory against Lightning Ridge trajectory for 21 camera exposure stations.

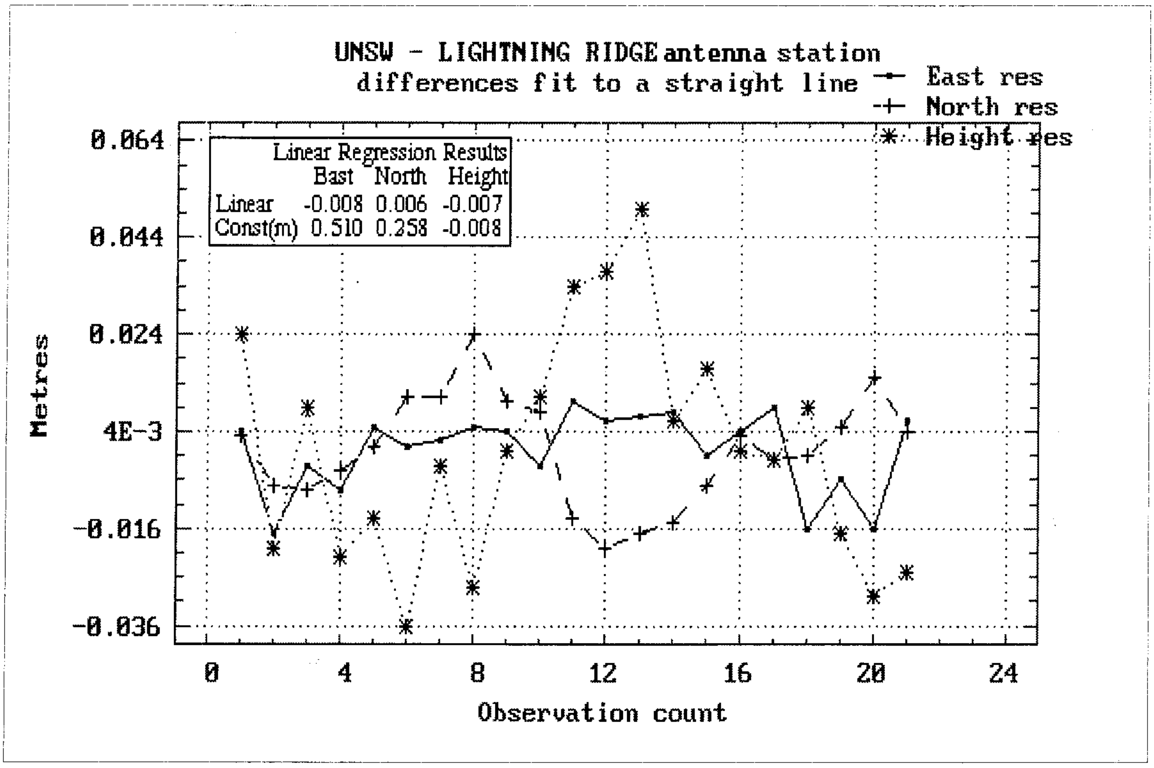


Figure 13.32 Linear regression of UNSW trajectory against Lightning Ridge trajectory for 21 camera exposure stations.

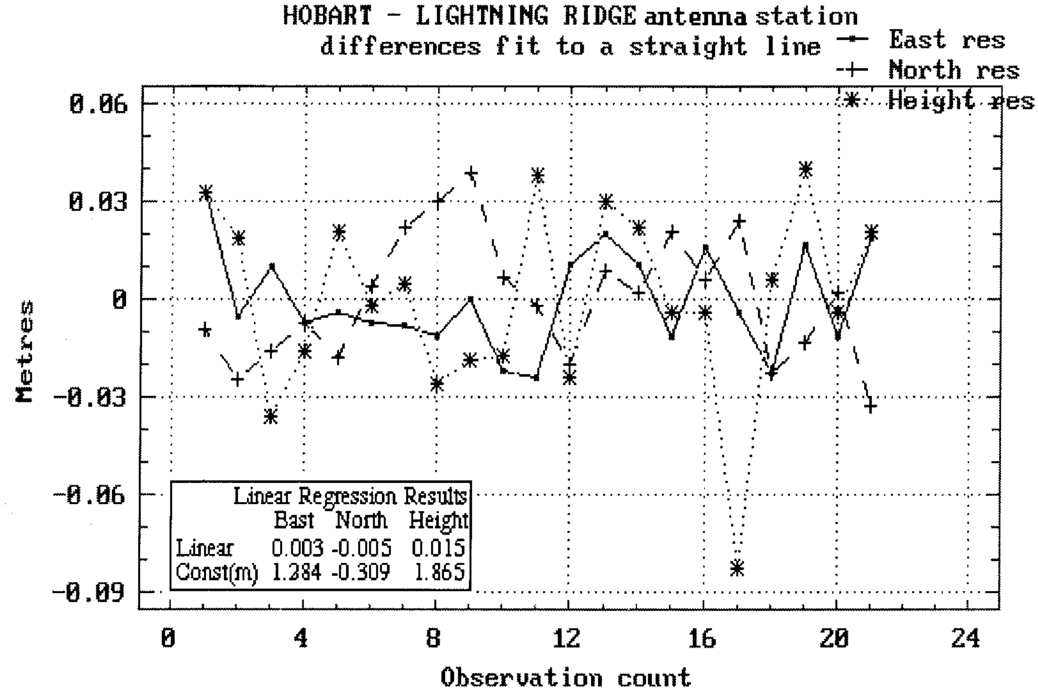


Figure 13.33 Linear regression of Hobart trajectory against Lightning Ridge trajectory for 21 camera exposure stations.

This random behaviour should be supported by the results of the adjusted camera station coordinates after aerial triangulation. As expected the height component is the poorest determined.

13.3.2 Linear behaviour of differential data

There has been reference earlier to the availability of redundant data. One type of redundant data is the position data recorded by the NAVPRO software. The important characteristic of this data is that it exhibits some linear behaviour after the application of drift corrections. The exposure positions for run 6 Lightning Ridge have been extracted from the aircraft's mission result file and differenced against the PNAV post-processed solutions for the Lightning Ridge trajectory. The differences have been modelled by a straight line. The residuals for easting, northing and up are plotted in figure 13.34.

The results of this linear regression are quite surprising. If this quality, ±1 m in horizontal and ±3 m in vertical, would be typical then it is difficult to justify post-processing to support small scale mapping applications. The height component again is the poorest performer. One aspect of these results is that they are based on an internal time interpolated solution within NAVPRO. The author has not investigated how this was achieved. It could be:

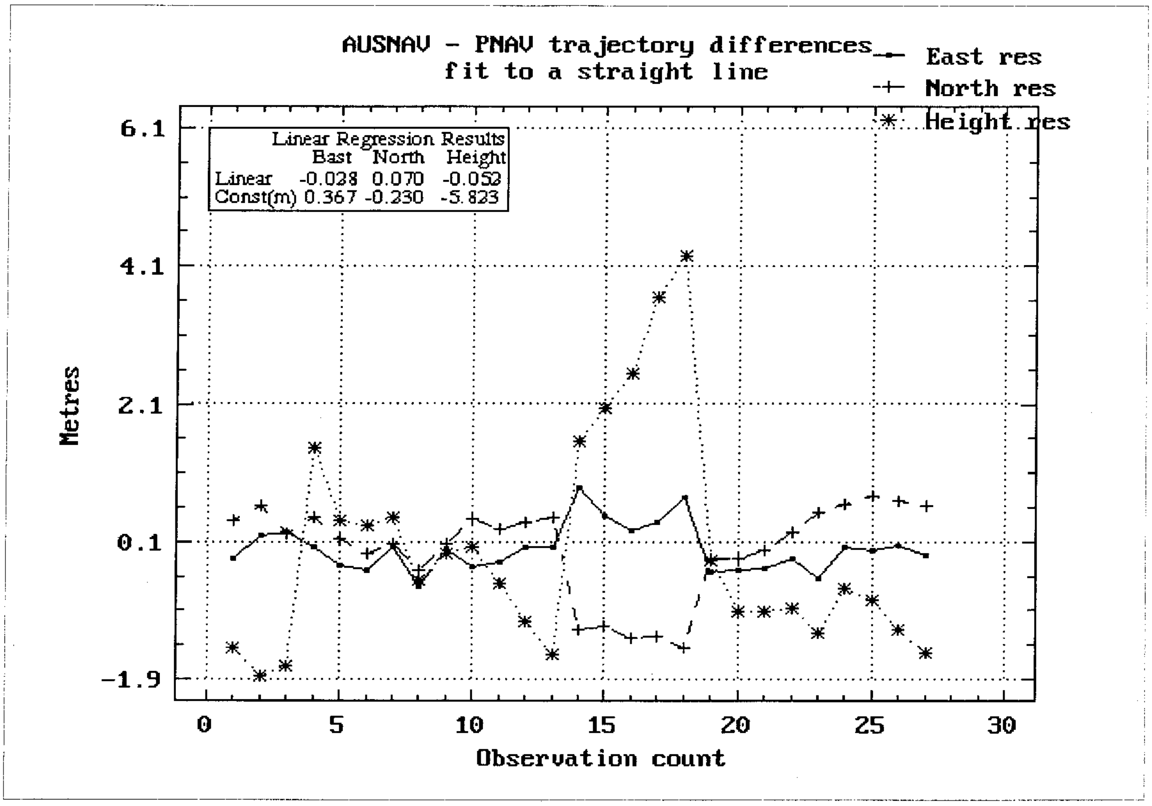


Figure 13.34 Fit of real time differentially corrected positions for run 6 after linear regression application for 21 camera exposure stations.

- based on the forward time projected position of the last known GPS location, based on the current trajectory calculated by NAVPRO, or
- based on the forward time projected position of the last known GPS location based on the Δ velocity values from the GPS receiver, or
- based on the time interpolated position between the last known location and next location.

All these methods are sensitive to timing errors and assumptions about the GPS antenna motion. The residual patterns displayed in figure 13.34 contain errors attributable to the above but the overall behaviour is typical of differentially corrected positioning over a 16 minute time interval. The suitability of this data will be tested in the aerotriangulation adjustment phase.

13.4 Aerotriangulation test

The second part of the Lightning Ridge test was to incorporate long-range kinematic data into the aerotriangulation process. The cost of establishing an aerotriangulation test range is high, especially one for 1:50000 photography. In 1993 the SGD established such a test range in northern NSW over the 1:250000 map tile, ANGLEDOOL SH/55-7. The test range was established to evaluate the capability of airborne GPS to support 1:50000 photography for the purposes of capturing digital mapping data at an accuracy better than 5m in planimetry (Fraser, 1994; Mitchell & Dickson, 1996).

This test range was originally photographed by 13 east-west runs and 5 north-south tie runs made up of 626 photographs. Extensive ground control was established so that a thorough evaluation could be made of the new methodology. Single frequency GPS was used to establish the kinematic antenna trajectory. Two trajectories were produced based on two ground stations located within the project block. This configuration did not investigate long-range applications, nor did it utilise dual frequency data.

The project was a combined public-private sector exercise. The private sector provided the GPS-supported photography and the ground control identification and survey. The SGD managed the project, conducted the photogrammetric observations and evaluated the results.

This existing test range data provided the opportunity for the SGD to evaluate the performance of long-range kinematic data and its impact on the results of aerotriangulation. The proposed test procedure was to re-fly three runs of the original Angledool aerotriangulation adjustment block using the SGD's own photogrammetric system. This new photography would be incorporated into the original Angledool aerotriangulation adjustment block and the various trajectory solutions from the kinematic test data would be evaluated as to their effect on the aerotriangulation adjustment and the derived image point coordinates. To do this the new photography had to be pugged and photogrammetrically observed. This task was completed by staff of the Aerial Triangulation Branch at the SGD using a WILD PUG4 for point marking (pugging) and a WILD BC3 for image observations.

Unfortunately the proposed test flight did not proceed as planned. Due to a number of unforeseen problems only one photographic strip, run 6, was successfully captured. Nevertheless, enough GPS-controlled photography was captured to perform an evaluation.

13.4.1 Validation of aerotriangulation adjustment configuration using original data

The planned aerotriangulation testing of the run 6 photography did not require the complete Angledool aerotriangulation data set. Hence the Angledool aerotriangulation data set was reduced from its original coverage area to a workable subset that was centred around run 6, see figure 13.14. The new aerotriangulation block consisted of east-west runs 4, 5, 6, 7 and 8 and north-south tie runs T1, T2 and T3. The configuration of this aerotriangulation block is:

- 1723 image points
- 134 photographs
- 13 horizontal control points
- 13 vertical control points
- 134 GPS points
- 8 profiles or runs

This aerotriangulation adjustment configuration, based on original data only, is validated in Appendix B. This validation was necessary for two reasons:

1. to demonstrate that the smaller aerotriangulation block did not suffer from control and integrity weaknesses, and

2. to provide an initial benchmark result that could be used to compare the quality of the new pugging and plate observations when they were incorporated into later aerotriangulation adjustments.

The results listed in Appendix B are based on standard deviations adopted for normal SGD 1:50000 aerotriangulation. The image point observations are entered with a standard deviation of 8μm (0.4m in terrain units), the ground control has a standard deviation of 0.5m and the standard deviation of the GPS observations is 0.25m. The adjustment result of 7.03 for sigma naught is similar to a variance factor of approximately 0.9 (7.03/8μm), which is satisfactory. This conclusion is supported by the residuals of all observation types falling within an acceptable statistical range.

The format of the results presented in Appendix B is as follows:

- Default values for the operation of the PATB-GPS adjustment software.
- Statistical results - residuals are displayed in either image system (μm) or terrain system (m). Orientation is defined by the photogrammetric system x, y and z.
- Control point residuals - divided into planimetry and height. Coordinates are defined by a local secant plane system.
- GPS observations and residuals - these are displayed as profiles and correspond to each photographic run. A linear and constant term is associated with each axis component, x, y and z, for each profile. The constant term is in metres.
- Coordinates and residuals of critical image observation points. Critical points are those that exceed three times the adjustment standard deviation of the image point observations.

The interesting part of the adjustment result is the GPS observation section. Table 13.7 is an extract of the constant and linear terms for each GPS profile in Appendix B. Note the magnitudes of the constant terms associated with each profile. Combining the linear and constant term in the equation of a straight line, $y = mx + b$, generates the drift correction at any station in the adjustment block. The largest drift correction is 3.96m for the x component of observation 601, profile 8. Profile 8 in this adjustment is a north-south tie run. Note also that no GPS residuals exceed the adjustment standard deviation of 0.25m.

Table 13.7 GPS drift results for original Angledool subset adjustment (see Appendix B).

	x (East)		y (North)		z (Up)	
	Linear	Constant (m)	Linear	Constant (m)	Linear	Constant (m)
Profile 1	-0.1606	-1.822	0.0162	-1.398	-0.1042	-3.302
Profile 2	0.1497	-1.518	-0.0496	-0.694	0.0640	-2.017
Profile 3	-0.1575	-1.378	0.0674	-0.224	0.0191	-3.319
Profile 4	0.1014	-1.078	-0.0828	-0.047	-0.0411	-1.657
Profile 5	-0.1122	-0.568	0.1100	-0.605	0.1414	-1.638
Profile 6	0.2278	-0.038	0.0530	-0.876	-0.0343	-1.112
Profile 7	-0.1521	-1.082	-0.0630	-0.479	-0.1708	-1.928
Profile 8	**0.3359**	**-2.280**	0.1376	0.051	0.3545	-1.755

The magnitude of the drift corrections is greater than expected given that the length of the kinematic baselines would not have exceeded 100km, but this may point out the limitations of using single frequency, non P-code receivers and the influence of inner camera orientation errors. Any error in camera calibration elements, such as the focal length of the lens, can be accommodated in the corrections to the camera station coordinates in the aerotriangulation adjustment process.

From these results it was concluded that the configuration of the aerotriangulation adjustment, and the quality of the observations were sound.

13.4.2 Aerotriangulation results using new trajectories

The hypothesis for this test is that the aerotriangulation statistical results and the derived image point coordinates should be essentially the same regardless of the baseline lengths used to derive the camera's kinematic GPS trajectory solutions. The difference in trajectory solutions should be evident in the offset (constant) and drift (linear) components, but as these are absorbed as nuisance parameters in the aerotriangulation adjustment the derived image point coordinates and σ_0 should be similar. This test is not concerned with the outcome of an aerotriangulation adjustment and its accuracy, but rather it is to evaluate the impact of different trajectory solutions on derived image point coordinates, and to investigate whether or not accommodating GPS "drift" will make long-range kinematic GPS positioning feasible.

Once the new run 6 photography had been pugged and observed a methodology for adjustment and testing was needed. Two options were available:

1. Retain the original run 6 observations and GPS data in the adjustment and overlay the new run 6 data, effectively increasing the number of profiles from 8 to 9, or,

2. Remove the original run 6 observations and GPS data and replace them with the new run 6 data, so that the number of profiles remains at 8.

Both options will have differing impact on the adjustment results.

Option one increases the amount of observations relative to image points. This has the effect of distorting the adjustment of the runs adjacent to the duplicated photography and will be sensitive to pugging errors of duplicated points. Adjusting an aerial triangulation block is a delicate process as the number of observations and the different types can significantly impact on one another in the adjustment process, particularly if the variances are not estimated correctly. This option requires significant "trial and error" to determine the correct variances. Yet this configuration of an aerotriangulation adjustment may not be suitable as a test because the adjustment configuration is no longer representative of a typical production photogrammetric adjustment.

Option two is the easiest to implement as it simply requires the removal of the original image point observations and GPS control for that run, and replacing them with the new ones. It must be noted that this procedure will result in different coordinates for the adjusted image points. The different dates of photography, film quality, and time of day also has a significant impact on the point transfer process (the pugging). A secondary factor is the different camera characteristics and antenna - camera offset vectors (the original photography was flown with a contractor's aircraft and camera). These factors can lead to derived image point coordinate changes, after adjustment, of up to 2m for 1:50000 photography, disregarding the effects of new GPS camera station coordinates. In this case the difference between the antenna - camera vectors for the different aircraft, *0.11, 0.13* and *0.23m,* is accommodated in the GPS drift solution and is considered insignificant.

It is reasonable to expect that if the adjustment block was re-flown and re-triangulated on the original image points, given that all components are kept as close as possible to the original with similar quality GPS, then the differences between the original adjustment image point coordinates and the new adjustment coordinates should be, on average, less than 2m in X, Y and Z for 1:50000 photography.

The results presented in Appendix C are generated from the new run 6 photography observations and the associated GPS trajectory which uses the Lightning Ridge base station data. This trajectory is a fixed-ambiguity solution so it is presumed to be the most accurate of the four trajectories. The format of the results presented in Appendix C is the same as that for Appendix B. Profile 8 contains the GPS results associated with the new run 6 photography.

Given that this is a fixed-ambiguity solution, note the large residuals for observation 9040 of profile 8, x (0.303m), y (-0.034m) and y (-0.299m). This is the only observation in the

GPS observation data set to exceed the adjustment standard deviation of 0.25m. The explanation for this could be some poor photogrammetry that has created a localised distortion in the adjustment. The original data set does not display similar residuals so the source must be the new observations. This observation is tied to the exposure occurring at UT1:05:02.419745. An extract of the trajectory data either side of this event is listed in table 13.8. There appears to be no indication of a bad position solution. The interpolation should also be good because the velocities in east, north and up (last three columns, in m/sec) are stable around this epoch.

Table 13.8 Extract of Lightning Ridge to Aircraft trajectory data.

1127	11/28/95	01:04:53.000000	6	2.2	S 29.42776112	E 147.75092646	7808.7034	0.055	0	-90.068	-1.849	0.102
1127	11/28/95	01:04:54.000000	6	2.2	S 29.42777667	E 147.74999970	7809.0691	0.055	0	-90.013	-1.598	0.435
1127	11/28/95	01:04:55.000000	5	1.8	S 29.42778997	E 147.74907345	7809.5582	0.059	0	-89.966	-1.354	0.504
1127	11/28/95	01:04:56.000000	6	1.7	S 29.42780183	E 147.74814751	7809.7663	0.055	0	-89.950	-1.257	0.128
1127	11/28/95	01:04:57.000000	6	2.2	S 29.42781294	E 147.74722160	7809 7915	0.054	0	-89.958	-1.203	-0.003
1127	11/28/95	01:04:58.000000	6	2.2	S 29.42782368	E 147.74629587	7809.9417	0.054	0	-89.926	-1.177	0.190
1127	11/28/95	01:04:59.000000	6	2.2	S 29.42783462	E 147.74537049	7810.2821	0.055	0	-89.886	-1.238	0.379
1127	11/28/95	01:05:00.000000	6	2.2	S 29.42784605	E 147.74444528	7810.4547	0.055	0	-89.885	-1.300	0.116
1127	11/28/95	01:05:01.000000	6	2.2	S 29.42785802	E 147.74352006	7810.5495	0.055	0	-89.892	-1.358	0.088
1127	**11/28/95**	**01:05:02.000000**	**6**	**2.2**	**S 29.42787053**	**E 147.74259475**	**7810.5813**	**0.056**	**0**	**-89.902**	**-1.420**	**0.015**
1127	11/28/95	01:05:03.000000	6	2.2	S 29.42788339	E 147.74166937	7810.5985	0.056	0	-89.909	-1.443	0.016
1127	11/28/95	01:05:04.000000	6	2.2	S 29.42789653	E 147.74074388	7810.5933	0.056	0	-89.920	-1.476	-0.013
1127	11/28/95	01:05:05.000000	6	2.2	S 29.42790992	E 147.73981834	7810.5418	0.056	0	-89.923	-1.500	-0.064
1127	11/28/95	01:05:06.000000	6	2.2	S 29.42792343	E 147.73889273	7810.5073	0.056	0	-89.930	-1.504	-0.029
1127	11/28/95	01:05:07.000000	6	2.2	S 29.42793690	E 147.73796713	7810.5251	0.056	0	-89.925	-1.491	0.028
1127	11/28/95	01:05:08.000000	6	2.2	S 29.42794949	E 147.73704152	7810.5028	0.056	0	-89.927	-1.328	-0.037
1127	11/28/95	01:05:09.000000	6	2.2	S 29.42796013	E 147.73611593	7810.4927	0.056	0	-89.924	-1.056	-0.004
1127	11/28/95	01:05:10.000000	6	2.2	S 29.42796810	E 147.73519036	7810.4862	0.056	0	-89.922	-0.728	-0.009
1127	11/28/95	01:05:11.000000	6	2.2	S 29.42797301	E 147.73426489	7810.5270	0.056	0	-89.906	-0.369	0.053

Table 13.9 lists the interpolated coordinates and an estimate of the combined east, north, up position RMS of each exposure station. This epoch is of similar quality to others in this data set, apart from the observation at 1:03:26.8. This observation falls outside of the aerotriangulation block and cannot be evaluated except to say that based on its RMS (0.114) it does not fit the quality trend. Note that as the distance from the base station increases and the PDOP decreases the combined RMS increases. This suggests that the RMS solution quality indicator is directly related to baseline length.

Although not conclusive this small investigation demonstrates that it may be possible to trace sources of aerotriangulation adjustment errors to aspects of the kinematic solution. It is suspected that the source of the larger residuals are poor image point observations.

Table 13.9 Extract of interpolation data.

```
Ashtech, Inc. GPPS-2      Program:  PPDIFF-PNAV    Version: 2.2.00P
          Tue Feb 02 15:46:05 1999   Differentially Corrected: Y
BASE: LTR1 29 27 07.45851 S  147 59 36.44557 E   173.096  0.000 0.000  0.000
ROVR:                                   0.000 0.000  0.000
SITE MM/DD/YY HH:MM:SS SVs PDOP LATITUDE     LONGITUDE     HI         RMS  FLAG V_EAST V_NORTH  V_UP
1127 11/28/95 00:58:34.470574  6  2.5  S 29.42362612 E 148.10469797 7811.5190  0.092  0  -87.657  -3.821   0.295
1127 11/28/95 00:59:24.877796  5  2.2  S 29.42490920 E 148.05888378 7808.8479  0.079  0  -89.304  -1.162  -0.542
1127 11/28/95 01:00:14.325022  6  2.4  S 29.42646759 E 148.01325625 7811.6427  0.065  0  -89.589  -1.688   0.196
1127 11/28/95 01:01:03.980942  6  2.4  S 29.42553187 E 147.96721318 7809.4048  0.064  0  -91.052   3.502   0.057
1127 11/28/95 01:01:51.720927  6  2.3  S 29.42512066 E 147.92200248 7807.3891  0.073  0  -92.645  -0.726   0.042
1127 11/28/95 01:02:39.575020  6  2.0  S 29.42584984 E 147.87657522 7807.3798  0.084  0  -91.824  -2.772   0.084
1127 11/28/95 01:03:26.829136  6  2.3  S 29.42689884 E 147.83205168 7810.2095  0.114  0  -91.387  -0.284   0.415
1127 11/28/95 01:04:14.608202  6  2.3  S 29.42710293 E 147.78683167 7805.0377  0.051  0  -91.803  -0.886  -0.287
1127 11/28/95 01:05:02.419745  6  2.2  S 29.42787593 E 147.74220633 7810.5885  0.056  0  -89.905  -1.430   0.015
1127 11/28/95 01:05:50.148191  6  2.2  S 29.42764585 E 147.69785549 7808.4039  0.059  0  -90.640   3.352  -0.249
1127 11/28/95 01:06:38.179367  6  2.2  S 29.42727952 E 147.65304116 7805.8779  0.063  0  -90.173  -0.542   0.223
1127 11/28/95 01:07:26.558703  6  2.2  S 29.42619011 E 147.60834125 7810.3591  0.067  0  -89.997   1.524  -0.106
1127 11/28/95 01:08:12.899833  6  2.1  S 29.42592285 E 147.56524587 7806.7721  0.070  0  -90.120   3.919   0.463
1127 11/28/95 01:08:58.955677  6  2.1  S 29.42502065 E 147.52235566 7808.5914  0.073  0  -90.827   1.799   0.022
1127 11/28/95 01:09:48.123214  6  2.1  S 29.42428726 E 147.47671899 7806.0616  0.077  0  -89.574  -1.332  -0.206
1127 11/28/95 01:10:37.755453  6  2.1  S 29.42352212 E 147.43091740 7808.4781  0.080  0  -90.126   4.190   0.252
1127 11/28/95 01:11:24.599545  6  2.0  S 29.42267684 E 147.38726145 7804.3221  0.083  0  -90.571   0.711   0.172
1127 11/28/95 01:12:09.186475  6  2.0  S 29.42221163 E 147.34584566 7807.6484  0.086  0  -90.147   0.986  -0.068
1127 11/28/95 01:12:54.351763  6  2.0  S 29.42159180 E 147.30426252 7805.0002  0.089  0  -88.821  -1.200  -0.289
1127 11/28/95 01:13:40.722325  6  2.0  S 29.42230217 E 147.26222377 7809.6867  0.091  0  -87.962  -1.860  -0.308
1127 11/28/95 01:14:29.451078  6  2.0  S 29.42347121 E 147.21761336 7803.6003  0.094  0  -89.202  -5.741  -0.196
1127 11/28/95 01:15:19.158002  6  1.9  S 29.42576928 E 147.17203426 7807.4813  0.097  0  -89.036  -4.233   0.573
1127 11/28/95 01:16:09.060568  6  1.9  S 29.42710521 E 147.12620237 7802.7539  0.100  0  -88.360  -3.049   0.030
1127 11/28/95 01:16:59.489113  6  1.9  S 29.42675775 E 147.08075292 7804.0372  0.103  0  -87.745   2.199  -0.137
1127 11/28/95 01:17:49.762804  6  1.9  S 29.42724602 E 147.03534803 7801.1289  0.105  0  -87.254  -3.589   0.282
1127 11/28/95 01:18:40.512095  6  1.9  S 29.42635468 E 146.99004774 7801.4904  0.108  0  -86.049   4.275  -0.111
1127 11/28/95 01:19:33.352194  6  1.9  S 29.42450073 E 146.94371422 7805.7657  0.111  0  -85.034   3.419   0.190
```

Critical image points are listed in the adjustment results but no attempt has been made to "clean" image point observations with high residuals because these observations will be common to all adjustment configurations. In this case the size of the aerotriangulation adjustment residuals are not statistically large enough to be flagged as outliers and the observation was retained.

The GPS trajectory for the new photography is a fixed-ambiguity solution. It was expected that the linear and constant terms associated with this fixed-ambiguity trajectory would approach zero. The linear and constant terms for profile 8 have been extracted from Appendix C and are listed in table 13.10, along with the maximum and minimum values of these terms.

Table 13.10 GPS drift components for the Lightning Ridge fixed-ambiguity trajectory - Profile 8.

	x	y	z
Linear	0.0955	0.0103	-0.0082
Constant (m)	-1.983	-1.330	-0.790
Maximum (m)	-2.842	-1.422	-0.872
Minimum (m)	-1.028	-1.227	-0.716

The drift results, particularly for the *x* component, are not zero. The *y* (range 0.2m) and *z* (range 0.16m) components are consistent, but the *x* component changed by 1.8m. The *x* component may be subject to an along-track cumulative scale influence due to the different lenses used for the photography in this test. Errors in image point observation, control identification, geoid modelling, camera - antenna vector and camera inner orientation (lens calibration, film distortion, etc) combine to relocate the best known fixed-ambiguity kinematic GPS coordinates to a best fit solution. In the light of the results in table 13.10 it may be unreasonable to expect GPS drift values of zero, but rather drift values of almost constant offset, implying very small linear terms for fixed-ambiguity solutions.

Further analysis of the fixed-ambiguity trajectories would require a different test environment than that used here.

13.4.3 Comparison of original Angledool aerotriangulation results (Appendix B) and aerotriangulation using new run 6 photography (Appendix C)

How do the results of the two adjustments compare? Appendix D is a comparison of the derived image point coordinates for the original Angledool aerotriangulation adjustment (Appendix B) and the aerotriangulation adjustment using the new run 6 data (Appendix C). The comparisons are excellent, bearing in mind that outlier image point observations have been removed from the Appendix B adjustment, whereas all image point observations for the new run 6 photography (Appendix C) have been retained without outlier filtering. Image point outlier detection was not considered necessary for the purposes of GPS trajectory comparisons. Table 13.11 is a summary of critical difference values and their occurrence. There are a number of image observations in the new photography that are flagged as critical points, which probably contribute to the larger errors in the comparison.

Table 13.11 Table of component differences from Appendix D (Appendix B - Appendix C).

Difference	Number of X	Number of Y	Number of Z
> 2.0m	1	0	0
1.5m - 2.0m	1	0	1
1.0m - 1.5m	5	4	7

The contention that the image points should be repeatable to better than 2.0m is supported by the results of this comparison test. For the purposes of further trajectory testing the aerotriangulation adjustment (Appendix C) using the Lightning Ridge fixed-ambiguity solution will be referred to as the benchmark solution.

13.4.4 Results for long-range kinematic GPS trajectories

Adjusted image point coordinates derived from other aerotriangulation adjustments using different trajectories could now be compared to a benchmark solution. For these tests the run 6 GPS trajectory solutions based on Bathurst, UNSW and Hobart base station data were each adjusted in PATB-GPS. Appendix E lists the results using Bathurst data, Appendix F lists the results using UNSW data, and Appendix G lists the results using the Hobart base station data.

Figures 13.19 to 13.27 illustrate the differences between the various long-range kinematic GPS trajectories and the Lightning Ridge benchmark trajectory. Even after the application of linear regression to these differences (figures 13.31 to 13.33) significant residuals remain, particularly in the height component (figure 13.31). The differential GPS data set (figure 13.34) is an extreme case example particularly for the height component. These same differences should be evident after the aerotriangulation adjustment in either the adjusted antenna station coordinates or their associated residuals.

For the aerotriangulation adjustment the standard deviations of the GPS antenna stations were 0.25m. The image point observations were 8μm (0.4m) and the ground control was 0.5m. The balance between the observation types will result in the GPS antenna station coordinates having a greater influence on the derived perspective centre and image point coordinates than the photogrammetric observations. Some loss of precision occurs because the geometry of the aerotriangulation adjustment is weakened when solving for the systematic GPS drift errors.

For this adjustment configuration the different antenna trajectories are reflected in the adjusted antenna station coordinates after the removal of GPS drift. If the standard deviation of the GPS had been greater than the image observation standard deviation then the different antenna trajectories would have resulted in larger antenna station residuals.

After aerotriangulation the adjusted antenna station coordinates for each of the long-range trajectories were differenced with the adjusted antenna station coordinates of the Lightning Ridge result to provide a comparison between antenna station trajectories after the removal of GPS drift. What remains is the actual noise between the trajectories because the drift components have been removed. Figures 13.35 to 13.37 are plots of these differences.

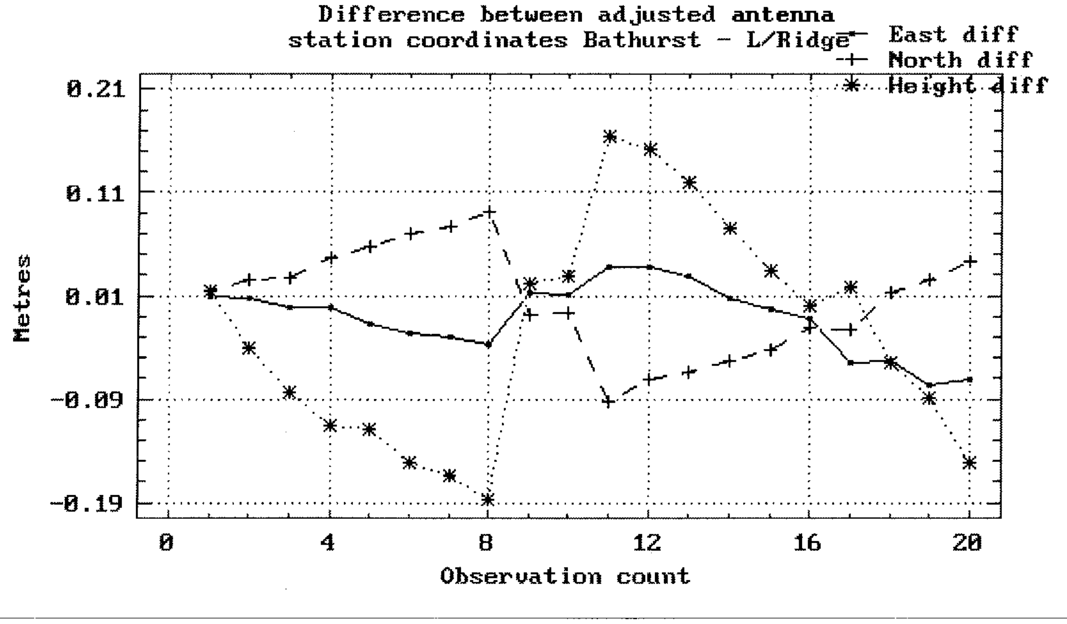


Figure 13.35 Difference between aerotriangulation adjusted antenna station coordinates for Bathurst and Lightning Ridge.

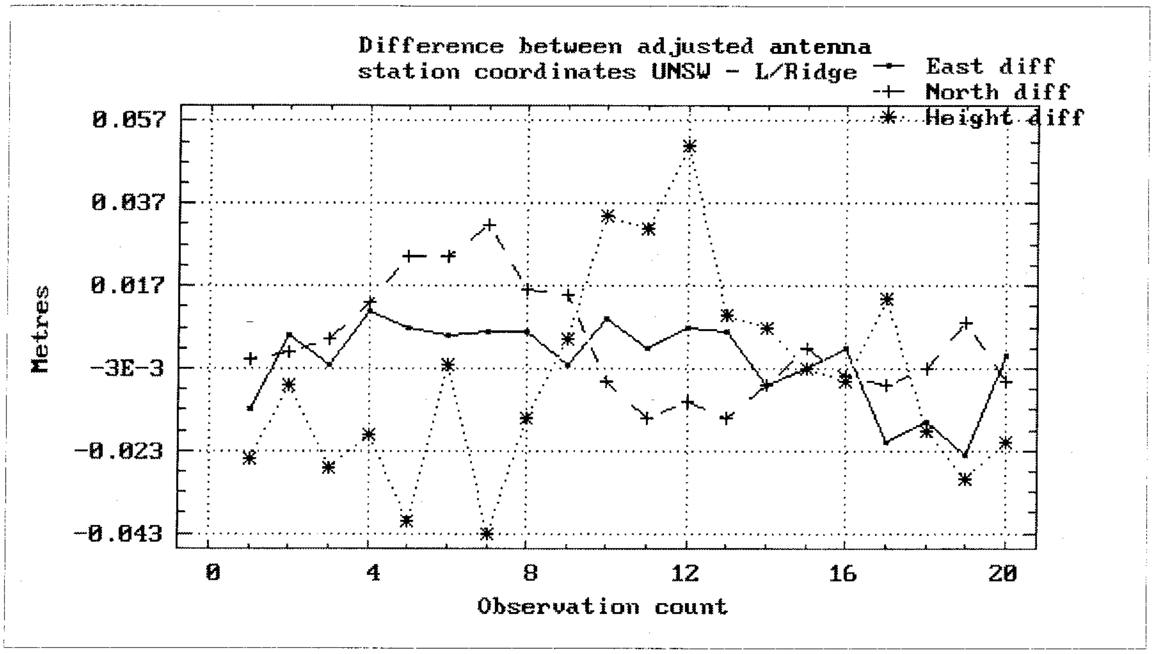


Figure 13.36 Difference between aerotriangulation adjusted antenna station coordinates for UNSW and Lightning Ridge.

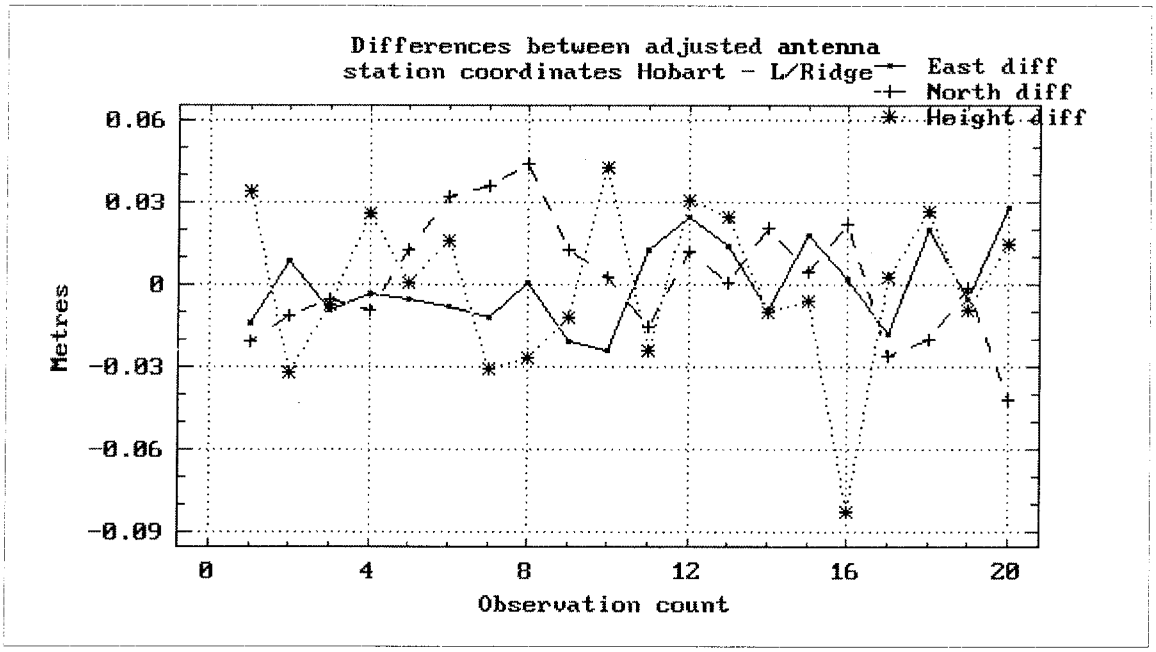


Figure 13.37 Difference between aerotriangulation adjusted antenna station coordinates for Hobart and Lightning Ridge.

These figures correlate strongly with figures 13.31 to 13.33, indicating that similar drift components are removed in the aerotriangulation process.

The linear regression components associated with figures 13.31 to 13.33 have been included in table 13.12 (column A Linear...). For comparison the derived aerotriangulation drift parameters have also been differenced using the Lightning Ridge drift components as reference values. These values are listed in column B. Table 13.12 summaries these results.

Table 13.12 Comparison between estimated linearised parameters from trajectory differences and differenced drift parameters derived from aerotriangulation.

		A - Linear regression of trajectory differences			B - Differences of PATB drift parameters			A - B		
		x	y	z	x	y	z	x	y	z
Bathurst - Lightning Ridge	Linear	0.005	-0.009	0.019	0.006	-0.004	0.013	0.001	0.005	-0.006
	Const(m)	0.537	0.261	0.342	0.542	0.262	0.365	0.005	0.001	0.023
UNSW - Lightning Ridge	Linear	-0.008	0.006	-0.007	-0.007	0.007	-0.008	0.001	0.001	-0.001
	Const(m)	0.510	0.258	-0.008	0.511	0.258	-0.001	0.001	0.000	0.007
Hobart - Lightning Ridge	Linear	0.003	-0.005	0.015	0.001	-0.004	0.017	-0.002	0.001	0.002
	Const(m)	1.284	-0.309	1.865	1.278	-0.304	1.875	-0.006	0.005	0.010
DGPS - Lightning Ridge	Linear	-0.028	0.070	-0.052	0.012	0.078	-0.058	0.040	0.008	-0.006
	Const(m)	0.367	-0.230	-5.823	0.463	-0.199	-5.857	0.096	0.031	-0.034

In each case, except for the DGPS data, the linear and constant terms compare very favourably. The estimated linear differences in the various trajectories are removed from the aerotriangulation adjustment leaving only those variations displayed in figures 13.31 to 13.37.

Upon examining the adjusted image point coordinates it is evident that the aerotriangulation adjustment is sensitive to these variations because of the adopted observational weighting. This sensitivity was evaluated by comparing the adjusted image point coordinates of the long-range trajectory solutions with the Lightning Ridge results. As suspected, the Bathurst solution (largest variation in height component) resulted in the largest differences. This comparison is given in Appendix H. Table 13.13 lists the statistics from the three comparisons.

Table 13.13 Comparison of 1718 adjusted image point coordinates for three solutions.

	Bathurst - Lightning Ridge			UNSW - Lighting Ridge			Hobart - Lightning Ridge		
	x	y	z	x	y	z	x	y	z
MIN (m)	-.04	-.04	**-.24**	-.01	-.01	-.06	-.01	-.01	-.04
MEAN (m)	.00	.00	-.01	.00	.00	.00	.00	.00	.00
MAX (m)	.04	.05	.17	.01	.02	.03	.01	.02	.01
RANGE (m)	.08	.09	.41	.01	.03	.10	.02	.03	.05

The relationship between those observations that do not fit the linear model and the resulting impact on the image point coordinate can be established by tracking those differences to the particular photograph, and hence the GPS observation. The component -0.24m in table 13.13 and the associated local distortions can be traced to the height components of observations 7045 to 7052 of the Bathurst trajectory set.

Having identified this as the largest error in the data set it is still well within the acceptable statistical range for this scale of photography. If a multitude of test points had been included in the aerotriangulation adjustment this change would be half the detectable error for this photography scale. These results demonstrate that aerotriangulation adjustments derived from 1:50000 photography, using long-range kinematic GPS drift modelling based on minimal ground control, can provide antenna station coordinates supporting image point accuracies in *x, y* and *z* better than 0.5m and possibly as low as 0.25m.

13.4.5 Aerotriangulation results using differentially corrected GPS

The differential position solutions that are stored by the NAVPRO software have been included in the aerotriangulation adjustment to evaluate the merit in using this data for aerotriangulation. The test could only be carried out for one run and it is difficult to extrapolate conclusions from this data set owing to the mixed quality of the GPS observations, i.e. one run of DGPS results combined with 7 runs of carrier phase results.

The test is worth doing as the situation may arise where only differentially corrected GPS data is available for one or two runs in a project area.

Based on the results of the linear regression in figure 13.34 (section 13.3.2) a suitable variance for these observations would appear to be 1.2m. A reasonable estimate given the variability of the height component. The results of this aerotriangulation adjustment are given in Appendix I. The residual results for profile 8 do correlate to a degree with the regression pattern in figure 13.34.

A comparison of adjusted antenna station positions, as in figures 13.35 to 13.37, is not warranted in this case as the differing standard deviations used for the antenna station observations creates a large ripple effect through all adjusted antenna stations. Increasing the standard deviation of these observations lowers the constraint of the overall adjustment, hence redistributing other errors. The overall effect can be examined by evaluating the adjusted image point coordinates.

Appendix J gives a comparison between the adjusted image point coordinates derived using the DGPS antenna stations and the image point coordinates derived from the Lightning Ridge benchmark solution. The results would suggest that DGPS determined camera stations can be used as "emergency" data without being detrimental to the overall adjustment result in cases where 1 to 2m image point accuracy is required. Table 13.14 lists the comparison statistics

.

Table 13.14 Comparison of 1718 adjusted image point coordinates.

	DGPS - Lightning Ridge		
	x	y	z
MIN	-.25	-.30	-.61
MEAN	-.02	.03	-.05
MAX	.39	.31	**.80**
RANGE	.63	.61	1.41

These comments can only be made for this type of configuration. One would expect that an adjustment block based on DGPS positions only would produce a totally different result. The author did not have the data to test this scenario.

Phase-smoothed single point positions similar to those used in the Bathurst tests have not been investigated further, and are considered unsuitable for this application in the light of the Bathurst results.

13.4.6 GPS-controlled photogrammetry without ground control

What are the results of an aerial triangulation adjustment without ground control? Even though this is not part of the objective of the project it is worthwhile evaluating. For this test the small data set was modified by removing the cross strips from the observation set. The GPS antenna observation standard deviations were set to 0.1m. This is significantly better than what the test results indicate. The previous aerotriangulation adjustments detected GPS drift constant terms in the trajectories, for various profiles, of the order of metres in magnitude. Ground control points were left within the block, but given a variance of 1000m. (PATB-GPS needs at least two ground coordinates to establish initial approximate coordinates for the image points). The data set used for run 6/profile 8 was the Hobart trajectory as it was most likely to show the greatest error, if in fact large propagation errors did exist. Up to this stage there was no evidence for this.

The results of this adjustment are presented in Appendix K. The results appear reasonable, σ_0 is 7.92, but the residuals on the control points have risen by a factor of three and the residuals on the GPS observations have dropped, as would be expected with the standard deviations as defined. The result would appear to be acceptable, but in this case if the ground control values were not in the adjustment there would be no indicators at all regarding the quality of the image points coordinates.

The adjusted image point coordinates from this adjustment are compared to the adjusted image point coordinates resulting from the fixed-ambiguity trajectory solution for the

Lightning Ridge reference station. This comparison is presented in Appendix L.

Taking into account that there may be some erroneous image point observations in the substitute data set, the impact should be the same for both adjustments. It is suspected that a strong influence on the solution may be the removal of the cross strips (in this case cross strips introduce redundant data). It is difficult to say whether their inclusion without ground control would help to identify erroneous GPS observations or not. The results indicate that the block is being distorted, in this case, by the non-homogeneity of the GPS observations and other influences. It is evident in this case, without ground control, that errors in the antenna station coordinates are projected directly into the adjusted image points. Any unmodelled errors in the inner camera orientation system (lens calibration errors, platen unflatness, film distortion, refraction, etc) will remain undetected, their effects compounding errors already existing in the antenna station coordinates, which are then propagated directly into the adjusted image point coordinates. It would appear that in this case the situation without ground control would quickly deteriorate as photo scales and image point specifications increase.

13.4.7 Comments

Studying the GPS residuals of Appendix G and Appendix K, which both use the Hobart trajectory data, there are marked differences between them. Appendix G's residuals are variable and some results can be traced to GPS processing events, whereas the absolute position approach of Appendix K shows none of these characteristics at all.

The derivation of image point coordinates using the GPS drift approach has been demonstrated many times within the SGD. Although technically not required, test points are still placed and identified as quality control measures for the aerial triangulation - GPS process. In every case the GPS drift methodology has proven to meet the specifications that are required for the digital image capture programs.

The results also support the proposal that operating a photographic aircraft up to 1500km from a ground GPS base station can deliver relative accuracies (of the order of 0.05m) to support 1:4000 mapping projects (see Table 1.2 for 1:5000 mapping height requirement for configuration 4). Special procedures would be required to ensure that data collected is of sufficient quality to meet these specifications.

The demonstrated fit of double-differenced kinematic solutions, using unfixed biases, to linear behaviour over long to very long baselines, encourages the use of this methodology for all but the largest of photogrammetric mapping scales. For the largest photogrammetric scales different data collection techniques would be required to maintain a rigorous solution to the exterior orientation problem.

14. Photography Management

Aspects of the problems associated with management of aerial photography were mentioned in chapter sections 8.2.3 and 12.3.4. Even though digital technology had been introduced for the capture of aerial photography it still did not address all the needs of an image management system.

The primary purpose of aerial photography is to capture images of the earth's surface. Introducing a metric (calibrated) camera to image capture provides a means to link images together and forms the basis of aerial triangulation. The process moves on to the stage where coordinated image points and stereo images provide means to make spatially referenced products. New technology and processes such as forward motion compensation, airborne GPS, digital workstations, image correlation, etc, continue to be introduced.

The basic product of all this is the photographic image. The aerial photograph contains so much data, it is a time slice of history and it is expensive to capture. It is therefore a value commodity. The management of such a valuable resource should ensure that it is retrievable, accessible and properly handled.

The SGD's management of aerial photography has always been a manual process with resources provided by the Aerial Survey Branch. A roll of film can contain up to 250 photographs. If a number of different jobs are on that roll then it may be cut up and spliced with other rolls so that one job will be on one roll of film. The roll number of a film is an attribute that is therefore sometimes changed after the photographic event. This is one example of the manual film management process that highlights how untidy the situation can become with regards to film tracking and handling

14.1 Indexing

How are these films managed? The manual processes associated with film management are complex, slow and labour intensive. All standard coverage, mapping and some project photography is identified by "run tag" information exposed on the margin of any print. A sample of a run tag is given in figure 14.1.

CANBERRA ENVIRONS
"NORTHBOURNE AVENUE"
NSW4428 (M2110)

RUN 8
25-02-98
214-240

1:5000 Approx. Scale
152.76 mm

© LAND INFORMATION
Panorama Avenue. B

Figure 14.1 Typical run tag on the margin of a photograph.

"Run tags" are the result of the following process:

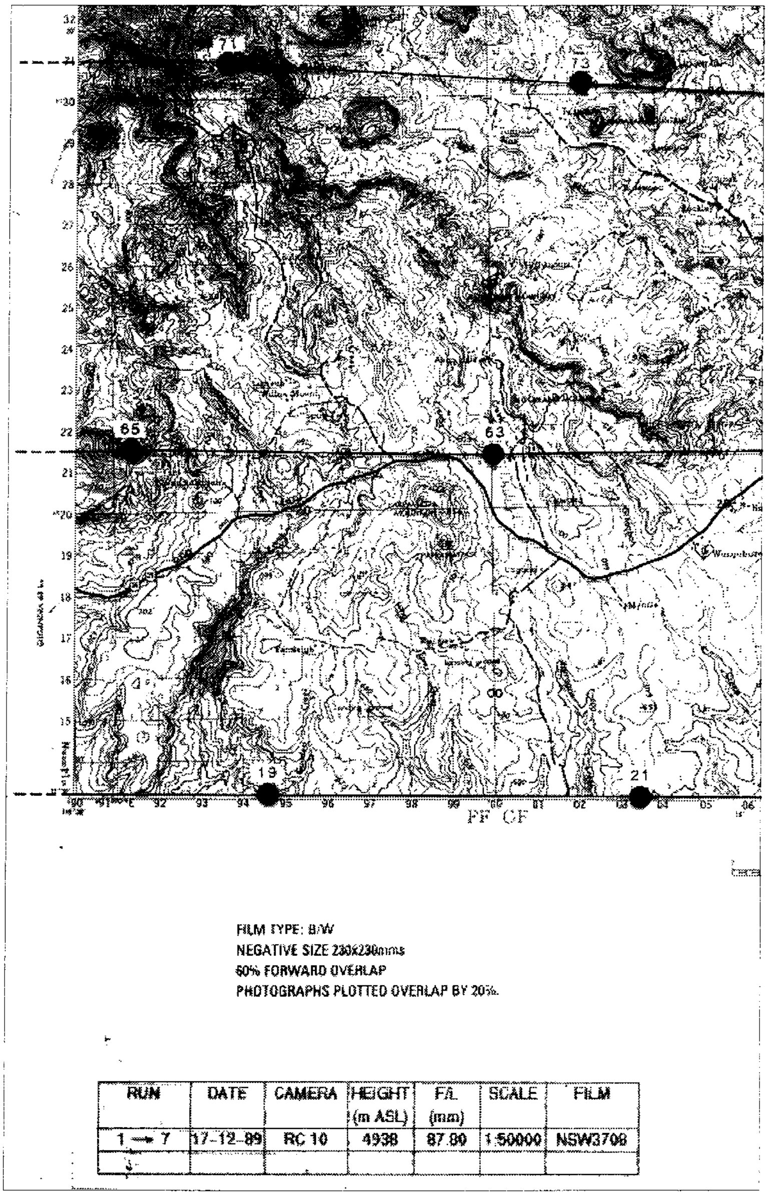
1. Photography on a negative roll is divided into runs. Runs begin with an exposure number and end with an exposure number. Each run is identified as part of a 1:100000 map tile, and each run is numbered according to a particular convention. A run is flown on a particular date, for a particular job number, at a particular scale, at a height above mean sea level. For any negative, north is somewhere on the photograph, indicated by an arrow on the print.

2. This data is collated and entered into a spreadsheet pro-forma for the purposes of creating a "run tag" on clear film. A laser jet printer is used to produce the tags on clear film.

3. The "run tag" is sent to the film lab where it is overlaid on the margin of each relevant negative and exposed as a print. A new "run tag" is used for the next group of relevant negatives making up a run. The "run tag" is not exposed on the negative.

4. The prints or negatives are studied to determine the approximate location of each photograph. The location of every second photograph is plotted onto a 1:100000 map, an index of photography is attached. This map is photographed onto clear film as a black and white image. This image becomes the record of photography and is stored in an appropriate location. This image, referred to as a "key diagram", can be used at any time to create a dye-line copy. A portion of such a diagram is shown in figure 14.2.

This process is resource intensive but is probably the most effective non-computer based system. It is a process that is not based on the uniqueness of the photograph, but is a retrieval methodology. It cannot account for photography that doesn't fit the particular storage model. Some data is recorded elsewhere but for photography that is outside of the system, only experience and the memory of Aerial Survey Unit staff can provide guidance.



FILM TYPE: B/W
NEGATIVE SIZE 230x230mms
60% FORWARD OVERLAP
PHOTOGRAPHS PLOTTED OVERLAP BY 20%.

RUN	DATE	CAMERA	HEIGHT (m ASL)	F/L (mm)	SCALE	FILM
1 → 7	17-12-89	RC 10	4938	87.80	1:50000	NSW3708

Figure 14.2 Portion of manually produced key diagram.

The introduction of a navigation control system to the photographic process appeared to promise a better retrieval system and management process to the handling of aerial photography. Where the production of a key diagram relied on plotting the position of photographs onto a map and so on, now the position of the photograph was known and could possibly be plotted electronically.

The processes used to produce the flight planning diagrams and satellite overlays could be expanded to produce digital key diagrams. This process begins with editing of the information contained in the result files that are transferred from the aircraft. The editing is mainly to do with corrections to exposure numbers. The Aerial Survey Unit has particular policies that do tend to complicate the numbering of exposures and films, and many errors occur as a result of this policy. When the files are considered correct the digital position data is imported into a GIS where a number of scripts are executed to produce a key diagram based on a standard output format. The only improvement over the original key diagram production system is using a GIS to produce a digital product. A process only made possible by the GPS spatial data component.

Even though a computer process was now used to create a key diagram, attribute data is still collated manually and entered into the diagram. This still produces errors that are difficult to track. A sample of a digital key diagram is given in figure 14.3.

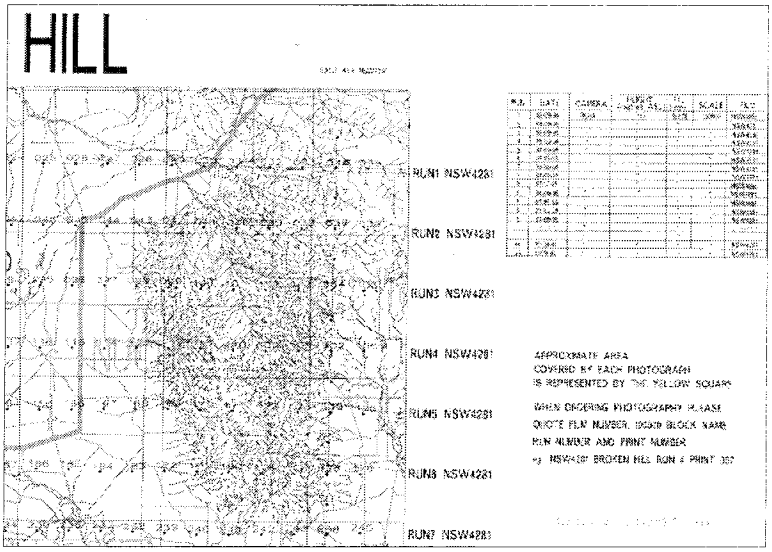


Figure 14.3 Portion of key diagram produced digitally. This image reproduction is poor but these diagrams are generally in full colour and the definition is excellent.

These manual processes, the amount of paperwork and the diverse locations of relevant data was a source of continual frustration to the author. The aircraft system had been developed to a stage where its reliability was proven, the operation of the system had been simplified to a stage that its day to day performance was taken for granted, problems or failures were identifiable and inconsequential.

There existed the opportunity to address the problem of photographic management and at the same time provide further information to the aircrew about their performance and current mission status.

14.2 Electronic runtags

The RC30 is a new generation aerial camera built to incorporate features such as forward motion compensation (FMC) and an electronic digital interface (EDI) (Leica, 1992). The EDI provides the means by which the NAVPRO software can control the exposure event of the camera. The camera also incorporates two text buffers which are located in opposite margins of the camera plane. The camera plane still retains the clock face, a static utility window and the exposure counter which is a LED display - unlike the old analog system in the former RC10 camera.

The two text buffers, referred to as left and right buffers, contain data which is exposed onto the negative at every exposure. Both these buffers accommodate up to 100 alphanumeric characters. The left buffer is not user definable, it continually updates and displays the current system status of the camera. The right buffer is user definable and it this feature which can be utilised to enhance the management of photographic images.

The SGD was using a rudimentary piece of software which did utilise this text buffer. A proficient operator could transfer a predetermined text string to the camera buffer before the beginning of a run. The problem with this system was that it was not real-time interactive nor did it provide any benefits apart from demonstrating that the electronic buffer did work. The author believed that the run tag data which was manually exposed onto the prints could actually be embedded on the negative at the time of exposure. The camera EDI uses standard RS232 communication protocols not only receiving data but capable of transmitting it. The opportunity was there if it could be utilised.

14.3 Software development

If data could be written to the text buffer in real-time the latest GPS position could be transmitted to the camera along with other information such as time, date, track and other attribute data. This would ensure that the very latest information would be in the text buffer before every exposure. When an exposure occurs the camera transmits the exposure number and the contents of both buffers to the EDI RS-232 port. This then makes it possible to record a multitude of attributes about that exposure in digital form. This data can form the basis of a photographic data base, not only for standard coverage photography but for all photography taken by the camera.

A number of problems existed in being able to do this, mainly the author's limited programming experience, particularly in C, and even less knowledge of RS232 communications. To begin the project two other problems had to be addressed, development would require real-time GPS data and an interactive RC30 camera. Neither of these were readily available, there was no spare capacity in the base station receiver and the option of developing software by travelling back and forth between the office and the aircraft's hangar was out of the question. Further to this, the Ashtech Z12 receiver on the aircraft was already operating using three I/O ports. The previous problems with firmware had created some cautiousness about updating the current version to enable all four of the Z12's I/O ports. One way to overcome this situation was to split the communication cable that was servicing the NAVPRO software so that the data stream could be read elsewhere. This option required that any software designed for this purpose would be locked into the same data string that NAVPRO was using.

The author elected to take up this challenge after investigating a number of options. The proposed software would be a DOS based application. Its basic operation being to read in user input, read in GPS position data, every second create a unique string made up of the user input and real-time data, and transmit this data to the camera. This would ensure that the camera's exposed position data would not be older than 1 second. The software would read all messages transmitted by the camera and record it to a file on a dedicated computer.

This was the basic proposal. The solution to the real-time data supply lay in a utility provided with the NAVPRO software. An option with the NAVPRO software is to capture all the incoming data strings and keyboard sequences to a debug file so that after the mission the whole scenario can be replayed in the office environment. This feature was designed as a de-bugging tool for NAVPRO and to determine where things went wrong on a mission. A mission could be replayed using the software SIMGPS.

SIMGPS simulates the behaviour of the GPS receiver. It actually plays back the Ashtech format PBEN data that has been recorded in the .DBG (**D**e**B**u**G**) file. The structure of the PBEN data is given in table 7.1, section 7.2.2. A mission can be played back for demonstration, training or analysis purposes. SIMGPS provided a means by which the real-time position data generated by the Ashtech Z12 receiver could be played back as if a Z12 receiver was actually being used. This provided the solution to one of the first of the software development problems.

The camera behaviour was another problem. But before this could even be addressed the actual programming issues had to be resolved. The C compiler in use is POWERC by MIX software. This is a low cost compiler purchased out of the shareware market, but it is a full featured compiler that is fully supported. Like most common C compilers the communication libraries are very limited and not really suited to this type of application. The author evaluated a C communication library from MarshallSoft Computing which was located on the Internet. It was cheap and it was available with POWERC library compatibility.

The author now had command over the communication ports of the PC. The initial programming was to read intelligent data from the PBEN data stream. It took some time to decipher what was actually going on as even though the binary string lengths were correct the data was unintelligible. By chance, during communications with SAGEM the author learned that the binary data strings of the Z12 are actually reversed. This obstacle was overcome by using a function out of the DATALOGR source code that the author had acquired from Ashtech. Having solved the incoming data problem the software was quickly assembled including data integrity checks and communication checking, until the incoming communications had reached a stable state.

The program was developed to a stage where incoming data on one RS232 computer port could be reformatted into ASCII text and transmitted out another RS232 port. The user input side of the program was developed around some screen utility source code written by James L. Pinson that was found on a shareware C/C++ CD-ROM. With this code the author was able to create an interactive data input screen and mission status screen. The input screens are pull down menu driven and data input is subject to validation checks. The development of this module required extensive modifications of the shareware source code.

Having solved the communication programming problems the author was able to write software that simulated the behaviour of the RC30 camera. This simulation exercise required a third computer to act as the camera. The simulator could read in the run tag information just as the camera would, it would also read in commands that would interrogate the camera. A number of camera dependent strings, typical of the contents of the left text buffer, are available in a rotating array. Basically any command that would be used on the aircraft related to the camera performance and status was built into the simulator.

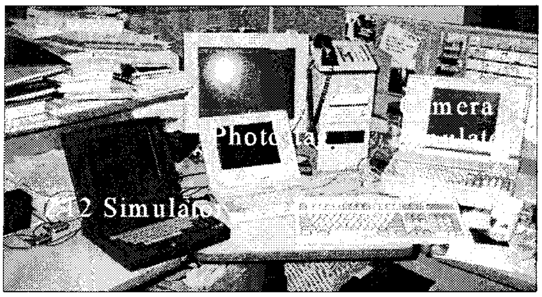


Figure 14.4 Photo-tag software under development using 3 PCS.

The configuration of the three computers used to develop the software and simulate the operation on the aircraft are illustrated in figure 14.4

14.4 The screens

Figure 14.5 is the initial screen where the user can either elect to nominate a job type or exit the program.

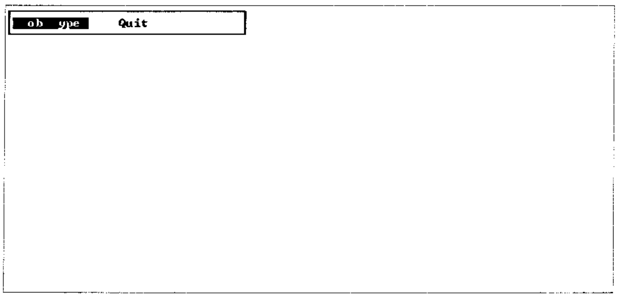


Figure 14.5 1st option input screen.

Selecting a job type provides three options displayed in figure 14.6. Photographic missions are either block photography (standard coverage), non-block (project coverage) and oblique photography. Each of these options create slightly different photo-tag information. The main difference between block and non-block tags being the text string that replaces the usual 1:100000 map name that appears on block photography.

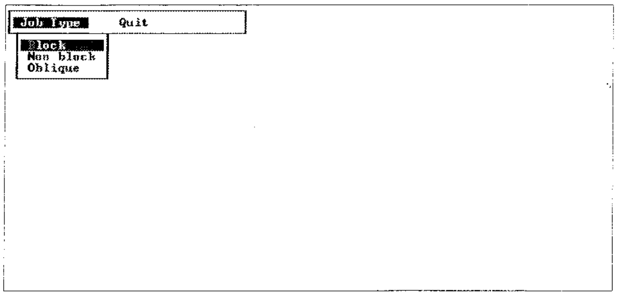
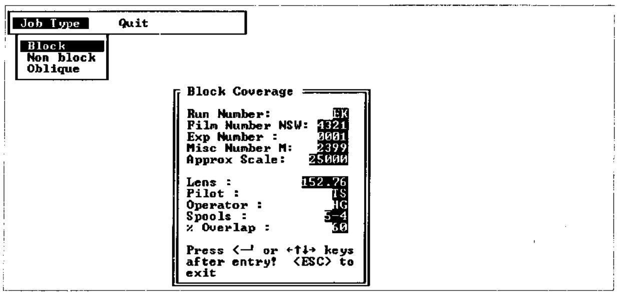


Figure 14.6 Options available under job types.

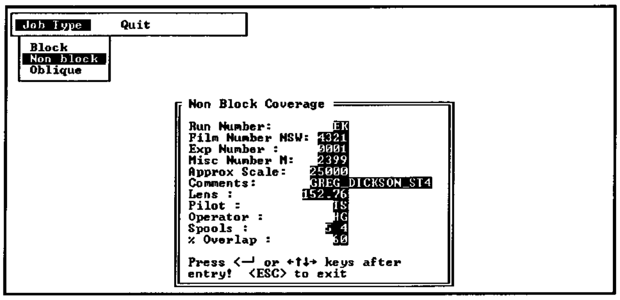
Figure 14.7 is the data input screen for the block photography menu. The data on this screen is used in different ways, the film number, exposure number, miscellaneous job number and scale are written to the photo tag string, the lens, pilot and operator initials and lens focal length are written to the .DAT file which records all camera messages. The exposure number information is transmitted to the camera as a separate string which will reset the exposure counter to the desired value corresponding to the start of the run or to any operator defined value.



```
Block Coverage

Run Number:          EK
Film Number NSW:   4321
Exp Number :       0001
Misc Number M:     2399
Approx Scale:     25000

Lens :           152.76
Pilot :              TS
Operator :           HG
Spools :            5-4
% Overlap :          60

Press <─┘ or ←↑↓→ keys
after entry!  <ESC> to
exit
```

Figure 14.7 Block photography user input screen.

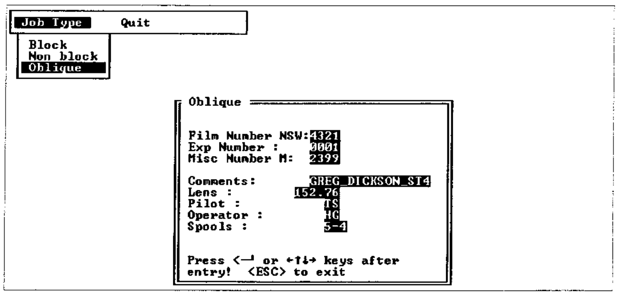
Figure 14.8 is the input screen for non-block or project photography. The only difference here is the option to enter a text string associated with the particular job. This is helpful in identifying various parts of project photography such as beach work.



```
Non Block Coverage

Run Number:          EK
Film Number NSW:   4321
Exp Number :       0001
Misc Number M:     2399
Approx Scale:     25000
Comments:         GREG_DICKSON_ST4
Lens :           152.76
Pilot :              TS
Operator :           HG
Spools :            5 4
% Overlap :          60

Press <─┘ or ←↑↓→ keys after
entry!  <ESC> to exit
```

Figure 14.8 Non-Block photography user input screen.

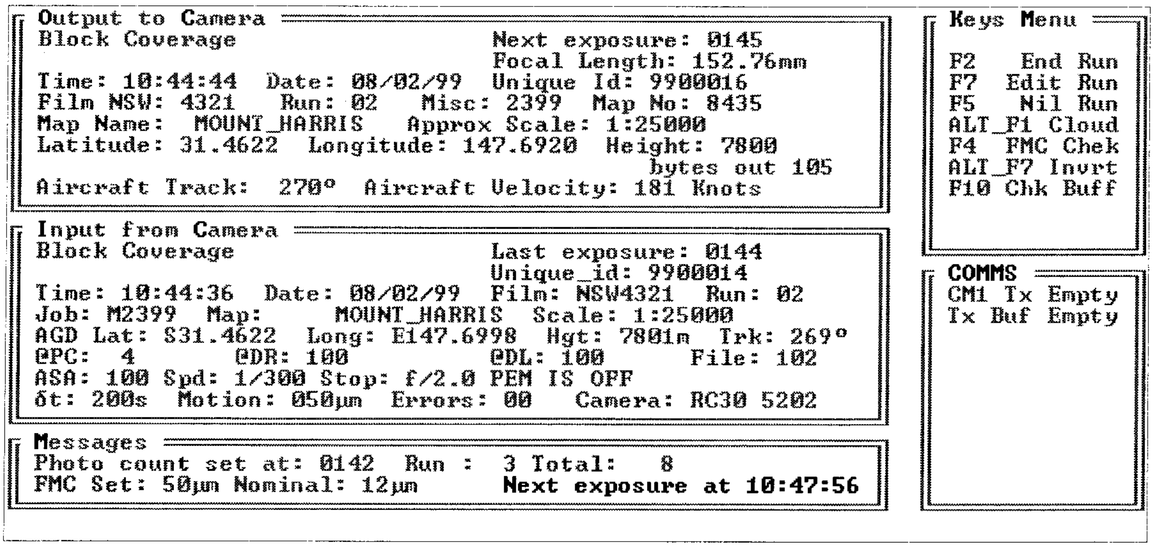
For the first time the SGD had a methodology for the collection of data related to oblique photography. Figure 14.9 is the input screen related to oblique photography. The user input for this type of photography is the same as non-block photography except for the exclusion of scale and run number, which are not valid details for this type of photography. The text string transmitted to the camera is the same as the non-block string apart from the exclusion of run number and scale.



```
Oblique

Film Number NSW:4321
Exp Number :    0001
Misc Number M:  2399

Comments:       GREG_DICKSON_ST4
Lens :        152.76
Pilot :           TS
Operator :        HG
Spools :          5-4

Press <—┘ or ←↑↓→ keys after
entry!  <ESC> to exit
```

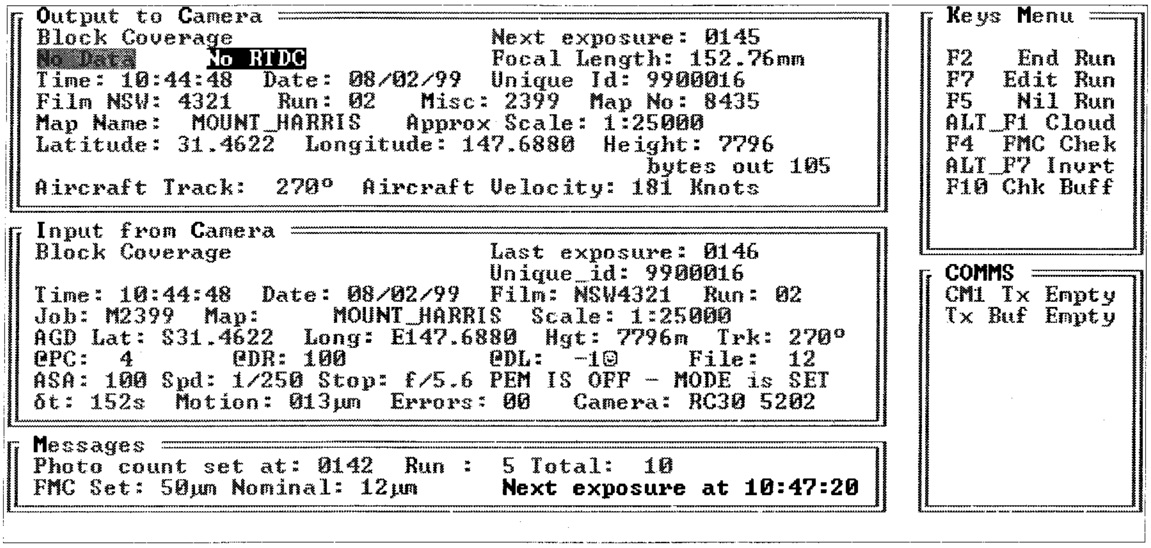
Figure 14.9 Oblique photography user input screen.

Escaping from these screens will put the user at the monitoring screen. This screen, shown in figures 14.10 through 14.13, is divided into 5 windows - Output to Camera, Input from Camera, Messages, Keys Menu and COMMS.



```
Output to Camera
Block Coverage                          Next exposure: 0145
                                        Focal Length: 152.76mm
Time: 10:44:44  Date: 08/02/99  Unique Id: 9900016
Film NSW: 4321    Run: 02   Misc: 2399  Map No: 8435
Map Name:  MOUNT_HARRIS   Approx Scale: 1:25000
Latitude: 31.4622  Longitude: 147.6920  Height: 7800
                                                bytes out 105
Aircraft Track:  270°  Aircraft Velocity: 181 Knots

Input from Camera
Block Coverage                          Last exposure: 0144
                                        Unique_id: 9900014
Time: 10:44:36  Date: 08/02/99  Film: NSW4321   Run: 02
Job: M2399  Map:       MOUNT_HARRIS  Scale: 1:25000
AGD Lat: S31.4622  Long: E147.6998  Hgt: 7801m  Trk: 269°
@PC:  4         @DR: 100          @DL: 100        File: 102
ASA: 100 Spd: 1/300 Stop: f/2.0 PEM IS OFF
δt: 200s  Motion: 050µm  Errors: 00   Camera: RC30 5202

Messages
Photo count set at: 0142  Run :  3 Total:   8
FMC Set: 50µm Nominal: 12µm     Next exposure at 10:47:56

Keys Menu
F2     End Run
F7    Edit Run
F5     Nil Run
ALT_F1 Cloud
F4   FMC Chek
ALT_F7 Invrt
F10 Chk Buff

COMMS
CM1 Tx Empty
Tx Buf Empty
```

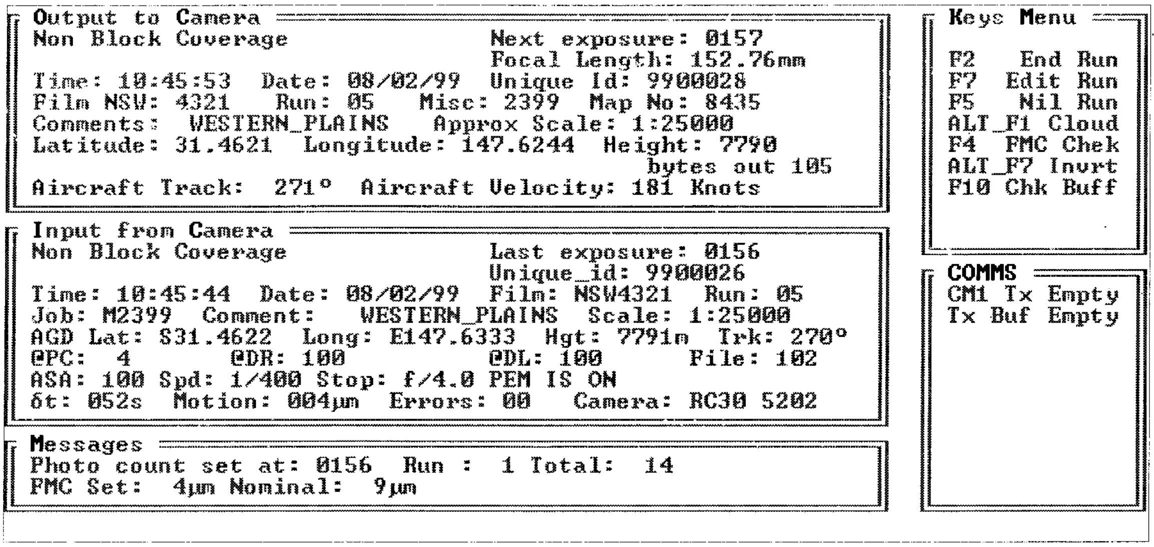
Figure 14.10 Mission screen for block photography. Note the information sent to the camera and the information received.



```
Output to Camera
Block Coverage                         Next exposure: 0145
No Data      No RTDC                   Focal Length: 152.76mm
Time: 10:44:48  Date: 08/02/99  Unique Id: 9900016
Film NSW: 4321   Run: 02   Misc: 2399  Map No: 8435
Map Name:  MOUNT_HARRIS   Approx Scale: 1:25000
Latitude: 31.4622  Longitude: 147.6880  Height: 7796
                                               bytes out 105
Aircraft Track:  270°  Aircraft Velocity: 181 Knots

Input from Camera
Block Coverage                         Last exposure: 0146
                                       Unique_id: 9900016
Time: 10:44:48  Date: 08/02/99  Film: NSW4321   Run: 02
Job: M2399  Map:      MOUNT_HARRIS  Scale: 1:25000
AGD Lat: S31.4622  Long: E147.6880  Hgt: 7796m  Trk: 270°
@PC:  4        @DR: 100              @DL:  -1☺      File:  12
ASA: 100 Spd: 1/250 Stop: f/5.6 PEM IS OFF - MODE is SET
δt: 152s  Motion: 013µm  Errors: 00   Camera: RC30 5202

Messages
Photo count set at: 0142  Run :  5 Total:  10
FMC Set: 50µm Nominal: 12µm      Next exposure at 10:47:20
```

```
Keys Menu

F2    End Run
F7   Edit Run
F5    Nil Run
ALT_F1 Cloud
F4   FMC Chek
ALT_F7 Inurt
F10 Chk Buff

COMMS
CM1 Tx Empty
Tx Buf Empty
```

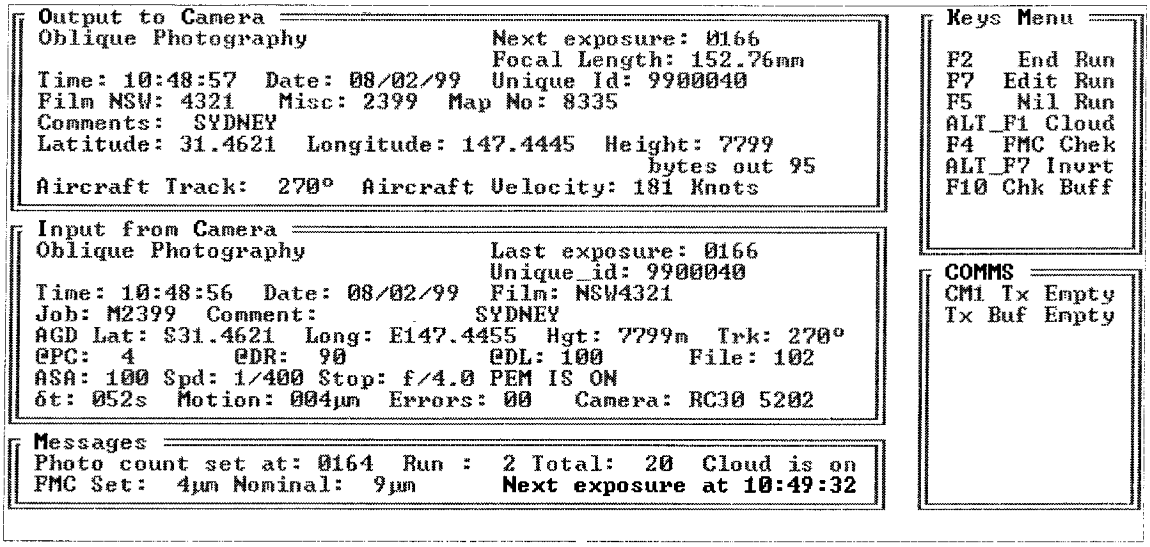
Figure 14.11 Mission screen for block photography showing flashing alarms for **No Data** and **No RTDC**. Note predicted time of next exposure in bottom message window.



```
Output to Camera
Non Block Coverage                     Next exposure: 0157
                                       Focal Length: 152.76mm
Time: 10:45:53  Date: 08/02/99  Unique Id: 9900028
Film NSW: 4321   Run: 05   Misc: 2399  Map No: 8435
Comments:  WESTERN_PLAINS   Approx Scale: 1:25000
Latitude: 31.4621  Longitude: 147.6244  Height: 7790
                                               bytes out 105
Aircraft Track:  271°  Aircraft Velocity: 181 Knots

Input from Camera
Non Block Coverage                     Last exposure: 0156
                                       Unique_id: 9900026
Time: 10:45:44  Date: 08/02/99  Film: NSW4321   Run: 05
Job: M2399  Comment:   WESTERN_PLAINS  Scale: 1:25000
AGD Lat: S31.4622  Long: E147.6333  Hgt: 7791m  Trk: 270°
@PC:  4        @DR: 100              @DL: 100        File: 102
ASA: 100 Spd: 1/400 Stop: f/4.0 PEM IS ON
δt: 052s  Motion: 004µm  Errors: 00   Camera: RC30 5202

Messages
Photo count set at: 0156  Run :  1 Total:  14
FMC Set:  4µm Nominal:  9µm
```

```
Keys Menu

F2    End Run
F7   Edit Run
F5    Nil Run
ALT_F1 Cloud
F4   FMC Chek
ALT_F7 Inurt
F10 Chk Buff

COMMS
CM1 Tx Empty
Tx Buf Empty
```

Figure 14.12 Mission screen for non-block photography. Map name is replaced by a text string.



```
Output to Camera
Oblique Photography                     Next exposure: 0166
                                        Focal Length: 152.76mm
Time: 10:48:57  Date: 08/02/99  Unique Id: 9900040
Film NSW: 4321   Misc: 2399  Map No: 8335
Comments:  SYDNEY
Latitude: 31.4621  Longitude: 147.4445  Height: 7799
                                                   bytes out 95
Aircraft Track:  270°  Aircraft Velocity: 181 Knots

Input from Camera
Oblique Photography                     Last exposure: 0166
                                        Unique_id: 9900040
Time: 10:48:56  Date: 08/02/99  Film: NSW4321
Job: M2399  Comment:                   SYDNEY
AGD Lat: S31.4621  Long: E147.4455  Hgt: 7799m  Trk: 270°
@PC:  4        @DR:  90            @DL: 100       File: 102
ASA: 100 Spd: 1/400 Stop: f/4.0 PEM IS ON
δt: 052s  Motion: 004µm  Errors: 00   Camera: RC30 5202

Messages
Photo count set at: 0164  Run :  2 Total:  20  Cloud is on
PMC Set:  4µm Nominal:  9µm       Next exposure at 10:49:32
```

```
Keys Menu

F2    End Run
F7   Edit Run
F5    Nil Run
ALT_F1 Cloud
F4  FMC Chek
ALT_F7 Invrt
F10 Chk Buff

COMMS
CM1 Tx Empty
Tx Buf Empty
```

Figure 14.13 Mission screen for oblique photography.

14.5 Features of mission screen

Each photograph that is taken has a wealth of information attached to it, the input screens summarise some of this information. Other information that is indirectly related to the photograph is also available, but from different sources. There is also information that is valuable to the operator and pilot which is related to the mission. Capturing this information at every camera event can lead to efficiencies later in the production or storage cycle.

The Output to Camera window contains some information that is not available on the photograph but is significant to the operator in real-time, or later in the image management process. There has been no way of knowing after a mission whether or not the GPS position data was differentially corrected or not. To verify the differential status required monitoring the LEDs of the RDS receiver or checking screen 5 of the Ashtech Z12 receiver for differential data. The operator could log the status of differential data in his camera report for the mission but this a very inefficient process.

There is one NMEA message that the Z12 can transmit that contains a flag which indicates the status of the real-time position data, whether it is currently differentially corrected or not. This would be of little value for the camera exposure data because of the delays already spoken of, but it could be used to track the quality of the real-time positions capture by NAVPRO in the mission result files. As previously stated, there was really no way of knowing other than writing it down in the camera report. Some tests were carried out with this NMEA message activated. The tests were to ensure that the new string that was being transmitted along with the PBEN data and the TTT string would not interfere with the operation of NAVPRO. This was necessary because the NAVPRO and PHOTOTAG software share the same data port from the Z12 receiver.

These tests were successful, hence the PHOTOTAG software was designed to read this string. The NMEA string containing the status flag is set to transmit every 5 seconds. Depending on the status of the flag, either the highlighted message "No RTDC" will flash or be blank. This provides an eye catching display for the operator. Each exposure has this status data stored as an attribute of the position data. This can be of value if for some reason raw GPS data is unavailable, hence in such circumstances differentially corrected data may have to suffice.

A similar flashing message is provided for the status of the PBEN data string. If the PBEN data should time out at the communication port for more than 1 sec then a message will flash "No Data". This provides an eye catching alarm for the operator. If this flashes then there may be a problem with the Z12 receiver, this can be immediately confirmed by checking the status of the NAVPRO and the DATALOGR software. There may be other problems but these can be traced by a process of elimination.

Each photograph has a heading associated with it, and this is recorded within the run tag data file. This information is also displayed on the monitor screen, and if consecutive photographs have headings that differ by more than 3 °, then a flag is shown against the heading value. The operator can then tell the pilot that he is exceeding the guideline specifications adopted for aerial photography. This information is also retained in the data file.

Problems associated with the NAVPRO software relating to UT0 are accepted as an operational occurrence, but it is difficult for the operators to be aware of this and to remember to be alert at that time. Part of the camera status information that is transmitted from the left buffer contains a value Δt. This is the time since the last exposure. This value is used by the program to calculate and predict when the next exposure will occur. If the next exposure is within seconds of 10:00AM then the operator is alerted to be prepared for a NAVPRO software lockup. This gives the operator a far better warning regarding this problem.

When camera data is transmitted, some of the contents of the left buffer are displayed. One of these is the error status message. The operator is alerted immediately to any camera errors if the status of this flag is anything but "00". At any time the operator can request a "FMC check" to confirm that the actual setting that the operator has manually dialled in for the FMC agrees with the calculated value based on scale, velocity and shutter speed. The operator can adjust the FMC setting and request another FMC check until the two values agree.

14.6 Text string design

The design of the text string that is transmitted to the camera is in one of the following formats:

```
Standard
0142  10:44:04 08/02 9900010 NSW4321 R02 M2399    MOUNT_HARRIS 1:25000 AGD S31.4617 E147.7312 7806m <-269
Project
0161  10:47:04 08/02 9900030 NSW4321 R05 M2399   WESTERN_PLAINS 1:25000 AGD S31.4617 E147.5552 7818m <-270
Oblique
0167  10:49:06 08/02 9900042 NSW4321 M2399          SYDNEY   AGD S31.4621 E147.4357 7801m <-269
```

The Standard photography string consists of:

Field 1: The exposure number, the initial number is nominated by the operator, which is transmitted to the camera, the camera automatically returns a string confirming the exposure number. After each photograph the camera will increment the exposure number, this is read back by the camera and displayed in a number of windows on the programs monitor screen. The user can always return to the user screen and change the value of the camera's exposure number.

Field 2: This is the GPS time plus 10 hours of the position data converted to hours, minutes and seconds, to express the time in terms of Eastern Standard GPS Time. EST is used as the standard of time of photography throughout the year. This standardises the time information and is easier for the general user to comprehend. This time stamp is far superior to the clock face view.

Field 3: This is a truncation of the current date. This information is extracted from the laptop's system date. The year is not included in this field as it is included in the next field.

Field 4: Field four is a unique identifying number for the exposure. This number is always unique. It is retained in binary format in a file, the retrieval of which is subject to an unlock code. This protection system is used so that the operator can not get into the file and edit the number if some photography is rejected. This number was to ensure that every exposure of the camera is recorded. This unique number is incremented by two to accommodate the situation where for some reason this system failed to operate. Incrementing by two would ensure that missing shots could be manually edited into the system.

Because the number of photographs taken per year exceed 9999, this necessitated that the width of the field had to be extended to 7 characters. This was to include the year as the prefix to the unique number and to maximise the use of the available spaces in the text buffer. Using the year as a prefix would group the photography by year and never create a duplicate number in our lifetime!

The unique number is incremented whenever an exposure occurs. The program also detects the year rollover and resets the unique number to the new year and zero.

Field 5: This field is the current film number of the exposure, this information is entered by the operator.

Field 6: This is the current run number of the exposure, entered by the operator

Field 7: This is the current miscellaneous job number, entered by the operator.

Field 8: This field contains the current 1:100000 map name that the aircraft is flying over. This is based on the current GPS position, a map look up table returns the map name and number associated with the current position. This will change in real-time as the aircraft travels along.

Field 9: This is the scale of the exposure, entered by the operator.

Field 10,11, 12 and 13: These fields are the current AGD66 position in decimal degrees of latitude and longitude, followed by the ellipsoid height.

Field 14: The last field is an arrow head followed by the current track of the aircraft. This was included in the string as a means to eliminate the north point on the photograph. The arrowhead is always the same, the photo user points the arrow in the direction of the track value, the photo's north point will then be at the top of the oriented photo. This aspect of the embedded photo-tags had the greatest resistance to acceptance as it was considered too difficult for the user to understand.

The Project photography string is the same as the Standard photography string except in heading change limits, those annotated with cloud or any that may have camera error messages.

The .DAT file data is being loaded into GIS packages to provide an image management environment. The author has demonstrated how products such as MICROSOFT ACCESS can be used to retrieve image information based on job name, job number, map name, map number, film number or geographic location. Sorts can be made on coverage whether it is block, non-block or oblique. As a production tool reports can be generated which cover the types of jobs, number of exposures, runs flown, map areas covered, even photography lost. With this sort of data base, qualitative information can be generated about the costs and productivity of aerial photography programs and operations. This information may help to identify where there is room for change and improvement.

The contents of a .DAT file are presented in table 14.1. Column headings have been added to aid interpretation.

14.9 Comments

It was extremely rewarding to witness the successful operation of this software. The software is a major undertaking containing over 3000 lines of C code which took over 12 months to make operational. In over 15 months of operation it has never stopped operating although on one occasion, for some unknown reason, data was not recorded. It is possibly the only one of its type operating in Australia offering interactive data stamping onto the margin of every camera exposure. The feedback from the aircrew has also been extremely encouraging, it seems their work can only get easier. It has also made the aerial camera - GPS navigation system a complete entity covering every aspect associated with aerial photography.

Table 14.1 Extract of 080299.DAT photo-tag file.

```
*LAND INFORMATION CENTRE    Aerial Survey Unit    VH-NSW    080299.dat
*CREW   Operator: H Gould    Pilot: T Sava         Date: 08/02/99
*CAMERA  Leica RC30                               RUNTAG Version 1.1
*
*  Job: M2399  Film No: NSW4321  Run: 02   Focal length: 152.76mm
*  First Exp: 0142          Cassettes - Supply: 5   Take up: 4
*

# Standard Coverage                                                              GPS Quality ↓ ↓ Heading change alarm
Exp No Time      Date Unq. ID  Film No  Run  Job       Map Name        Scale        Latitude  Longitude Ell Hgt Track      MapNo Lens  Cloud ASA Speed Aperature Filter                     Over  Lapse   FMC               Errors
 0142  10:44:04 08/02 9900010 NSW4321 R02 M2399   MOUNT_HARRIS 1:25000 AGD S31.4617 E147.7312 7806m <-269 2 . 8435 152.76  ---  FS100  1/ 400  f/4.0    FF2.0 EC 0    SP- v/h.01112  60% dt052.0  ds004  26.7V -65mb ER00 CAM5202
 0143  10:44:20 08/02 9900012 NSW4321 R02 M2399   MOUNT_HARRIS 1:25000 AGD S31.4619 E147.7155 7798m <-269 2 . 8435 152.76  ---  FS100  1/1000  f/4.0    FF2.0 EC *    SP- v/h.01112  60% dt152.0  ds013  26.7V -65mb ER00 CAM5202
 0144  10:44:36 08/02 9900014 NSW4321 R02 M2399   MOUNT_HARRIS 1:25000 AGD S31.4622 E147.6998 7801m <-269 2 . 8435 152.76  ---  FS100  1/ 300  f/2.0    FF2.0 EC----  SP- v/h.01112  60% dt200.0  ds050  26.7V -65mb ER00 CAM5202
 0145  10:44:48 08/02 9900016 NSW4321 R02 M2399   MOUNT_HARRIS 1:25000 AGD S31.4622 E147.6880 7796m <-270 0 . 8435 152.76  ---  FS100  1/ 250  f/5.6    FF2.0 EC-SET- SP- v/h.01112  60% dt152.0  ds013  26.7V -65mb ER00 CAM5202
 0146  10:44:48 08/02 9900016 NSW4321 R02 M2399   MOUNT_HARRIS 1:25000 AGD S31.4622 E147.6880 7796m <-270 0 . 8435 152.76  ---  FS100  1/  400  f/4.0    FF2.0 EC 0    SP- v/h.01112  60% dt052.0  ds004  26.7V -65mb ER00 CAM5202
 0152  10:44:48 08/02 9900016 NSW4321 R02 M2399   MOUNT_HARRIS 1:25000 AGD S31.4622 E147.6880 7796m <-270 0 . 8435 152.76  ---  FS100  1/ 300  f/2.0    FF2.0 EC----  SP- v/h.01112  60% dt200.0  ds050  26.7V -65mb ER00 CAM5202
 0153  10:44:48 08/02 9900016 NSW4321 R02 M2399   MOUNT_HARRIS 1:25000 AGD S31.4622 E147.6880 7796m <-270 0 . 8435 152.76  ---  FS100  1/  250  f/5.6    FF2.0 EC-SET- SP- v/h.01112  60% dt152.0  ds013  26.7V -65mb ER00 CAM5202
 0155  10:44:56 08/02 9900024 NSW4321 R02 M2399   MOUNT_HARRIS 1:25000 AGD S31.4622 E147.6802 7799m <-270 2 . 8435 152.76  ---  FS100  1/1000  f/4.0    FF2.0 EC *    SP- v/h.01112  60% dt152.0  ds013  26.7V -65mb ER00 CAM5202
#
*
* Run 02 of M2399 complete    8 frames    last exposure:  155
*
*        -------------------------------------------------------
*
*
*  Job: M2399  Film No: NSW4321  Run: 05   Focal length: 152.76mm
*  First Exp: 0156          Cassettes - Supply: 5   Take up: 4
*
# Project                                          Text String
 0156  10:45:44 08/02 9900026 NSW4321 R05 M2399   WESTERN_PLAINS 1:25000 AGD S31.4622 E147.6333 7791m <-270 2 . 8435 152.76  ---  FS100  1/ 400  f/4.0    FF2.0 EC 0    SP- v/h.01112  60% dt052.0  ds004  26.7V -65mb ER00 CAM5202
 0157  10:45:57 08/02 9900028 NSW4321 R05 M2399   WESTERN_PLAINS 1:25000 AGD S31.4621 E147.6204 7783m <-271 2 . 8435 152.76  ---  FS100  1/1/1000  f/4.0  FF2.0 EC *    SP- v/h.01112  60% dt152.0  ds013  26.7V -65mb ER00 CAM5202
 0161  10:47:04 08/02 9900030 NSW4321 R05 M2399   WESTERN_PLAINS 1:25000 AGD S31.4617 E147.5552 7818m <-270 2 . 8435 152.76  ---  FS100  1/1000  f/4.0    FF2.0 EC *    SP- v/h.01112  60% dt152.0  ds013  26.7V -65mb ER00 CAM5202
 0162  10:47:20 08/02 9900032 NSW4321 R05 M2399   WESTERN_PLAINS 1:25000 AGD S31.4618 E147.5398 7822m <-269 2 . 8435 152.76  ---  FS100  1/ 250  f/5.6    FF2.0 EC-SET- SP- v/h.01112  60% dt152.0  ds013  26.7V -65mb ER00 CAM5202
 0163  10:47:36 08/02 9900034 NSW4321 R05 M2399   WESTERN_PLAINS 1:25000 AGD S31.4621 E147.5243 7815m <-269 2 . 8435 152.76  ---  FS100  1/ 400  f/4.0    FF2.0 EC 0    SP- v/h.01112  60% dt052.0  ds004  26.7V -65mb ER00 CAM5202
#
*
* Run 05 of M2399 complete    5 frames    last exposure:  163
*
*        -------------------------------------------------------
*
*
*  Job: M2399  Film No: NSW4321  Run: 05   Focal length: 152.76mm
*  First Exp: 0164          Cassettes - Supply: 5   Take up: 4
*
# Oblique                                          Text String
 0164  10:48:24 08/02 9900036 NSW4321 M2399       SYDNEY   AGD S31.4622 E147.4772 7806m <-270 2 . 8335 152.76 Cloud FS100  1/ 250  f/5.6    FF2.0 EC-SET- SP- v/h.01112  60% dt152.0  ds013  26.7V -65mb ER00 CAM5202
 0165  10:48:40 08/02 9900038 NSW4321 M2399       SYDNEY   AGD S31.4622 E147.4614 7793m <-270 2 . 8335 152.76  ---  FS100  1/ 400  f/4.0    FF2.0 EC 0    SP- v/h.01112  60% dt052.0  ds004  26.7V -65mb ER00 CAM5202
 0166  10:48:56 08/02 9900040 NSW4321 M2399       SYDNEY   AGD S31.4621 E147.4455 7799m <-270 2 . 8335 152.76 Cloud FS100  1/1000  f/4.0    FF2.0 EC *    SP- v/h.01112  60% dt152.0  ds013  26.7V -65mb ER00 CAM5202
 0167  10:49:06 08/02 9900042 NSW4321 M2399       SYDNEY   AGD S31.4621 E147.4357 7801m <-269 0 . 8335 152.76 Cloud FS100  1/ 300  f/2.0    FF2.0 EC----  SP- v/h.01112  60% dt200.0  ds050  26.7V -65mb ER00 CAM5202
```

Some other tricks have been learned. Splitting the output from one communication port requires some innovative thinking. It was quickly discovered that shared COMMS data requires that both computers need to be running otherwise the transmit and receive status of the communication ports will not be set. To overcome this situation, the terminals of each computer's COMM ports were bridged so that the COMMS status was always ON. The identification of the problem with the FIFO levels came after the program had been modified to include a multitude of communication system time-out checks. These probably contribute significantly to the software's current reliability.

15. Future Developments

A number of challenges still exist in using GPS to support aerial triangulation. Current usage is limited by a number of operational issues:

- The camera-antenna relationship.
- The interpolated position of the camera between GPS positions.
- The ongoing requirements for some measure of ground control.
- The determination of camera attitude data of high enough quality to support stereo modelling without triangulation.
- Solving the problems of very long-range fixed ambiguity kinematic GPS.

These issues may not be of consequence for the photographic scales currently being captured by the SGD, but solving these problems will result in increases in efficiency, and ultimately in reduced costs.

15.1 Camera-antenna vector

With current technology and operational procedures there will remain a degree of error in knowledge of the relationship between the camera and the GPS antenna. Although the camera-antenna offset can be modelled in the aerotriangulation adjustment, it requires that some conditions are enforced during photographic capture. The camera-antenna relationship needs to be fixed, preferably for the entire photo strip. This relationship can be modelled within the block adjustment as part of the exterior orientation process.

The design of the modern camera is such that it can be rotated around the pitch, roll and yaw axis of the aircraft local reference system. Requirements of the aerotriangulation process dictate that minimal changes in image orientation occur between successive frames. It is the operator's job to ensure that the camera is as vertical as possible and that the drift setting maintains a geometric overlap. This impacts on the camera antenna vector, the effect of which grows as the vector length increases. It has already been mentioned that the ideal location for the GPS antenna is directly above the camera perspective centre. In this case rotations about the camera axis are of no consequence. The effects of pitch and roll are a function of vertical vector length.

An alternative is to record information concerning the camera attitude (in relation to a reference position/orientation). This information need only be known per strip. If such capability, to the necessary accuracy (< second of arc), could be built into the camera system and logged with each exposure, the camera-antenna relationship could always be mathematically derived.

15.2 Position Interpolation

This is one aspect of GPS-controlled photogrammetry that has not been dealt with in the literature. One approach to reduce the interpolation error is to increase the GPS data collection rates. Increasing data rates from one second to 0.1 seconds increases the amount of data ten fold for both GPS receivers, further complicates the data handling, extends the post-processing time but reduces the interpolation distance to 10m for an aircraft flying 100m/sec. Lapine (1996) and Kusevic & Mrstik (1998) have proposed polynomial interpolation algorithms based on dynamic trajectory data but the fact remains that the position for the exposure station is not observed, it is estimated.

Another approach suggested by Lapine (1996) is to activate the camera exposure using the one second timing pulse from the GPS receiver (the same instant that GPS data is recorded). This process suffers from various time delays within the camera which depend on the mechanical shutter, aperture setting and vacuum status. This method also introduces problems in controlling photography overlap.

Unfortunately, the interpolation problem grows as photographic scales increase. Apart from the higher accuracy requirements of larger scale photography, it also requires lower level flying, which increases aircraft dynamics due to turbulence, compounding the of interpolation problem.

An alternative to this methodology may lay in different GPS data gathering techniques. Some manufacturers can provide data recording on a mark or event. In aerial photography applications, for example, along with the regular data acquisition rate (1 sec) extra GPS observations could be made instantaneously with the camera exposure.

Unfortunately, to process this data requires reference station data which includes time tagged data that matches the camera event data. This is difficult, as the camera event times are not known at the reference receiver.

A special characteristic of the reference station receiver is that it is stationary. The behaviour of the L1 and L2 frequency data will behave in a predictable manner for short periods of time, even if biased by error sources such as multipath, receiver and satellite clocks, the ionosphere and the troposphere. It may be possible to run an interpolator on the reference station data and create the matching observations where they are missing. Figures 15.1 and 15.2 are plots of single second L1 frequency carrier phase data for SV24 and SV16 over a time period of 120 seconds. This is just a small sample of data recorded at a reference station to investigate the signal's behaviour. At this scale the data appears to plot as a straight line but on closer examination it certainly is not!

Predicting an observation requires a mathematical model. The first option tested was a

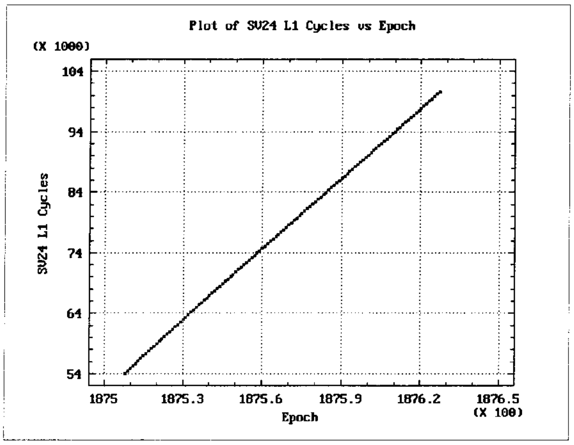


Figure 15.1 Plot of SV24 L1 cycles vs time.

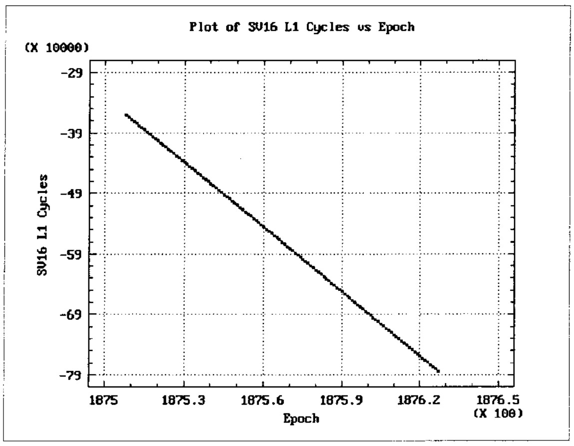


Figure 15.2 Plot of SV16 L1 cycles vs time.

linear model. The 120 epoch L1 frequency data set for SV24 was reduced to three 10 second sample sets. Ten seconds was considered as the smallest workable sample for the modelling process. Three samples are used so as to be representative of modelling at random time tags. Figure 15.3 is a 10 second subset of SV24 L1 frequency data illustrating the non-linear nature of the data, figures 15.4 and 15.5 are similar 10 second subsets at other sample times. The graphs show the residuals after modelling the data by a straight line. In all plots the solid horizontal line represents the true value. Note the different non-linear behaviour for each subset and the variation from the sub-cycle levels (figs 15.4 & 15.5) to a number of cycles (fig 15.3).

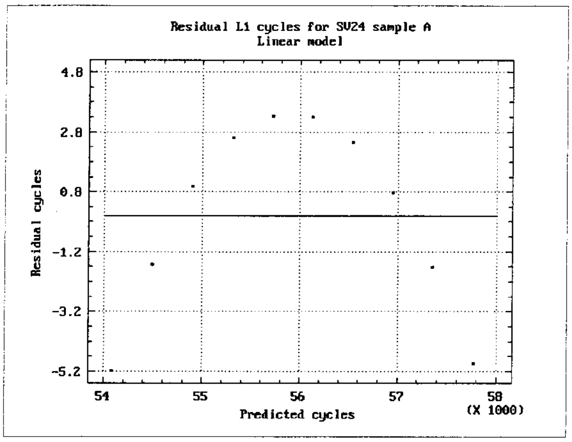


Figure 15.3 Residual L1 cycles for SV24 sample A linear model.

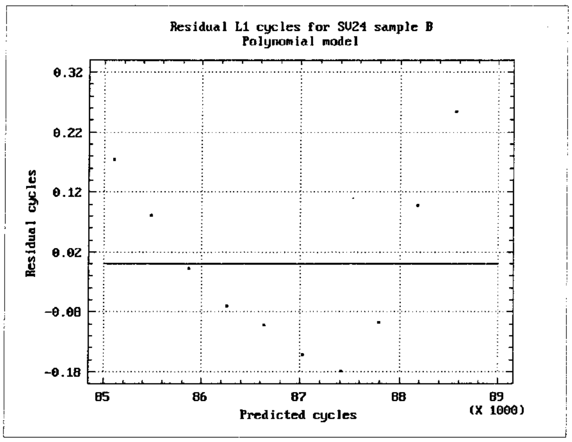


Figure 15.4 Residual L1 cycles for SV24 sample B linear model.

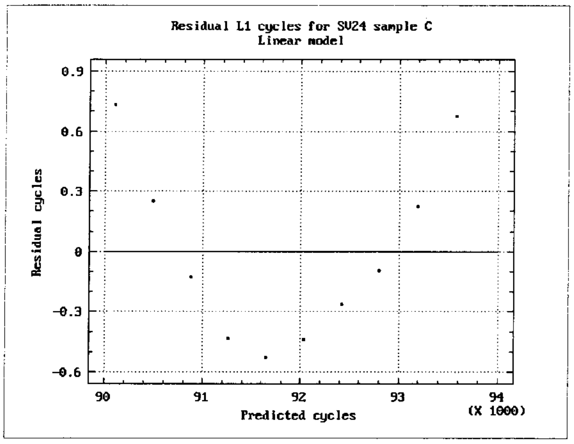


Figure 15.5 Residual L1 cycles for SV24 sample C linear model.

To be useful the model must fit to better than a cycle (0.19m). Figures 15.6, 15.7 and 15.8 are the residuals for the same data after modelling each set's behaviour using a second degree polynomial. These results indicate better than half a cycle predication accuracy using 10 second data samples.

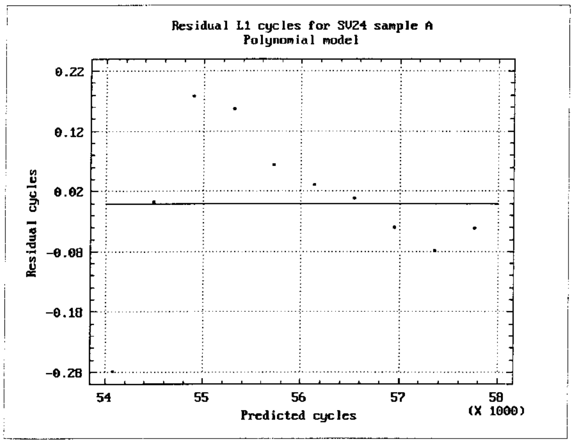


Figure 15.6 Residual L1 cycles for SV24 sample A polynomial model.

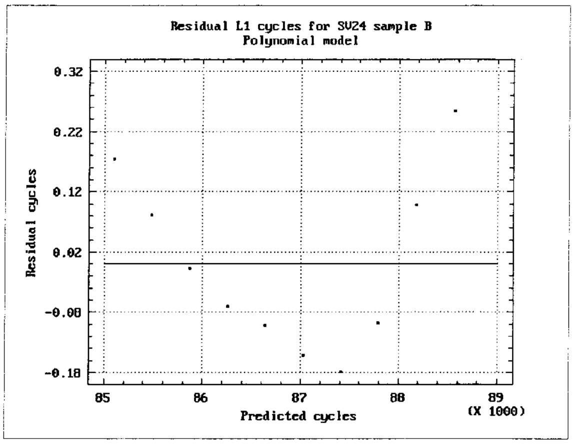


Figure 15.7 Residual L1 cycles for SV24 sample B after polynomial fit.

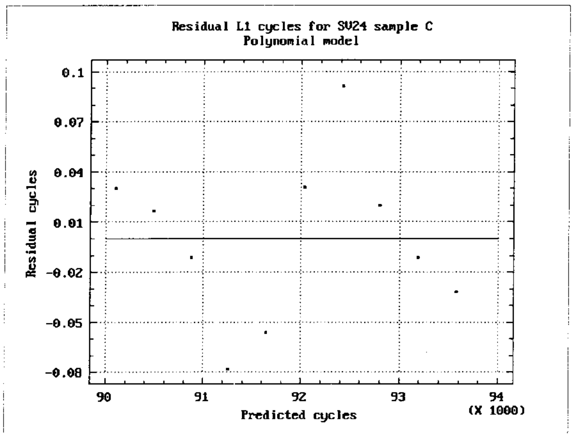


Figure 15.8 Residual L1 cycles for SV24 sample C after polynomial fit.

Other data manipulation techniques can assist in this process. Single and double-differencing of GPS data can also be modelled. Ten seconds of simultaneous data recorded on the aircraft and at the Hobart reference station for satellites four and seven are listed in table 15.1. The "single" columns difference SVs 4 and 7 L1 cycles. The "double" column differences the two "single" columns. The "triple" column differences consecutive "doubles". A pseudo observation has been added to table 15.1 at 176903.345678 seconds, simulating a camera event. In this case the GPS observation values for the camera event are known for the aircraft receiver, it follows that the single-differences are also known. The double-difference is not known because the matching single-difference observation for the reference receiver is unknown. The triple-difference can be modelled to make an estimate of the double-difference, or alternatively to model the double-differences directly. This is sufficient if only double-differences are needed to determine the baseline.

Table 15.1 Differencing table demonstrating the prediction problem.

	Hobart			Aircraft				
Time	SV4 L1	SV7 L1	**Single diff**	SV4 L1	SV7 L1	**Single diff**	**Double diff**	**Triple diff**
176900.000	-28341497.212	-25818763.779	2522733.433	-53298604.610	-18967640.957	34330963.653	-31808230.220	
176901.000	-28343581.184	-25816618.725	2526962.459	-53302632.597	-18968447.110	34334185.487	-31807223.028	-1007.192
176902.000	-28345664.535	-25814473.404	2531191.131	-53306661.594	-18969254.428	34337407.166	-31806216.035	-1006.993
176903.000	-28347747.221	-25812327.809	2535419.412	-53310689.340	-18970061.415	34340627.925	-31805208.513	-1007.552
176903.345678	Unknown	Unknown	Estimate	Known	Known	Known	Estimate	Estimate
176904.000	-28349829.251	-25810181.928	2539647.323	-53314715.393	-18970867.955	34343847.438	-31804200.115	-1008.398
176905.000	-28351910.688	-25808035.841	2543874.847	-53318739.897	-18971674.244	34347065.653	-31803190.806	-1009.309
176906.000	-28353991.511	-25805889.529	2548101.982	-53322762.616	-18972480.183	34350282.433	-31802180.451	-1010.355
176907.000	-28356071.762	-25803743.031	2552328.731	-53326784.246	-18973286.491	34353497.755	-31801169.024	-1011.427
176908.000	-28358151.457	-25801596.344	2556555.113	-53330804.820	-18974093.300	34356711.520	-31800156.407	-1012.617
176909.000	-28360230.533	-25799449.407	2560781.126	-53334825.201	-18974901.415	34359923.786	-31799142.660	-1013.747

If single-differences are required for kinematic baseline recovery the double-difference estimate can be used to estimate the single-difference for the reference station, or alternatively to model the single-differences directly. If direct satellite observations are required then an estimate of at least one satellite as a reference will be required to recover all other satellites for the observation epoch.

Simple linear modelling has been applied to the four differencing types. The results are plotted in figures 15.9 to 15.12. Only triple-differencing, figure 15.12, demonstrates <u>reasonable</u> linear behaviour for this data set. Unlike static GPS modelling of double and

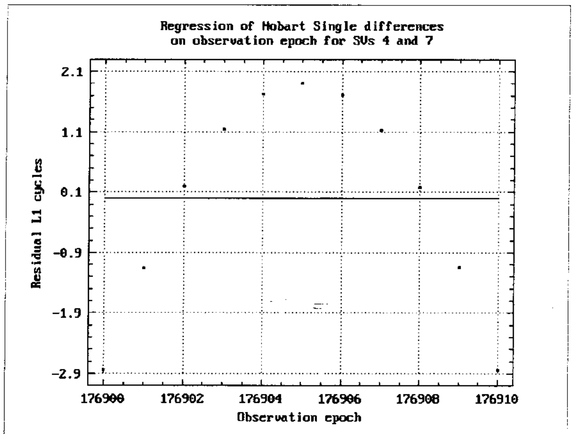


Figure 15.9 Hobart residual single-difference cycles for SVs 4 and 7 using linear model.

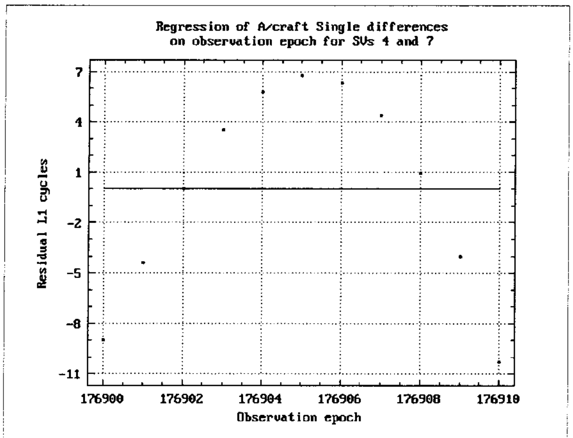


Figure 15.10 Aircraft residual single-difference cycles for SVs 4 and 7 using linear model.

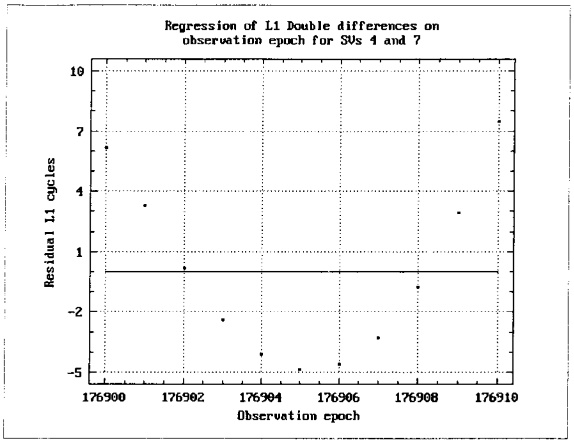


Figure 15.11 Double-difference residual cycles for SVs 4 and 7 using linear model.

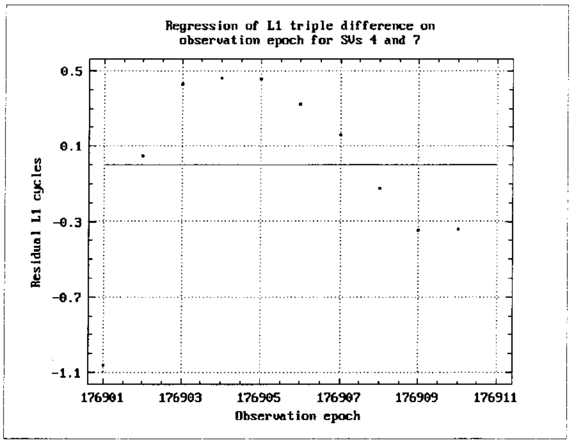


Figure 15.12 Triple-difference residual cycles for SVs 4 and 7 using linear model.

triple-differences, which tend to be consistent from epoch to epoch, this data reflects the dynamic nature of the aircraft. The behaviour of the differencing is very dependent on the dynamics of the aircraft antenna. This case is really no better than interpolating position after post-processing. The behaviour of the other combinations (double and single-differences) does not improve upon modelling the individual satellites as in figures 15.3 to 15.5, as originally proposed. The overriding requirement for this estimation technique is that the data must be cycle slip free.

This proposal is really of no value unless instantaneous observations on demand are available from GPS receivers. The technique of modelling the base station raw data behaviour would eliminate the unknown aircraft dynamics from the antenna coordinates and reduce the associated error budget to a function of the observation modelling accuracy.

15.3 Elimination of ground control

Improvements to systems are generally designed to drive costs down. GPS-controlled photography has already benefitted significantly from the reductions in surveyed ground control to support aerial triangulation. The total elimination of ground control requires the adoption of a methodology which isn't supported by redundant information.

Ackermann (1992) has expressed his reservations concerning triangulation without ground control. He believes that the "*interior camera calibration errors would create a new, most serious problem*". Merchant (1993) has suggested camera calibration test fields to identify and eliminate camera errors. He acknowledges that:

> "*For aerial photogrammetric methods, control is traditionally provided on the ground. This allows the systematic errors remaining in the photogrammetric system to be compensated by a fitting of the imagery within regions bracketed by control-essentially an interpolative process. Errors caused by incomplete camera calibration, non-linear film deformation, or platen unflatness can be accommodated by a false exposure station. With GPS, the exposure station position is forced on the solution and the "protective compensation" mechanism is no longer free to work. This suggests that what was only an ideal before, i.e., a full calibration of the total system under operational conditions, may now become a necessity.*"

This problem is probably the most formidable to overcome. Photogrammetry without ground control can be likened to levelling in one direction or not closing a loop. There are no quality control measures to confirm the quality of the result.

With current technology, four ground control points are a small price to pay for "peace of mind".

15.4 Camera attitude data

Unless camera attitude angle values with accuracies approaching one arc second are available it is not worth considering this data any further. The author is not aware of any inertial or GPS equipment currently capable of reliably delivering data of this quality for *operational photogrammetric applications*.

If the technology becomes available, then in principle aerotriangulation could be dispensed with altogether. The relationship between successive photographs can be directly re-established through the GPS camera station coordinates and the angular components provided by the attitude data. The problems associated with camera calibration still remain, complicating efforts to achieve consistent results without the inclusion of ground control.

15.5 Long-range kinematic GPS - ambiguity resolution

This has been an ongoing quest for many researchers. If this challenge is met, and reliable methodologies are developed, then those who wish to aerotriangulate without ground control will be able to do so without the requirements of base stations located close to the project area. The practical use of long-range fixed ambiguity GPS will also have to address the issues associated with low satellite elevation tracking. The test results presented in this document were only possible by accepting low elevation tracking data.

The problem associated with fixed ambiguity long-range kinematic GPS and aerotriangulation without ground control is the realisation of the ground datum. Geodetic networks tend to propagate with various error characteristics. The problems of fitting observations made with GPS, which defines its own datum, into another previously defined datum are well known. There are two issues, the difference in scale and the definition of the relationship between the two datums.

A fixed ambiguity solution is considered to be error free. If, for example, a baseline is 1000km in length and a fixed ambiguity solution is obtained, what is its expected error budget? If constrained centring is used one might say zero. This assumption translates the reference point coordinate of the baseline to the unknown end implicitly. The geodetic network which is realised on the ground may have a propagation error of 5ppm, hence over a 1000km this is 5m. There exists then a 5m difference between the local datum and the baseline determination. Hardly good enough when 1:50000 image processing can determine image points to 2m.

The use of ground control provides the means to overcome both these problems. The true value in this development will lie in a combination with the solution to the other challenges outlined above.

16. Concluding Remarks

There are no instruction books on how to design, implement and develop a GPS controlled aerial camera platform. This document has outlined the initial concepts, identified the many problems that can occur when implementing the technology, and described how complex systems have been simplified for everyday use. The author concurs with the comments of Earls & Byrne (1996) and Anderson (1994). It is not a challenge to be taken lightly and does require extensive knowledge of photogrammetry, surveying and adjustment theory.

The initial directions have proven to be correct, perseverance and determination has resulted in a data capture platform that is now reliable. The same can be said for the ground based aspects of this project.

The aim to build a reliable, low-cost, GPS controlled aerial camera system has been realised but the system operation is unique to this installation. With the addition of the photographic management software it is a complete package, but it cannot be said that it is a "turn key" installation. It is the author's opinion that it is the commitment (or lack of it) needed to build such systems that restricts the proliferation of the technology. It is still the domain of the "big players" who can afford the luxury of research and development, and the associated costs.

The approach of compensating for the elements of GPS drift within the aerial triangulation adjustment has been adopted as the technique for utilising GPS-controlled photogrammetry at the SGD. A number of long-range kinematic GPS and aerial triangulation adjustment tests have been conducted using Ashtech Z12 dual frequency GPS technology and the stated PNAV kinematic post-processing software. These tests have confirmed that:

- Between successive GPS epochs of phase locked, unfixed-ambiguity, long-range solutions up to 1500km from a reference station, relative precisions are highly correlated. Based on two comparisons with fixed-ambiguity benchmark trajectories the relative precisions are at the sub centimetre level for 1 second epochs.

- Based on comparisons with fixed-ambiguity benchmark trajectories the behaviour of phase locked, unfixed-ambiguity, long-range kinematic GPS displays elements of drift. In the test data this drift can be modelled as linear with standard deviations from a straight line less than 0.05m in east and north, and 0.1m in height, for periods up to 25 minutes in duration.

- Low elevation tracking angles, less than 10°, required for long-range kinematic GPS is not detrimental to the photogrammetric process when GPS drift is modelled. Low tracking angles may partially contribute to the drift behaviour.

- In the data sets studied, real-time differentially corrected, dynamic position data agrees, after linear regression, with fixed-ambiguity benchmark trajectories to 1.0-1.5m in east and north and 5.0m in height. Differential data can be evaluated for consistency by comparing along track real-time position values with those of pre-planned exposure points, but cross track and height data is indeterminate.

- Under the current operational status of the NAVSTAR GPS system, errors in phase smoothed single point positioning cannot be modelled as linear behaviour. Its performance does not fit the adopted model for GPS drift.

- Aerial triangulation adjustment results based on interpolated, phase locked, unfixed-ambiguity, antenna trajectories, determined from different reference stations up to 1500km from the project area, are fundamentally the same when GPS drift is a modelled unknown parameter.

- For situations where post-processed phase data is unavailable for **one** photo strip of an adjustment block, interpolated real-time differential positions can be used as "emergency" values provided suitable estimates of observation standard deviations are adopted. Results of an aerial triangulation adjustment using **one** photo strip of interpolated real-time differential positions, modelled for GPS drift, are still within 1.5m of the established benchmark results.

- Aerial triangulation adjustment configurations without ground control display significant shifts from benchmark results. These shifts, it is suspected, result not only from absolute trajectory errors but also errors of interior camera calibration and geoid modelling.

- Results of aerial triangulation adjustments and linear regression models indicate that this long range methodology is capable of supporting spatial resolution of image points from 1:16000 photography, i.e. better than 0.1m in X, Y and Z.

The combination of GPS controlled aerial photography and aerial triangulation adjustment procedures using linear GPS drift models is the most cost effective, reliable and proven methodology for the determination of spatial positions from aerial imagery. The cost of minimal ground control to support this methodology is a small price to pay to ensure a proven solution.

These comments are supported by the results of the 1:250000 map tiles which have been triangulated by the SGD over the past four years.

The current operational procedures outlined in this document face some future challenges. The alarm bells are ringing regarding the GPS week rollover in August 1999 and the subsequent problems of Year 2000. The current in-house nature of the operational procedures should ensure that these problems can be adequately addressed.

Whether or not commercial systems described here will migrate forward in the near future it is difficult to foresee, the developments in the space based market may make aerial photography obsolete. Even so, the aircraft operation as it is today, and the associated processing procedures, ensures that this is still the most sophisticated operation of its type in Australia.

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Appendix A

Extract of PNAV post-processing event log for the forward solution Lightning Ridge base station to the aircraft, VH-NSW.

```
176040.00 Changed reference satellite from SV# 4(60.3) to SV# 9(49.5) ...
176040.00 Eliminating SV# 4 at an elevation of 60 60.
176041.00 Add SV# 4 at an elevation of 60 60.
176041.00 Fixing L1 cycle-slip   -6347541.00 for SV# 4
176041.00 Fixing WL cycle-slip    4960234.00 for SV# 4
176041.00 Searching Ambiguity ...  Ratio=1.5646 2
176042.00 Changed reference satellite from SV# 9(49.6) to SV# 4(60.3) ...
176042.00 Searching Ambiguity ...  Ratio=2.61477 2 Fixed.
176042.00 Changes in fixed L1 ambiguities:
    6347541.00000 for SV26 in channel 05
    6347541.00000 for SV24 in channel 08
    6347541.00000 for SV05 in channel 10
    6347541.00000 for SV07 in channel 02
176042.00 Changes in fixed WL ambiguities:
    1387308.00000 for SV26 in channel 05
    1387308.00000 for SV24 in channel 08
    1387308.00000 for SV05 in channel 10
    1387308.00000 for SV07 in channel 02
176152.00 Changed reference satellite from SV# 4(60.6) to SV# 9(50.3) ...
176154.00 Changed reference satellite from SV# 9(50.3) to SV# 4(60.6) ...
176296.00 Reforming the Kalman filter ...
176296.00 Searching Ambiguity ...  Ratio=2.86722e+10 2 Fixed.
176296.00 Changes in fixed L1 ambiguities:
176296.00 Changes in fixed WL ambiguities:
176324.00 Changed reference satellite from SV# 4(61.1) to SV# 9(51.4) ...
176326.00 Changed reference satellite from SV# 9(51.5) to SV# 4(61.1) ...
176329.00 Changed reference satellite from SV# 4(61.1) to SV# 9(51.5) ...
176331.00 Changed reference satellite from SV# 9(51.5) to SV# 4(61.1) ...
176332.00 Changed reference satellite from SV# 4(61.1) to SV# 9(51.5) ...
176334.00 Changed reference satellite from SV# 9(51.5) to SV# 4(61.1) ...
176365.00 Changed reference satellite from SV# 4(61.2) to SV# 9(51.7) ...
176367.00 Changed reference satellite from SV# 9(51.7) to SV# 4(61.2) ...
176393.00 Changed reference satellite from SV# 4(61.2) to SV# 9(51.9) ...
176395.00 Changed reference satellite from SV# 9(51.9) to SV# 4(61.2) ...
176558.00 Changed reference satellite from SV# 4(61.6) to SV# 9(53.0) ...
176560.00 Changed reference satellite from SV# 9(53.0) to SV# 4(61.6) ...
176575.00 Reforming the Kalman filter ...
176575.00 Searching Ambiguity ...  Ratio=6.53126e+08 2 Fixed.
176575.00 Changes in fixed L1 ambiguities:
176575.00 Changes in fixed WL ambiguities:
176589.00 Changed reference satellite from SV# 4(61.6) to SV# 9(53.2) ...
```

```
176591.00 Changed reference satellite from SV# 9(53.2) to SV# 4(61.6) ...
176650.00 Changed reference satellite from SV# 4(61.7) to SV# 9(53.6) ...
176652.00 Changed reference satellite from SV# 9(53.6) to SV# 4(61.7) ...
176695.00 Changed reference satellite from SV# 4(61.8) to SV# 9(53.9) ...
176697.00 Changed reference satellite from SV# 9(53.9) to SV# 4(61.8) ...
176714.00 Changed reference satellite from SV# 4(61.8) to SV# 9(54.0) ...
176716.00 Changed reference satellite from SV# 9(54.0) to SV# 4(61.8) ...
176841.00 Changed reference satellite from SV# 4(61.9) to SV# 9(54.8) ...
176843.00 Changed reference satellite from SV# 9(54.8) to SV# 4(61.9) ...
176863.00 Changed reference satellite from SV# 4(61.9) to SV# 5(22.8) ...
176863.00 Total number of SVS is less than 3.
176865.00 Changed reference satellite from SV# 5(22.8) to SV# 4(61.9) ...
176866.00 Changed reference satellite from SV# 4(61.9) to SV# 9(55.0) ...
176871.00 Changed reference satellite from SV# 9(55.0) to SV# 4(61.9) ...
176901.00 Changed reference satellite from SV# 4(62.0) to SV# 9(55.2) ...
176903.00 Changed reference satellite from SV# 9(55.2) to SV# 4(62.0) ...
176965.00 Changed reference satellite from SV# 4(62.0) to SV# 9(55.6) ...
176967.00 Changed reference satellite from SV# 9(55.6) to SV# 4(62.0) ...
176998.00 Changed reference satellite from SV# 4(62.0) to SV# 9(55.8) ...
177000.00 Changed reference satellite from SV# 9(55.8) to SV# 4(62.0) ...
177002.00 Changed reference satellite from SV# 4(62.0) to SV# 9(55.8) ...
177004.00 Changed reference satellite from SV# 9(55.8) to SV# 4(62.0) ...
177049.00 Changed reference satellite from SV# 4(62.0) to SV# 9(56.1) ...
177051.00 Changed reference satellite from SV# 9(56.1) to SV# 4(62.0) ...
177139.00 Changed reference satellite from SV# 4(62.0) to SV# 9(56.6) ...
177141.00 Changed reference satellite from SV# 9(56.6) to SV# 4(62.0) ...
177448.00 Changed reference satellite from SV# 9(58.3) to SV# 4(61.9) ...
177479.00 Changed reference satellite from SV# 4(61.8) to SV# 9(58.5) ...
177481.00 Changed reference satellite from SV# 9(58.5) to SV# 4(61.8) ...
177624.00 Changed reference satellite from SV# 4(61.7) to SV# 9(59.2) ...
177626.00 Changed reference satellite from SV# 9(59.2) to SV# 4(61.7) ...
177814.00 Changed reference satellite from SV# 4(61.4) to SV# 9(60.0) ...
177816.00 Changed reference satellite from SV# 9(60.0) to SV# 4(61.4) ...
177869.00 Changed reference satellite from SV# 4(61.3) to SV# 9(60.2) ...
177871.00 Changed reference satellite from SV# 9(60.2) to SV# 4(61.3) ...
177943.00 Changed reference satellite from SV# 4(61.2) to SV# 9(60.4) ...
177945.00 Changed reference satellite from SV# 9(60.4) to SV# 4(61.2) ...
177978.00 Changed reference satellite from SV# 4(61.1) to SV# 9(60.5) ...
177978.00 Ambiguity Search not started:
        ((ml1+ml2=6<8) || (ml1=3<4 && ml2=3<4))
177980.00 Changed reference satellite from SV# 9(60.6) to SV# 4(61.1) ...
178006.00 Changed reference satellite from SV# 4(61.1) to SV# 9(60.6) ...
178006.00 Ambiguity Search not started:
        ((ml1+ml2=6<8) || (ml1=3<4 && ml2=3<4))
178008.00 Changed reference satellite from SV# 9(60.6) to SV# 4(61.1) ...
178010.00 Changed reference satellite from SV# 4(61.1) to SV# 9(60.6) ...
```

```
178010.00 Ambiguity Search not started:
        ((ml1+ml2=6<8) || (ml1=3<4 && ml2=3<4))
178012.00 Changed reference satellite from SV# 9(60.6) to SV# 4(61.1) ...
178020.00 Eliminating SV#26 at an elevation of  9  8.
178038.00 Changed reference satellite from SV# 4(61.1) to SV# 9(60.7) ...
178038.00 Ambiguity Search not started:
        ((ml1+ml2=6<8) || (ml1=3<4 && ml2=3<4))
178040.00 Changed reference satellite from SV# 9(60.7) to SV# 4(61.1) ...
178042.00 Changed reference satellite from SV# 4(61.1) to SV# 9(60.7) ...
178042.00 Ambiguity Search not started:
        ((ml1+ml2=6<8) || (ml1=3<4 && ml2=3<4))
178043.00 Ambiguity Search not started:
        ((ml1+ml2=6<8) || (ml1=3<4 && ml2=3<4))
178045.00 Changed reference satellite from SV# 9(60.7) to SV# 4(61.1) ...
178056.00 Changed reference satellite from SV# 4(61.1) to SV# 9(60.7) ...
178056.00 Ambiguity Search not started:
        ((ml1+ml2=6<8) || (ml1=3<4 && ml2=3<4))
178058.00 Changed reference satellite from SV# 9(60.7) to SV# 4(61.1) ...
178058.00 Add SV#26 at an elevation of  9  8.
178058.00 Fixing L1 cycle-slip    -32739872.00 for SV#26
178058.00 Searching Ambiguity ...  Ratio=1.14138 2
178059.00 Searching Ambiguity ...  Ratio=1.16368 2
```

Appendix B

PATB-GPS aerial triangulation results using original data subset 5 X 3 (134 photographs) photography runs over Angledool test block.

```
1
 PATB-GPS :                       COPYRIGHT :  H.KLEIN/F.ACKERMANN 1988-1994

 BLOCK ADJUSTMENT WITH BUNDLES                               REVISION Jun-94

 PROJECT  : Range test 1
 USER-ID. : gd

 START OF EXECUTION : 02-FEB-99 14:53:15

 ****************************************************************************
 ****************************************************************************
 **                                                                        **
 ** PROGRAM VERSION  PATB-GPS                                              **
 ** =========================                                              **
 **                                                                        **
 ** DIRECTORY FOR INPUT AND OUTPUT FILES :  PRESENT WORKING DIRECTORY      **
 ** INPUT                                                                  **
 ** BASIC DATA                                          FROM FILE rt1.bas  **
 ** PHOTOGRAPHS                                         FROM FILE rt1.obs  **
 ** CONTROL POINTS                                      FROM FILE rt1.ctl  **
 **                                                                        **
 ** INITIAL VALUES FOR EXTERIOR ORIENTATION             FROM FILE tst.ori  **
 **                                                                        **
 ** WITHOUT AUTOMATIC GROSS ERROR DETECTION                                **
 ** NO CORRECTION OF SYSTEMATIC ERRORS                                     **
 ** ADJUSTMENT WITH GPS-OBSERVATIONS                                       **
 **            WITH DETERMINATION OF GPS-DRIFT PARAMETERS                  **
 **            NO DETERMINATION OF GPS-ANTENNA OFFSET                      **
 ** NO INVERSION OF NORMAL EQUATIONS                                       **
 **                                                                        **
 ** ITERATION SEQUENCE WILL BE TERMINATED :                                **
 ** 1. IF 10 ITERATION STEPS ARE PERFORMED                                 **
 ** 2. IF CHANGE OF ADJUSTED TERRAIN COORDINATES                           **
 **    BETWEEN TWO ITERATION STEPS FOR ALL POINTS       <    0.300         **
 **    IN THE TERRAIN SYSTEM                                               **
 ** 3. IF CHANGE OF SIGMA LESS THAN 0.001%                                 **
 ** 4. IF SIGMA DOES NOT CONFIRM WITH READ IN STANDARD DEVIATIONS          **
 ** 5. IF THE RMS-VALUE OF OBSERVATIONS DIVERGES                           **
 **                                                                        **
 ** INPUT FORMATS AND INPUT SEQUENCES :                                    **
 ** PHOTOGRAPH NUMBERS          (I10,F10.3,I5)                             **
 ** PHOTOGRAPH POINTS           (I10,2F10.1,i5)                            **
 ** SEQUENCE OF READ IN COORDINATES OF PHOTO POINTS                  = X Y **
 ** HORIZONTAL CONTROL          (I8,2f15.3,15x,i5)                         **
 ** SEQUENCE OF READ IN COORDINATES OF HORIZONTAL CONTROL POINTS     = X Y **
 ** VERTICAL CONTROL            (I8,30x,f15.3,i5)                          **
 ** GPS-OBSERVATIONS            (I8,3f15.3,f8.0,i5)                        **
 **                                                                        **
 ** READ IN IMVK                                        =   25             **
 **                                                                        **
 ** LIMITATIONS                                                            **
 ** NUMBER OF POINTS IN ONE PHOTO          RESTRICTED TO   60              **
 ** NUMBER OF CONTROL POINTS IN ONE LIST   RESTRICTED TO  750              **
 ** NUMBER OF PHOTOS IN ONE PHOTO GROUP    RESTRICTED TO   60              **
 ** DIMENSIONS OF ADDRESS MATRIX           RESTRICTED TO   50,10           **
 ** NUMBER OF PHOTOS/SUBMATRIX             RESTRICTED TO   20              **
 ** NUMBER OF DIFFERENT FOCAL LENGTHS      RESTRICTED TO   30              **
 ** NUMBER OF POINT RECORDS                RESTRICTED TO  165              **
 ** NUMBER OF PHOTO RECORDS                RESTRICTED TO   60              **
 **                                                                        **
 ** REQUIRED WORKING AREA FOR THESE SPECIFICATIONS    =    108670          **
 ** REQUIRED SCRATCH FILE : BLKSZ = 8192 BYTES,  BLOCKS=     8316          **
 **                                                                        **
 ** BREAK UP LIMIT FOR THE SIZE OF PHOTO GROUPS       =     60             **
 **                                                                        **
 ** PHOTO NUMBERS OF THE FIRST PHOTO GROUP :                               **
 **                                       FIRST READ IN PHOTOGRAPH ASSUMED **
 ** NUMBER OF PHOTOS IN THE FIRST PHOTO GROUP           =    1             **
 **                                                                        **
 ** FOCAL LENGTH IN UNITS OF IMAGE SYSTEM AND CORRESPONDING FL-NUMBER      **
 ** NUMBER OF FOCAL LENGTHS                             =    0             **
 **                                                                        **
 ** SIZE OF PHOTOGRAPHS IN UNITS OF IMAGE SYSTEM                           **
 **   IN X :     230000.000   IN Y :     230000.000                        **
 **                                                                        **
 ** STANDARD DEVIATIONS OF OBSERVATIONS :                                  **
 **                                                                        **
 **   FOR IMAGE POINTS IN X AND Y IN UNITS OF IMAGE SYSTEM                 **
 **   DEFAULT SET (SDS NO. 0 OR BLANK) :          8.000                    **
 **                                                                        **
 **   FOR CONTROL POINTS IN UNITS OF TERRAIN SYSTEM                        **
 **                                        PLANIMETRY    HEIGHT            **
 **   1.SET FOR CONTROL POINTS         :        0.500     0.500            **
 **                                                                        **
 **   FOR GPS OBSERVATIONS IN UNITS OF TERRAIN SYSTEM                      **
 **                                        PLANIMETRY    AND HEIGHT        **
 **   1.SET FOR GPS OBSERVATIONS          :    0.250                       **
 **                                                                        **
 **                                                                        **
 ** COMMON OFFSET FROM CAMERA TO GPS ANTENNA :                             **
 **                         0.105          -0.052          1.000           **
 **                       IN UNITS OF TERRAIN SYSTEM                       **
 **                                                                        **
```

```
** PRINTOUT                                                                 **
** COORDINATES OF CONTROL POINTS AND RESIDUALS                              **
** COORDINATES AND RESIDUALS OF CRITICAL POINTS IN SEQUENCE                 **
**                                                                          **
** ADDITIONAL OUTPUT                                                        **
** ADJUSTED TERRAIN COORDINATES IN SEQUENCE       ON FILE rt1.fv1           **
** EXTERIOR ORIENTATION PARAMETERS                ON FILE rt1.ori           **
**                                                                          **
******************************************************************************
******************************************************************************


      read in image points ...........................  1723
      stored unsorted point records ..................    33
      read in photographs ............................   134
      stored unsorted photo records ..................     3
      read in horizontal control points ..............    71
      read in vertical control points ................    71
      read in gps antenna points......................   141
      read in gps profiles............................     8
      stored control point records ...................     1



      PHOTO GROUPS AND PHOTO CONNECTIONS
      ----------------------------------
      photo group   1 has   1 photo
      photo group   2 has   9 photos
      photo group   3 has  10 photos
      photo group   4 has  14 photos
      photo group   5 has  19 photos
      photo group   6 has  23 photos
      photo group   7 has  11 photos
      photo group   8 has  11 photos
      photo group   9 has  11 photos
      photo group  10 has  19 photos
      photo group  11 has   6 photos



      COMPUTATION OF ADJUSTED TERRAIN COORDINATES
      -------------------------------------------

      dimensions of submatrices     = ( 120 ,120 )
      dimensions of address matrix = (  50 , 11 )
      maximum number of photos/submatrix    =  20

      standard deviations for image points in x and y (in image system)
      default set :    8.000

      standard deviations for control points (in terrain system)
                         planimetry    height
      1. set :                0.500     0.500


      iteration step no.   1
      ------------------
      iteration step with gps

      number of hyperrows    =   11
      number of hypercolumns =    3
      plus 1 column border part for gps

      maximum change of exterior orientation parameters :
      da,db,dc = parameters of rodrigues-matrix
      px,py,pz = coordinates of perspective centers (in terrain system)

                  da =0.000000                px =      0.000
                  db =0.000000                py =      0.000
                  dc =0.000000                pz =      0.000

      maximum change of adjusted terrain coordinates (in terrain system) :

            in x at point-no.              51          0.021
            in y at point-no.            7321          0.021
            in z at point-no.            7321          0.037


      end of adjustment  --  due to condition 2



      STATISTICS
      ----------

       1-fold points        =    2
       2-fold points        =   39
       3-fold points        =   94
       4-fold points        =   33
       5-fold points        =   97
       6-fold points        =   67
       7-fold points        =   12
       8-fold points        =   17
       9-fold points        =    9
      number of block points =  370


      number of observations = 3805
      number of unknowns     = 1962
      redundancy             = 1843
```

```
number of outliers for image observations    =    0
number of outliers for control observations  =    0
number of outliers for gps observations      =    0

ROOT MEAN SQUARE VALUES AND CHECK VALUES OF RESIDUALS OF PHOTOGRAMMETRIC OBSERVATIONS
-------------------------------------------------------------------------------------
                  image system      terrain system        image system

image points
------------
obs x = 1682  rms x =     4.79   rms x =    0.235   chv vx =    14.37
obs y = 1682  rms y =     5.34   rms y =    0.262   chv vy =    16.02

ROOT MEAN SQUARE VALUES AND CHECK VALUES OF RESIDUALS OF NON-PHOTOGRAMMETRIC OBSERVATIONS
-----------------------------------------------------------------------------------------
                  image system      terrain system      terrain system

control points with sds-no.  1
---------------------------
obs x =   13  rms x =    16.08   rms x =    0.789   chv vx =     2.37
obs y =   13  rms y =     5.60   rms y =    0.274   chv vy =     0.82
obs z =   13  rms z =     3.54   rms z =    0.174   chv vz =     0.52

ROOT MEAN SQUARE VALUES AND CHECK VALUES OF RESIDUALS OF GPS OBSERVATIONS
-------------------------------------------------------------------------
                                    terrain system      terrain system

gps observations with sds-no.  1
------------------------------
obs x =  134                         rms x =    0.063   chv vx =     0.19
obs y =  134                         rms y =    0.065   chv vy =     0.19
obs z =  134                         rms z =    0.088   chv vz =     0.26


SIGMA NAUGHT      7.03          =    0.345
------------


COORDINATES OF CONTROL POINTS AND RESIDUALS
-------------------------------------------
in units of terrain system


horizontal control points
                                           code of point
point-no.        x              y          input -> used           rx          ry     sds check

   25     -69873.014     -15726.485         HV 1                -0.091      -0.130     1    .  .
   26     -72653.385      -1847.868         HV 4                -0.244      -0.092     1    .  .
   27     -73912.981      20027.308         HV 4                 0.184       0.066     1    .  .
   28     -71645.884      29937.296         HV 2                 0.434       0.341     1    .  .
   29     -31262.676      29465.355         HV 3                 0.510       0.109     1    .  .
   42     -31772.848      22556.965         HV 3                -1.151       0.054     1    .  .
   43     -35590.100      13370.653         HV 6                 0.834      -0.287     1    .  .
   44     -40395.315       6452.354         HV 3                -1.001      -0.078     1    .  .
   45     -47988.815      -4332.370         HV 4                 1.352       0.004     1    .  .
   46     -36058.591     -12463.704         HV 4                -0.375      -0.288     1    .  .
   51     -14225.594       4533.696         HV 3                -1.430       0.739     1    .  .
   52      -8939.231      -4353.436         HV 2                 0.590      -0.174     1    .  .
   53        415.646     -14504.899         HV 1                 0.389      -0.264     1    .  .


vertical control points
                                           code of point
point-no.                       z          input -> used                       rz     sds check

   25                      66.104         HV 1                              0.019     1       .
   26                      56.264         HV 4                             -0.236     1       .
   27                      14.268         HV 4                              0.132     1       .
   28                       3.531         HV 2                             -0.076     1       .
   29                     339.449         HV 3                             -0.084     1       .
   42                     363.035         HV 3                              0.197     1       .
   43                     366.988         HV 6                              0.229     1       .
   44                     346.695         HV 3                             -0.078     1       .
   45                     292.006         HV 4                              0.009     1       .
   46                     360.655         HV 4                              0.260     1       .
   51                     464.848         HV 3                             -0.337     1       .
   52                     468.576         HV 2                             -0.130     1       .
   53                     464.971         HV 1                              0.096     1       .


COORDINATES OF GPS OBSERVATIONS AND RESIDUALS
---------------------------------------------
in units of terrain system

gps antenna offset     x` =  0.105    y` = -0.052    z` =  1.000


photo-no.        x              y              z              t                rx          ry          rz     sds
check

profile-no.          1

drift parameters:

linear      -0.1606        0.0162        -0.1042
constant     -1.822        -1.398         -3.302
```

```
  123    -78565.769    25038.886     7456.415       -10.000          -0.027     0.008     0.072    1
  124    -74353.326    24916.580     7519.970        -9.000          -0.001    -0.071    -0.168    1
  125    -69985.531    24833.123     7557.125        -8.000          -0.102     0.000     0.034    1
  126    -65685.068    24946.862     7607.182        -7.000           0.063     0.010    -0.003    1
  127    -61386.493    25159.963     7644.873        -6.000          -0.051    -0.010     0.077    1
  128    -57125.509    25295.024     7673.909        -5.000           0.113     0.025    -0.030    1
  129    -52888.337    25391.523     7701.649        -4.000          -0.051    -0.037     0.040    1
  130    -48580.458    25410.769     7747.415        -3.000           0.008     0.147     0.140    1
  131    -44270.736    25469.494     7776.492        -2.000          -0.019     0.051     0.038    1
  132    -40008.990    25427.740     7801.265        -1.000           0.092    -0.061    -0.045    1
  133    -35721.285    25373.376     7836.552         0.000          -0.100    -0.004    -0.024    1
  134    -31423.352    25306.347     7857.972         1.000           0.081     0.034    -0.221    1
  135    -27168.023    25279.153     7872.501         2.000          -0.007    -0.145     0.025    1
  136    -22849.048    25262.212     7875.854         3.000           0.057     0.044    -0.080    1
  137    -18542.277    25226.131     7905.209         4.000           0.019    -0.045     0.125    1
  138    -14309.985    25229.912     7913.377         5.000           0.056    -0.021    -0.076    1
  139    -10017.524    25183.145     7921.329         6.000          -0.036     0.036    -0.021    1
  140     -5729.636    25164.721     7933.491         7.000           0.091     0.107     0.036    1
  141     -1516.199    25109.960     7946.211         8.000          -0.152     0.043     0.169    1
  142      2761.961    25142.466     7950.862         9.000          -0.035    -0.110    -0.089    1
  143      6987.834    25179.783     7941.317        10.000          --  not in the block --

profile-no.        2

drift parameters:

linear        0.1497      -0.0496       0.0640
constant     -1.518       -0.694       -2.017

  178      8543.141    16694.203     7961.079       -10.000          --  not in the block --
  179      4059.179    16699.343     7953.380        -9.000          -0.049     0.033    -0.021    1
  180      -560.776    16702.558     7961.750        -8.000           0.089    -0.105    -0.020    1
  181     -4940.924    16696.734     7948.854        -7.000           0.020     0.059     0.047    1
  182     -9234.977    16592.671     7952.829        -6.000          -0.036     0.008     0.001    1
  183    -13547.489    16501.544     7950.504        -5.000           0.043    -0.002     0.062    1
  184    -17835.357    16382.631     7956.539        -4.000          -0.067    -0.033     0.022    1
  185    -22232.996    16463.425     7924.190        -3.000           0.034     0.020    -0.025    1
  186    -26491.721    16630.874     7921.795        -2.000           0.036    -0.062     0.138    1
  187    -30768.582    16786.851     7893.551        -1.000           0.012     0.089    -0.037    1
  188    -35216.752    16700.133     7858.531         0.000          -0.114    -0.056    -0.115    1
  189    -39544.717    16665.237     7844.904         1.000          -0.086    -0.027    -0.076    1
  190    -43824.577    16596.935     7811.133         2.000           0.046    -0.007     0.054    1
  191    -48352.947    16554.928     7791.382         3.000           0.039     0.087    -0.067    1
  192    -52994.676    16298.918     7734.813         4.000           0.037     0.030    -0.039    1
  193    -57666.285    16158.041     7702.023         5.000          -0.039     0.041    -0.023    1
  194    -62166.037    16266.610     7664.416         6.000           0.033     0.009     0.009    1
  195    -66680.965    16297.205     7617.819         7.000          -0.003    -0.012     0.025    1
  196    -71129.597    16370.681     7558.231         8.000          -0.045    -0.007    -0.086    1
  197    -75511.848    16427.433     7513.513         9.000           0.080     0.004     0.060    1
  198    -79952.216    16375.984     7450.761        10.000          -0.030    -0.069     0.091    1
```

```
profile-no.        3    Original run 6

drift parameters:

linear       -0.1575       0.0674       0.0191
constant     -1.378       -0.224       -3.319

  267    -78348.031     7890.249     7493.169       -10.000           0.085    -0.013    -0.065    1
  268    -73848.679     7759.940     7541.277        -9.000           0.040     0.060    -0.155    1
  269    -69450.839     7677.276     7587.154        -8.000           0.009    -0.072     0.068    1
  270    -65033.001     7733.743     7628.979        -7.000          -0.005     0.041    -0.098    1
  271    -60623.709     7805.114     7666.101        -6.000          -0.043    -0.077    -0.043    1
  272    -56165.509     7952.934     7707.744        -5.000           0.099     0.032     0.057    1
  273    -51737.367     8167.765     7739.775        -4.000          -0.011    -0.059     0.078    1
  274    -47405.571     8348.150     7782.292        -3.000          -0.089     0.126     0.116    1
  275    -43320.783     8396.080     7817.423        -2.000          -0.048    -0.067     0.159    1
  276    -39283.238     8380.846     7847.668        -1.000          -0.022     0.022    -0.005    1
  277    -35251.809     8347.344     7881.822         0.000          -0.066    -0.045     0.023    1
  278    -31015.622     8241.927     7897.833         1.000          -0.028     0.068    -0.097    1
  279    -26552.469     8154.952     7906.158         2.000          -0.071    -0.087    -0.034    1
  280    -22124.524     8125.384     7917.730         3.000           0.065     0.057     0.040    1
  281    -17965.200     8059.184     7935.642         4.000          -0.071     0.035     0.184    1
  282    -13779.223     7952.603     7953.684         5.000          -0.015     0.030    -0.019    1
  283     -9429.484     7916.694     7949.739         6.000           0.034     0.066     0.117    1
  284     -5082.147     7874.102     7960.040         7.000           0.023    -0.003    -0.132    1
  285      -764.916     7866.281     7959.997         8.000          -0.030    -0.120    -0.181    1
  286      3567.394     7884.823     7960.277         9.000           0.142     0.008    -0.012    1
  287      7959.684     7956.767     7954.449        10.000          --  not in the block --
```

```
profile-no.        4

drift parameters:

linear        0.1014      -0.0828      -0.0411
constant     -1.078       -0.047       -1.657

  321      5817.231     -516.196     7958.372       -10.000          -0.051    -0.116    -0.008    1
  322      1635.297     -570.871     7971.225        -9.000          -0.136     0.023     0.015    1
  323     -2499.373     -566.476     7958.166        -8.000           0.090    -0.047    -0.022    1
  324     -6607.817     -489.812     7970.655        -7.000           0.020     0.102     0.059    1
  325    -10763.505     -417.711     7970.632        -6.000          -0.003     0.002     0.060    1
  326    -14902.120     -363.152     7966.805        -5.000           0.075     0.173    -0.065    1
  327    -19061.410     -311.668     7939.926        -4.000          -0.044    -0.056     0.000    1
  328    -23297.894     -160.785     7939.403        -3.000           0.047     0.004     0.076    1
  329    -27659.847      -13.212     7900.346        -2.000           0.092    -0.034    -0.065    1
  330    -31980.747        0.036     7890.335        -1.000           0.066    -0.052     0.002    1
  331    -36104.909      -27.811     7858.437         0.000          -0.027    -0.031    -0.037    1
  332    -40184.577     -149.323     7851.697         1.000          -0.048     0.050    -0.085    1
  333    -44515.516     -286.653     7818.043         2.000          -0.016    -0.013     0.012    1
```

```
  334    -48956.143       -442.141       7790.731          3.000           0.000     -0.018       0.048    1
  335    -53486.843       -526.409       7757.963          4.000          -0.002      0.008       0.007    1
  336    -57721.256       -512.613       7719.043          5.000          -0.023      0.058      -0.069    1
  337    -61979.318       -521.063       7674.816          6.000          -0.037     -0.040      -0.075    1
  338    -66309.155       -499.130       7628.150          7.000           0.004      0.021       0.029    1
  339    -70584.782       -519.787       7574.316          8.000          -0.106     -0.076       0.142    1
  340    -74776.665       -489.034       7549.487          9.000           0.079      0.084      -0.021    1
  341    -79040.122       -467.661       7501.481         10.000           0.022     -0.042      -0.003    1

profile-no.         5

drift parameters:

linear      -0.1122          0.1100         0.1414
constant     -0.568          -0.605         -1.638

  342    -77952.443      -9077.862       7494.777         -9.500           0.015     -0.012      -0.025    1
  343    -73779.969      -9093.420       7544.237         -8.500          -0.053      0.029       0.173    1
  344    -69531.391      -9093.064       7571.912         -7.500           0.017     -0.066      -0.144    1
  345    -65149.608      -9067.900       7618.577         -6.500           0.018      0.043       0.184    1
  346    -60804.348      -9065.890       7670.499         -5.500          -0.029     -0.008      -0.050    1
  347    -56463.513      -9036.379       7710.694         -4.500           0.029      0.001       0.054    1
  348    -52125.434      -9035.733       7747.609         -3.500          -0.019     -0.022      -0.091    1
  349    -47757.724      -9023.447       7770.527         -2.500           0.011      0.040      -0.074    1
  350    -43393.032      -9032.992       7804.777         -1.500           0.006      0.028       0.030    1
  351    -39039.430      -9025.168       7834.234         -0.500           0.002      0.018      -0.089    1
  352    -34693.898      -8997.961       7861.400          0.500          -0.011     -0.096      -0.059    1
  353    -30270.515      -8897.519       7874.711          1.500           0.033      0.032      -0.014    1
  354    -25796.902      -8754.083       7908.483          2.500          -0.027     -0.013       0.060    1
  355    -21203.120      -8738.457       7938.445          3.500           0.068      0.042       0.025    1
  356    -16712.356      -8744.088       7948.808          4.500          -0.075     -0.013       0.048    1
  357    -12251.454      -8827.015       7948.561          5.500           0.106      0.107      -0.151    1
  358     -7821.105      -8856.370       7969.747          6.500          -0.109     -0.070       0.045    1
  359     -3489.706      -8885.027       7972.299          7.500           0.040     -0.045      -0.069    1
  360       802.328      -8992.362       7962.251          8.500          -0.025     -0.041      -0.063    1
  361      5116.912      -9031.829       7940.776          9.500           0.003      0.047       0.210    1

profile-no.         6

drift parameters:

linear       0.2278          0.0530        -0.0343
constant     -0.038          -0.876         -1.112

  386    -72923.431      31026.348       7499.494         -5.500          -0.042      0.020       0.024    1
  387    -72966.530      26630.556       7512.100         -4.500           0.093     -0.092      -0.032    1
  388    -72931.480      22165.443       7531.381         -3.500           0.008      0.101      -0.011    1
  389    -72824.887      17742.423       7536.534         -2.500           0.025     -0.076      -0.116    1
  390    -72661.739      13290.399       7534.462         -1.500          -0.113      0.075       0.059    1
  391    -72504.266       8781.544       7534.443         -0.500           0.065      0.012       0.106    1
  392    -72468.138       4340.361       7554.704          0.500          -0.055      0.033       0.026    1
  393    -72577.112        -18.797       7539.935          1.500          -0.053     -0.092      -0.030    1
  394    -72740.940      -4221.742       7534.568          2.500          -0.028     -0.007       0.024    1
  395    -72691.928      -8455.926       7539.512          3.500           0.120     -0.013       0.009    1
  396    -72663.741     -12679.410       7538.190          4.500          -0.022      0.037      -0.058    1
  397    -72481.365     -16883.831       7549.946          5.500          --  not in the block --

profile-no.         7

drift parameters:

linear      -0.1521         -0.0630        -0.1708
constant     -1.082          -0.479         -1.928

  575    -40320.537     -16840.603       7745.465         -5.500          --  not in the block --
  576    -40337.716     -12720.670       7752.902         -4.500          -0.065      0.080       0.159    1
  577    -40345.544      -8545.180       7759.795         -3.500           0.011     -0.114      -0.109    1
  578    -40329.801      -4142.000       7768.248         -2.500           0.059     -0.066       0.054    1
  579    -40384.605        337.400       7757.311         -1.500           0.022      0.154       0.108    1
  580    -40393.516       4823.108       7759.284         -0.500          -0.017      0.008      -0.238    1
  581    -40347.879       9303.994       7768.395          0.500           0.078     -0.147      -0.061    1
  582    -40302.307      13800.434       7777.114          1.500          -0.108      0.162      -0.017    1
  583    -40317.871      18324.751       7752.536          2.500           0.055     -0.147      -0.034    1
  584    -40378.238      22877.845       7734.342          3.500          -0.087      0.071      -0.027    1
  585    -40459.599      27447.794       7728.172          4.500           0.085      0.016       0.165    1
  586    -40502.040      32049.811       7681.691          5.500          -0.032     -0.017       0.001    1

profile-no.         8

drift parameters:

linear       0.3359          0.1376         0.3545
constant     -2.280           0.051         -1.755

  600       162.500      33865.484       7806.720         -6.000          --  not in the block --
  601       140.800      29702.547       7827.195         -5.000           0.030     -0.041       0.054    1
  602       212.012      25471.042       7824.196         -4.000           0.164     -0.108      -0.156    1
  603       197.785      21271.560       7849.508         -3.000          -0.137      0.066       0.025    1
  604       206.435      17073.794       7837.070         -2.000          -0.087     -0.009       0.092    1
  605       237.118      12789.283       7862.886         -1.000          -0.057      0.121      -0.071    1
  606       189.825       8619.280       7891.492          0.000          -0.062      0.020       0.094    1
  607       229.218       4458.950       7888.886          1.000           0.043      0.080       0.061    1
  608       232.290        231.263       7891.630          2.000           0.155     -0.077       0.031    1
  609       208.491      -3904.790       7889.092          3.000          -0.056      0.013      -0.077    1
  610       185.647      -8067.723       7880.649          4.000           0.051     -0.008      -0.209    1
  611       168.817     -12191.031       7871.838          5.000          -0.044     -0.054       0.156    1
  612       147.087     -16439.124       7832.430          6.000          --  not in the block --


COORDINATES AND RESIDUALS OF CRITICAL POINTS
--------------------------------------------
arranged by increasing point numbers
```

```
photo-no.     x           y              rx          ry  sds check

            point-no.                 43   HV 6

 187      97175.4     78581.8            7.3       -3.0   0    .  .
 583    -100805.6    -94352.5           10.4       16.1   0    .  1
  VE                  366.988                     0.229   1       .
 581      86227.4    -93376.8           -1.9       -7.3   0    .  .
 582      -8349.9   -100941.6           -2.9       -6.9   0    .  .
 188       5654.8     65467.9            2.7        2.9   0    .  .
 189     -82125.8     66307.4           -1.1        2.2   0    .  .

  HO   -35590.100   13370.653          0.834     -0.287   1    .  .

            point-no.                 46   HV 4

  VE                  360.655                     0.260   1       .
 576       3494.6    -83900.2            3.2        4.5   0    .  .
 352     -28474.0    -71272.2            4.4        2.0   0    .  .
 351      60461.2    -72221.0           15.7        3.1   0    1  .

  HO   -36058.591  -12463.704         -0.375     -0.288   1    .  .
 577     -79563.4    -86101.4           -4.5       11.0   0    .  .


            point-no.               3085   TP 4

 124     -77015.1     88432.1           -9.8      -13.7   0    .  .
 123       7715.0     89135.2            8.6       -3.4   0    .  .
 387     -55052.6    -96877.2          -15.8        0.0   0    1  .
 386      30385.1   -103648.3           -1.3        1.4   0    .  .

            point-no.               4142   TP 7

 604     -79613.4     52998.5          -11.8       -8.9   0    .  .
 179      30339.5    -90144.0           -1.6        3.4   0    .  .
 602      92976.2     56053.3           -9.0      -11.6   0    .  .
 142       -557.7    -86168.2           17.7       -5.6   0    3  .
 180     -65593.6    -86662.3           -7.2        6.9   0    .  .
 141      90376.2    -80593.7            2.3      -15.8   0    .  .
 603       3944.4     51530.1          -10.3       -7.6   0    .  .

            point-no.               5188   TP 8

 276      67712.1     79609.3          -11.8       -8.3   0    .  .
 187      98720.0     99928.4            0.0        5.4   0    .  .
 582     -29551.7    -99152.9           15.4        1.0   0    1  .
 277     -16557.5     79812.8           -2.1        1.0   0    .  .
 188       6752.7     85927.7           -5.2        4.7   0    .  .
 581      65364.7    -91939.1           10.0        2.1   0    .  .
 189     -80716.8     87197.8           -8.0        6.1   0    .  .
 278     -99544.2     74977.8            4.5       -2.6   0    .  .

            point-no.               6285   TP 8

 322      65755.1    -84332.7            5.5       -1.9   0    .  .
 285     -12280.8    -94944.5            2.3       16.4   0    .  1
 607      22266.2    -36104.1            3.1       -3.2   0    .  .
 286    -103532.2    -91298.6            4.9      -17.5   0    .  1
 323     -19810.6    -82552.0            0.5        3.9   0    .  .
 284      77305.4    -91534.5            1.1        0.2   0    .  .
 608     -65477.6    -30926.7           -9.0        2.3   0    .  .
 324    -103475.8    -82250.6            1.7        3.5   0    .  .

            point-no.               8350   TP 4

 351     -90180.8    -96143.7            7.8        3.5   0    .  .
 576     -16262.6     67208.5           -9.2       18.3   0    .  2
 349      90668.6    -99457.0            2.9        3.8   0    .  .
 350       -871.8    -95756.6            7.6        2.2   0    .  .

            point-no.             123602   TP 4

 142      39505.8       341.4          -15.9      -15.5   0    2  .
 603     -83784.7     91197.0           -1.3        8.5   0    .  .
 602       3849.4     93891.0           -4.6        6.3   0    .  .
 601      94155.3     95079.3           -9.6        1.0   0    .  .

            point-no.             123603   TP 4

 604     -89274.5     95793.3            0.6       -5.4   0    .  .
 142      41810.5    -76921.2            1.9      -18.5   0    .  2
 603      -5638.2     93836.3           -3.9        4.3   0    .  .
 602      82459.4     98815.0          -14.8       -1.1   0    1  .

            point-no.             123605   TP 5

 604      86780.4    102941.0            3.9       -9.6   0    .  .
 286      32273.6    100927.7           27.4       -1.3   0    9  .
 606     -91013.8     99990.2           -8.8       -6.7   0    .  .
 179     -27004.6     71116.0            1.2        9.7   0    .  .
 605      -7319.5     95736.0           -5.0       -9.5   0    .  .

            point-no.             204142   TP 5

 603     -83164.1     46886.7          -10.3      -11.8   0    .  .
 142      -4433.4      -128.6           26.9       -2.4   0    9  .
 602       5630.6     49335.8           -3.3      -12.5   0    .  .
 601      93895.5     50312.8           -1.3      -23.2   0    .  5
 141      84856.8      4882.2           21.4      -12.6   0    5  .

            point-no.             205179   TP 5

 179      -3026.5     -1090.9           13.6       -0.7   0    .  .
 605     -81899.8     74643.8            3.3       16.8   0    .  1
```

```
   604      11003.0      81842.7           -0.2      11.4   0  .  .
   603      93073.1      78921.4            5.6       1.9   0  .  .
   180     -96832.9       1424.2           16.5       4.2   0  2  .

               point-no.          206275   TP 5

   276     -81044.2      -5890.3           -7.1      13.1   0  .  .
   580      73142.2      61238.9          -15.8      -1.7   0  1  .
   275       1472.0      -1642.6            0.4      11.7   0  .  .
   274      83470.5       1490.6            4.6       7.4   0  .  .
   581     -19406.5      60267.3          -16.3       0.1   0  2  .

               point-no.          206275   TP 5

   276     -81044.2      -5890.3           -7.1      13.1   0  .  .
   275       1472.0      -1642.6            0.4      11.7   0  .  .
   580      73142.2      61238.9          -15.8      -1.7   0  1  .
   274      83470.5       1490.6            4.6       7.4   0  .  .
   581     -19406.5      60267.3          -16.3       0.1   0  2  .

               point-no.          207331   TP 6

   580     -94412.0     -96009.4           14.1      -0.2   0  .  .
   332     -91593.0      -8025.5            3.1       7.1   0  .  .
   330      74431.4      -5621.7            3.2       9.2   0  .  .
   579       1092.4     -97348.0           10.5      -6.6   0  .  .
   578      90036.6     -94416.8            7.7      -1.8   0  .  .
   331      -8564.8      -6046.6            3.5      16.1   0  .  1

               point-no.          223605   TP 9

   604      91684.9      -2816.3            6.5     -12.5   0  .  .
   284     100474.1      99043.6            4.2     -10.6   0  .  .
   286     -71157.1      98005.2            4.6      -3.8   0  .  .
   179      74558.8      80841.5           -2.9      -5.6   0  .  .
   605       -404.8      -7856.0           -4.3     -20.1   0  .  3
   180     -15633.2      83292.2          -11.8      -2.6   0  .  .
   285      14627.4      95225.9            6.6       4.1   0  .  .
   606     -84760.2      -5020.5           -2.6      -4.6   0  .  .
   181    -102258.4      80108.4           -7.4      -1.9   0  .  .

               point-no.          322583   TP 5

   191     -68691.6     -49182.0           -2.7      -4.3   0  .  .
   584     -75564.7      89371.0           -5.1       9.0   0  .  .
   190      27001.4     -47416.8           11.0      -8.4   0  .  .
   583      13822.5      98894.5           -1.8       0.7   0  .  .
   582     103202.0      92324.2           -6.3     -18.1   0  .  2

               point-no.          904142   TP 4

   602     -87548.9      55208.4            7.3       9.0   0  .  .
   142       4323.3      91281.1           -4.5       7.7   0  .  .
   141      91990.4      97803.2          -15.1       2.2   0  1  .
   601        765.6      60499.5            2.5      10.7   0  .  .

               point-no.          904142   TP 4

   601        765.6      60499.5            2.5      10.7   0  .  .
   602     -87548.9      55208.4            7.3       9.0   0  .  .
   141      91990.4      97803.2          -15.1       2.2   0  1  .
   142       4323.3      91281.1           -4.5       7.7   0  .  .

               point-no.          907322   TP 7

   608     -79848.8      39331.4          -17.6      10.4   0  3  .
   321      81032.8     -90156.3            7.7       6.7   0  .  .
   286     -33813.6     -80095.1           -0.7      -2.3   0  .  .
   285      57762.4     -81757.0            1.7      -6.5   0  .  .
   607       9417.2      33942.7          -23.5       9.3   0  7  .
   322      -4430.3     -97361.9           10.7      15.9   0  .  .

               point-no.          904142   TP 4

   601        765.6      60499.5            2.5      10.7   0  .  .
   602     -87548.9      55208.4            7.3       9.0   0  .  .
   141      91990.4      97803.2          -15.1       2.2   0  1  .
   142       4323.3      91281.1           -4.5       7.7   0  .  .

               point-no.          904142   TP 4

   141      91990.4      97803.2          -15.1       2.2   0  1  .
   601        765.6      60499.5            2.5      10.7   0  .  .
   142       4323.3      91281.1           -4.5       7.7   0  .  .
   602     -87548.9      55208.4            7.3       9.0   0  .  .

END OF EXECUTION : 02-FEB-99 14:54:52

PATB-GPS END
```

Appendix C

PATB-GPS aerial triangulation results using new photography for run 6. Antenna station coordinates based on Lightning Ridge base station trajectory (fixed-ambiguities). New results for run 6 are listed under profile 8. ***This result is adopted as the benchmark solution.***

```
1
    PATB-GPS :                      COPYRIGHT :  H.KLEIN/F.ACKERMANN 1988-1994

    BLOCK ADJUSTMENT WITH BUNDLES                               REVISION Jun-94

    PROJECT  : Range test 1
    USER-ID. : gd

    START OF EXECUTION : 03-FEB-99 13:50:25

    ***************************************************************************
    ***************************************************************************
    **                                                                       **
    ** PROGRAM VERSION  PATB-GPS                                             **
    ** ========================                                              **
    **                                                                       **
    ** DIRECTORY FOR INPUT AND OUTPUT FILES :  PRESENT WORKING DIRECTORY     **
    ** INPUT                                                                 **
    ** BASIC DATA                                         FROM FILE rt3.bas  **
    ** PHOTOGRAPHS                                        FROM FILE rt3.obs  **
    ** CONTROL POINTS                                     FROM FILE gd3.ctl  **
    **                                                                       **
    ** INITIAL VALUES FOR EXTERIOR ORIENTATION PARAMETERS ARE CALCULATED     **
    **                                                                       **
    ** WITHOUT AUTOMATIC GROSS ERROR DETECTION                               **
    ** NO CORRECTION OF SYSTEMATIC ERRORS                                    **
    ** ADJUSTMENT WITH GPS-OBSERVATIONS                                      **
    **            WITH DETERMINATION OF GPS-DRIFT PARAMETERS                 **
    **            NO DETERMINATION OF GPS-ANTENNA OFFSET                     **
    ** NO INVERSION OF NORMAL EQUATIONS                                      **
    **                                                                       **
    ** ITERATION SEQUENCE WILL BE TERMINATED :                               **
    ** 1. IF 10 ITERATION STEPS ARE PERFORMED                                **
    ** 2. IF CHANGE OF ADJUSTED TERRAIN COORDINATES                          **
    **    BETWEEN TWO ITERATION STEPS FOR ALL POINTS      <    0.300         **
    **    IN THE TERRAIN SYSTEM                                              **
    ** 3. IF CHANGE OF SIGMA LESS THAN 0.001%                                **
    ** 4. IF SIGMA DOES NOT CONFIRM WITH READ IN STANDARD DEVIATIONS         **
    ** 5. IF THE RMS-VALUE OF OBSERVATIONS DIVERGES                          **
    **                                                                       **
    ** INPUT FORMATS AND INPUT SEQUENCES :                                   **
    ** PHOTOGRAPH NUMBERS         (I10,F10.3,I5)                             **
    ** PHOTOGRAPH POINTS          (I10,2F10.1,i5)                            **
    ** SEQUENCE OF READ IN COORDINATES OF PHOTO POINTS                 = X Y **
    ** HORIZONTAL CONTROL         (I8,2f15.3,15x,i5)                         **
    ** SEQUENCE OF READ IN COORDINATES OF HORIZONTAL CONTROL POINTS    = X Y **
    ** VERTICAL CONTROL           (I8,30x,f15.3,i5)                          **
    ** GPS-OBSERVATIONS           (I8,3f15.3,f8.0,i5)                        **
    **                                                                       **
    ** READ IN IMVK                                       =   25             **
    **                                                                       **
    ** LIMITATIONS                                                           **
    ** NUMBER OF POINTS IN ONE PHOTO          RESTRICTED TO   60             **
    ** NUMBER OF CONTROL POINTS IN ONE LIST   RESTRICTED TO  750             **
    ** NUMBER OF PHOTOS IN ONE PHOTO GROUP    RESTRICTED TO   60             **
    ** DIMENSIONS OF ADDRESS MATRIX           RESTRICTED TO   50,10          **
    ** NUMBER OF PHOTOS/SUBMATRIX             RESTRICTED TO   20             **
    ** NUMBER OF DIFFERENT FOCAL LENGTHS      RESTRICTED TO   30             **
    ** NUMBER OF POINT RECORDS                RESTRICTED TO  165             **
    ** NUMBER OF PHOTO RECORDS                RESTRICTED TO   60             **
    **                                                                       **
    ** REQUIRED WORKING AREA FOR THESE SPECIFICATIONS     =  108670          **
    ** REQUIRED SCRATCH FILE : BLKSZ = 8192 BYTES,  BLOCKS=    8316          **
    **                                                                       **
    ** BREAK UP LIMIT FOR THE SIZE OF PHOTO GROUPS        =   60             **
    **                                                                       **
    ** PHOTO NUMBERS OF THE FIRST PHOTO GROUP :                              **
    **                                      FIRST READ IN PHOTOGRAPH ASSUMED **
    ** NUMBER OF PHOTOS IN THE FIRST PHOTO GROUP          =    1             **
    **                                                                       **
    ** FOCAL LENGTH IN UNITS OF IMAGE SYSTEM AND CORRESPONDING FL-NUMBER     **
    ** NUMBER OF FOCAL LENGTHS                            =    0             **
    **                                                                       **
    ** SIZE OF PHOTOGRAPHS IN UNITS OF IMAGE SYSTEM                          **
    **   IN X :     230000.000   IN Y :     230000.000                       **
    **                                                                       **
    ** STANDARD DEVIATIONS OF OBSERVATIONS :                                 **
    **                                                                       **
    **   FOR IMAGE POINTS IN X AND Y IN UNITS OF IMAGE SYSTEM                **
    **   DEFAULT SET (SDS NO. 0 OR BLANK) :        8.000                     **
    **                                                                       **
    **   FOR CONTROL POINTS IN UNITS OF TERRAIN SYSTEM                       **
    **                                        PLANIMETRY   HEIGHT            **
    **   1.SET FOR CONTROL POINTS          :       0.500    0.500            **
    **                                                                       **
    **   FOR GPS OBSERVATIONS IN UNITS OF TERRAIN SYSTEM                     **
    **                                        PLANIMETRY   AND HEIGHT        **
    **   1.SET FOR GPS OBSERVATIONS          :    0.250                      **
    **   2.SET FOR GPS OBSERVATIONS          :    0.250                      **
```

```
**                                                                      **
**                                                                      **
** COMMON OFFSET FROM CAMERA TO GPS ANTENNA :                           **
**                          0.105          -0.052           1.000       **
**                        IN UNITS OF TERRAIN SYSTEM                    **
**                                                                      **
** PRINTOUT                                                             **
** COORDINATES OF CONTROL POINTS AND RESIDUALS                          **
** COORDINATES AND RESIDUALS OF CRITICAL POINTS IN SEQUENCE             **
**                                                                      **
** ADDITIONAL OUTPUT                                                    **
** ADJUSTED TERRAIN COORDINATES IN SEQUENCE       ON FILE rt3.fvl       **
** EXTERIOR ORIENTATION PARAMETERS                ON FILE rt3.ori       **
**                                                                      **
**************************************************************************
**************************************************************************


      read in image points ............................  1718
      stored unsorted point records ...................    33
      read in photographs .............................   134
      stored unsorted photo records ...................     3
      read in horizontal control points ...............    71
      read in vertical control points .................    71
      read in gps antenna points.......................   141
      read in gps profiles.............................     8
      stored control point records ....................     1



      PHOTO GROUPS AND PHOTO CONNECTIONS
      ----------------------------------
      photo group   1 has   1 photo
      photo group   2 has   9 photos
      photo group   3 has  10 photos
      photo group   4 has  14 photos
      photo group   5 has  18 photos
      photo group   6 has  23 photos
      photo group   7 has  11 photos
      photo group   8 has  10 photos
      photo group   9 has  10 photos
      photo group  10 has  15 photos
      photo group  11 has  13 photos

      COMPUTATION OF INITIAL VALUES OF EXTERIOR ORIENTATION PARAMETERS
      ----------------------------------------------------------------

      dimensions of submatrices    = ( 120 ,120 )
      dimensions of address matrix = (  50 , 11 )
      maximum number of photos/submatrix    =  30

      initial iteration step
      ----------------------

      number of hyperrows     =    8
      number of hypercolumns =     2



      COMPUTATION OF ADJUSTED TERRAIN COORDINATES
      -------------------------------------------

      dimensions of submatrices    = ( 120 ,120 )
      dimensions of address matrix = (  50 , 11 )
      maximum number of photos/submatrix    =  20

      standard deviations for image points in x and y (in image system)
      default set :    8.000

      standard deviations for control points (in terrain system)
                        planimetry    height
      1. set :               0.500     0.500


      iteration step no.   1
      ------------------
      iteration step with gps

      number of hyperrows     =   10
      number of hypercolumns =     3
      plus 1 column border part for gps

      maximum change of exterior orientation parameters :
      da,db,dc = parameters of rodrigues-matrix
      px,py,pz = coordinates of perspective centers (in terrain system)

                  da =0.071653              px =   400.079
                  db =0.056277              py =   610.326
                  dc =0.023223              pz =   320.768

      maximum change of adjusted terrain coordinates (in terrain system) :

            in x at point-no.          8357        174.224
            in y at point-no.          8346        127.800
            in z at point-no.          8359        367.114

      sigma reached =      53.3994  (in image system)


      iteration step no.   2
      ------------------
```

```
iteration step with gps

number of hyperrows     =   10
number of hypercolumns  =    3
plus 1 column border part for gps

maximum change of exterior orientation parameters :
da,db,dc = parameters of rodrigues-matrix
px,py,pz = coordinates of perspective centers (in terrain system)

            da =0.001674              px =      6.876
            db =0.001138              py =     11.595
            dc =0.001026              pz =     16.521

maximum change of adjusted terrain coordinates (in terrain system) :

      in x at point-no.          805179          5.024
      in y at point-no.            8358         14.081
      in z at point-no.            7320         23.980

sigma reached =       7.3681  (in image system)


iteration step no.   3
------------------
iteration step with gps

number of hyperrows     =   10
number of hypercolumns  =    3
plus 1 column border part for gps

maximum change of exterior orientation parameters :
da,db,dc = parameters of rodrigues-matrix
px,py,pz = coordinates of perspective centers (in terrain system)

            da =0.000003              px =      0.028
            db =0.000003              py =      0.031
            dc =0.000002              pz =      0.033

maximum change of adjusted terrain coordinates (in terrain system) :

      in x at point-no.            7320          0.036
      in y at point-no.            7320          0.044
      in z at point-no.            7320          0.104


end of adjustment  --  due to condition 2


STATISTICS
----------

 1-fold points          =    2
 2-fold points          =   40
 3-fold points          =  102
 4-fold points          =   34
 5-fold points          =   92
 6-fold points          =   64
 7-fold points          =   13
 8-fold points          =   16
 9-fold points          =   10
number of block points =  373


number of observations = 3789
number of unknowns     = 1971
redundancy             = 1818


number of outliers for image observations   =    0
number of outliers for control observations =    0
number of outliers for gps observations     =    0

ROOT MEAN SQUARE VALUES AND CHECK VALUES OF RESIDUALS OF PHOTOGRAMMETRIC OBSERVATIONS
-------------------------------------------------------------------------------------
                  image system     terrain system        image system

image points
------------
obs x = 1677  rms x =      5.25   rms x =     0.258   chv vx =     15.75
obs y = 1677  rms y =      5.53   rms y =     0.272   chv vy =     16.60

ROOT MEAN SQUARE VALUES AND CHECK VALUES OF RESIDUALS OF NON-PHOTOGRAMMETRIC OBSERVATIONS
-----------------------------------------------------------------------------------------
                  image system     terrain system      terrain system

control points with sds-no.  1
---------------------------
obs x =   11  rms x =     12.72   rms x =     0.626   chv vx =      1.88
obs y =   11  rms y =      3.45   rms y =     0.170   chv vy =      0.51
obs z =   11  rms z =      2.97   rms z =     0.146   chv vz =      0.44

ROOT MEAN SQUARE VALUES AND CHECK VALUES OF RESIDUALS OF GPS OBSERVATIONS
-------------------------------------------------------------------------
                                   terrain system      terrain system

gps observations with sds-no.  1
-----------------------------
obs x =  114                      rms x =     0.069   chv vx =      0.21
obs y =  114                      rms y =     0.064   chv vy =      0.19
obs z =  114                      rms z =     0.084   chv vz =      0.25
```

```
gps observations with sds-no.  2
------------------------------
obs x =   20                    rms x =    0.101  chv vx =    0.30
obs y =   20                    rms y =    0.077  chv vy =    0.23
obs z =   20                    rms z =    0.126  chv vz =    0.38


SIGMA NAUGHT      7.46         =    0.367
------------


COORDINATES OF CONTROL POINTS AND RESIDUALS
-------------------------------------------
in units of terrain system


horizontal control points
                                             code of point
point-no.       x            y               input -> used           rx          ry    sds check

   25     -69873.014    -15726.485          HV 1                    -0.110       0.007    1   .  .
   26     -72653.385     -1847.868          HV 4                    -0.315       0.114    1   .  .
   27     -73912.981     20027.308          HV 4                    -0.130      -0.114    1   .  .
   28     -71645.884     29937.296          HV 2                     0.301       0.157    1   .  .
   29     -31262.676     29465.355          HV 3                     0.222       0.105    1   .  .
   42     -31772.848     22556.965          HV 3                    -1.438       0.027    1   .  .
   43     -35590.100     13370.653          HV 6                     0.661      -0.454    1   .  .
   45     -47988.815     -4332.370          HV 4                     1.094       0.205    1   .  .
   46     -36058.591    -12463.704          HV 4                    -0.546      -0.019    1   .  .
   52      -8939.231     -4353.436          HV 2                     0.121       0.036    1   .  .
   53        415.646    -14504.899          HV 1                     0.140      -0.065    1   .  .



vertical control points
                                             code of point
point-no.                    z               input -> used                        rz    sds check

   25                     66.104             HV 1                                 -0.044    1      .
   26                     56.264             HV 4                                 -0.200    1      .
   27                     14.268             HV 4                                  0.183    1      .
   28                      3.531             HV 2                                 -0.102    1      .
   29                    339.449             HV 3                                 -0.150    1      .
   42                    363.035             HV 3                                  0.152    1      .
   43                    366.988             HV 6                                  0.092    1      .
   45                    292.006             HV 4                                  0.060    1      .
   46                    360.655             HV 4                                  0.205    1      .
   52                    468.576             HV 2                                 -0.220    1      .
   53                    464.971             HV 1                                  0.025    1      .


COORDINATES OF GPS OBSERVATIONS AND RESIDUALS
---------------------------------------------
in units of terrain system

gps antenna offset     x` =  0.105    y` = -0.052    z` =  1.000

photo-no.       x              y              z              t                rx          ry          rz       sds
check

profile-no.          1

drift parameters:

linear       -0.1688        -0.0098        -0.0881
constant      -1.466         -1.217         -3.273

   123    -78566.205     25038.444      7456.547      -10.000            -0.019       0.022       0.060     1
   124    -74353.755     24916.163      7520.086       -9.000             0.028      -0.052      -0.163     1
   125    -69985.952     24832.733      7557.225       -8.000            -0.084      -0.002       0.034     1
   126    -65685.480     24946.498      7607.267       -7.000             0.078       0.002      -0.004     1
   127    -61386.897     25159.625      7644.941       -6.000            -0.049      -0.020       0.081     1
   128    -57125.905     25294.712      7673.961       -5.000             0.106       0.008      -0.026     1
   129    -52888.725     25391.237      7701.685       -4.000            -0.066      -0.050       0.038     1
   130    -48580.838     25410.509      7747.435       -3.000            -0.018       0.138       0.137     1
   131    -44271.107     25469.260      7776.496       -2.000            -0.043       0.043       0.037     1
   132    -40009.354     25427.532      7801.253       -1.000             0.068      -0.053      -0.053     1
   133    -35721.641     25373.195      7836.523        0.000            -0.116       0.000      -0.002     1
   134    -31423.699     25306.192      7857.927        1.000             0.082       0.044      -0.217     1
   135    -27168.362     25279.023      7872.440        2.000            -0.011      -0.134       0.033     1
   136    -22849.379     25262.108      7875.777        3.000             0.054       0.051      -0.068     1
   137    -18542.600     25226.054      7905.117        4.000             0.017      -0.041       0.132     1
   138    -14310.300     25229.861      7913.269        5.000             0.058      -0.021      -0.085     1
   139    -10017.830     25183.120      7921.204        6.000            -0.028       0.031      -0.045     1
   140     -5729.935     25164.722      7933.350        7.000             0.108       0.095       0.003     1
   141     -1516.490     25109.986      7946.054        8.000            -0.143       0.036       0.151     1
   142      2761.679     25142.519      7950.689        9.000            -0.020      -0.098      -0.044     1
   143      6987.560     25179.862      7941.128       10.000           --  not in the block --
profile-no.          2

drift parameters:

linear        0.1724        -0.0518         0.0381
constant      -1.224         -0.464         -1.966

   178      8543.075     16693.950      7960.769      -10.000           --  not in the block --
   179      4059.090     16699.093      7953.096       -9.000             0.022       0.025       0.073     1
   180      -560.887     16702.310      7961.492       -8.000             0.065      -0.024       0.047     1
   181     -4941.058     16696.488      7948.622       -7.000             0.013      -0.003      -0.059     1
```

```
   182     -9235.134     16592.427      7952.623          -6.000          -0.032     -0.009     -0.060    1
   183    -13547.668     16501.302      7950.324          -5.000           0.042     -0.013      0.020    1
   184    -17835.560     16382.392      7956.384          -4.000          -0.088      0.005      0.046    1
   185    -22233.221     16463.188      7924.061          -3.000           0.007      0.031     -0.031    1
   186    -26491.969     16630.639      7921.692          -2.000          -0.013     -0.053      0.121    1
   187    -30768.853     16786.618      7893.474          -1.000           0.001     -0.023     -0.161    1
   188    -35217.046     16699.903      7858.480           0.000          -0.044     -0.051     -0.114    1
   189    -39545.033     16665.009      7844.879           1.000          -0.083      0.046      0.004    1
   190    -43824.916     16596.708      7811.134           2.000           0.050     -0.008      0.090    1
   191    -48353.309     16554.704      7791.409           3.000           0.013      0.104     -0.013    1
   192    -52995.060     16298.696      7734.866           4.000           0.052      0.005     -0.012    1
   193    -57666.693     16157.822      7702.102           5.000          -0.049      0.052      0.031    1
   194    -62166.467     16266.393      7664.521           6.000          -0.005      0.030      0.051    1
   195    -66681.418     16296.990      7617.950           7.000          -0.019     -0.059     -0.022    1
   196    -71130.073     16370.468      7558.388           8.000          -0.025     -0.019     -0.142    1
   197    -75512.347     16427.223      7513.696           9.000           0.124      0.016      0.046    1
   198    -79952.737     16375.776      7450.970          10.000          -0.029     -0.051      0.085    1

profile-no.         3

drift parameters:

linear        0.0617       -0.1002       -0.0348
constant     -0.658        -0.382        -1.643

   321      5816.414      -516.035      7958.421         -10.000          -0.059     -0.112     -0.044    1
   322      1634.519      -570.693      7971.268          -9.000          -0.131      0.028     -0.008    1
   323     -2500.111      -566.281      7958.203          -8.000           0.096     -0.104      0.035    1
   324     -6608.515      -489.599      7970.686          -7.000          -0.007      0.110      0.030    1
   325    -10764.164      -417.480      7970.656          -6.000           0.061      0.050      0.033    1
   326    -14902.739      -362.904      7966.823          -5.000           0.099      0.141     -0.005    1
   327    -19061.990      -311.403      7939.938          -4.000          -0.072     -0.072      0.029    1
   328    -23298.433      -160.503      7939.409          -3.000           0.068      0.078      0.008    1
   329    -27660.347       -12.912      7900.345          -2.000           0.084     -0.049     -0.046    1
   330    -31981.207         0.354      7890.328          -1.000           0.070     -0.061      0.048    1
   331    -36105.329       -27.476      7858.423           0.000          -0.042     -0.060      0.009    1
   332    -40184.958      -148.971      7851.677           1.000          -0.085      0.026     -0.033    1
   333    -44515.857      -286.283      7818.017           2.000          -0.078     -0.022     -0.013    1
   334    -48956.445      -441.754      7790.699           3.000           0.037      0.079     -0.056    1
   335    -53487.104      -526.004      7757.925           4.000          -0.020     -0.018      0.026    1
   336    -57721.478      -512.191      7718.998           5.000          -0.021      0.085     -0.115    1
   337    -61979.500      -520.623      7674.765           6.000          -0.062     -0.080     -0.066    1
   338    -66309.297      -498.673      7628.093           7.000           0.012      0.029      0.013    1
   339    -70584.885      -519.313      7574.253           8.000          -0.093     -0.074      0.148    1
   340    -74776.728      -488.542      7549.418           9.000           0.124      0.091     -0.004    1
   341    -79040.146      -467.151      7501.405          10.000           0.020     -0.065      0.011    1

profile-no.         4

drift parameters:

linear       -0.0776        0.1044        0.1510
constant     -0.216        -1.005        -1.680

   342    -77952.467     -9077.516      7494.911          -9.500           0.013     -0.015     -0.010    1
   343    -73780.027     -9093.068      7544.361          -8.500          -0.043      0.027      0.176    1
   344    -69531.483     -9092.706      7572.026          -7.500           0.021     -0.071     -0.158    1
   345    -65149.735     -9067.537      7618.682          -6.500           0.013      0.042      0.172    1
   346    -60804.510     -9065.521      7670.594          -5.500          -0.030     -0.009     -0.042    1
   347    -56463.709     -9036.005      7710.780          -4.500           0.026      0.002      0.054    1
   348    -52125.665     -9035.353      7747.685          -3.500          -0.021     -0.026     -0.089    1
   349    -47757.989     -9023.061      7770.593          -2.500           0.008      0.039     -0.082    1
   350    -43393.332     -9032.601      7804.834          -1.500          -0.004      0.026      0.023    1
   351    -39039.765     -9024.771      7834.281          -0.500           0.001      0.019     -0.063    1
   352    -34694.267     -8997.559      7861.437           0.500           0.009     -0.091     -0.048    1
   353    -30270.919     -8897.112      7874.739           1.500           0.040      0.044     -0.024    1
   354    -25797.340     -8753.670      7908.501           2.500          -0.027      0.007      0.050    1
   355    -21203.592     -8738.039      7938.454           3.500           0.063      0.051      0.018    1
   356    -16712.863     -8743.664      7948.807           4.500          -0.084     -0.010      0.048    1
   357    -12251.996     -8826.586      7948.550           5.500           0.100      0.105     -0.156    1
   358     -7821.681     -8855.935      7969.727           6.500          -0.116     -0.079      0.032    1
   359     -3490.317     -8884.586      7972.269           7.500           0.039     -0.061     -0.065    1
   360       801.683     -8991.916      7962.211           8.500          -0.018     -0.051     -0.058    1
   361      5116.233     -9031.377      7940.727           9.500           0.012      0.053      0.222    1

profile-no.         5

drift parameters:

linear        0.2039       -0.0238       -0.0348
constant     -0.080        -0.940        -1.214

   386    -72923.520     31025.990      7499.593          -5.500          -0.031      0.032      0.049    1
   387    -72966.595     26630.275      7512.199          -4.500           0.083     -0.094     -0.029    1
   388    -72931.521     22165.239      7531.481          -3.500          -0.014      0.101     -0.027    1
   389    -72824.904     17742.295      7536.635          -2.500          -0.004     -0.080     -0.100    1
   390    -72661.732     13290.348      7534.562          -1.500          -0.157      0.039      0.020    1
   391    -72504.236      8781.570      7534.544          -0.500           0.203      0.051      0.120    1
   392    -72468.084      4340.464      7554.806           0.500          -0.065      0.007      0.027    1
   393    -72577.034       -18.617      7540.037           1.500          -0.053     -0.079     -0.058    1
   394    -72740.838     -4221.486      7534.671           2.500          -0.021     -0.001      0.007    1
   395    -72691.802     -8455.593      7539.615           3.500           0.098     -0.008      0.010    1
   396    -72663.592    -12679.000      7538.294           4.500          -0.037      0.032     -0.021    1
   397    -72481.192    -16883.344      7550.050           5.500          --  not in the block --

profile-no.         6

drift parameters:

linear       -0.1373        0.0007       -0.1603
constant     -0.631        -0.602        -2.004

   575    -40320.907    -16840.130      7745.599          -5.500          --  not in the block --
   576    -40338.101    -12720.260      7753.026          -4.500          -0.057      0.074      0.160    1
   577    -40345.943     -8544.834      7759.908          -3.500           0.024     -0.106     -0.142    1
   578    -40330.215     -4141.718      7768.351          -2.500           0.059     -0.059      0.018    1
```

```
   579    -40385.034      337.619      7757.403          -1.500          0.024      0.152      0.093    1
   580    -40393.959     4823.263      7759.366          -0.500         -0.022     -0.039     -0.102    1
   581    -40348.337     9304.085      7768.467           0.500          0.017     -0.075     -0.093    1
   582    -40302.780    13800.462      7777.175           1.500         -0.114      0.155      0.044    1
   583    -40318.358    18324.714      7752.586           2.500          0.092     -0.171     -0.070    1
   584    -40378.740    22877.744      7734.383           3.500         -0.072      0.056     -0.073    1
   585    -40460.117    27447.630      7728.202           4.500          0.086      0.017      0.141    1
   586    -40502.572    32049.583      7681.710           5.500         -0.037     -0.003      0.024    1

profile-no.         7

drift parameters:

linear        0.3717       0.1032       0.3382
constant      -1.826       -0.008       -1.660

   600       162.260    33865.337      7806.527          -6.000        --  not in the block --
   601       140.524    29702.435      7827.018          -5.000          0.016     -0.015      0.118    1
   602       211.700    25470.963      7824.035          -4.000          0.176     -0.082     -0.159    1
   603       197.438    21271.516      7849.363          -3.000         -0.113      0.061     -0.038    1
   604       206.052    17073.784      7836.942          -2.000         -0.053     -0.007      0.041    1
   605       236.699    12789.308      7862.774          -1.000         -0.111      0.098      0.068    1
   606       189.371     8619.339      7891.397           0.000         -0.065     -0.080     -0.064    1
   607       228.727     4459.043      7888.806           1.000          0.044      0.115      0.049    1
   608       231.763      231.391      7891.567           2.000          0.152     -0.085      0.099    1
   609       207.929    -3904.628      7889.045           3.000         -0.074      0.022     -0.050    1
   610       185.049    -8067.526      7880.619           4.000          0.044      0.015     -0.216    1
   611       168.183   -12190.800      7871.824           5.000         -0.015     -0.042      0.152    1
   612       146.418   -16438.859      7832.432           6.000        --  not in the block --
```

```
profile-no.         8   LIGHTNING RIDGE BASE STATION TRAJECTORY

drift parameters:

linear        0.0955       0.0103      -0.0082
constant      -1.983       -1.330       -0.790

  9038      7974.698     8111.174      8120.778         -10.000        --  not in the block --
  9039      3581.233     8090.820      8119.601          -9.000         -0.085      0.140     -0.043    2
  9040      -754.408     8005.568      8126.235          -8.000          0.303     -0.034     -0.299    2
  9041     -5063.358     8029.979      8122.059          -7.000         -0.074     -0.109      0.063    2
  9042     -9417.367     8067.825      8114.565          -6.000         -0.001      0.053      0.128    2
  9043    -13760.394     8184.267      8111.028          -5.000         -0.126     -0.007     -0.038    2
  9044    -17947.451     8208.037      8097.027          -4.000         -0.088     -0.041     -0.143    2
  9045    -22114.739     8300.773      8085.683          -3.000         -0.029      0.031      0.156    2
  9046    -26548.867     8372.606      8066.185          -2.000         -0.072     -0.046      0.154    2
  9047    -30999.093     8446.182      8048.468          -1.000          0.037     -0.133      0.162    2
  9048    -35240.897     8527.546      8022.224           0.000         -0.009     -0.023      0.031    2
  9049    -39264.998     8565.907      8002.055           1.000          0.106      0.193     -0.073    2
  9050    -43305.409     8619.925      7973.238           2.000          0.069     -0.089      0.018    2
  9051    -47389.539     8524.705      7949.085           3.000          0.019      0.042      0.073    2
  9052    -51723.120     8375.947      7909.607           4.000         -0.010     -0.010     -0.112    2
  9053    -56150.143     8099.776      7876.490           5.000          0.008      0.006      0.012    2
  9054    -60601.984     7928.509      7831.320           6.000         -0.042      0.021      0.002    2
  9055    -65017.642     7942.524      7789.192           7.000          0.135      0.068      0.053    2
  9056    -69428.347     7862.092      7740.005           8.000         -0.145     -0.059      0.019    2
  9057    -73829.838     7933.109      7690.952           9.000         -0.065      0.039      0.105    2
  9058    -78332.522     8108.555      7641.405          10.000          0.071     -0.040     -0.267    2
```

```
COORDINATES AND RESIDUALS OF CRITICAL POINTS
--------------------------------------------
arranged by increasing point numbers


photo-no.      x            y              rx          ry     sds check


               point-no.              46   HV 4

 352      -28474.0     -71272.2          6.1         0.8     0   .  .
 576        3494.6     -83900.2          1.7         4.6     0   .  .
 351       60461.2     -72221.0         16.3         2.5     0   1  .
 577      -79563.4     -86101.4         -4.6        10.9     0   .  .

 HO    -36058.591   -12463.704       -0.546      -0.019     1   .  .
 VE                    360.655                    0.205     1      .

               point-no.              47


               point-no.            4142   TP 7

 604      -79613.4      52998.5        -11.4        -8.5     0   .  .
 141       90376.2     -80593.7          2.2       -15.1     0   .  .
 179       30339.5     -90144.0         -1.1         2.5     0   .  .
 602       92976.2      56053.3         -9.0       -11.2     0   .  .
 603        3944.4      51530.1         -9.7        -7.5     0   .  .
 180      -65593.6     -86662.3         -6.4         7.3     0   .  .
 142        -557.7     -86168.2         18.3        -5.9     0   2  .

               point-no.            5188   TP 8

9048        9837.4     -77754.3         20.8        11.7     0   4  .
 188        6752.7      85927.7        -18.1         0.9     0   2  .
9049      -72204.4     -77329.1         37.4         6.8     0   9  .
 581       65364.7     -91939.1          7.5       -10.3     0   .  .
 582      -29551.7     -99152.9         18.6        -8.9     0   2  .
 187       98720.0      99928.4        -12.8         5.1     0   .  .
```

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 9047       97948.5     -82219.4          12.2       -3.4   0  .  .
  189      -80716.8      87197.8         -18.0        1.1   0  2  .

              point-no.          6284   TP 6

  323       64810.1     -85305.1          10.7       -1.9   0  .  .
  325     -103996.5     -87214.5           8.5       -5.7   0  .  .
 9040      101615.5      82811.8          -8.8       16.8   0  .  1
 9042      -72472.9      85275.7          -8.7       -4.0   0  .  .
 9041       11566.0      84423.4          -6.0       -8.8   0  .  .
  324      -18509.3     -85932.0           4.5        4.9   0  .  .

              point-no.          6869   TP 8

 9057      -75331.8      94792.1          -5.9        6.4   0  .  .
 9055      101456.5      88543.5         -15.1       17.8   0  .  1
  393      -66204.1      49762.5          -3.1        4.4   0  .  .
  392       22228.5      48620.9          -7.0       -2.0   0  .  .
  339      -14130.4     -81262.8           6.4       -7.3   0  .  .
  338       71313.4     -77120.0           3.7       -1.7   0  .  .
  340     -100253.1     -77395.2          15.7        1.7   0  .  .
 9056       18646.5      88517.7          -2.3       -5.4   0  .  .

              point-no.          8350   TP 4

  351      -90180.8     -96143.7           7.4        3.7   0  .  .
  576      -16262.6      67208.5          -9.3       17.9   0  .  1
  349       90668.6     -99457.0           2.9        4.0   0  .  .
  350        -871.8     -95756.6           7.6        2.0   0  .  .


              point-no.        123602   TP 4

  602        3849.4      93891.0          -5.0        5.8   0  .  .
  142       39505.8        341.4         -16.1      -15.4   0  1  .
  603      -83784.7      91197.0          -0.9        7.4   0  .  .
  601       94155.3      95079.3          -9.4        2.8   0  .  .

              point-no         123603   TP 4

  602       82459.4      98815.0         -15.0       -0.5   0  .  .
  604      -89274.5      95793.3           0.3       -6.2   0  .  .
  142       41810.5     -76921.2           2.6      -18.8   0  .  2
  603       -5638.2      93836.3          -3.7        3.7   0  .  .

              point-no.        123604   TP 4

  604       -1676.3     100259.3           0.5        1.4   0  .  .
  603       80608.9      96981.0           8.9      -10.1   0  .  .
  179      -20514.8     -14551.2         -16.5       -4.1   0  1  .
  605      -94713.1      92605.6          -5.9       -8.2   0  .  .

              point-no.        204142   TP 5

  141       84856.8       4882.2          21.1      -12.4   0  4  .
  602        5630.6      49335.8          -3.6      -12.7   0  .  .
  603      -83164.1      46886.7         -10.0      -11.9   0  .  .
  601       93895.5      50312.8          -1.1      -22.5   0  .  4
  142       -4433.4       -128.6          26.7       -2.3   0  7  .

              point-no.        205179   TP 5

  180      -96832.9       1424.2          17.8        5.8   0  2  .
  604       11003.0      81842.7           0.9       11.5   0  .  .
  603       93073.1      78921.4          -6.6        2.2   0  .  .
  179       -3026.5      -1090.9          11.6        0.6   0  .  .
  605      -81899.8      74643.8           0.3       15.8   0  .  .

              point-no.        222582   TP 9

 9048      101087.2    -111115.5         -16.3      -26.8   0  1  7
  582         863.5      -3922.4          -8.4        6.4   0  .  .
 9050      -64389.7     -96663.1          15.7       -8.0   0  .  .
  188      100317.8      59685.7         -15.0       -1.8   0  .  .
  583      -91703.1        719.1          -0.3       13.2   0  .  .
 9049       18270.4    -112759.2           0.4      -11.4   0  .  .
  190      -72916.2      53253.1           2.4       12.4   0  .  .
  581       93948.6       2175.3         -17.2       -8.2   0  1  .
  189       13136.4      58502.7          -1.2        7.7   0  .  .

              point-no.        223605   TP 9

  180      -15633.2      83292.2          -6.6       -2.7   0  .  .
  606      -84760.2      -5020.5           4.8       -7.7   0  .  .
  604       91684.9      -2816.3           5.7      -14.2   0  .  .
  181     -102258.4      80108.4          -3.1       -0.4   0  .  .
 9041      -97442.8     -95955.8          -6.8       -8.8   0  .  .
 9040      -16578.7     -93351.2         -11.6        1.3   0  .  .
  605        -404.8      -7856.0          -3.6      -19.0   0  .  2
 9039       70915.5     -93709.4         -14.9        8.5   0  .  .
  179       74558.8      80841.5           1.5       -3.7   0  .  .

              point-no.        321391   TP 5

  392      -90185.2    -101724.7           3.4       12.8   0  .  .
  391       -2328.1     -96591.5           5.1        2.3   0  .  .
 9057       64473.9     -22182.0          21.8      -10.5   0  4  .
 9058      -25585.9     -16285.5          -3.9       -2.4   0  .  .
  390       88491.7     -91386.5           3.4        2.3   0  .  .

              point-no.        321392   TP 5

 9057       69314.6      60703.9         -18.1       -5.5   0  2  .
 9058      -20122.1      65984.7          -6.6      -10.4   0  .  .
  391       83925.3    -100784.2           4.0       -5.1   0  .  .
  393      -91658.2     -99858.6           5.0      -10.3   0  .  .
```

```
      392      -4729.7   -102411.1          7.5       -7.4    0  .  .

              point-no.          322583   TP 5

      583      13822.5     98894.5         -2.4        0.3    0  .  .
      191     -68691.6    -49182.0         -2.0       -4.5    0  .  .
      584     -75564.7     89371.0         -5.3        8.6    0  .  .
      190      27001.4    -47416.8         10.4       -8.6    0  .  .
      582     103202.0     92324.2         -5.9      -17.2    0  .  1

              point-no.          323605   TP 9

     9040      73597.0    -90382.4         -6.4      -17.7    0  .  1
      180      76027.7     92789.2         -6.3        0.5    0  .  .
      605       8760.0   -101702.4          8.9       -2.8    0  .  .
     9041      -8207.4    -89064.8          1.9       -2.4    0  .  .
      181     -10619.5     86835.6         -0.4       -3.1    0  .  .
      606     -76403.6    -97309.6         16.7       -6.5    0  1  .
      604      98924.5    -96067.7         -1.0        1.8    0  .  .
      182     -97761.6     79261.0         -0.2       -0.3    0  .  .
     9042    -100462.7    -86851.1          2.5       -2.3    0  .  .

              point-no.          907322   TP 7

      608     -79848.8     39331.4        -17.6        9.5    0  2  .
     9040     -49868.8     81596.0         -2.1        1.7    0  .  .
     9039      36637.8     82236.5          0.2        6.6    0  .  .
      322      -4430.3    -97361.9         11.9       15.7    0  .  .
      607       9417.2     33942.7        -23.1        7.9    0  5  .
      323     -89653.6    -98052.3          0.1       11.6    0  .  .

END OF EXECUTION : 03-FEB-99 13:53:47

PATB-GPS END
```

Appendix D

Comparison between Appendix B (original observations) and Appendix C (new run 6 trajectory) adjusted image point coordinates after aerial triangulation.

```
PROGRAM: COMPARE                 COMPARES DATA SETS                    3-Feb-99

                               COMPARISON OF COMMON POINTS
                                                                  DIFFERENCES
  LABEL          X                  Y                   Z          X     Y      Z      XY

     25   -69873.105323   -15726.615257          66.123019   -.02   .14   -.06    .14
     26   -72653.628543    -1847.959969          56.027574   -.07   .21    .04    .22
     27   -73912.796973    20027.373631          14.399656   -.31  -.18    .05    .36
     28   -71645.449793    29937.637148           3.454872   -.13  -.18   -.03    .23
     29   -31262.166368    29465.464108         339.364990   -.29   .00   -.07    .29
     42   -31773.999051    22557.019281         363.232425   -.29  -.03   -.05    .29
     43   -35589.266177    13370.365738         367.217248   -.17  -.17   -.14    .24
     45   -47987.462573    -4332.365880         292.014753   -.26   .20    .05    .33
     46   -36058.966495   -12463.992370         360.915363   -.17   .27   -.06    .32
     52    -8938.641382    -4353.609741         468.445810   -.47   .21   -.09    .51
     53      416.035251   -14505.163069         465.066509   -.25   .20   -.07    .32
   3085   -78011.417944    29609.542507         -70.636316   -.27  -.12    .11    .30
   3086   -74203.131025    29440.409432         -24.931152   -.21  -.20    .14    .29
   3087   -70885.135376    29433.110468          13.762367   -.21  -.27    .11    .34
   3088   -66155.951461    29127.545400          66.321605   -.24  -.43    .21    .50
   3089   -61813.697808    28825.133752         110.880923   -.34  -.53    .26    .63
   3091   -54278.557112    29579.797010         179.485676   -.55  -.52    .19    .76
   3092   -50148.925273    29273.398103         216.012100   -.64  -.42    .12    .77
   3093   -46578.118978    29262.859265         243.822536   -.67  -.28    .00    .73
   3094   -41810.562126    29050.493314         279.258896   -.62  -.12   -.11    .63
   3095   -37430.543534    29420.406930         304.997786   -.54   .00   -.19    .54
   3096   -32961.256030    29440.008937         330.285467   -.36   .06   -.19    .37
   3097   -29149.942012    29884.539006         346.593129   -.31  -.03   -.03    .31
   3098   -24484.279595    29098.079844         370.636337   -.34  -.12    .09    .36
   3099   -20203.314950    29713.492574         385.248233   -.42  -.14    .08    .44
   3100   -15653.190811    28909.305749         405.099657   -.46  -.04   -.07    .46
   3101   -11507.011903    29022.779337         413.591329   -.43   .06   -.23    .43
   3102    -7518.924266    29046.256519         421.127248   -.34   .14   -.32    .37
   3103    -2529.736976    28665.278254         426.506670   -.23   .15   -.25    .27
   3104     1197.528629    28447.904819         428.168259   -.18   .22   -.14    .28
   4123   -79244.259347    21209.133472         -55.049362   -.41  -.18    .00    .44
   4125   -70660.836609    20476.016012          49.586400   -.38  -.26    .12    .46
   4126   -65994.625290    20802.313793          99.319871   -.40  -.39    .09    .56
   4127   -61469.030138    20385.153395         147.176933   -.43  -.49    .06    .66
   4128   -57182.363490    20810.670641         187.235209   -.45  -.49    .08    .67
   4129   -52564.467277    20707.060159         227.909814   -.48  -.45    .05    .66
   4130   -48179.965522    20741.915107         264.233183   -.51  -.39   -.03    .64
   4131   -43847.183770    21245.030866         294.225034   -.51  -.28   -.10    .58
   4132   -39664.984941    20850.792728         323.247132   -.47  -.19   -.15    .50
   4133   -35490.780294    20976.880480         348.571734   -.41  -.09   -.14    .42
   4134   -31762.079290    20810.928986         368.547048   -.36  -.04   -.09    .36
   4135   -26582.473318    20802.692237         393.534149   -.38   .03    .03    .38
   4136   -22644.657320    21009.283642         408.826488   -.38   .00    .04    .38
   4137   -18214.640333    20593.538917         426.241427   -.39  -.04   -.09    .39
   4138   -13788.511301    20594.338303         439.234494   -.35  -.06   -.23    .36
   4139    -9823.987468    20673.212509         447.111768   -.28  -.08   -.39    .29
   4140    -5256.925960    20612.010254         453.669207   -.15  -.09   -.51    .17
   4141    -1465.816597    20190.463255         458.655973   -.03  -.03   -.52    .05
   4142     2810.469051    20938.360712         465.007284    .10   .11   -.43    .15
   5125   -71010.273663    11940.572945          65.966121   -.47  -.11    .36    .48
   5179     4060.314767    12663.615788         471.975165    .30   .51    .65    .59
   5182    -9353.207153    12074.166014         467.269700   -.25  -.60  -1.05    .65
   5183   -13586.131285    11912.671184         458.661322   -.36   .01   -.24    .36
   5184   -18069.879002    11900.069689         446.562980   -.60  -.14   -.34    .62
   5185   -22276.207076    12249.108501         431.879627   -.44   .26    .22    .51
   5186   -26719.345382    12006.758305         413.688988   -.68   .16   -.21    .70
   5187   -30679.371136    12632.024463         393.648096   -.27  -.17   -.41    .33
   5188   -35689.701039    12354.949636         367.394417    .45  -.17   -.37    .48
   5189   -39320.922405    12628.968022         346.243985   -.65   .07    .52    .65
   5190   -43843.332815    11897.423560         315.472297   -.44  -.29    .26    .52
   5191   -48270.683301    12896.947422         281.811284   -.64  -.68   -.07    .94
   5192   -53210.948220    12158.329349         241.695625   -.44  -.14    .60    .46
   5193   -57722.288477    11583.233169         203.309619   -.43  -.28    .50    .51
   5194   -62702.536180    12145.998806         153.809245   -.74  -.83   -.33   1.11
```

5195	-67355.906095	11830.487072	106.278694	-.60	-.44	.13	.74
5196	-71010.113208	11940.618735	66.027579	-.34	-.26	.23	.43
5197	-76153.527722	12334.473170	6.174094	-.28	-.03	.57	.28
5198	-78230.279988	12362.944367	-19.499795	-.46	-.61	-.21	.77
6267	-79017.550620	3934.051799	-20.930171	.45	-.13	.72	.47
6268	-73924.972793	12257.899859	32.547027	-.37	.10	.46	.38
6269	-68449.788849	11916.858065	94.704576	-.90	-.33	.21	.96
6270	-64602.658792	3067.370479	144.418446	.04	-.16	.32	.16
6271	-60399.744148	3490.072064	185.055367	-.35	.06	.01	.36
6272	-56473.632156	3404.594609	222.249640	-.63	-.11	.08	.64
6273	-51582.346187	3405.624071	264.820568	-.06	1.08	-1.39	1.08
6274	-48531.372296	3949.336447	289.861775	-.28	.05	-.10	.29
6275	-44205.692236	3922.848585	322.231121	-.70	.29	-.16	.76
6278	-31756.619680	4069.577374	397.223417	-.51	.25	.16	.57
6279	-27207.425841	4456.324369	419.114670	-.38	1.26	-.77	1.32
6280	-22705.901723	3782.012197	437.841457	-.50	.29	.29	.58
6281	-18533.279368	3878.018373	452.430394	-.73	.57	.03	.93
6282	-14139.014939	3540.064462	468.736861	-.36	.41	.17	.55
6283	-10069.152758	4277.870454	480.239318	-.36	.18	.25	.41
6284	-5611.278132	3736.592280	480.401351	-.94	.28	.12	.98
6285	-1465.370084	3397.201642	482.079956	-.39	.37	-.08	.54
6286	3725.028950	3816.056713	483.543052	-.93	-.25	.92	.97
6287	7860.473148	3495.665743	479.009558	-1.75	-.72	1.99	1.89
6868	-74215.295475	3756.044682	37.248344	.22	-.32	.73	.39
6869	-69745.322123	3236.186358	88.821095	-.16	.42	-.34	.45
7320	9520.725289	-5176.030635	473.930437	-.85	.57	.15	1.03
7321	5474.663027	-4437.804892	478.715761	-.77	.39	.17	.86
7322	1072.233055	-4869.116742	480.249684	-.66	.31	.09	.73
7323	-3267.243734	-5002.925603	480.216689	-.62	.28	-.05	.68
7324	-7775.884541	-4865.543428	469.154668	-.61	.28	-.06	.67
7325	-11526.650599	-5120.121340	462.567857	-.59	.33	-.03	.68
7326	-16076.053616	-4358.243315	453.761655	-.57	.43	.03	.71
7327	-20292.717667	-3973.968030	443.594430	-.53	.52	.05	.74
7328	-23253.924712	-4526.288820	431.951975	-.51	.55	.01	.75
7329	-27113.021800	-4736.368143	416.468200	-.46	.60	-.07	.76
7330	-30714.425136	-4072.610544	401.145154	-.45	.53	.01	.70
7331	-35288.007551	-5299.285313	375.602723	-.38	.39	.07	.54
7332	-39152.747928	-4302.851440	353.525082	-.38	.31	.07	.49
7333	-44086.197175	-4150.534803	320.214876	-.35	.23	.08	.42
7334	-48254.089693	-4938.842104	288.709800	-.30	.24	.05	.38
7335	-52606.219484	-4356.244660	252.577895	-.29	.26	.02	.39
7336	-57103.617746	-4784.238948	213.228855	-.25	.23	.15	.34
7337	-61678.575055	-4813.961778	170.537840	-.20	.24	.18	.32
7338	-65592.007014	-5166.689844	130.349544	-.14	.26	.12	.29
7339	-70083.568504	-5319.537908	83.332467	-.10	.26	.10	.28
7340	-74411.302794	-4407.833316	34.396263	-.06	.24	.18	.25
7341	-78507.001050	-4677.409578	-15.432216	-.06	.34	.10	.35
7727	-73915.568288	20024.229635	13.977455	-.40	-.22	.05	.46
7728	-71649.447669	29937.886718	2.323093	-.21	-.25	.15	.33
7751	-14224.759431	4534.750311	464.784355	-.47	.39	.14	.61
7752	-8940.693526	-4354.226318	466.801117	-.59	.30	-.06	.66
8343	-73608.543678	-13039.221478	31.980886	-.10	.29	.16	.31
8344	-69517.187069	-13524.792447	76.857248	-.11	.28	.12	.30
8345	-65025.247080	-13031.087923	126.213161	-.10	.27	.10	.29
8346	-60974.907850	-13366.732522	166.338548	-.21	.40	.33	.45
8347	-56593.377067	-13258.524278	204.646737	-.28	.33	.22	.43
8348	-52137.587485	-13218.053025	243.403344	-.30	.26	.10	.40
8349	-48661.399912	-13416.612354	271.585100	-.29	.24	.07	.38
8350	-43406.229975	-13554.560325	310.083682	-.27	.28	.09	.39
8351	-39457.088795	-12426.069913	339.689626	-.26	.30	.03	.40
8353	-30474.633408	-12869.672543	391.349792	-.30	.59	.21	.66
8354	-25609.319052	-12811.258816	420.385978	-.46	.67	.24	.81
8355	-21492.098179	-12785.692610	432.895484	-.60	.65	.22	.88
8356	-17437.984022	-12431.245598	438.205870	-.69	.52	.12	.87
8357	-12951.112357	-13345.688010	447.577738	-.74	.35	-.04	.81
8358	-8480.480646	-12886.130330	456.445733	-.66	.20	-.19	.69
8359	-4119.471041	-13525.797768	478.569354	-.54	.15	-.24	.56
8360	241.356497	-12982.560057	464.683985	-.45	.31	-.09	.55
8361	5021.674261	-12977.043867	465.095242	-.44	.49	.03	.66
41342	-48788.026371	-3636.864810	286.963589	-.29	.25	.07	.38
41357	-33494.644531	15680.911729	372.915677	-.24	-.11	-.21	.27
101326	-6642.232626	-8199.694031	472.174199	-.61	.31	-.13	.68
104128	-57507.879494	29505.105761	149.736564	-.46	-.57	.26	.73
121386	-68488.252057	31043.541783	33.002464	-.14	-.31	.00	.35
121387	-68531.879450	26909.982857	50.412110	-.28	-.32	.01	.42
121388	-68312.262299	22342.205498	69.215730	-.37	-.34	.00	.50
121389	-67803.280334	18167.464241	87.724454	-.43	-.31	.00	.53
121390	-67501.300927	13109.000389	102.377541	-.62	-.23	.23	.66
121391	-67557.867032	9228.332909	108.213193	-1.00	.12	.77	1.01

121392	-67408.688094	4255.375432	114.159502	-.09	.44	-.20	.45
121393	-67597.755496	-174.250454	113.861449	-.07	.27	-.08	.28
121394	-67628.741550	-4472.461265	110.492665	-.13	.26	.05	.29
121395	-67931.316850	-8468.186767	102.789879	-.12	.27	.02	.29
121396	-68242.683241	-13027.807164	91.329740	-.12	.28	.08	.30
122576	-35450.166916	-12552.195301	363.507883	-.24	.37	.07	.44
122577	-35410.805577	-8029.915202	371.407862	-.32	.38	.07	.50
122578	-35399.247136	-3958.707533	376.306508	-.40	.39	.06	.56
122579	-35576.646876	808.814181	377.403008	-.54	.36	.15	.65
122580	-35594.005255	4750.455220	376.829460	-.84	.12	.57	.85
122581	-35711.151151	9460.045955	371.811372	-.74	.10	.77	.75
122582	-35847.949677	14012.031638	362.958745	-.21	-.19	-.17	.28
122583	-35700.906501	18075.020161	355.450376	-.34	-.14	-.13	.37
122584	-35739.020892	22977.318041	340.011494	-.41	-.09	-.18	.42
122585	-36048.407549	27369.604610	321.684662	-.46	.00	-.25	.46
123601	4894.544419	29386.877392	423.633982	-.22	.30	.04	.37
123602	4775.541638	25181.973951	439.066990	-.05	.31	-.18	.31
123603	4890.707599	21385.059061	462.290510	.15	.21	-.34	.25
123604	5041.161968	17137.884769	471.540216	.50	-.09	-.71	.51
123605	5102.872712	12884.897758	481.182382	1.26	-.63	-1.42	1.41
123606	4885.797402	8621.936432	490.040919	-.59	-.82	.74	1.01
123607	4507.108689	4411.881004	489.278694	-.90	-.04	.61	.90
123608	4677.364623	181.222768	495.172080	-.90	.18	.46	.92
123609	4381.239822	-3699.250331	492.487919	-.75	.37	.18	.84
123610	4244.628937	-8105.206511	474.768207	-.61	.45	.06	.76
123611	4756.537779	-12163.010996	466.815383	-.47	.48	.00	.67
204123	-78237.367086	25081.956356	-54.623180	-.32	-.17	.16	.36
204124	-74275.459117	24832.217398	-6.727400	-.30	-.23	.09	.37
204125	-69742.542484	24528.005692	45.792328	-.32	-.31	.09	.44
204126	-65602.770578	24865.829764	89.277598	-.33	-.38	.17	.51
204127	-61503.670698	25386.072931	128.656875	-.38	-.44	.21	.58
204128	-57044.804265	24962.572982	173.915417	-.46	-.44	.21	.64
204129	-53484.017058	25226.971705	204.544784	-.53	-.41	.19	.67
204130	-48780.469498	25256.715628	243.481225	-.58	-.33	.07	.67
204131	-43976.762198	25709.289360	278.573386	-.58	-.22	-.08	.62
204132	-39997.856477	25262.201430	306.712377	-.52	-.14	-.17	.53
204133	-35225.512432	25481.707225	334.151427	-.41	-.05	-.22	.42
204134	-31342.604437	25569.160817	355.145068	-.35	-.04	-.11	.35
204135	-27373.230716	25340.408868	373.672120	-.34	-.05	.01	.35
204136	-22643.167025	25318.809276	396.036621	-.38	-.07	.05	.39
204137	-18587.752093	25052.124016	410.971991	-.41	-.05	-.04	.42
204138	-14411.941790	25364.032977	421.859170	-.41	-.02	-.18	.41
204139	-9745.088666	24936.991059	433.803256	-.33	.02	-.34	.33
204140	-5836.945636	25363.369280	437.375646	-.24	.07	-.41	.25
204141	-1924.974093	25111.607339	441.212785	-.14	.11	-.38	.18
204142	2609.868606	25154.015473	444.122218	-.07	.24	-.24	.25
205179	4144.701639	16535.880982	471.863444	.43	-.13	-.71	.45
205181	-5568.442928	16342.738251	464.599203	-.16	-.22	-.69	.27
205182	-9371.349406	16780.959597	458.752893	-.30	-.16	-.54	.34
205183	-13584.776691	16675.392411	449.750300	-.40	-.11	-.32	.41
205184	-18085.920762	16399.877885	437.888914	-.46	-.06	-.19	.46
205185	-22055.107468	16076.095751	424.846145	-.44	.01	.01	.44
205186	-26549.264066	16501.580525	405.296410	-.38	.05	.03	.39
205187	-30761.274987	16953.911103	384.472063	-.31	-.03	-.07	.31
205188	-35426.461440	16485.507326	361.145686	-.27	-.15	-.17	.31
205189	-39443.911558	16637.372527	336.724449	-.40	-.25	-.15	.47
205190	-44145.511717	16515.962597	304.555614	-.45	-.34	-.02	.56
205191	-48343.359454	16600.818777	274.088082	-.50	-.42	.06	.65
205192	-52958.299744	16545.412224	235.863399	-.46	-.44	.17	.63
205193	-57582.659859	16290.775744	195.816991	-.46	-.46	.15	.65
205194	-62231.168549	16165.503373	150.837214	-.50	-.47	-.01	.68
205195	-66846.176647	16008.084088	103.265865	-.51	-.35	.14	.62
205196	-71055.704636	16328.845832	56.479525	-.43	-.25	.28	.50
205197	-75057.118603	16339.471763	10.238001	-.36	-.21	.26	.42
205198	-79784.647215	16330.086313	-46.876588	-.38	-.27	.11	.47
206267	-78515.246288	8522.674005	-17.462443	-.16	1.61	.89	1.62
206268	-74133.444920	8407.206366	35.204137	-.04	.13	.60	.13
206269	-69468.811387	7574.834230	89.275234	-.16	-.06	.07	.17
206270	-64812.995294	7705.016870	138.843470	-.28	.06	-.04	.29
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206272	-55679.610010	7801.953076	226.240705	.04	.25	1.26	.25
206273	-52121.100510	7587.224019	256.794211	-.22	.64	.16	.68
206274	-47113.571738	8218.177097	296.594572	-1.40	-1.25	-.06	1.88
206275	-43223.159824	8438.204046	325.628503	-.25	.88	.83	.91
206276	-39132.452479	8324.478077	352.252017	-.81	.26	.51	.85
206277	-34871.539344	8034.360362	377.928472	-1.15	-.54	.93	1.27
206278	-30903.311687	7900.698151	399.463190	-1.23	1.28	.41	1.78
206279	-26745.408456	8200.992282	418.531993	-2.32	-.02	.27	2.32
206280	-22377.231485	7417.937074	437.284489	-.51	.02	1.16	.51

206281	-18305.683506	7519.645701	450.698350	-.06	.04	1.04	.07
206282	-13886.349502	7747.572747	463.074294	-.85	.45	.53	.96
206283	-9295.306523	7421.527099	477.601538	.38	.09	.40	.39
206284	-4913.410678	7805.591723	478.828879	-.15	-.44	.35	.47
206286	3770.242836	7856.599050	479.014509	-1.05	-.79	1.24	1.32
207321	5547.168475	-643.205192	480.629636	-.88	.30	.45	.92
207322	1650.044622	-462.855261	498.554093	-.71	.25	.32	.75
207323	-2690.489045	-592.737538	481.042437	-.63	.30	.03	.70
207324	-6813.432520	-437.488681	485.284187	-.62	.29	.07	.69
207325	-10498.874796	-159.394181	467.487978	-.56	.30	.14	.64
207326	-15089.820755	-427.890648	459.058029	-.54	.40	.06	.67
207327	-18876.842605	-278.842900	450.234678	-.53	.45	.08	.69
207328	-23483.642022	-21.027286	434.773779	-.48	.49	.08	.68
207329	-27566.920632	-57.159114	418.147923	-.50	.56	-.19	.75
207330	-31792.428353	-2.862794	397.323692	-.53	.47	-.06	.71
207331	-35653.927223	216.199049	376.547114	-.55	.36	.17	.65
207332	-40007.026648	-481.871502	349.708655	-.46	.28	.15	.54
207333	-44430.038229	-94.320919	320.374337	-.41	.21	.14	.46
207335	-53565.408756	-276.160248	248.076831	-.30	.25	-.21	.39
207336	-57991.203479	-188.417121	208.713092	-.28	.18	.11	.33
207337	-61726.001797	-628.353977	172.586117	-.22	.19	.11	.29
207338	-66594.773720	-335.722908	124.324407	-.15	.23	-.03	.27
207339	-70281.608382	-403.382483	83.928692	-.08	.24	.02	.25
207340	-74731.065845	-173.424149	31.915738	.02	.18	.33	.19
207341	-79287.926808	-46.212168	-23.547337	.27	.32	.46	.41
207384	-48902.050656	-506.602626	286.778216	-.31	.23	-.02	.39
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208343	-74366.598457	-8798.870884	29.862394	-.08	.29	.16	.30
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208345	-65018.338131	-9020.422976	133.353085	-.12	.29	.09	.31
208346	-60885.657394	-9133.331947	173.592484	-.21	.30	.26	.37
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208358	-7588.856702	-9097.644921	469.378308	-.62	.30	-.14	.69
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221390	-72493.444566	13481.121146	46.414701	-.43	-.16	.34	.46
221391	-72300.264793	9113.293539	55.740004	-.40	.10	.63	.41
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221393	-72151.110317	-13.459752	62.323527	-.07	.22	.12	.23
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221395	-72522.613974	-8275.841610	52.465147	-.09	.28	.12	.29
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222582	-40240.596740	13871.133654	337.260294	-.40	-.78	-.74	.88
222583	-39894.959074	18268.451039	329.307393	-.44	-.24	-.12	.50
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222585	-40386.478618	27469.072158	295.031074	-.56	-.10	-.17	.57
223601	174.005927	30160.097894	421.439641	-.23	.20	-.11	.30
223602	194.795636	25670.408779	439.270751	-.12	.18	-.29	.21
223603	4.230179	21377.694697	455.620845	-.01	.04	-.52	.04
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223605	17.408214	12700.671354	476.613734	-.02	-.53	-.96	.53
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223607	-128.871663	4186.521103	483.021909	-.67	.13	.53	.69
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323606    -4525.187651    9010.441159    478.808227  -.30  -.08  -.08   .31
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323610    -4501.238850   -7806.084217    472.899557  -.60   .27  -.12   .66
323611    -4685.118009  -12107.622376    469.470877  -.56   .18  -.26   .59
722586   -44488.876377   32027.812472    246.887726  -.73  -.14  -.03   .75
805179     4060.590440   12665.232460    473.022285   .49  -.60  -.85   .78
822586   -35979.899643   32087.031724    301.424934  -.59   .08  -.15   .59
904129   -52949.052588   30114.915637    188.009527  -.60  -.53   .21   .80
904130   -48975.103496   29169.828330    225.907203  -.66  -.38   .09   .76
904131   -44078.266409   29881.294581    259.574939  -.68  -.17  -.09   .70
904132   -39639.651170   30100.672546    288.074667  -.60  -.03  -.18   .60
904133   -35138.162046   29879.437839    316.082002  -.46   .08  -.26   .47
904135   -26883.887246   30006.888849    356.117720  -.33  -.08   .05   .34
904136   -22471.438215   30218.584074    374.136635  -.38  -.16   .12   .41
904137   -18626.307516   29918.960737    391.086584  -.43  -.11   .04   .45
904138   -13949.065960   29758.599989    405.754934  -.45   .00  -.14   .45
904139    -9969.452967   29699.301069    414.079206  -.40   .11  -.29   .41
904140    -5670.065361   29990.391098    418.823055  -.32   .17  -.31   .36
904141    -1259.264272   29904.373423    422.115303  -.24   .18  -.19   .30
904142     3029.122954   29674.248969    422.519523  -.21   .26  -.03   .34
904187   -30669.100076   21484.843484    372.269953  -.38  -.01  -.05   .38
905179     4062.581369   21299.516360    464.939129   .14   .17  -.39   .22
905197   -74839.491305   20894.412929       .060965  -.36  -.20   .10   .41
906270   -64792.388002   12294.904207    132.311428  -.61  -.50  -.19   .79
906271   -60987.807372   12404.127717    170.439533  -.64  -.63  -.08   .90
906272   -56058.380004   12097.577176    217.658640  -.40  -.62   .16   .74
906273   -51935.674334   12630.907394    251.871109  -.25  -.57  -.01   .62
907321     5554.439593    3952.832943    481.823194  -.81   .10   .46   .82
907322     1942.295424    3979.381528    485.543577  -.75  -.04   .63   .75
907335   -52735.490916    4343.226599    254.605776  -.25   .61  -.69   .65
907336   -57955.097538    4452.678138    207.884729  -.13  -.07   .21   .14
907337   -62206.191851    3645.895409    168.049416  -.29   .31  -.22   .42
907338   -66627.422560    4060.312655    122.885539  -.28   .13  -.15   .31
908354   -25081.711507   -4390.625719    424.632278  -.49   .58   .03   .76
922586   -40345.942372   32003.656519    275.135753  -.67  -.04  -.09   .67

                                         MIN      : -2.32 -1.25 -1.42   .04
                                         MEAN     :  -.38   .05   .05   .53
                                         MAX      :  1.26  1.61  1.99  2.32
                                         RANGE    :  3.58  2.86  3.41  2.28

                                         STD DEVS:    .48   .35   .36   .60
                                         STD DEV VECTOR:          .70
```

Appendix E

PATB-GPS aerial triangulation results using new photography for run 6. Antenna station coordinates based on Bathurst base station trajectory (un-fixed ambiguities). New results for run 6 are listed under profile 8.

```
1
    PATB-GPS :                        COPYRIGHT :  H.KLEIN/F.ACKERMANN 1988-1994

    BLOCK ADJUSTMENT WITH BUNDLES                                REVISION Jun-94

    PROJECT  : Range test 1
    USER-ID. : gd

    START OF EXECUTION : 03-FEB-99 14:24:52

    ***************************************************************************
    ***************************************************************************
    **                                                                       **
    ** PROGRAM VERSION  PATB-GPS                                             **
    ** ========================                                              **
    **                                                                       **
    ** DIRECTORY FOR INPUT AND OUTPUT FILES :  PRESENT WORKING DIRECTORY     **
    ** INPUT                                                                 **
    ** BASIC DATA                                         FROM FILE rt5.bas  **
    ** PHOTOGRAPHS                                        FROM FILE rt5.obs  **
    ** CONTROL POINTS                                     FROM FILE gd5.ctl  **
    **                                                                       **
    ** INITIAL VALUES FOR EXTERIOR ORIENTATION PARAMETERS ARE CALCULATED     **
    **                                                                       **
    ** WITHOUT AUTOMATIC GROSS ERROR DETECTION                               **
    ** NO CORRECTION OF SYSTEMATIC ERRORS                                    **
    ** ADJUSTMENT WITH GPS-OBSERVATIONS                                      **
    **            WITH DETERMINATION OF GPS-DRIFT PARAMETERS                 **
    **            NO DETERMINATION OF GPS-ANTENNA OFFSET                     **
    ** NO INVERSION OF NORMAL EQUATIONS                                      **
    **                                                                       **
    ** ITERATION SEQUENCE WILL BE TERMINATED :                               **
    ** 1. IF 10 ITERATION STEPS ARE PERFORMED                                **
    ** 2. IF CHANGE OF ADJUSTED TERRAIN COORDINATES                          **
    **    BETWEEN TWO ITERATION STEPS FOR ALL POINTS       <     0.300       **
    **    IN THE TERRAIN SYSTEM                                              **
    ** 3. IF CHANGE OF SIGMA LESS THAN 0.001%                                **
    ** 4. IF SIGMA DOES NOT CONFIRM WITH READ IN STANDARD DEVIATIONS         **
    ** 5. IF THE RMS-VALUE OF OBSERVATIONS DIVERGES                          **
    **                                                                       **
    ** INPUT FORMATS AND INPUT SEQUENCES :                                   **
    ** PHOTOGRAPH NUMBERS          (I10,F10.3,I5)                            **
    ** PHOTOGRAPH POINTS           (I10,2F10.1,i5)                           **
    ** SEQUENCE OF READ IN COORDINATES OF PHOTO POINTS             = X Y **
    ** HORIZONTAL CONTROL          (I8,2f15.3,15x,i5)                        **
    ** SEQUENCE OF READ IN COORDINATES OF HORIZONTAL CONTROL POINTS   = X Y **
    ** VERTICAL CONTROL            (I8,30x,f15.3,i5)                         **
    ** GPS-OBSERVATIONS            (I8,3f15.3,f8.0,i5)                       **
    **                                                                       **
    ** READ IN IMVK                                        =   25            **
    **                                                                       **
    ** LIMITATIONS                                                           **
    ** NUMBER OF POINTS IN ONE PHOTO          RESTRICTED TO   60             **
    ** NUMBER OF CONTROL POINTS IN ONE LIST   RESTRICTED TO  750             **
    ** NUMBER OF PHOTOS IN ONE PHOTO GROUP    RESTRICTED TO   60             **
    ** DIMENSIONS OF ADDRESS MATRIX           RESTRICTED TO   50,10          **
    ** NUMBER OF PHOTOS/SUBMATRIX             RESTRICTED TO   20             **
    ** NUMBER OF DIFFERENT FOCAL LENGTHS      RESTRICTED TO   30             **
    ** NUMBER OF POINT RECORDS                RESTRICTED TO  165             **
    ** NUMBER OF PHOTO RECORDS                RESTRICTED TO   60             **
    **                                                                       **
    ** REQUIRED WORKING AREA FOR THESE SPECIFICATIONS    =  108670           **
    ** REQUIRED SCRATCH FILE : BLKSZ = 8192 BYTES,  BLOCKS=    8316           **
    **                                                                       **
    ** BREAK UP LIMIT FOR THE SIZE OF PHOTO GROUPS        =   60             **
    **                                                                       **
    ** PHOTO NUMBERS OF THE FIRST PHOTO GROUP :                              **
    **                                      FIRST READ IN PHOTOGRAPH ASSUMED **
    ** NUMBER OF PHOTOS IN THE FIRST PHOTO GROUP          =    1             **
    **                                                                       **
    ** FOCAL LENGTH IN UNITS OF IMAGE SYSTEM AND CORRESPONDING FL-NUMBER     **
    ** NUMBER OF FOCAL LENGTHS                            =    0             **
    **                                                                       **
    ** SIZE OF PHOTOGRAPHS IN UNITS OF IMAGE SYSTEM                          **
    **   IN X :      230000.000    IN Y :      230000.000                    **
    **                                                                       **
    ** STANDARD DEVIATIONS OF OBSERVATIONS :                                 **
    **                                                                       **
    **    FOR IMAGE POINTS IN X AND Y IN UNITS OF IMAGE SYSTEM               **
    **    DEFAULT SET (SDS NO. 0 OR BLANK) :          8.000                  **
    **                                                                       **
    **    FOR CONTROL POINTS IN UNITS OF TERRAIN SYSTEM                      **
    **                                       PLANIMETRY   HEIGHT             **
    **    1.SET FOR CONTROL POINTS          :       0.500     0.500          **
    **                                                                       **
    **    FOR GPS OBSERVATIONS IN UNITS OF TERRAIN SYSTEM                    **
    **                                       PLANIMETRY   AND HEIGHT         **
    **    1.SET FOR GPS OBSERVATIONS          :      0.250                   **
    **    2.SET FOR GPS OBSERVATIONS          :      0.250                   **
    **                                                                       **
    **                                                                       **
```

```
** COMMON OFFSET FROM CAMERA TO GPS ANTENNA :                                 **
**                           0.105          -0.052           1.000            **
**                          IN UNITS OF TERRAIN SYSTEM                        **
**                                                                            **
** PRINTOUT                                                                   **
** COORDINATES OF CONTROL POINTS AND RESIDUALS                                **
** COORDINATES AND RESIDUALS OF CRITICAL POINTS IN SEQUENCE                   **
**                                                                            **
** ADDITIONAL OUTPUT                                                          **
** ADJUSTED TERRAIN COORDINATES IN SEQUENCE       ON FILE rt5.fvl             **
** EXTERIOR ORIENTATION PARAMETERS                ON FILE rt5.ori             **
**                                                                            **
********************************************************************************
********************************************************************************


        read in image points ...........................  1718
        stored unsorted point records ..................    33
        read in photographs ............................   134
        stored unsorted photo records ..................     3
        read in horizontal control points ..............    71
        read in vertical control points ................    71
        read in gps antenna points......................   141
        read in gps profiles............................     8
        stored control point records ...................     1



        PHOTO GROUPS AND PHOTO CONNECTIONS
        ----------------------------------
        photo group   1 has   1 photo
        photo group   2 has   9 photos
        photo group   3 has  10 photos
        photo group   4 has  14 photos
        photo group   5 has  18 photos
        photo group   6 has  23 photos
        photo group   7 has  11 photos
        photo group   8 has  10 photos
        photo group   9 has  10 photos
        photo group  10 has  15 photos
        photo group  11 has  13 photos

        COMPUTATION OF INITIAL VALUES OF EXTERIOR ORIENTATION PARAMETERS
        -----------------------------------------------------------------

        dimensions of submatrices     = ( 120 ,120 )
        dimensions of address matrix = (  50 , 11 )
        maximum number of photos/submatrix     =  30

        initial iteration step
        ----------------------

        number of hyperrows     =     8
        number of hypercolumns =     2


        COMPUTATION OF ADJUSTED TERRAIN COORDINATES
        -------------------------------------------

        dimensions of submatrices     = ( 120 ,120 )
        dimensions of address matrix = (  50 , 11 )
        maximum number of photos/submatrix     =  20

        standard deviations for image points in x and y (in image system)
        default set :    8.000

        standard deviations for control points (in terrain system)
                           planimetry    height
        1. set :                0.500      0.500


        iteration step no.   1
        ------------------
        iteration step with gps

        number of hyperrows     =    10
        number of hypercolumns =     3
        plus 1 column border part for gps

        maximum change of exterior orientation parameters :
        da,db,dc = parameters of rodrigues-matrix
        px,py,pz = coordinates of perspective centers (in terrain system)

                   da =0.071653                px =   400.088
                   db =0.056279                py =   610.345
                   dc =0.023221                pz =   320.750

        maximum change of adjusted terrain coordinates (in terrain system) :

              in x at point-no.             8357        174.215
              in y at point-no.             8346        127.810
              in z at point-no.             8359        367.089

        sigma reached =      53.3999  (in image system)


        iteration step no.   2
        ------------------
        iteration step with gps

        number of hyperrows     =    10
```

```
number of hypercolumns =    3
plus 1 column border part for gps

maximum change of exterior orientation parameters :
da,db,dc = parameters of rodrigues-matrix
px,py,pz = coordinates of perspective centers (in terrain system)

            da =0.001674              px =     6.876
            db =0.001138              py =    11.598
            dc =0.001026              pz =    16.523

maximum change of adjusted terrain coordinates (in terrain system) :

      in x at point-no.         805179         5.024
      in y at point-no.           8358        14.081
      in z at point-no.           7320        23.978

sigma reached =       7.3709  (in image system)


iteration step no.   3
------------------
iteration step with gps

number of hyperrows    =   10
number of hypercolumns =    3
plus 1 column border part for gps

maximum change of exterior orientation parameters :
da,db,dc = parameters of rodrigues-matrix
px,py,pz = coordinates of perspective centers (in terrain system)

            da =0.000003              px =     0.028
            db =0.000003              py =     0.031
            dc =0.000002              pz =     0.033

maximum change of adjusted terrain coordinates (in terrain system) :

      in x at point-no.           7320         0.036
      in y at point-no.           7320         0.044
      in z at point-no.           7320         0.104


end of adjustment  --  due to condition 2


STATISTICS
----------

 1-fold points         =    2
 2-fold points         =   40
 3-fold points         =  102
 4-fold points         =   34
 5-fold points         =   92
 6-fold points         =   64
 7-fold points         =   13
 8-fold points         =   16
 9-fold points         =   10
number of block points =  373


number of observations = 3789
number of unknowns     = 1971
redundancy             = 1818


number of outliers for image observations   =    0
number of outliers for control observations =    0
number of outliers for gps observations     =    0

ROOT MEAN SQUARE VALUES AND CHECK VALUES OF RESIDUALS OF PHOTOGRAMMETRIC OBSERVATIONS
-------------------------------------------------------------------------------------
                  image system     terrain system        image system

image points
------------
obs x = 1677  rms x =      5.25   rms x =     0.258   chv vx =     15.76
obs y = 1677  rms y =      5.53   rms y =     0.272   chv vy =     16.59

ROOT MEAN SQUARE VALUES AND CHECK VALUES OF RESIDUALS OF NON-PHOTOGRAMMETRIC OBSERVATIONS
-----------------------------------------------------------------------------------------
                  image system     terrain system      terrain system

control points with sds-no.  1
---------------------------
obs x =   11  rms x =     12.75   rms x =     0.627   chv vx =      1.88
obs y =   11  rms y =      3.45   rms y =     0.170   chv vy =      0.51
obs z =   11  rms z =      3.02   rms z =     0.148   chv vz =      0.45

ROOT MEAN SQUARE VALUES AND CHECK VALUES OF RESIDUALS OF GPS OBSERVATIONS
-------------------------------------------------------------------------
                                   terrain system      terrain system

gps observations with sds-no.  1
-----------------------------
obs x =  114                      rms x =     0.068   chv vx =      0.21
obs y =  114                      rms y =     0.065   chv vy =      0.19
obs z =  114                      rms z =     0.084   chv vz =      0.25

gps observations with sds-no.  2
-----------------------------
obs x =   20                      rms x =     0.100   chv vx =      0.30
```

```
obs y =   20                      rms y =    0.078   chv vy =      0.23
obs z =   20                      rms z =    0.132   chv vz =      0.40


SIGMA NAUGHT     7.47          =    0.367
------------


COORDINATES OF CONTROL POINTS AND RESIDUALS
-------------------------------------------
in units of terrain system


horizontal control points
                                        code of point
point-no.      x              y         input -> used          rx          ry    sds check

   25    -69873.014    -15726.485        HV 1              -0.113       0.006    1   .  .
   26    -72653.385     -1847.868        HV 4              -0.319       0.116    1   .  .
   27    -73912.981     20027.308        HV 4              -0.121      -0.111    1   .  .
   28    -71645.884     29937.296        HV 2               0.305       0.156    1   .  .
   29    -31262.676     29465.355        HV 3               0.214       0.102    1   .  .
   42    -31772.848     22556.965        HV 3              -1.443       0.025    1   .  .
   43    -35590.100     13370.653        HV 6               0.659      -0.455    1   .  .
   45    -47988.815     -4332.370        HV 4               1.093       0.205    1   .  .
   46    -36058.591    -12463.704        HV 4              -0.554      -0.016    1   .  .
   52     -8939.231     -4353.436        HV 2               0.131       0.039    1   .  .
   53       415.646    -14504.899        HV 1               0.147      -0.066    1   .  .


vertical control points
                                        code of point
point-no.                     z         input -> used                      rz    sds check

   25                      66.104        HV 1                          -0.045    1      .
   26                      56.264        HV 4                          -0.208    1      .
   27                      14.268        HV 4                           0.183    1      .
   28                       3.531        HV 2                          -0.101    1      .
   29                     339.449        HV 3                          -0.152    1      .
   42                     363.035        HV 3                           0.154    1      .
   43                     366.988        HV 6                           0.105    1      .
   45                     292.006        HV 4                           0.063    1      .
   46                     360.655        HV 4                           0.201    1      .
   52                     468.576        HV 2                          -0.225    1      .
   53                     464.971        HV 1                           0.026    1      .


COORDINATES OF GPS OBSERVATIONS AND RESIDUALS
---------------------------------------------
in units of terrain system

gps antenna offset    x` =  0.105   y` = -0.052   z` =  1.000

photo-no.     x             y              z              t               rx          ry          rz     sds
check

profile-no.         1

drift parameters:

linear      -0.1675       -0.0120        -0.0874
constant     -1.467        -1.222         -3.272

  123    -78566.193    25038.427      7456.553       -10.000          -0.019       0.022       0.057    1
  124    -74353.743    24916.149      7520.092        -9.000           0.027      -0.051      -0.167    1
  125    -69985.942    24832.721      7557.230        -8.000          -0.085      -0.001       0.032    1
  126    -65685.471    24946.488      7607.270        -7.000           0.079       0.003      -0.004    1
  127    -61386.890    25159.617      7644.944        -6.000          -0.048      -0.019       0.081    1
  128    -57125.898    25294.706      7673.963        -5.000           0.107       0.008      -0.026    1
  129    -52888.720    25391.234      7701.686        -4.000          -0.065      -0.051       0.039    1
  130    -48580.834    25410.508      7747.436        -3.000          -0.019       0.138       0.140    1
  131    -44271.105    25469.261      7776.496        -2.000          -0.045       0.042       0.041    1
  132    -40009.352    25427.535      7801.252        -1.000           0.069      -0.054      -0.046    1
  133    -35721.640    25373.200      7836.522         0.000          -0.116      -0.001       0.000    1
  134    -31423.700    25306.200      7857.925         1.000           0.082       0.043      -0.217    1
  135    -27168.364    25279.034      7872.438         2.000          -0.012      -0.135       0.033    1
  136    -22849.382    25262.121      7875.774         3.000           0.052       0.050      -0.069    1
  137    -18542.604    25226.069      7905.112         4.000           0.016      -0.041       0.131    1
  138    -14310.306    25229.878      7913.264         5.000           0.058      -0.021      -0.086    1
  139    -10017.837    25183.139      7921.198         6.000          -0.028       0.031      -0.046    1
  140     -5729.943    25164.743      7933.343         7.000           0.109       0.095       0.001    1
  141     -1516.499    25110.010      7946.047         8.000          -0.142       0.037       0.149    1
  142      2761.668    25142.545      7950.681         9.000          -0.020      -0.097      -0.044    1
  143      6987.548    25179.890      7941.119        10.000        --  not in the block --
profile-no.         2

drift parameters:

linear       0.1724       -0.0523         0.0363
constant     -1.232        -0.462         -1.959

  178      8543.082    16693.943      7960.745       -10.000        --  not in the block --
  179      4059.097    16699.087      7953.073        -9.000           0.023       0.026       0.076    1
  180      -560.880    16702.304      7961.471        -8.000           0.064      -0.022       0.045    1
  181     -4941.052    16696.483      7948.603        -7.000           0.013      -0.005      -0.065    1
  182     -9235.127    16592.422      7952.605        -6.000          -0.033      -0.014      -0.069    1
  183    -13547.661    16501.298      7950.308        -5.000           0.043      -0.014       0.017    1
  184    -17835.553    16382.388      7956.371        -4.000          -0.088       0.003       0.041    1
```

```
  185    -22233.214     16463.184     7924.049       -3.000          0.007     0.030    -0.033   1
  186    -26491.962     16630.636     7921.682       -2.000         -0.015    -0.054     0.121   1
  187    -30768.846     16786.616     7893.466       -1.000          0.003    -0.024    -0.159   1
  188    -35217.038     16699.901     7858.473        0.000         -0.041    -0.050    -0.106   1
  189    -39545.026     16665.007     7844.874        1.000         -0.082     0.051     0.018   1
  190    -43824.909     16596.708     7811.131        2.000          0.046    -0.006     0.100   1
  191    -48353.302     16554.704     7791.407        3.000          0.011     0.107    -0.004   1
  192    -52995.053     16298.696     7734.866        4.000          0.053     0.005    -0.008   1
  193    -57666.685     16157.822     7702.104        5.000         -0.049     0.055     0.035   1
  194    -62166.460     16266.394     7664.524        6.000         -0.006     0.031     0.052   1
  195    -66681.410     16296.992     7617.955        7.000         -0.020    -0.060    -0.025   1
  196    -71130.065     16370.470     7558.395        8.000         -0.027    -0.023    -0.151   1
  197    -75512.339     16427.225     7513.705        9.000          0.125     0.012     0.035   1
  198    -79952.729     16375.779     7450.980       10.000         -0.027    -0.051     0.081   1

profile-no.        3

drift parameters:

linear       0.0631       -0.0973       -0.0367
constant    -0.662        -0.384        -1.631

  321      5816.432      -516.004     7958.390      -10.000         -0.057    -0.115    -0.038   1
  322      1634.536      -570.664     7971.239       -9.000         -0.131     0.025    -0.004   1
  323     -2500.095      -566.255     7958.176       -8.000          0.097    -0.105     0.034   1
  324     -6608.501      -489.577     7970.660       -7.000         -0.007     0.112     0.027   1
  325    -10764.151      -417.460     7970.633       -6.000          0.061     0.052     0.028   1
  326    -14902.727      -362.887     7966.802       -5.000          0.098     0.144    -0.011   1
  327    -19061.979      -311.389     7939.918       -4.000         -0.073    -0.069     0.021   1
  328    -23298.424      -160.492     7939.391       -3.000          0.068     0.081    -0.001   1
  329    -27660.340       -12.904     7900.329       -2.000          0.084    -0.045    -0.052   1
  330    -31981.201         0.359     7890.314       -1.000          0.070    -0.061     0.050   1
  331    -36105.325       -27.474     7858.411        0.000         -0.041    -0.061     0.015   1
  332    -40184.955      -148.971     7851.667        1.000         -0.086     0.023    -0.021   1
  333    -44515.855      -286.287     7818.009        2.000         -0.079    -0.027    -0.001   1
  334    -48956.444      -441.761     7790.693        3.000          0.034     0.075    -0.046   1
  335    -53487.105      -526.013     7757.920        4.000         -0.021    -0.022     0.032   1
  336    -57721.480      -512.203     7718.996        5.000         -0.020     0.084    -0.113   1
  337    -61979.503      -520.639     7674.765        6.000         -0.061    -0.080    -0.066   1
  338    -66309.302      -498.691     7628.095        7.000          0.012     0.030     0.009   1
  339    -70584.891      -519.334     7574.256        8.000         -0.094    -0.071     0.141   1
  340    -74776.736      -488.566     7549.423        9.000          0.125     0.092    -0.011   1
  341    -79040.155      -467.178     7501.413       10.000          0.021    -0.064     0.008   1

profile-no.        4

drift parameters:

linear      -0.0788        0.1057        0.1518
constant    -0.216        -0.995        -1.667

  342    -77952.477     -9077.513     7494.905       -9.500          0.013    -0.015    -0.012   1
  343    -73780.037     -9093.066     7544.355       -8.500         -0.043     0.027     0.172   1
  344    -69531.492     -9092.706     7572.019       -7.500          0.020    -0.071    -0.160   1
  345    -65149.742     -9067.538     7618.674       -6.500          0.013     0.042     0.172   1
  346    -60804.516     -9065.523     7670.585       -5.500         -0.030    -0.009    -0.044   1
  347    -56463.714     -9036.008     7710.770       -4.500          0.027     0.002     0.055   1
  348    -52125.669     -9035.358     7747.675       -3.500         -0.021    -0.026    -0.087   1
  349    -47757.992     -9023.067     7770.582       -2.500          0.007     0.038    -0.078   1
  350    -43393.333     -9032.608     7804.822       -1.500         -0.005     0.026     0.029   1
  351    -39039.765     -9024.780     7834.268       -0.500          0.001     0.019    -0.057   1
  352    -34694.266     -8997.568     7861.423        0.500          0.008    -0.091    -0.046   1
  353    -30270.916     -8897.123     7874.725        1.500          0.039     0.044    -0.024   1
  354    -25797.337     -8753.683     7908.486        2.500         -0.029     0.007     0.050   1
  355    -21203.588     -8738.053     7938.438        3.500          0.062     0.051     0.016   1
  356    -16712.857     -8743.679     7948.790        4.500         -0.085    -0.010     0.047   1
  357    -12251.989     -8826.602     7948.533        5.500          0.100     0.105    -0.158   1
  358     -7821.673     -8855.953     7969.709        6.500         -0.115    -0.079     0.030   1
  359     -3490.307     -8884.605     7972.250        7.500          0.041    -0.061    -0.067   1
  360       801.693     -8991.936     7962.191        8.500         -0.018    -0.051    -0.059   1
  361      5116.244     -9031.399     7940.706        9.500          0.012     0.053     0.224   1

profile-no.        5

drift parameters:

linear       0.2059       -0.0248       -0.0334
constant    -0.071        -0.939        -1.200

  386    -72923.519     31025.984     7499.587       -5.500         -0.031     0.033     0.051   1
  387    -72966.596     26630.270     7512.192       -4.500          0.084    -0.093    -0.024   1
  388    -72931.524     22165.235     7531.472       -3.500         -0.013     0.101    -0.024   1
  389    -72824.909     17742.292     7536.625       -2.500         -0.003    -0.080    -0.098   1
  390    -72661.738     13290.346     7534.551       -1.500         -0.156     0.035     0.018   1
  391    -72504.244      8781.569     7534.531       -0.500          0.198     0.049     0.107   1
  392    -72468.094      4340.464     7554.792        0.500         -0.066     0.013     0.022   1
  393    -72577.046       -18.616     7540.021        1.500         -0.052    -0.077    -0.057   1
  394    -72740.852     -4221.484     7534.654        2.500         -0.021    -0.002     0.009   1
  395    -72691.818     -8455.590     7539.597        3.500          0.099    -0.009     0.014   1
  396    -72663.610    -12678.996     7538.274        4.500         -0.037     0.031    -0.017   1
  397    -72481.212    -16883.339     7550.029        5.500        --  not in the block --

profile-no.        6

drift parameters:

linear      -0.1386        0.0002       -0.1620
constant    -0.640        -0.596        -2.018

  575    -40320.905    -16840.138     7745.603       -5.500        --  not in the block --
  576    -40338.097    -12720.268     7753.032       -4.500         -0.057     0.075     0.154   1
  577    -40345.939     -8544.841     7759.916       -3.500          0.023    -0.105    -0.149   1
  578    -40330.209     -4141.724     7768.360       -2.500          0.058    -0.060     0.015   1
  579    -40385.027       337.612     7757.414       -1.500          0.024     0.148     0.093   1
  580    -40393.951      4823.257     7759.379       -0.500         -0.021    -0.046    -0.093   1
  581    -40348.327      9304.080     7768.481        0.500          0.020    -0.073    -0.075   1
```

```
  582    -40302.769      13800.457       7777.191           1.500           -0.114       0.163       0.050    1
  583    -40318.346      18324.709       7752.604           2.500            0.091      -0.170      -0.071    1
  584    -40378.727      22877.740       7734.402           3.500           -0.073       0.057      -0.077    1
  585    -40460.102      27447.626       7728.223           4.500            0.086       0.015       0.134    1
  586    -40502.557      32049.580       7681.733           5.500           -0.037      -0.005       0.020    1

profile-no.         7

drift parameters:

linear        0.3690          0.1085          0.3399
constant      -1.827          -0.019          -1.637

  600        162.245      33865.381       7806.514          -6.000          --  not in the block --
  601        140.512      29702.473       7827.003          -5.000           0.015      -0.015       0.120    1
  602        211.691      25470.997       7824.019          -4.000           0.176      -0.082      -0.154    1
  603        197.431      21271.544       7849.345          -3.000          -0.113       0.061      -0.036    1
  604        206.048      17073.806       7836.922          -2.000          -0.053      -0.009       0.040    1
  605        236.698      12789.325       7862.753          -1.000          -0.111       0.098       0.064    1
  606        189.372       8619.350       7891.374           0.000          -0.067      -0.079      -0.071    1
  607        228.731       4459.050       7888.782           1.000           0.044       0.115       0.045    1
  608        231.770        231.392       7891.541           2.000           0.153      -0.083       0.097    1
  609        207.938      -3904.632       7889.017           3.000          -0.074       0.022      -0.048    1
  610        185.061      -8067.536       7880.589           4.000           0.045       0.015      -0.212    1
  611        168.198     -12190.815       7871.792           5.000          -0.016      -0.043       0.154    1
  612        146.435     -16438.879       7832.399           6.000          --  not in the block --
```

```
profile-no.         8           BATHURST BASE STATION TRAJECTORY

          drift parameters:

          linear        0.1019          0.0061          0.0050
          constant      -1.441          -1.068          -0.425

           7038      7974.709        8111.267        8120.823        -10.000            --  not in the block --
           7039      3581.243        8090.834        8119.615         -9.000            -0.089       0.138      -0.060     2
           7040      -754.400        8005.593        8126.195         -8.000             0.299      -0.036      -0.297     2
           7041     -5063.359        8030.006        8121.976         -7.000            -0.080      -0.110       0.078     2
           7042     -9417.369        8067.872        8114.450         -6.000            -0.007       0.050       0.150     2
           7043    -13760.411        8184.324        8110.909         -5.000            -0.128      -0.004      -0.032     2
           7044    -17947.477        8208.106        8096.876         -4.000            -0.089      -0.040      -0.124     2
           7045    -22114.770        8300.850        8085.519         -3.000            -0.021       0.033       0.180     2
           7046    -26548.904        8372.697        8065.997         -2.000            -0.055      -0.045       0.198     2
           7047    -30999.081        8446.173        8048.489         -1.000             0.047      -0.133       0.134     2
           7048    -35240.886        8527.539        8022.252          0.000             0.003      -0.027       0.022     2
           7049    -39264.960        8565.815        8002.219          1.000             0.100       0.200      -0.146     2
           7050    -43305.372        8619.853        7973.390          2.000             0.068      -0.089      -0.032     2
           7051    -47389.510        8524.641        7949.204          3.000             0.012       0.041       0.050     2
           7052    -51723.113        8375.893        7909.683          4.000            -0.019      -0.011      -0.117     2
           7053    -56150.146        8099.733        7876.524          5.000             0.002       0.007       0.018     2
           7054    -60601.997        7928.488        7831.320          6.000            -0.044       0.022       0.014     2
           7055    -65017.698        7942.501        7789.210          7.000             0.139       0.071       0.043     2
           7056    -69428.401        7862.105        7739.950          8.000            -0.141      -0.060       0.043     2
           7057    -73829.914        7933.135        7690.863          9.000            -0.063       0.035       0.129     2
           7058    -78332.594        8108.598        7641.253         10.000             0.065      -0.042      -0.252     2
```

```
   COORDINATES AND RESIDUALS OF CRITICAL POINTS
   --------------------------------------------
   arranged by increasing point numbers


photo-no.       x              y              rx          ry    sds check


              point-no.                 46    HV 4

  352      -28474.0       -71272.2          6.1         0.8    0    .  .
  576        3494.6       -83900.2          1.8         4.6    0    .  .
  351       60461.2       -72221.0         16.3         2.4    0    1  .
  577      -79563.4       -86101.4         -4.6        10.9    0    .  .

   HO    -36058.591     -12463.704       -0.554      -0.016    1    .  .
   VE                      360.655                    0.201    1       .


              point-no.               4142    TP 7

  604      -79613.4        52998.5        -11.4        -8.5    0    .  .
  141       90376.2       -80593.7          2.2       -15.1    0    .  .
  179       30339.5       -90144.0         -1.0         2.5    0    .  .
  602       92976.2        56053.3         -9.0       -11.2    0    .  .
  603        3944.4        51530.1         -9.7        -7.5    0    .  .
  180      -65593.6       -86662.3         -6.3         7.3    0    .  .
  142        -557.7       -86168.2         18.3        -5.9    0    2  .

              point-no.               5188    TP 8

 7048        9837.4       -77754.3         20.7        11.6    0    4  .
  188        6752.7        85927.7        -18.3         1.0    0    2  .
 7049      -72204.4       -77329.1         38.2         7.2    0    9  .
  581       65364.7       -91939.1          7.6       -10.4    0    .  .
  582      -29551.7       -99152.9         18.7        -9.0    0    2  .
  187       98720.0        99928.4        -12.7         5.2    0    .  .
 7047       97948.5       -82219.4         12.1        -3.7    0    .  .
  189      -80716.8        87197.8        -18.2         1.1    0    2  .

              point-no.               6284    TP 6
```

```
  323      64810.1     -85305.1          10.6        -1.9   0  .  .
  325    -103996.5     -87214.5           8.7        -5.8   0     .
 7040     101615.5      82811.8          -8.9        16.7   0  .  1
 7042     -72472.9      85275.7          -8.8        -3.9   0  .  .
 7041      11566.0      84423.4          -6.0        -8.7   0  .  .
  324     -18509.3     -85932.0           4.5         4.8   0  .  .

            point-no.           6869   TP 8

 7057     -75331.8      94792.1          -6.1         6.4   0  .  .
 7055     101456.5      88543.5         -15.0        17.8   0  .  1
  393     -66204.1      49762.5          -3.2         4.4   0  .  .
  392      22228.5      48620.9          -7.1        -2.0   0  .  .
  339     -14130.4     -81262.8           6.5        -7.3   0  .  .
  338      71313.4     -77120.0           3.5        -1.7   0  .  .
  340    -100253.1     -77395.2          15.9         1.8   0  1  .
 7056      18646.5      88517.7          -2.4        -5.3   0  .  .

            point-no.           8350   TP 4

  351     -90180.8     -96143.7           7.4         3.7   0  .  .
  576     -16262.6      67208.5          -9.3        17.8   0  .  1
  349      90668.6     -99457.0           2.8         3.9   0  .  .
  350       -871.8     -95756.6           7.6         2.0   0  .  .


            point-no.         123602   TP 4

  602       3849.4      93891.0          -5.0         5.8   0  .  .
  142      39505.8        341.4         -16.2       -15.4   0  1  .
  603     -83784.7      91197.0          -0.9         7.4   0  .  .
  601      94155.3      95079.3          -9.4         2.8   0  .  .

            point-no.         123603   TP 4

  602      82459.4      98815.0         -15.0        -0.4   0  .  .
  604     -89274.5      95793.3           0.3        -6.2   0  .  .
  142      41810.5     -76921.2           2.6       -18.8   0  .  2
  603      -5638.2      93836.3          -3.7         3.7   0  .  .

            point-no.         123604   TP 4

  604      -1676.3     100259.3           0.6         1.4   0  .  .
  603      80608.9      96981.0           8.9       -10.1   0  .  .
  179     -20514.8     -14551.2         -16.5        -4.1   0  1  .
  605     -94713.1      92605.6          -6.0        -8.2   0  .  .

            point-no.         204142   TP 5

  141      84856.8       4882.2          21.1       -12.4   0  4  .
  602       5630.6      49335.8          -3.6       -12.7   0  .  .
  603     -83164.1      46886.7         -10.0       -11.9   0  .  .
  601      93895.5      50312.8          -1.0       -22.4   0  .  4
  142      -4433.4       -128.6          26.7        -2.3   0  7  .

            point-no.         205179   TP 5

  180     -96832.9       1424.2          17.8         5.8   0  2  .
  604      11003.0      81842.7           0.9        11.5   0  .  .
  603      93073.1      78921.4          -6.6         2.2   0  .  .
  179      -3026.5      -1090.9          11.7         0.5   0  .  .
  605     -81899.8      74643.8           0.3        15.8   0  .  .

            point-no.         222582   TP 9

 7048     101087.2    -111115.5         -16.3       -27.1   0  1  7
  582        863.5      -3922.4          -8.0         6.4   0  .  .
 7050     -64389.7     -96663.1          15.9        -7.4   0  1  .
  188     100317.8      59685.7         -14.7        -1.8   0  .  .
  583     -91703.1        719.1          -0.4        13.2   0  .  .
 7049      18270.4    -112759.2           0.3       -10.7   0  .  .
  190     -72916.2      53253.1           2.1        12.4   0  .  .
  581      93948.6       2175.3         -16.7        -8.3   0  1  .
  189      13136.4      58502.7          -1.2         7.7   0  .  .

            point-no.         223605   TP 9

  180     -15633.2      83292.2          -6.6        -2.7   0  .  .
  606     -84760.2      -5020.5           4.9        -7.7   0  .  .
  604      91684.9      -2816.3           5.7       -14.2   0  .  .
  181    -102258.4      80108.4          -3.0        -0.4   0  .  .
 7041     -97442.8     -95955.8          -7.0        -9.1   0  .  .
 7040     -16578.7     -93351.2         -11.5         1.3   0  .  .
  605       -404.8      -7856.0          -3.6       -19.0   0  .  2
 7039      70915.5     -93709.4         -15.0         8.8   0  .  .
  179      74558.8      80841.5           1.6        -3.7   0  .  .

            point-no.         321391   TP 5

  392     -90185.2    -101724.7           3.4        12.9   0  .  .
  391      -2328.1     -96591.5           5.1         2.3   0  .  .
 7057      64473.9     -22182.0          22.1       -10.5   0  4  .
 7058     -25585.9     -16285.5          -4.0        -2.4   0  .  .
  390      88491.7     -91386.5           3.4         2.4   0  .  .

            point-no.         321392   TP 5

 7057      69314.6      60703.9         -17.8        -5.3   0  2  .
 7058     -20122.1      65984.7          -6.4        -9.9   0  .  .
  391      83925.3    -100784.2           3.7        -5.1   0  .  .
  393     -91658.2     -99858.6           4.9       -10.0   0  .  .
  392      -4729.7    -102411.1           7.3        -7.3   0  .  .

            point-no.         322583   TP 5

  583      13822.5      98894.5          -2.4         0.3   0  .  .
```

```
     191       -68691.6      -49182.0             -2.0        -4.6    0    .  .
     584       -75564.7       89371.0             -5.3         8.6    0    .  .
     190        27001.4      -47416.8             10.5        -8.7    0    .  .
     582       103202.0       92324.2             -6.0       -17.3    0    .  1

                 point-no.             323605   TP 9

    7040        73597.0      -90382.4             -6.3       -17.5    0    .  1
     180        76027.7       92789.2             -6.3         0.4    0    .  .
     605         8760.0     -101702.4              9.1        -2.6    0    .  .
    7041        -8207.4      -89064.8              2.0        -2.5    0    .  .
     181       -10619.5       86835.6             -0.3        -3.1    0    .  .
     606       -76403.6      -97309.6             16.9        -6.4    0    1  .
     604        98924.5      -96067.7             -1.0         1.8    0    .  .
     182       -97761.6       79261.0              0.1        -0.3    0    .  .
    7042      -100462.7      -86851.1              2.1        -2.6    0    .  .

                 point-no.             907322   TP 7

     608       -79848.8       39331.4            -17.5         9.5    0    2  .
    7040       -49868.8       81596.0             -2.1         1.7    0    .  .
    7039        36637.8       82236.5              0.1         6.5    0    .  .
     322        -4430.3      -97361.9             11.9        15.7    0    .  .
     607         9417.2       33942.7            -23.1         7.9    0    5  .
     323       -89653.6      -98052.3              0.0        11.6    0    .  .

END OF EXECUTION : 03-FEB-99 14:28:10

PATB-GPS END
```

Appendix F

PATB-GPS aerial triangulation results using new photography for run 6. Antenna station coordinates based on University of New South Wales base station trajectory (un-fixed ambiguities). New results for run 6 are listed under profile 8.

```
1
    PATB-GPS :                      COPYRIGHT :  H.KLEIN/F.ACKERMANN 1988-1994

    BLOCK ADJUSTMENT WITH BUNDLES                              REVISION Jun-94

    PROJECT  : Range test 1
    USER-ID. : gd

    START OF EXECUTION : 03-FEB-99 14:33:25

    ***************************************************************************
    ***************************************************************************
    **                                                                       **
    ** PROGRAM VERSION  PATB-GPS                                             **
    ** ========================                                              **
    **                                                                       **
    ** DIRECTORY FOR INPUT AND OUTPUT FILES :  PRESENT WORKING DIRECTORY     **
    ** INPUT                                                                 **
    ** BASIC DATA                                      FROM FILE rt6.bas     **
    ** PHOTOGRAPHS                                     FROM FILE rt6.obs     **
    ** CONTROL POINTS                                  FROM FILE gd6.ctl     **
    **                                                                       **
    ** INITIAL VALUES FOR EXTERIOR ORIENTATION PARAMETERS ARE CALCULATED     **
    **                                                                       **
    ** WITHOUT AUTOMATIC GROSS ERROR DETECTION                                **
    ** NO CORRECTION OF SYSTEMATIC ERRORS                                    **
    ** ADJUSTMENT WITH GPS-OBSERVATIONS                                      **
    **            WITH DETERMINATION OF GPS-DRIFT PARAMETERS                 **
    **            NO DETERMINATION OF GPS-ANTENNA OFFSET                     **
    ** NO INVERSION OF NORMAL EQUATIONS                                      **
    **                                                                       **
    ** ITERATION SEQUENCE WILL BE TERMINATED :                               **
    ** 1. IF 10 ITERATION STEPS ARE PERFORMED                                **
    ** 2. IF CHANGE OF ADJUSTED TERRAIN COORDINATES                          **
    **    BETWEEN TWO ITERATION STEPS FOR ALL POINTS      <     0.300        **
    **    IN THE TERRAIN SYSTEM                                              **
    ** 3. IF CHANGE OF SIGMA LESS THAN 0.001%                                **
    ** 4. IF SIGMA DOES NOT CONFIRM WITH READ IN STANDARD DEVIATIONS         **
    ** 5. IF THE RMS-VALUE OF OBSERVATIONS DIVERGES                          **
    **                                                                       **
    ** INPUT FORMATS AND INPUT SEQUENCES :                                   **
    ** PHOTOGRAPH NUMBERS          (I10,F10.3,I5)                            **
    ** PHOTOGRAPH POINTS           (I10,2F10.1,i5)                           **
    ** SEQUENCE OF READ IN COORDINATES OF PHOTO POINTS               = X Y **
    ** HORIZONTAL CONTROL          (I8,2f15.3,15x,i5)                        **
    ** SEQUENCE OF READ IN COORDINATES OF HORIZONTAL CONTROL POINTS  = X Y **
    ** VERTICAL CONTROL            (I8,30x,f15.3,i5)                         **
    ** GPS-OBSERVATIONS            (I8,3f15.3,f8.0,i5)                       **
    **                                                                       **
    ** READ IN IMVK                                     =   25               **
    **                                                                       **
    ** LIMITATIONS                                                           **
    ** NUMBER OF POINTS IN ONE PHOTO         RESTRICTED TO   60              **
    ** NUMBER OF CONTROL POINTS IN ONE LIST  RESTRICTED TO  750              **
    ** NUMBER OF PHOTOS IN ONE PHOTO GROUP   RESTRICTED TO   60              **
    ** DIMENSIONS OF ADDRESS MATRIX          RESTRICTED TO   50,10           **
    ** NUMBER OF PHOTOS/SUBMATRIX            RESTRICTED TO   20              **
    ** NUMBER OF DIFFERENT FOCAL LENGTHS     RESTRICTED TO   30              **
    ** NUMBER OF POINT RECORDS               RESTRICTED TO  165              **
    ** NUMBER OF PHOTO RECORDS               RESTRICTED TO   60              **
    **                                                                       **
    ** REQUIRED WORKING AREA FOR THESE SPECIFICATIONS    =  108670           **
    ** REQUIRED SCRATCH FILE : BLKSZ = 8192 BYTES,  BLOCKS=    8316          **
    **                                                                       **
    ** BREAK UP LIMIT FOR THE SIZE OF PHOTO GROUPS        =   60             **
    **                                                                       **
    ** PHOTO NUMBERS OF THE FIRST PHOTO GROUP :                              **
    **                                   FIRST READ IN PHOTOGRAPH ASSUMED **
    ** NUMBER OF PHOTOS IN THE FIRST PHOTO GROUP          =    1             **
    **                                                                       **
    ** FOCAL LENGTH IN UNITS OF IMAGE SYSTEM AND CORRESPONDING FL-NUMBER     **
    ** NUMBER OF FOCAL LENGTHS                            =    0             **
    **                                                                       **
    ** SIZE OF PHOTOGRAPHS IN UNITS OF IMAGE SYSTEM                          **
    **   IN X :      230000.000    IN Y :      230000.000                    **
    **                                                                       **
    ** STANDARD DEVIATIONS OF OBSERVATIONS :                                 **
    **                                                                       **
    **   FOR IMAGE POINTS IN X AND Y IN UNITS OF IMAGE SYSTEM                **
    **   DEFAULT SET (SDS NO. 0 OR BLANK) :         8.000                    **
    **                                                                       **
    **   FOR CONTROL POINTS IN UNITS OF TERRAIN SYSTEM                       **
    **                                    PLANIMETRY   HEIGHT                **
    **   1.SET FOR CONTROL POINTS         :      0.500    0.500              **
    **                                                                       **
    **   FOR GPS OBSERVATIONS IN UNITS OF TERRAIN SYSTEM                     **
    **                                    PLANIMETRY   AND HEIGHT            **
    **   1.SET FOR GPS OBSERVATIONS         :     0.250                      **
    **   2.SET FOR GPS OBSERVATIONS         :     0.250                      **
    **                                                                       **
    **                                                                       **
```

```
** COMMON OFFSET FROM CAMERA TO GPS ANTENNA :                                **
**                        0.105          -0.052          1.000               **
**                        IN UNITS OF TERRAIN SYSTEM                         **
**                                                                           **
** PRINTOUT                                                                  **
** COORDINATES OF CONTROL POINTS AND RESIDUALS                               **
** COORDINATES AND RESIDUALS OF CRITICAL POINTS IN SEQUENCE                  **
**                                                                           **
** ADDITIONAL OUTPUT                                                         **
** ADJUSTED TERRAIN COORDINATES IN SEQUENCE       ON FILE rt6.fvl            **
** EXTERIOR ORIENTATION PARAMETERS                ON FILE rt6.ori            **
**                                                                           **
*******************************************************************************
*******************************************************************************


       read in image points ............................  1718
       stored unsorted point records ...................    33
       read in photographs .............................   134
       stored unsorted photo records ...................     3
       read in horizontal control points ...............    71
       read in vertical control points .................    71
       read in gps antenna points.......................   141
       read in gps profiles.............................     8
       stored control point records ....................     1



       PHOTO GROUPS AND PHOTO CONNECTIONS
       ----------------------------------
       photo group   1 has   1 photo
       photo group   2 has   9 photos
       photo group   3 has  10 photos
       photo group   4 has  14 photos
       photo group   5 has  18 photos
       photo group   6 has  23 photos
       photo group   7 has  11 photos
       photo group   8 has  10 photos
       photo group   9 has  10 photos
       photo group  10 has  15 photos
       photo group  11 has  13 photos

       COMPUTATION OF INITIAL VALUES OF EXTERIOR ORIENTATION PARAMETERS
       -----------------------------------------------------------------

       dimensions of submatrices    = ( 120 ,120 )
       dimensions of address matrix = (  50 , 11 )
       maximum number of photos/submatrix    =  30

       initial iteration step
       ----------------------

       number of hyperrows     =    8
       number of hypercolumns =    2


       COMPUTATION OF ADJUSTED TERRAIN COORDINATES
       -------------------------------------------

       dimensions of submatrices    = ( 120 ,120 )
       dimensions of address matrix = (  50 , 11 )
       maximum number of photos/submatrix    =  20

       standard deviations for image points in x and y (in image system)
       default set :    8.000

       standard deviations for control points (in terrain system)
                          planimetry    height
       1. set :                0.500     0.500


       iteration step no.   1
       ------------------
       iteration step with gps

       number of hyperrows     =   10
       number of hypercolumns =    3
       plus 1 column border part for gps

       maximum change of exterior orientation parameters :
       da,db,dc = parameters of rodrigues-matrix
       px,py,pz = coordinates of perspective centers (in terrain system)

                   da =0.071653                px =   400.080
                   db =0.056277                py =   610.328
                   dc =0.023223                pz =   320.763

       maximum change of adjusted terrain coordinates (in terrain system) :

             in x at point-no.           8357         174.225
             in y at point-no.           8346         127.804
             in z at point-no.           8359         367.108

       sigma reached =      53.3997  (in image system)


       iteration step no.   2
       ------------------
       iteration step with gps

       number of hyperrows     =   10
```

```
number of hypercolumns =    3
plus 1 column border part for gps

maximum change of exterior orientation parameters :
da,db,dc = parameters of rodrigues-matrix
px,py,pz = coordinates of perspective centers (in terrain system)

           da =0.001674              px =     6.876
           db =0.001138              py =    11.596
           dc =0.001026              pz =    16.522

maximum change of adjusted terrain coordinates (in terrain system) :

      in x at point-no.         805179         5.024
      in y at point-no.           8358        14.081
      in z at point-no.           7320        23.979

sigma reached =      7.3688  (in image system)


iteration step no.   3
------------------
iteration step with gps

number of hyperrows    =   10
number of hypercolumns =    3
plus 1 column border part for gps

maximum change of exterior orientation parameters :
da,db,dc = parameters of rodrigues-matrix
px,py,pz = coordinates of perspective centers (in terrain system)

           da =0.000003              px =     0.028
           db =0.000003              py =     0.031
           dc =0.000002              pz =     0.033

maximum change of adjusted terrain coordinates (in terrain system) :

      in x at point-no.           7320         0.036
      in y at point-no.           7320         0.044
      in z at point-no.           7320         0.104


end of adjustment  --  due to condition 2


STATISTICS
----------

 1-fold points         =    2
 2-fold points         =   40
 3-fold points         =  102
 4-fold points         =   34
 5-fold points         =   92
 6-fold points         =   64
 7-fold points         =   13
 8-fold points         =   16
 9-fold points         =   10
number of block points =  373


number of observations = 3789
number of unknowns     = 1971
redundancy             = 1818


number of outliers for image observations    =    0
number of outliers for control observations =    0
number of outliers for gps observations      =    0

ROOT MEAN SQUARE VALUES AND CHECK VALUES OF RESIDUALS OF PHOTOGRAMMETRIC OBSERVATIONS
-------------------------------------------------------------------------------------
                  image system     terrain system        image system

image points
------------
obs x = 1677  rms x =      5.25   rms x =     0.258   chv vx =     15.75
obs y = 1677  rms y =      5.53   rms y =     0.272   chv vy =     16.59

ROOT MEAN SQUARE VALUES AND CHECK VALUES OF RESIDUALS OF NON-PHOTOGRAMMETRIC OBSERVATIONS
-----------------------------------------------------------------------------------------
                  image system     terrain system      terrain system

control points with sds-no.  1
---------------------------
obs x =   11  rms x =     12.72   rms x =     0.626   chv vx =      1.88
obs y =   11  rms y =      3.45   rms y =     0.170   chv vy =      0.51
obs z =   11  rms z =      2.98   rms z =     0.147   chv vz =      0.44

ROOT MEAN SQUARE VALUES AND CHECK VALUES OF RESIDUALS OF GPS OBSERVATIONS
-------------------------------------------------------------------------
                                   terrain system      terrain system

gps observations with sds-no.  1
-----------------------------
obs x =  114                      rms x =     0.069   chv vx =      0.21
obs y =  114                      rms y =     0.064   chv vy =      0.19
obs z =  114                      rms z =     0.084   chv vz =      0.25

gps observations with sds-no.  2
-----------------------------
obs x =   20                      rms x =     0.100   chv vx =      0.30
```

```
obs y =   20                  rms y =    0.077   chv vy =     0.23
obs z =   20                  rms z =    0.128   chv vz =     0.38


SIGMA NAUGHT      7.46         =    0.367
------------


COORDINATES OF CONTROL POINTS AND RESIDUALS
-------------------------------------------
in units of terrain system


horizontal control points
                                        code of point
point-no.       x           y           input -> used          rx          ry    sds check

   25    -69873.014   -15726.485        HV 1                 -0.111       0.006    1   .  .
   26    -72653.385    -1847.868        HV 4                 -0.317       0.113    1   .  .
   27    -73912.981    20027.308        HV 4                 -0.129      -0.112    1   .  .
   28    -71645.884    29937.296        HV 2                  0.301       0.158    1   .  .
   29    -31262.676    29465.355        HV 3                  0.222       0.104    1   .  .
   42    -31772.848    22556.965        HV 3                 -1.438       0.026    1   .  .
   43    -35590.100    13370.653        HV 6                  0.662      -0.455    1   .  .
   45    -47988.815    -4332.370        HV 4                  1.095       0.205    1   .  .
   46    -36058.591   -12463.704        HV 4                 -0.547      -0.018    1   .  .
   52     -8939.231    -4353.436        HV 2                  0.122       0.037    1   .  .
   53       415.646   -14504.899        HV 1                  0.140      -0.064    1   .  .


vertical control points
                                        code of point
point-no.                   z           input -> used                      rz    sds check

   25                    66.104         HV 1                             -0.044    1      .
   26                    56.264         HV 4                             -0.202    1      .
   27                    14.268         HV 4                              0.183    1      .
   28                     3.531         HV 2                             -0.102    1      .
   29                   339.449         HV 3                             -0.151    1      .
   42                   363.035         HV 3                              0.152    1      .
   43                   366.988         HV 6                              0.096    1      .
   45                   292.006         HV 4                              0.060    1      .
   46                   360.655         HV 4                              0.204    1      .
   52                   468.576         HV 2                             -0.221    1      .
   53                   464.971         HV 1                              0.025    1      .


COORDINATES OF GPS OBSERVATIONS AND RESIDUALS
---------------------------------------------
in units of terrain system

gps antenna offset     x` =  0.105    y` = -0.052    z` =  1.000

photo-no.        x             y             z              t               rx          ry          rz       sds
check

profile-no.         1

drift parameters:

linear      -0.1688       -0.0098       -0.0877
constant     -1.468        -1.217        -3.272

  123    -78566.204    25038.443     7456.550       -10.000          -0.019       0.022       0.059     1
  124    -74353.753    24916.163     7520.089        -9.000           0.028      -0.052      -0.164     1
  125    -69985.950    24832.733     7557.227        -8.000          -0.084      -0.001       0.034     1
  126    -65685.478    24946.498     7607.268        -7.000           0.078       0.002      -0.004     1
  127    -61386.895    25159.625     7644.942        -6.000          -0.049      -0.020       0.081     1
  128    -57125.903    25294.712     7673.961        -5.000           0.106       0.008      -0.026     1
  129    -52888.723    25391.237     7701.685        -4.000          -0.066      -0.051       0.038     1
  130    -48580.836    25410.509     7747.435        -3.000          -0.018       0.138       0.138     1
  131    -44271.105    25469.260     7776.495        -2.000          -0.044       0.043       0.038     1
  132    -40009.351    25427.532     7801.252        -1.000           0.068      -0.053      -0.051     1
  133    -35721.639    25373.195     7836.522         0.000          -0.116       0.000      -0.001     1
  134    -31423.697    25306.191     7857.925         1.000           0.082       0.044      -0.217     1
  135    -27168.360    25279.023     7872.438         2.000          -0.011      -0.134       0.033     1
  136    -22849.376    25262.108     7875.774         3.000           0.053       0.051      -0.068     1
  137    -18542.598    25226.054     7905.113         4.000           0.017      -0.041       0.132     1
  138    -14310.298    25229.861     7913.265         5.000           0.058      -0.021      -0.085     1
  139    -10017.828    25183.119     7921.199         6.000          -0.028       0.031      -0.045     1
  140     -5729.932    25164.721     7933.345         7.000           0.108       0.095       0.002     1
  141     -1516.487    25109.986     7946.049         8.000          -0.143       0.036       0.150     1
  142      2761.681    25142.519     7950.683         9.000          -0.020      -0.098      -0.044     1
  143      6987.562    25179.862     7941.122        10.000         --  not in the block --
profile-no.         2

drift parameters:

linear       0.1727       -0.0521        0.0375
constant     -1.227        -0.462        -1.963

  178      8543.080    16693.944     7960.760       -10.000         --  not in the block --
  179      4059.095    16699.088     7953.088        -9.000           0.022       0.025       0.073     1
  180      -560.883    16702.305     7961.484        -8.000           0.065      -0.024       0.046     1
  181     -4941.054    16696.484     7948.615        -7.000           0.013      -0.004      -0.061     1
  182     -9235.130    16592.423     7952.616        -6.000          -0.032      -0.010      -0.062     1
  183    -13547.665    16501.298     7950.318        -5.000           0.043      -0.014       0.019     1
  184    -17835.556    16382.388     7956.379        -4.000          -0.088       0.005       0.045     1
```

```
  185  -22233.218    16463.184    7924.057      -3.000         0.007     0.031     -0.032    1
  186  -26491.966    16630.637    7921.688      -2.000        -0.013    -0.053      0.121    1
  187  -30768.850    16786.616    7893.471      -1.000         0.001    -0.023     -0.160    1
  188  -35217.043    16699.901    7858.477       0.000        -0.043    -0.050     -0.111    1
  189  -39545.031    16665.007    7844.877       1.000        -0.083     0.047      0.008    1
  190  -43824.914    16596.707    7811.132       2.000         0.049    -0.007      0.093    1
  191  -48353.307    16554.703    7791.408       3.000         0.013     0.105     -0.011    1
  192  -52995.059    16298.696    7734.866       4.000         0.052     0.005     -0.012    1
  193  -57666.691    16157.822    7702.102       5.000        -0.049     0.052      0.031    1
  194  -62166.466    16266.393    7664.522       6.000        -0.005     0.030      0.051    1
  195  -66681.417    16296.991    7617.951       7.000        -0.020    -0.059     -0.023    1
  196  -71130.072    16370.469    7558.390       8.000        -0.026    -0.020     -0.144    1
  197  -75512.346    16427.224    7513.698       9.000         0.124     0.015      0.043    1
  198  -79952.737    16375.777    7450.973      10.000        -0.029    -0.051      0.085    1

profile-no.         3

drift parameters:

linear     0.0619      -0.0995     -0.0354
constant   -0.658       -0.381      -1.641

  321    5816.417     -516.030    7958.413     -10.000        -0.059    -0.112     -0.045    1
  322    1634.522     -570.688    7971.261      -9.000        -0.132     0.028     -0.009    1
  323   -2500.108     -566.277    7958.196      -8.000         0.096    -0.104      0.034    1
  324   -6608.513     -489.596    7970.680      -7.000        -0.007     0.111      0.029    1
  325  -10764.162     -417.478    7970.651      -6.000         0.061     0.051      0.032    1
  326  -14902.737     -362.902    7966.818      -5.000         0.099     0.142     -0.006    1
  327  -19061.988     -311.401    7939.934      -4.000        -0.072    -0.072      0.028    1
  328  -23298.432     -160.502    7939.405      -3.000         0.068     0.078      0.007    1
  329  -27660.346      -12.912    7900.341      -2.000         0.084    -0.049     -0.045    1
  330  -31981.206        0.353    7890.325      -1.000         0.070    -0.062      0.050    1
  331  -36105.329      -27.477    7858.421       0.000        -0.042    -0.061      0.012    1
  332  -40184.958     -148.973    7851.675       1.000        -0.085     0.025     -0.030    1
  333  -44515.857     -286.286    7818.016       2.000        -0.078    -0.024     -0.010    1
  334  -48956.445     -441.758    7790.698       3.000         0.036     0.079     -0.054    1
  335  -53487.105     -526.008    7757.924       4.000        -0.020    -0.019      0.027    1
  336  -57721.479     -512.196    7718.999       5.000        -0.021     0.085     -0.115    1
  337  -61979.501     -520.629    7674.766       6.000        -0.062    -0.079     -0.066    1
  338  -66309.298     -498.679    7628.095       7.000         0.012     0.029      0.011    1
  339  -70584.886     -519.320    7574.255       8.000        -0.093    -0.073      0.146    1
  340  -74776.729     -488.549    7549.420       9.000         0.124     0.091     -0.006    1
  341  -79040.147     -467.160    7501.409      10.000         0.021    -0.065      0.010    1

profile-no.         4

drift parameters:

linear    -0.0777       0.1045      0.1513
constant   -0.216       -1.003      -1.677

  342  -77952.467    -9077.517    7494.911      -9.500         0.013    -0.015     -0.010    1
  343  -73780.028    -9093.069    7544.360      -8.500        -0.043     0.027      0.175    1
  344  -69531.484    -9092.708    7572.025      -7.500         0.020    -0.071     -0.159    1
  345  -65149.735    -9067.538    7618.681      -6.500         0.013     0.042      0.172    1
  346  -60804.510    -9065.523    7670.592      -5.500        -0.030    -0.009     -0.043    1
  347  -56463.710    -9036.006    7710.778      -4.500         0.026     0.002      0.054    1
  348  -52125.665    -9035.354    7747.683      -3.500        -0.021    -0.026     -0.089    1
  349  -47757.989    -9023.063    7770.590      -2.500         0.008     0.039     -0.082    1
  350  -43393.332    -9032.602    7804.831      -1.500        -0.004     0.026      0.025    1
  351  -39039.765    -9024.773    7834.278      -0.500         0.001     0.019     -0.061    1
  352  -34694.267    -8997.560    7861.433       0.500         0.009    -0.091     -0.047    1
  353  -30270.918    -8897.114    7874.735       1.500         0.040     0.044     -0.024    1
  354  -25797.340    -8753.672    7908.497       2.500        -0.027     0.007      0.050    1
  355  -21203.592    -8738.041    7938.449       3.500         0.063     0.051      0.018    1
  356  -16712.862    -8743.666    7948.802       4.500        -0.084    -0.010      0.048    1
  357  -12251.996    -8826.588    7948.545       5.500         0.099     0.105     -0.156    1
  358   -7821.681    -8855.937    7969.721       6.500        -0.116    -0.079      0.032    1
  359   -3490.316    -8884.589    7972.263       7.500         0.040    -0.061     -0.065    1
  360     801.684    -8991.918    7962.205       8.500        -0.018    -0.051     -0.058    1
  361    5116.233    -9031.380    7940.720       9.500         0.012     0.053      0.222    1

profile-no.         5

drift parameters:

linear     0.2043      -0.0236     -0.0345
constant   -0.077       -0.939      -1.210

  386  -72923.522    31025.990    7499.592      -5.500        -0.031     0.032      0.049    1
  387  -72966.597    26630.275    7512.197      -4.500         0.083    -0.093     -0.027    1
  388  -72931.523    22165.238    7531.479      -3.500        -0.014     0.101     -0.026    1
  389  -72824.906    17742.295    7536.632      -2.500        -0.004    -0.080     -0.100    1
  390  -72661.735    13290.348    7534.560      -1.500        -0.157     0.038      0.020    1
  391  -72504.239     8781.569    7534.541      -0.500         0.201     0.050      0.117    1
  392  -72468.087     4340.463    7554.803       0.500        -0.065     0.008      0.025    1
  393  -72577.037      -18.618    7540.033       1.500        -0.053    -0.079     -0.057    1
  394  -72740.842    -4221.487    7534.667       2.500        -0.021    -0.002      0.008    1
  395  -72691.806    -8455.594    7539.611       3.500         0.098    -0.008      0.011    1
  396  -72663.596   -12679.001    7538.290       4.500        -0.037     0.031     -0.020    1
  397  -72481.196   -16883.346    7550.045       5.500       --  not in the block --

profile-no.         6

drift parameters:

linear    -0.1378       0.0006     -0.1606
constant   -0.634       -0.601      -2.008

  575  -40320.907   -16840.131    7745.600      -5.500       --  not in the block --
  576  -40338.100   -12720.262    7753.028      -4.500        -0.057     0.074      0.158    1
  577  -40345.943    -8544.835    7759.911      -3.500         0.024    -0.106     -0.144    1
  578  -40330.214    -4141.719    7768.353      -2.500         0.059    -0.060      0.017    1
  579  -40385.032      337.618    7757.406      -1.500         0.024     0.151      0.093    1
  580  -40393.957     4823.262    7759.370      -0.500        -0.022    -0.040     -0.099    1
  581  -40348.334     9304.084    7768.470       0.500         0.017    -0.074     -0.088    1
```

```
  582    -40302.777     13800.461      7777.179          1.500          -0.114      0.157      0.045   1
  583    -40318.355     18324.713      7752.591          2.500           0.092     -0.171     -0.070   1
  584    -40378.736     22877.743      7734.387          3.500          -0.072      0.056     -0.074   1
  585    -40460.112     27447.629      7728.207          4.500           0.086      0.016      0.139   1
  586    -40502.568     32049.582      7681.716          5.500          -0.037     -0.003      0.023   1

profile-no.        7

drift parameters:

linear       0.3719        0.1033        0.3383
constant     -1.827        -0.007        -1.651

  600       162.263     33865.336      7806.519         -6.000         --  not in the block --
  601       140.527     29702.434      7827.009         -5.000          0.016     -0.015      0.119   1
  602       211.703     25470.963      7824.027         -4.000          0.176     -0.082     -0.157   1
  603       197.440     21271.516      7849.355         -3.000         -0.113      0.061     -0.037   1
  604       206.054     17073.783      7836.933         -2.000         -0.053     -0.008      0.041   1
  605       236.701     12789.307      7862.765         -1.000         -0.111      0.098      0.067   1
  606       189.372      8619.338      7891.388          0.000         -0.065     -0.080     -0.066   1
  607       228.729      4459.042      7888.798          1.000          0.044      0.115      0.048   1
  608       231.765       231.390      7891.558          2.000          0.152     -0.084      0.099   1
  609       207.930     -3904.629      7889.036          3.000         -0.074      0.022     -0.050   1
  610       185.050     -8067.527      7880.610          4.000          0.044      0.015     -0.215   1
  611       168.184    -12190.802      7871.814          5.000         -0.015     -0.042      0.152   1
  612       146.418    -16438.860      7832.423          6.000         --  not in the block --
```

```
profile-no.        8         UNSW BASE STATION TRAJECTORY

drift parameters:

linear       0.0881        0.0174        -0.0166
constant     -1.472        -1.072         -0.791

 8038      7974.678      8111.257      8120.794        -10.000         --  not in the block --
 8039      3581.220      8090.819      8119.576         -9.000         -0.083      0.141     -0.036    2
 8040      -754.403      8005.569      8126.228         -8.000          0.303     -0.035     -0.304    2
 8041     -5063.360      8029.983      8122.032         -7.000         -0.075     -0.109      0.069    2
 8042     -9417.356      8067.838      8114.546         -6.000         -0.003      0.052      0.129    2
 8043    -13760.387      8184.291      8110.988         -5.000         -0.126     -0.006     -0.030    2
 8044    -17947.446      8208.061      8097.025         -4.000         -0.089     -0.042     -0.151    2
 8045    -22114.733      8300.805      8085.640         -3.000         -0.028      0.031      0.167    2
 8046    -26548.861      8372.622      8066.170         -2.000         -0.070     -0.046      0.156    2
 8047    -30999.095      8446.197      8048.472         -1.000          0.039     -0.135      0.160    2
 8048    -35240.888      8527.540      8022.258          0.000         -0.009     -0.022      0.017    2
 8049    -39264.996      8565.892      8002.086          1.000          0.106      0.193     -0.085    2
 8050    -43305.402      8619.914      7973.289          2.000          0.067     -0.090     -0.003    2
 8051    -47389.533      8524.690      7949.095          3.000          0.017      0.043      0.075    2
 8052    -51723.127      8375.940      7909.614          4.000         -0.011     -0.010     -0.110    2
 8053    -56150.146      8099.778      7876.487          5.000          0.008      0.006      0.017    2
 8054    -60601.982      7928.504      7831.314          6.000         -0.042      0.021      0.007    2
 8055    -65017.663      7942.517      7789.206          7.000          0.136      0.069      0.044    2
 8056    -69428.363      7862.089      7739.987          8.000         -0.145     -0.059      0.028    2
 8057    -73829.862      7933.117      7690.922          9.000         -0.064      0.037      0.116    2
 8058    -78332.522      8108.549      7641.384         10.000          0.070     -0.040     -0.266    2
```

```
   COORDINATES AND RESIDUALS OF CRITICAL POINTS
   --------------------------------------------
   arranged by increasing point numbers


photo-no.       x              y              rx          ry    sds check


               point-no.              46   HV 4

  352      -28474.0       -71272.2           6.1         0.8    0   .  .
  576        3494.6       -83900.2           1.7         4.6    0   .  .
  351       60461.2       -72221.0          16.3         2.4    0   1  .
  577      -79563.4       -86101.4          -4.6        10.9    0   .  .

   HO    -36058.591     -12463.704        -0.547      -0.018    1   .  .
   VE                      360.655                     0.204    1      .


               point-no.            4142   TP 7

  604      -79613.4        52998.5         -11.4        -8.5    0   .  .
  141       90376.2       -80593.7           2.2       -15.1    0   .  .
  179       30339.5       -90144.0          -1.0         2.5    0   .  .
  602       92976.2        56053.3          -9.0       -11.2    0   .  .
  603        3944.4        51530.1          -9.7        -7.5    0   .  .
  180      -65593.6       -86662.3          -6.4         7.3    0   .  .
  142        -557.7       -86168.2          18.3        -5.9    0   2  .

               point-no.            5188   TP 8

 8048        9837.4       -77754.3          20.8        11.8    0   4  .
  188        6752.7        85927.7         -18.2         0.9    0   2  .
 8049      -72204.4       -77329.1          37.5         6.9    0   9  .
  581       65364.7       -91939.1           7.5       -10.3    0   .  .
  582      -29551.7       -99152.9          18.6        -8.9    0   2  .
  187       98720.0        99928.4         -12.8         5.1    0   .  .
 8047       97948.5       -82219.4          12.2        -3.5    0   .  .
  189      -80716.8        87197.8         -18.1         1.1    0   2  .
```

```
              point-no.            6284   TP 6

  323      64810.1      -85305.1          10.7        -1.9    0   .  .
  325    -103996.5      -87214.5           8.6        -5.7    0   .  .
 8040     101615.5       82811.8          -8.8        16.7    0   .  1
 8042     -72472.9       85275.7          -8.7        -4.0    0   .  .
 8041      11566.0       84423.4          -6.0        -8.7    0   .  .
  324     -18509.3      -85932.0           4.5         4.9    0   .  .

              point-no.            6869   TP 8

 8057     -75331.8       94792.1          -6.0         6.4    0   .  .
 8055     101456.5       88543.5         -15.1        17.8    0   .  1
  393     -66204.1       49762.5          -3.2         4.4    0   .  .
  392      22228.5       48620.9          -7.1        -2.0    0   .  .
  339     -14130.4      -81262.8           6.5        -7.3    0   .  .
  338      71313.4      -77120.0           3.6        -1.7    0   .  .
  340    -100253.1      -77395.2          15.8         1.7    0   1  .
 8056      18646.5       88517.7          -2.3        -5.3    0   .  .

              point-no.            8350   TP 4

  351     -90180.8      -96143.7           7.4         3.7    0   .  .
  576     -16262.6       67208.5          -9.3        17.9    0   .  1
  349      90668.6      -99457.0           2.9         4.0    0   .  .
  350       -871.8      -95756.6           7.6         2.0    0   .  .


              point-no.          123602   TP 4

  602       3849.4       93891.0          -5.0         5.8    0   .  .
  142      39505.8         341.4         -16.2       -15.4    0   1  .
  603     -83784.7       91197.0          -0.9         7.4    0   .  .
  601      94155.3       95079.3          -9.4         2.8    0   .  .

              point-no.          123603   TP 4

  602      82459.4       98815.0         -15.0        -0.5    0   .  .
  604     -89274.5       95793.3           0.3        -6.2    0   .  .
  142      41810.5      -76921.2           2.6       -18.8    0   .  2
  603      -5638.2       93836.3          -3.7         3.7    0   .  .

              point-no.          123604   TP 4

  604      -1676.3      100259.3           0.5         1.4    0   .  .
  603      80608.9       96981.0           8.9       -10.1    0   .  .
  179     -20514.8      -14551.2         -16.5        -4.1    0   1  .
  605     -94713.1       92605.6          -6.0        -8.2    0   .  .

              point-no.          204142   TP 5

  141      84856.8        4882.2          21.1       -12.4    0   4  .
  602       5630.6       49335.8          -3.6       -12.7    0   .  .
  603     -83164.1       46886.7         -10.0       -11.9    0   .  .
  601      93895.5       50312.8          -1.1       -22.4    0   .  4
  142      -4433.4        -128.6          26.7        -2.3    0   7  .

              point-no.          205179   TP 5

  180     -96832.9        1424.2          17.8         5.8    0   2  .
  604      11003.0       81842.7           0.9        11.5    0   .  .
  603      93073.1       78921.4          -6.6         2.2    0   .  .
  179      -3026.5       -1090.9          11.6         0.6    0   .  .
  605     -81899.8       74643.8           0.3        15.8    0   .  .

              point-no.          222582   TP 9

 8048     101087.2     -111115.5         -16.4       -26.7    0   1  7
  582        863.5       -3922.4          -8.3         6.4    0   .  .
 8050     -64389.7      -96663.1          15.7        -7.8    0   .  .
  188     100317.8       59685.7         -14.9        -1.8    0   .  .
  583     -91703.1         719.1          -0.4        13.2    0   .  .
 8049      18270.4     -112759.2           0.4       -11.3    0   .  .
  190     -72916.2       53253.1           2.3        12.4    0   .  .
  581      93948.6        2175.3         -17.0        -8.3    0   1  .
  189      13136.4       58502.7          -1.1         7.7    0   .  .

              point-no.          223605   TP 9

  180     -15633.2       83292.2          -6.6        -2.7    0   .  .
  606     -84760.2       -5020.5           4.9        -7.7    0   .  .
  604      91684.9       -2816.3           5.7       -14.2    0   .  .
  181    -102258.4       80108.4          -3.0        -0.4    0   .  .
 8041     -97442.8      -95955.8          -6.9        -8.8    0   .  .
 8040     -16578.7      -93351.2         -11.5         1.4    0   .  .
  605       -404.8       -7856.0          -3.6       -19.0    0   .  2
 8039      70915.5      -93709.4         -14.9         8.4    0   .  .
  179      74558.8       80841.5           1.5        -3.8    0   .  .

              point-no.          321391   TP 5

  392     -90185.2     -101724.7           3.4        12.8    0   .  .
  391      -2328.1      -96591.5           5.1         2.3    0   .  .
 8057      64473.9      -22182.0          21.9       -10.5    0   4  .
 8058     -25585.9      -16285.5          -4.0        -2.5    0   .  .
  390      88491.7      -91386.5           3.4         2.4    0   .  .

              point-no.          321392   TP 5

 8057      69314.6       60703.9         -18.0        -5.4    0   2  .
 8058     -20122.1       65984.7          -6.6       -10.4    0   .  .
  391      83925.3     -100784.2           3.9        -5.1    0   .  .
  393     -91658.2      -99858.6           5.0       -10.2    0   .  .
  392      -4729.7     -102411.1           7.5        -7.4    0   .  .

              point-no.          322583   TP 5
```

```
       583     13822.5     98894.5          -2.4       0.3   0  .  .
       191    -68691.6    -49182.0          -2.0      -4.6   0  .  .
       584    -75564.7     89371.0          -5.3       8.6   0  .  .
       190     27001.4    -47416.8          10.4      -8.6   0  .  .
       582    103202.0     92324.2          -5.9     -17.2   0  .  1

                point-no.          323605   TP 9

      8040     73597.0    -90382.4          -6.4     -17.6   0  .  1
       180     76027.7     92789.2          -6.3       0.5   0  .  .
       605      8760.0   -101702.4           9.0      -2.7   0  .  .
      8041     -8207.4    -89064.8           1.9      -2.4   0  .  .
       181    -10619.5     86835.6          -0.4      -3.1   0  .  .
       606    -76403.6    -97309.6          16.8      -6.5   0  1  .
       604     98924.5    -96067.7          -1.0       1.8   0  .  .
       182    -97761.6     79261.0          -0.1      -0.3   0  .  .
      8042   -100462.7    -86851.1           2.4      -2.4   0  .  .

                point-no.          907322   TP 7

       608    -79848.8     39331.4         -17.6       9.5   0  2  .
      8040    -49868.8     81596.0          -2.1       1.7   0  .  .
      8039     36637.8     82236.5           0.2       6.6   0  .  .
       322     -4430.3    -97361.9          11.9      15.7   0  .  .
       607      9417.2     33942.7         -23.1       7.9   0  5  .
       323    -89653.6    -98052.3           0.1      11.5   0  .  .

END OF EXECUTION : 03-FEB-99 14:36:43

PATB-GPS END
```

Appendix G

PATB-GPS aerial triangulation results using new photography for run 6. Antenna station coordinates based on Hobart base station trajectory (un-fixed ambiguities). New results for run 6 are listed under profile 8.

```
1
    PATB-GPS :                      COPYRIGHT :  H.KLEIN/F.ACKERMANN 1988-1994

    BLOCK ADJUSTMENT WITH BUNDLES                              REVISION Jun-94

    PROJECT  : Range test 1
    USER-ID. : gd

    START OF EXECUTION : 03-FEB-99 14:14:59

    **************************************************************************
    **************************************************************************
    **                                                                      **
    ** PROGRAM VERSION  PATB-GPS                                            **
    ** =========================                                            **
    **                                                                      **
    ** DIRECTORY FOR INPUT AND OUTPUT FILES :  PRESENT WORKING DIRECTORY    **
    ** INPUT                                                                **
    ** BASIC DATA                                        FROM FILE rt4.bas  **
    ** PHOTOGRAPHS                                       FROM FILE rt4.obs  **
    ** CONTROL POINTS                                    FROM FILE gd4.ctl  **
    **                                                                      **
    ** INITIAL VALUES FOR EXTERIOR ORIENTATION PARAMETERS ARE CALCULATED    **
    **                                                                      **
    ** WITHOUT AUTOMATIC GROSS ERROR DETECTION                              **
    ** NO CORRECTION OF SYSTEMATIC ERRORS                                   **
    ** ADJUSTMENT WITH GPS-OBSERVATIONS                                     **
    **            WITH DETERMINATION OF GPS-DRIFT PARAMETERS                **
    **            NO DETERMINATION OF GPS-ANTENNA OFFSET                    **
    ** NO INVERSION OF NORMAL EQUATIONS                                     **
    **                                                                      **
    ** ITERATION SEQUENCE WILL BE TERMINATED :                              **
    ** 1. IF 10 ITERATION STEPS ARE PERFORMED                               **
    ** 2. IF CHANGE OF ADJUSTED TERRAIN COORDINATES                         **
    **    BETWEEN TWO ITERATION STEPS FOR ALL POINTS     <    0.300         **
    **    IN THE TERRAIN SYSTEM                                             **
    ** 3. IF CHANGE OF SIGMA LESS THAN 0.001%                               **
    ** 4. IF SIGMA DOES NOT CONFIRM WITH READ IN STANDARD DEVIATIONS        **
    ** 5. IF THE RMS-VALUE OF OBSERVATIONS DIVERGES                         **
    **                                                                      **
    ** INPUT FORMATS AND INPUT SEQUENCES :                                  **
    ** PHOTOGRAPH NUMBERS         (I10,F10.3,I5)                            **
    ** PHOTOGRAPH POINTS          (I10,2F10.1,i5)                           **
    ** SEQUENCE OF READ IN COORDINATES OF PHOTO POINTS                = X Y **
    ** HORIZONTAL CONTROL         (I8,2f15.3,15x,i5)                        **
    ** SEQUENCE OF READ IN COORDINATES OF HORIZONTAL CONTROL POINTS   = X Y **
    ** VERTICAL CONTROL           (I8,30x,f15.3,i5)                         **
    ** GPS-OBSERVATIONS           (I8,3f15.3,f8.0,i5)                       **
    **                                                                      **
    ** READ IN IMVK                                      =   25             **
    **                                                                      **
    ** LIMITATIONS                                                          **
    ** NUMBER OF POINTS IN ONE PHOTO         RESTRICTED TO   60             **
    ** NUMBER OF CONTROL POINTS IN ONE LIST  RESTRICTED TO  750             **
    ** NUMBER OF PHOTOS IN ONE PHOTO GROUP   RESTRICTED TO   60             **
    ** DIMENSIONS OF ADDRESS MATRIX          RESTRICTED TO   50,10          **
    ** NUMBER OF PHOTOS/SUBMATRIX            RESTRICTED TO   20             **
    ** NUMBER OF DIFFERENT FOCAL LENGTHS     RESTRICTED TO   30             **
    ** NUMBER OF POINT RECORDS               RESTRICTED TO  165             **
    ** NUMBER OF PHOTO RECORDS               RESTRICTED TO   60             **
    **                                                                      **
    ** REQUIRED WORKING AREA FOR THESE SPECIFICATIONS    =  108670          **
    ** REQUIRED SCRATCH FILE : BLKSZ = 8192 BYTES,  BLOCKS=   8316          **
    **                                                                      **
    ** BREAK UP LIMIT FOR THE SIZE OF PHOTO GROUPS       =   60             **
    **                                                                      **
    ** PHOTO NUMBERS OF THE FIRST PHOTO GROUP :                             **
    **                                    FIRST READ IN PHOTOGRAPH ASSUMED  **
    ** NUMBER OF PHOTOS IN THE FIRST PHOTO GROUP         =    1             **
    **                                                                      **
    ** FOCAL LENGTH IN UNITS OF IMAGE SYSTEM AND CORRESPONDING FL-NUMBER    **
    ** NUMBER OF FOCAL LENGTHS                           =    0             **
    **                                                                      **
    ** SIZE OF PHOTOGRAPHS IN UNITS OF IMAGE SYSTEM                         **
    **   IN X :     230000.000   IN Y :     230000.000                      **
    **                                                                      **
    ** STANDARD DEVIATIONS OF OBSERVATIONS :                                **
    **                                                                      **
    **   FOR IMAGE POINTS IN X AND Y IN UNITS OF IMAGE SYSTEM               **
    **   DEFAULT SET (SDS NO. 0 OR BLANK) :       8.000                     **
    **                                                                      **
    **   FOR CONTROL POINTS IN UNITS OF TERRAIN SYSTEM                      **
    **                                       PLANIMETRY   HEIGHT            **
    **   1.SET FOR CONTROL POINTS        :         0.500   0.500            **
    **                                                                      **
    **   FOR GPS OBSERVATIONS IN UNITS OF TERRAIN SYSTEM                    **
    **                                       PLANIMETRY   AND HEIGHT        **
    **   1.SET FOR GPS OBSERVATIONS        :     0.250                      **
    **   2.SET FOR GPS OBSERVATIONS        :     0.250                      **
    **                                                                      **
    **                                                                      **
```

```
** COMMON OFFSET FROM CAMERA TO GPS ANTENNA :                            **
**                          0.105          -0.052          1.000         **
**                        IN UNITS OF TERRAIN SYSTEM                     **
**                                                                       **
** PRINTOUT                                                              **
** COORDINATES OF CONTROL POINTS AND RESIDUALS                           **
** COORDINATES AND RESIDUALS OF CRITICAL POINTS IN SEQUENCE              **
**                                                                       **
** ADDITIONAL OUTPUT                                                     **
** ADJUSTED TERRAIN COORDINATES IN SEQUENCE       ON FILE rt4.fvl        **
** EXTERIOR ORIENTATION PARAMETERS                ON FILE rt4.ori        **
**                                                                       **
***************************************************************************
***************************************************************************


      read in image points ...........................  1718
      stored unsorted point records ..................    33
      read in photographs ............................   134
      stored unsorted photo records ..................     3
      read in horizontal control points ..............    71
      read in vertical control points ................    71
      read in gps antenna points......................   141
      read in gps profiles............................     8
      stored control point records ...................     1



      PHOTO GROUPS AND PHOTO CONNECTIONS
      ----------------------------------
      photo group   1 has   1 photo
      photo group   2 has   9 photos
      photo group   3 has  10 photos
      photo group   4 has  14 photos
      photo group   5 has  18 photos
      photo group   6 has  23 photos
      photo group   7 has  11 photos
      photo group   8 has  10 photos
      photo group   9 has  10 photos
      photo group  10 has  15 photos
      photo group  11 has  13 photos

      COMPUTATION OF INITIAL VALUES OF EXTERIOR ORIENTATION PARAMETERS
      ----------------------------------------------------------------

      dimensions of submatrices    = ( 120 ,120 )
      dimensions of address matrix = (  50 , 11 )
      maximum number of photos/submatrix    =  30

      initial iteration step
      ----------------------

      number of hyperrows     =    8
      number of hypercolumns  =    2


      COMPUTATION OF ADJUSTED TERRAIN COORDINATES
      -------------------------------------------

      dimensions of submatrices    = ( 120 ,120 )
      dimensions of address matrix = (  50 , 11 )
      maximum number of photos/submatrix    =  20

      standard deviations for image points in x and y (in image system)
      default set :    8.000

      standard deviations for control points (in terrain system)
                         planimetry    height
      1. set :                0.500     0.500


      iteration step no.   1
      ------------------
      iteration step with gps

      number of hyperrows     =   10
      number of hypercolumns  =    3
      plus 1 column border part for gps

      maximum change of exterior orientation parameters :
      da,db,dc = parameters of rodrigues-matrix
      px,py,pz = coordinates of perspective centers (in terrain system)

                  da =0.071653               px =   400.080
                  db =0.056277               py =   610.328
                  dc =0.023223               pz =   320.765

      maximum change of adjusted terrain coordinates (in terrain system) :

            in x at point-no.          8357        174.228
            in y at point-no.          8346        127.803
            in z at point-no.          8359        367.110

      sigma reached =      53.3994  (in image system)


      iteration step no.   2
      ------------------
      iteration step with gps

      number of hyperrows     =   10
```

```
number of hypercolumns =    3
plus 1 column border part for gps

maximum change of exterior orientation parameters :
da,db,dc = parameters of rodrigues-matrix
px,py,pz = coordinates of perspective centers (in terrain system)

            da =0.001674              px =     6.876
            db =0.001138              py =    11.595
            dc =0.001026              pz =    16.520

maximum change of adjusted terrain coordinates (in terrain system) :

      in x at point-no.         805179          5.024
      in y at point-no.           8358         14.081
      in z at point-no.           7320         23.980

sigma reached =      7.3687  (in image system)


iteration step no.  3
------------------
iteration step with gps

number of hyperrows    =   10
number of hypercolumns =    3
plus 1 column border part for gps

maximum change of exterior orientation parameters :
da,db,dc = parameters of rodrigues-matrix
px,py,pz = coordinates of perspective centers (in terrain system)

            da =0.000003              px =     0.028
            db =0.000003              py =     0.031
            dc =0.000002              pz =     0.033

maximum change of adjusted terrain coordinates (in terrain system) :

      in x at point-no.           7320         0.036
      in y at point-no.           7320         0.044
      in z at point-no.           7320         0.104


end of adjustment  --  due to condition 2


STATISTICS
----------

 1-fold points         =    2
 2-fold points         =   40
 3-fold points         =  102
 4-fold points         =   34
 5-fold points         =   92
 6-fold points         =   64
 7-fold points         =   13
 8-fold points         =   16
 9-fold points         =   10
number of block points =  373


number of observations = 3789
number of unknowns     = 1971
redundancy             = 1818


number of outliers for image observations    =    0
number of outliers for control observations =    0
number of outliers for gps observations      =    0

ROOT MEAN SQUARE VALUES AND CHECK VALUES OF RESIDUALS OF PHOTOGRAMMETRIC OBSERVATIONS
-------------------------------------------------------------------------------------
                  image system     terrain system       image system

image points
------------
obs x = 1677  rms x =     5.25   rms x =     0.258   chv vx =    15.74
obs y = 1677  rms y =     5.53   rms y =     0.272   chv vy =    16.60

ROOT MEAN SQUARE VALUES AND CHECK VALUES OF RESIDUALS OF NON-PHOTOGRAMMETRIC OBSERVATIONS
-----------------------------------------------------------------------------------------
                  image system     terrain system      terrain system

control points with sds-no.  1
---------------------------
obs x =    11  rms x =    12.71   rms x =     0.625   chv vx =     1.88
obs y =    11  rms y =     3.46   rms y =     0.170   chv vy =     0.51
obs z =    11  rms z =     2.97   rms z =     0.146   chv vz =     0.44

ROOT MEAN SQUARE VALUES AND CHECK VALUES OF RESIDUALS OF GPS OBSERVATIONS
-------------------------------------------------------------------------
                                   terrain system      terrain system

gps observations with sds-no.  1
-----------------------------
obs x =  114                     rms x =     0.069   chv vx =     0.21
obs y =  114                     rms y =     0.064   chv vy =     0.19
obs z =  114                     rms z =     0.084   chv vz =     0.25

gps observations with sds-no.  2
-----------------------------
obs x =   20                     rms x =     0.101   chv vx =     0.30
```

```
obs y =   20                       rms y =    0.077   chv vy =     0.23
obs z =   20                       rms z =    0.125   chv vz =     0.37


SIGMA NAUGHT      7.46          =    0.367
------------


COORDINATES OF CONTROL POINTS AND RESIDUALS
-------------------------------------------
in units of terrain system


horizontal control points
                                         code of point
point-no.       x              y         input -> used           rx          ry    sds check

   25    -69873.014    -15726.485         HV 1                  -0.110       0.007    1   .  .
   26    -72653.385     -1847.868         HV 4                  -0.315       0.113    1   .  .
   27    -73912.981     20027.308         HV 4                  -0.131      -0.115    1   .  .
   28    -71645.884     29937.296         HV 2                   0.299       0.157    1   .  .
   29    -31262.676     29465.355         HV 3                   0.223       0.105    1   .  .
   42    -31772.848     22556.965         HV 3                  -1.436       0.026    1   .  .
   43    -35590.100     13370.653         HV 6                   0.663      -0.455    1   .  .
   45    -47988.815     -4332.370         HV 4                   1.095       0.207    1   .  .
   46    -36058.591    -12463.704         HV 4                  -0.546      -0.017    1   .  .
   52     -8939.231     -4353.436         HV 2                   0.121       0.036    1   .  .
   53       415.646    -14504.899         HV 1                   0.139      -0.066    1   .  .


vertical control points
                                         code of point
point-no.                      z         input -> used                       rz    sds check

   25                       66.104        HV 1                             -0.044    1      .
   26                       56.264        HV 4                             -0.200    1      .
   27                       14.268        HV 4                              0.183    1      .
   28                        3.531        HV 2                             -0.102    1      .
   29                      339.449        HV 3                             -0.150    1      .
   42                      363.035        HV 3                              0.153    1      .
   43                      366.988        HV 6                              0.092    1      .
   45                      292.006        HV 4                              0.060    1      .
   46                      360.655        HV 4                              0.204    1      .
   52                      468.576        HV 2                             -0.220    1      .
   53                      464.971        HV 1                              0.025    1      .


COORDINATES OF GPS OBSERVATIONS AND RESIDUALS
---------------------------------------------
in units of terrain system

gps antenna offset    x` =  0.105    y` = -0.052    z` =  1.000

photo-no.        x               y               z              t                  rx          ry           rz      sds
check

profile-no.         1

drift parameters:

linear       -0.1691        -0.0097        -0.0880
constant      -1.469         -1.216         -3.274

   123    -78566.206      25038.444       7456.549        -10.000            -0.019       0.021        0.060     1
   124    -74353.755      24916.164       7520.088         -9.000             0.028      -0.052       -0.163     1
   125    -69985.952      24832.734       7557.227         -8.000            -0.084      -0.002        0.034     1
   126    -65685.480      24946.498       7607.268         -7.000             0.078       0.002       -0.004     1
   127    -61386.897      25159.625       7644.942         -6.000            -0.049      -0.020        0.080     1
   128    -57125.903      25294.712       7673.962         -5.000             0.106       0.008       -0.026     1
   129    -52888.723      25391.237       7701.686         -4.000            -0.066      -0.050        0.038     1
   130    -48580.836      25410.509       7747.436         -3.000            -0.018       0.138        0.138     1
   131    -44271.105      25469.260       7776.497         -2.000            -0.043       0.043        0.037     1
   132    -40009.351      25427.532       7801.254         -1.000             0.068      -0.053       -0.052     1
   133    -35721.638      25373.194       7836.524          0.000            -0.116       0.000       -0.002     1
   134    -31423.696      25306.191       7857.928          1.000             0.082       0.044       -0.218     1
   135    -27168.359      25279.023       7872.442          2.000            -0.011      -0.134        0.033     1
   136    -22849.375      25262.107       7875.779          3.000             0.053       0.051       -0.068     1
   137    -18542.596      25226.053       7905.118          4.000             0.017      -0.041        0.132     1
   138    -14310.296      25229.860       7913.270          5.000             0.058      -0.021       -0.085     1
   139    -10017.826      25183.119       7921.205          6.000            -0.028       0.031       -0.045     1
   140     -5729.930      25164.720       7933.351          7.000             0.108       0.095        0.003     1
   141     -1516.485      25109.985       7946.055          8.000            -0.143       0.036        0.151     1
   142      2761.684      25142.518       7950.690          9.000            -0.020      -0.098       -0.044     1
   143      6987.566      25179.860       7941.129         10.000          --  not in the block --
profile-no.         2

drift parameters:

linear        0.1727        -0.0514         0.0382
constant      -1.227         -0.462         -1.966

   178      8543.080      16693.952       7960.770        -10.000          --  not in the block --
   179      4059.095      16699.094       7953.097         -9.000             0.023       0.025        0.073     1
   180      -560.882      16702.311       7961.493         -8.000             0.065      -0.024        0.047     1
   181     -4941.054      16696.489       7948.622         -7.000             0.013      -0.003       -0.059     1
   182     -9235.130      16592.428       7952.623         -6.000            -0.032      -0.009       -0.060     1
   183    -13547.665      16501.302       7950.324         -5.000             0.042      -0.013        0.020     1
   184    -17835.556      16382.391       7956.385         -4.000            -0.088       0.005        0.046     1
```

```
  185    -22233.218     16463.187      7924.062        -3.000          0.007      0.031     -0.032    1
  186    -26491.966     16630.638      7921.693        -2.000         -0.013     -0.053      0.120    1
  187    -30768.850     16786.616      7893.474        -1.000          0.001     -0.024     -0.162    1
  188    -35217.043     16699.901      7858.480         0.000         -0.044     -0.050     -0.113    1
  189    -39545.031     16665.006      7844.879         1.000         -0.083      0.046      0.005    1
  190    -43824.914     16596.705      7811.134         2.000          0.049     -0.008      0.091    1
  191    -48353.307     16554.701      7791.409         3.000          0.013      0.105     -0.013    1
  192    -52995.059     16298.692      7734.866         4.000          0.052      0.004     -0.014    1
  193    -57666.692     16157.817      7702.101         5.000         -0.049      0.051      0.029    1
  194    -62166.466     16266.388      7664.520         6.000         -0.004      0.029      0.050    1
  195    -66681.417     16296.985      7617.949         7.000         -0.019     -0.059     -0.022    1
  196    -71130.073     16370.463      7558.387         8.000         -0.025     -0.019     -0.141    1
  197    -75512.346     16427.217      7513.695         9.000          0.123      0.016      0.047    1
  198    -79952.737     16375.769      7450.969        10.000         -0.029     -0.051      0.086    1

profile-no.        3

drift parameters:

linear        0.0618       -0.1007       -0.0347
constant     -0.657        -0.381        -1.643

  321      5816.414      -516.040      7958.421       -10.000         -0.059     -0.113     -0.044    1
  322      1634.519      -570.697      7971.268        -9.000         -0.131      0.028     -0.008    1
  323     -2500.110      -566.285      7958.203        -8.000          0.096     -0.103      0.034    1
  324     -6608.515      -489.603      7970.686        -7.000         -0.007      0.111      0.029    1
  325    -10764.164      -417.483      7970.656        -6.000          0.061      0.050      0.033    1
  326    -14902.739      -362.907      7966.823        -5.000          0.099      0.141     -0.004    1
  327    -19061.989      -311.405      7939.938        -4.000         -0.072     -0.072      0.030    1
  328    -23298.433      -160.505      7939.409        -3.000          0.068      0.078      0.008    1
  329    -27660.347       -12.914      7900.344        -2.000          0.084     -0.049     -0.045    1
  330    -31981.207         0.353      7890.327        -1.000          0.070     -0.061      0.048    1
  331    -36105.330       -27.477      7858.423         0.000         -0.042     -0.060      0.010    1
  332    -40184.958      -148.971      7851.677         1.000         -0.085      0.026     -0.033    1
  333    -44515.857      -286.283      7818.016         2.000         -0.078     -0.023     -0.011    1
  334    -48956.445      -441.754      7790.698         3.000          0.036      0.079     -0.055    1
  335    -53487.105      -526.003      7757.924         4.000         -0.021     -0.018      0.026    1
  336    -57721.479      -512.189      7718.998         5.000         -0.021      0.086     -0.116    1
  337    -61979.500      -520.622      7674.764         6.000         -0.062     -0.079     -0.067    1
  338    -66309.298      -498.671      7628.092         7.000          0.012      0.029      0.011    1
  339    -70584.886      -519.310      7574.252         8.000         -0.093     -0.074      0.148    1
  340    -74776.729      -488.539      7549.417         9.000          0.124      0.090     -0.004    1
  341    -79040.146      -467.148      7501.404        10.000          0.020     -0.065      0.011    1

profile-no.        4

drift parameters:

linear       -0.0774        0.1045        0.1512
constant     -0.216        -1.004        -1.679

  342    -77952.465     -9077.515      7494.911        -9.500          0.013     -0.015     -0.009    1
  343    -73780.025     -9093.068      7544.361        -8.500         -0.043      0.027      0.176    1
  344    -69531.482     -9092.706      7572.026        -7.500          0.021     -0.072     -0.158    1
  345    -65149.733     -9067.537      7618.682        -6.500          0.012      0.042      0.172    1
  346    -60804.509     -9065.521      7670.594        -5.500         -0.030     -0.009     -0.043    1
  347    -56463.708     -9036.005      7710.779        -4.500          0.026      0.002      0.054    1
  348    -52125.664     -9035.353      7747.684        -3.500         -0.021     -0.025     -0.089    1
  349    -47757.989     -9023.061      7770.592        -2.500          0.008      0.039     -0.082    1
  350    -43393.331     -9032.601      7804.833        -1.500         -0.004      0.026      0.024    1
  351    -39039.765     -9024.771      7834.280        -0.500          0.001      0.019     -0.063    1
  352    -34694.267     -8997.559      7861.436         0.500          0.009     -0.091     -0.048    1
  353    -30270.919     -8897.112      7874.738         1.500          0.040      0.044     -0.025    1
  354    -25797.340     -8753.671      7908.499         2.500         -0.027      0.007      0.050    1
  355    -21203.593     -8738.039      7938.452         3.500          0.063      0.051      0.018    1
  356    -16712.864     -8743.665      7948.805         4.500         -0.084     -0.010      0.048    1
  357    -12251.997     -8826.586      7948.548         5.500          0.099      0.105     -0.156    1
  358     -7821.683     -8855.936      7969.725         6.500         -0.116     -0.079      0.032    1
  359     -3490.318     -8884.587      7972.267         7.500          0.039     -0.061     -0.065    1
  360       801.681     -8991.916      7962.208         8.500         -0.018     -0.052     -0.057    1
  361      5116.231     -9031.378      7940.724         9.500          0.012      0.053      0.223    1

profile-no.        5

drift parameters:

linear        0.2038       -0.0237       -0.0346
constant     -0.081        -0.938        -1.214

  386    -72923.520     31025.989      7499.595        -5.500         -0.031      0.032      0.049    1
  387    -72966.595     26630.274      7512.201        -4.500          0.083     -0.094     -0.029    1
  388    -72931.521     22165.237      7531.482        -3.500         -0.014      0.101     -0.027    1
  389    -72824.904     17742.294      7536.636        -2.500         -0.004     -0.080     -0.100    1
  390    -72661.731     13290.347      7534.563        -1.500         -0.157      0.040      0.021    1
  391    -72504.235      8781.568      7534.545        -0.500          0.203      0.051      0.120    1
  392    -72468.083      4340.462      7554.806         0.500         -0.065      0.006      0.027    1
  393    -72577.033       -18.619      7540.037         1.500         -0.053     -0.079     -0.058    1
  394    -72740.837     -4221.488      7534.670         2.500         -0.021     -0.001      0.008    1
  395    -72691.800     -8455.595      7539.615         3.500          0.097     -0.008      0.011    1
  396    -72663.590    -12679.002      7538.294         4.500         -0.037      0.032     -0.021    1
  397    -72481.190    -16883.346      7550.049         5.500        --  not in the block --

profile-no.        6

drift parameters:

linear       -0.1378        0.0012       -0.1607
constant     -0.635        -0.602        -2.005

  575    -40320.905    -16840.126      7745.597        -5.500        --  not in the block --
  576    -40338.098    -12720.257      7753.025        -4.500         -0.057      0.074      0.160    1
  577    -40345.941     -8544.831      7759.908        -3.500          0.024     -0.106     -0.142    1
  578    -40330.212     -4141.716      7768.350        -2.500          0.059     -0.059      0.018    1
  579    -40385.030       337.620      7757.403        -1.500          0.024      0.152      0.093    1
  580    -40393.955      4823.264      7759.367        -0.500         -0.021     -0.039     -0.101    1
  581    -40348.333      9304.086      7768.468         0.500          0.017     -0.075     -0.093    1
```

```
  582    -40302.775     13800.462       7777.176          1.500           -0.114      0.155      0.044    1
  583    -40318.353     18324.713       7752.588          2.500            0.091     -0.171     -0.070    1
  584    -40378.734     22877.743       7734.385          3.500           -0.072      0.056     -0.073    1
  585    -40460.111     27447.628       7728.204          4.500            0.086      0.016      0.140    1
  586    -40502.566     32049.581       7681.713          5.500           -0.037     -0.003      0.024    1

profile-no.        7

drift parameters:

linear       0.3724         0.1034         0.3385
constant    -1.829         -0.005         -1.659

  600       162.268     33865.335       7806.528         -6.000         --  not in the block --
  601       140.531     29702.433       7827.019         -5.000           0.016     -0.015      0.118    1
  602       211.707     25470.962       7824.036         -4.000           0.176     -0.082     -0.159    1
  603       197.443     21271.514       7849.364         -3.000          -0.113      0.061     -0.038    1
  604       206.057     17073.782       7836.942         -2.000          -0.053     -0.007      0.042    1
  605       236.703     12789.305       7862.774         -1.000          -0.111      0.098      0.068    1
  606       189.374      8619.336       7891.396          0.000          -0.065     -0.080     -0.064    1
  607       228.730      4459.041       7888.805          1.000           0.045      0.115      0.049    1
  608       231.765       231.388       7891.566          2.000           0.152     -0.085      0.099    1
  609       207.930     -3904.631       7889.043          3.000          -0.074      0.022     -0.050    1
  610       185.049     -8067.530       7880.617          4.000           0.044      0.015     -0.216    1
  611       168.183    -12190.804       7871.821          5.000          -0.015     -0.042      0.152    1
  612       146.417    -16438.862       7832.430          6.000         --  not in the block --
```

```
profile-no.        8           HOBART BASE STATION TRAJECTORY

        drift parameters:

        linear       0.0963          0.0059         0.0084
        constant    -0.705          -1.634          1.085

         6038      7974.692       8111.237       8120.817        -10.000          --  not in the block --
         6039      3581.219       8090.799       8119.635         -9.000          -0.087      0.140     -0.056     2
         6040      -754.399       8005.557       8126.203         -8.000           0.300     -0.033     -0.277     2
         6041     -5063.367       8029.974       8122.052         -7.000          -0.071     -0.109      0.067     2
         6042     -9417.370       8067.816       8114.591         -6.000           0.001      0.054      0.115     2
         6043    -13760.399       8184.280       8111.029         -5.000          -0.126     -0.007     -0.039     2
         6044    -17947.459       8208.069       8097.043         -4.000          -0.091     -0.042     -0.152     2
         6045    -22114.751       8300.809       8085.652         -3.000          -0.029      0.031      0.166     2
         6046    -26548.866       8372.650       8066.158         -2.000          -0.070     -0.048      0.163     2
         6047    -30999.114       8446.195       8048.456         -1.000           0.041     -0.134      0.167     2
         6048    -35240.921       8527.549       8022.267          0.000          -0.007     -0.023      0.009     2
         6049    -39264.985       8565.892       8002.031          1.000           0.107      0.195     -0.059     2
         6050    -43305.384       8619.937       7973.269          2.000           0.066     -0.091      0.002     2
         6051    -47389.525       8524.706       7949.110          3.000           0.016      0.041      0.063     2
         6052    -51723.129       8375.968       7909.597          4.000          -0.014     -0.011     -0.108     2
         6053    -56150.125       8099.781       7876.484          5.000           0.002      0.006      0.009     2
         6054    -60601.982       7928.531       7831.237          6.000          -0.042      0.018      0.044     2
         6055    -65017.660       7942.498       7789.195          7.000           0.142      0.071      0.046     2
         6056    -69428.327       7862.072       7740.032          8.000          -0.146     -0.058     -0.002     2
         6057    -73829.843       7933.108       7690.943          9.000          -0.064      0.037      0.111     2
         6058    -78332.494       8108.513       7641.420         10.000           0.071     -0.038     -0.269     2
```

```
    COORDINATES AND RESIDUALS OF CRITICAL POINTS
    ----------------------------------------------
    arranged by increasing point numbers


photo-no.      x              y              rx          ry     sds  check


              point-no.                46    HV 4

  352      -28474.0      -71272.2           6.1         0.8    0    .  .
  576        3494.6      -83900.2           1.7         4.6    0    .  .
  351       60461.2      -72221.0          16.3         2.4    0    1  .
  577      -79563.4      -86101.4          -4.6        10.9    0    .  .

   HO    -36058.591    -12463.704        -0.546      -0.017    1    .  .
   VE                     360.655                     0.204    1       .


              point-no.              4142    TP 7

  604      -79613.4       52998.5         -11.4        -8.5    0    .  .
  141       90376.2      -80593.7           2.2       -15.1    0    .  .
  179       30339.5      -90144.0          -1.1         2.5    0    .  .
  602       92976.2       56053.3          -9.0       -11.2    0    .  .
  603        3944.4       51530.1          -9.7        -7.5    0    .  .
  180      -65593.6      -86662.3          -6.4         7.3    0    .  .
  142        -557.7      -86168.2          18.3        -5.9    0    2  .

              point-no.              5188    TP 8

 6048        9837.4      -77754.3          20.7        11.9    0    4  .
  188        6752.7       85927.7         -18.1         0.9    0    2  .
 6049      -72204.4      -77329.1          37.3         6.7    0    9  .
  581       65364.7      -91939.1           7.5       -10.3    0    .  .
  582      -29551.7      -99152.9          18.6        -8.8    0    2  .
  187       98720.0       99928.4         -12.8         5.1    0    .  .
 6047       97948.5      -82219.4          12.3        -3.6    0    .  .
  189      -80716.8       87197.8         -18.0         1.1    0    2  .

              point-no.              6284    TP 6

  323       64810.1      -85305.1          10.6        -1.9    0    .  .
  325     -103996.5      -87214.5           8.5        -5.7    0    .  .
```

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6040     101615.5      82811.8          -8.7       16.8   0   .  1
6042     -72472.9      85275.7          -8.7       -4.1   0   .  .
6041      11566.0      84423.4          -6.1       -8.8   0   .  .
 324     -18509.3     -85932.0           4.5        4.9   0   .  .

            point-no.            6869   TP 8

6057     -75331.8      94792.1          -5.9        6.4   0   .  .
6055     101456.5      88543.5         -15.0       17.9   0   .  1
 393     -66204.1      49762.5          -3.1        4.4   0   .  .
 392      22228.5      48620.9          -7.0       -2.0   0   .  .
 339     -14130.4     -81262.8           6.4       -7.3   0   .  .
 338      71313.4     -77120.0           3.6       -1.7   0   .  .
 340    -100253.1     -77395.2          15.7        1.7   0   .  .
6056      18646.5      88517.7          -2.3       -5.5   0   .  .

            point-no.            8350   TP 4

 351     -90180.8     -96143.7           7.4        3.7   0   .  .
 576     -16262.6      67208.5          -9.3       17.9   0   .  1
 349      90668.6     -99457.0           2.9        4.0   0   .  .
 350       -871.8     -95756.6           7.6        2.0   0   .  .


            point-no.          123602   TP 4

 602       3849.4      93891.0          -5.0        5.8   0   .  .
 142      39505.8        341.4         -16.2      -15.4   0   1  .
 603     -83784.7      91197.0          -0.9        7.4   0   .  .
 601      94155.3      95079.3          -9.4        2.8   0   .  .

            point-no.          123603   TP 4

 602      82459.4      98815.0         -15.0       -0.5   0   .  .
 604     -89274.5      95793.3           0.3       -6.2   0   .  .
 142      41810.5     -76921.2           2.6      -18.8   0   .  2
 603      -5638.2      93836.3          -3.7        3.7   0   .  .

            point-no.          123604   TP 4

 604      -1676.3     100259.3           0.5        1.4   0   .  .
 603      80608.9      96981.0           8.9      -10.1   0   .  .
 179     -20514.8     -14551.2         -16.5       -4.1   0   1  .
 605     -94713.1      92605.6          -5.9       -8.2   0   .  .

            point-no.          204142   TP 5

 141      84856.8       4882.2          21.1      -12.4   0   4  .
 602       5630.6      49335.8          -3.6      -12.7   0   .  .
 603     -83164.1      46886.7         -10.0      -11.9   0   .  .
 601      93895.5      50312.8          -1.1      -22.5   0   .  4
 142      -4433.4       -128.6          26.7       -2.3   0   7  .

            point-no.          205179   TP 5

 180     -96832.9       1424.2          17.9        5.8   0   2  .
 604      11003.0      81842.7           0.9       11.5   0   .  .
 603      93073.1      78921.4          -6.6        2.2   0   .  .
 179      -3026.5      -1090.9          11.6        0.6   0   .  .
 605     -81899.8      74643.8           0.3       15.8   0   .  .

            point-no.          222582   TP 9

6048     101087.2    -111115.5         -16.4      -26.7   0   1  7
 582        863.5      -3922.4          -8.3        6.4   0   .  .
6050     -64389.7     -96663.1          15.7       -7.9   0   .  .
 188     100317.8      59685.7         -15.0       -1.8   0   .  .
 583     -91703.1        719.1          -0.3       13.2   0   .  .
6049      18270.4    -112759.2           0.4      -11.4   0   .  .
 190     -72916.2      53253.1           2.3       12.4   0   .  .
 581      93948.6       2175.3         -17.2       -8.2   0   1  .
 189      13136.4      58502.7          -1.2        7.7   0   .  .

            point-no.          223605   TP 9

 180     -15633.2      83292.2          -6.6       -2.7   0   .  .
 606     -84760.2      -5020.5           4.8       -7.7   0   .  .
 604      91684.9      -2816.3           5.8      -14.2   0   .  .
 181    -102258.4      80108.4          -3.1       -0.4   0   .  .
6041     -97442.8     -95955.8          -6.8       -8.8   0   .  .
6040     -16578.7     -93351.2         -11.5        1.2   0   .  .
 605       -404.8      -7856.0          -3.6      -19.0   0   .  2
6039      70915.5     -93709.4         -15.0        8.7   0   .  .
 179      74558.8      80841.5           1.5       -3.7   0   .  .

            point-no.          321391   TP 5

 392     -90185.2    -101724.7           3.4       12.8   0   .  .
 391      -2328.1     -96591.5           5.1        2.3   0   .  .
6057      64473.9     -22182.0          21.8      -10.4   0   4  .
6058     -25585.9     -16285.5          -3.9       -2.5   0   .  .
 390      88491.7     -91386.5           3.4        2.4   0   .  .

            point-no.          321392   TP 5

6057      69314.6      60703.9         -18.1       -5.4   0   2  .
6058     -20122.1      65984.7          -6.6      -10.5   0   .  .
 391      83925.3    -100784.2           4.0       -5.1   0   .  .
 393     -91658.2     -99858.6           5.0      -10.3   0   .  .
 392      -4729.7    -102411.1           7.5       -7.4   0   .  .

            point-no.          322583   TP 5

 583      13822.5      98894.5          -2.4        0.3   0   .  .
 191     -68691.6     -49182.0          -2.0       -4.5   0   .  .
 584     -75564.7      89371.0          -5.3        8.6   0   .  .
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 190      27001.4     -47416.8          10.4       -8.6    0  .  .
 582     103202.0      92324.2          -5.9      -17.2    0  .  1

           point-no.           323605   TP 9

6040      73597.0     -90382.4          -6.3      -17.8    0  .  1
 180      76027.7      92789.2          -6.3        0.5    0  .  .
 605       8760.0    -101702.4           8.9       -2.8    0  .  .
6041      -8207.4     -89064.8           1.8       -2.4    0  .  .
 181     -10619.5      86835.6          -0.4       -3.1    0  .  .
 606     -76403.6     -97309.6          16.7       -6.5    0  1  .
 604      98924.5     -96067.7          -1.0        1.8    0  .  .
 182     -97761.6      79261.0          -0.2       -0.3    0  .  .
6042    -100462.7     -86851.1           2.6       -2.1    0  .  .

           point-no.           907322   TP 7

 608     -79848.8      39331.4         -17.6        9.5    0  2  .
6040     -49868.8      81596.0          -2.1        1.8    0  .  .
6039      36637.8      82236.5           0.1        6.5    0  .  .
 322      -4430.3     -97361.9          11.9       15.7    0  .  .
 607       9417.2      33942.7         -23.1        7.9    0  5  .
 323     -89653.6     -98052.3           0.1       11.6    0  .  .

END OF EXECUTION : 03-FEB-99 14:18:39

PATB-GPS END
```

Appendix H

Comparison of adjusted image point coordinates derived from aerial triangulation using Lightning Ridge base station fixed-ambiguity solution (Appendix C) and Bathurst base station unfixed-ambiguity solution.

```
PROGRAM: COMPARE                 COMPARES DATA SETS                    3-Feb-99
                              COMPARISON OF COMMON POINTS
                                                              DIFFERENCES
 LABEL          X               Y                  Z         X      Y      Z      XY
    25   -69873.124284  -15726.477652         66.059812    .00    .00    .00    .00
    26   -72653.700016   -1847.753551         56.063601    .00    .00   -.01    .00
    27   -73913.110772   20027.194040         14.450727    .01    .00    .00    .01
    28   -71645.583325   29937.452956          3.428724    .00    .00    .00    .00
    29   -31262.453952   29465.460461        339.298610   -.01    .00    .00    .01
    42   -31774.286079   22556.991965        363.187351    .00    .00    .00    .00
    43   -35589.438678   13370.198924        367.080352    .00    .00    .01    .00
    45   -47987.720585   -4332.164885        292.065776    .00    .00    .00    .00
    46   -36059.137465  -12463.723057        360.859667   -.01    .00    .00    .01
    52    -8939.109716   -4353.400247        468.356407    .01    .00   -.01    .01
    53      415.785873  -14504.963955        464.995974    .01    .00    .00    .01
  3085   -78011.689277   29609.425817        -70.523770    .01    .00    .01    .01
  3086   -74203.341329   29440.211143        -24.788811    .01    .00    .01    .01
  3087   -70885.344780   29432.840857         13.867487    .01    .00    .01    .01
  3088   -66156.191517   29127.111660         66.532419    .01    .00    .00    .01
  3089   -61814.034217   28824.606290        111.140260    .02    .00    .00    .02
  3091   -54279.104560   29579.276048        179.677035    .02   -.01    .01    .02
  3092   -50149.566340   29272.976887        216.127970    .01   -.01    .01    .02
  3093   -46578.792269   29262.579440        243.819199    .00   -.01    .01    .01
  3094   -41811.180098   29050.378195        279.149560    .00   -.01    .02    .01
  3095   -37431.087168   29420.408075        304.809253    .00   -.01    .01    .01
  3096   -32961.620498   29440.069246        330.093366   -.01    .00    .00    .01
  3097   -29150.250320   29884.507145        346.562679   -.01    .00    .00    .01
  3098   -24484.624427   29097.963781        370.723261   -.01    .00    .00    .01
  3099   -20203.733303   29713.357370        385.330478   -.02    .01    .00    .02
  3100   -15653.647923   28909.265865        405.028637   -.02    .02   -.01    .03
  3101   -11507.438581   29022.842523        413.364360   -.02    .03   -.01    .03
  3102    -7519.266762   29046.400027        420.804065   -.01    .03   -.01    .03
  3103    -2529.962423   28665.430317        426.256831   -.01    .03   -.01    .03
  3104     1197.350588   28448.126133        428.030619   -.01    .04    .00    .04
  4123   -79244.666966   21208.957353        -55.052899    .02    .00    .01    .02
  4125   -70661.213522   20475.758262         49.703032    .01    .00    .00    .01
  4126   -65995.025755   20801.921831         99.406429    .01    .00    .00    .01
  4127   -61469.464124   20384.661088        147.232672    .01    .00    .00    .01
  4128   -57182.817739   20810.182374        187.314531    .01    .00    .00    .01
  4129   -52564.947834   20706.611516        227.956414    .01   -.01    .01    .01
  4130   -48180.473523   20741.522695        264.200841    .01   -.01    .01    .01
  4131   -43847.695081   21244.749154        294.124602    .00   -.01    .01    .01
  4132   -39665.451025   20850.604071        323.092250    .00   -.01    .01    .01
  4133   -35491.186050   20976.792982        348.431059   -.01   -.01    .00    .01
  4134   -31762.441593   20810.889634        368.454547   -.01   -.01    .00    .01
  4135   -26582.851022   20802.721000        393.567869   -.01    .00   -.01    .01
  4136   -22645.039009   21009.286300        408.864913   -.01    .01    .00    .01
  4137   -18215.029379   20593.497191        426.154958   -.01    .02    .00    .02
  4138   -13788.861900   20594.280379        439.004624   -.01    .02   -.01    .02
  4139    -9824.262829   20673.131909        446.723121    .00    .02   -.02    .02
  4140    -5257.072676   20611.920818        453.156518    .00    .03   -.02    .03
  4141    -1465.850204   20190.432707        458.137303    .01    .03   -.02    .03
  4142     2810.572910   20938.473728        464.578792    .00    .04   -.01    .04
  5125   -71010.743060   11940.462830         66.330167    .01    .00   -.01    .01
  5141   -48270.922303   12896.572279        280.515984   -.01   -.04    .17    .04
  5179     4060.611575   12664.124393        472.621883    .03    .04   -.05    .05
  5182    -9353.460082   12073.562112        466.217668    .01    .00   -.08    .01
  5183   -13586.488615   11912.679240        458.425030    .00   -.01   -.09    .01
  5184   -18070.481478   11899.929666        446.224975    .00    .03   -.01    .03
  5185   -22276.645679   12249.368690        432.101779    .01    .02    .00    .02
  5186   -26720.029989   12006.915435        413.476418    .00   -.03   -.06    .03
  5187   -30679.645813   12631.850109        393.233176    .01   -.02   -.04    .02
  5188   -35689.249589   12354.782815        367.028407    .00    .00    .02    .00
  5189   -39321.569406   12629.038061        346.766589    .00    .01    .04    .01
  5190   -43843.768011   11897.132560        315.729889    .00    .01    .06    .01
  5191   -48271.325856   12896.263247        281.739044    .01   -.01    .01    .01
  5192   -53211.383241   12158.187991        242.297020    .01    .01    .03    .02
  5193   -57722.714692   11582.948471        203.804710    .01    .00    .02    .01
  5194   -62703.272553   12145.169851        153.479387    .01    .00    .01    .01
```

5195	-67356.509897	11830.051142	106.406148	.00	.00	.00	.00
5196	-71010.453907	11940.360417	66.257031	.00	.00	-.02	.01
5197	-76153.808832	12334.448116	6.742408	.01	-.01	-.03	.01
5198	-78230.744274	12362.329890	-19.710719	.02	-.02	-.06	.03
5784	-18071.840689	11898.610172	446.173109	-.01	.05	-.22	.05
6267	-79017.099647	3933.921874	-20.205611	-.03	.02	-.02	.04
6268	-73925.344602	12257.999741	33.009241	.01	-.01	-.03	.01
6269	-68450.689870	11916.525679	94.915351	.00	.00	-.01	.00
6270	-64602.615747	3067.214053	144.737189	.00	.00	.00	.00
6271	-60400.096045	3490.129003	185.061424	.01	.00	.00	.01
6272	-56474.264991	3404.481232	222.333092	.01	-.01	.02	.01
6273	-51582.408379	3406.703470	263.432322	.00	-.02	.05	.02
6274	-48531.654972	3949.388595	289.765698	.00	-.03	.06	.03
6275	-44206.390827	3923.135301	322.070633	.00	-.02	.04	.02
6278	-31757.131530	4069.831583	397.385692	-.01	.00	-.02	.01
6279	-27207.810065	4457.585214	418.343594	-.01	.01	-.05	.02
6280	-22706.398103	3782.305715	438.132715	-.01	.03	-.09	.03
6281	-18534.009338	3878.587271	452.460935	.00	.03	-.09	.03
6282	-14139.370880	3540.478702	468.909482	.01	.02	-.08	.02
6283	-10069.516656	4278.049909	480.487161	.02	.01	-.07	.02
6284	-5612.218360	3736.875230	480.519346	.02	.01	-.06	.02
6285	-1465.764941	3397.576321	482.003455	.02	.00	-.05	.02
6286	3724.094771	3815.809962	484.458651	.03	.00	-.04	.03
6287	7858.727889	3494.950128	481.001880	.04	-.01	-.03	.04
6868	-74215.079772	3755.722330	37.974022	.00	.02	-.03	.02
6869	-69745.484910	3236.608424	88.485004	.00	.01	-.02	.01
7320	9519.870309	-5175.456176	474.081352	.03	-.02	-.02	.04
7321	5473.893875	-4437.417001	478.884992	.03	-.01	-.02	.03
7322	1071.573438	-4868.807181	480.340033	.02	-.01	-.02	.02
7323	-3267.866167	-5002.641775	480.163443	.02	.00	-.02	.02
7324	-7776.490622	-4865.260794	469.091563	.01	.00	-.02	.01
7325	-11527.243541	-5119.794169	462.537225	.01	-.01	-.02	.01
7326	-16076.619898	-4357.810316	453.788196	.00	.00	-.03	.01
7327	-20293.250575	-3973.450714	443.645003	.00	.00	-.03	.00
7328	-23254.430219	-4525.736541	431.958143	-.01	.00	-.02	.01
7329	-27113.483766	-4735.769197	416.399379	-.01	.00	-.02	.01
7330	-30714.878483	-4072.082516	401.158614	-.01	.00	-.01	.01
7331	-35288.388065	-5298.895415	375.676100	-.01	.00	.00	.01
7332	-39153.128641	-4302.542388	353.593814	-.01	.00	.00	.01
7333	-44086.549340	-4150.299942	320.292582	-.01	.00	.01	.01
7334	-48254.388431	-4938.602322	288.754804	.00	.00	.00	.00
7335	-52606.505287	-4355.983019	252.593074	.00	.00	.00	.00
7336	-57103.868674	-4784.007177	213.376842	.00	.00	-.01	.00
7337	-61678.774911	-4813.718276	170.719297	.00	.00	-.01	.00
7338	-65592.151147	-5166.434152	130.470694	.00	.00	-.01	.00
7339	-70083.670022	-5319.281176	83.436408	.00	.00	-.02	.00
7340	-74411.362710	-4407.594434	34.578321	-.01	.00	-.03	.01
7341	-78507.065824	-4677.070059	-15.328569	-.01	.00	-.02	.02
7727	-73915.970259	20024.008365	14.023461	.01	.00	.00	.01
7728	-71649.657164	29937.634406	2.474307	.01	.00	.01	.01
7751	-14225.226732	4535.142056	464.926029	.01	.01	-.06	.01
7752	-8941.278760	-4353.925210	466.744562	.01	.00	-.02	.01
8343	-73608.646153	-13038.928470	32.142221	.00	-.01	-.01	.01
8344	-69517.298495	-13524.511173	76.974131	.00	-.01	-.01	.01
8345	-65025.349221	-13030.815466	126.310375	.00	.00	.00	.00
8346	-60975.117651	-13366.332395	166.668420	.01	-.01	-.02	.01
8347	-56593.660107	-13258.195502	204.864220	.01	.00	-.01	.01
8348	-52137.888735	-13217.790520	243.506995	.01	.01	.00	.01
8349	-48661.689291	-13416.369375	271.659742	.00	.01	.00	.01
8350	-43406.500642	-13554.284018	310.176087	-.01	.00	.00	.01
8351	-39457.349384	-12425.772808	339.717503	-.01	.00	.00	.01
8353	-30474.937694	-12869.081607	391.557658	-.02	.00	-.01	.02
8354	-25609.778418	-12810.586348	420.623667	-.01	-.01	-.03	.02
8355	-21492.696496	-12785.044607	433.120381	-.01	-.02	-.04	.02
8356	-17438.674602	-12430.723998	438.327358	.00	-.02	-.04	.02
8357	-12951.848153	-13345.340711	447.534402	.01	-.01	-.03	.02
8358	-8481.141965	-12885.927016	456.256572	.01	-.01	-.03	.01
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8360	240.902648	-12982.247961	464.592213	.01	-.01	-.03	.02
8361	5021.232573	-12976.554002	465.123044	.01	-.02	-.03	.02
41342	-48788.312914	-3636.615417	287.029239	.00	.00	.01	.00
41357	-33494.886183	15680.800260	372.705594	-.01	.00	.00	.01
101326	-6642.841495	-8199.383259	472.041139	.01	-.01	-.03	.01
104128	-57508.339029	29504.539760	149.992995	.02	-.01	.00	.02
106045	-22382.577672	13197.144110	429.580951	-.04	.05	-.24	.06
121386	-68488.396275	31043.227210	32.998117	.00	.00	.01	.00
121387	-68532.155722	26909.661100	50.420884	.01	.00	.00	.01
121388	-68312.629461	22341.861267	69.217454	.01	.00	.00	.01
121389	-67803.712167	18167.152880	87.725853	.01	.00	.00	.01

121390	-67501.924236	13108.772117	102.604809	.01	.00	.00	.01
121391	-67558.869223	9228.455859	108.982678	.00	.00	-.01	.00
121392	-67408.775503	4255.818665	113.960210	.00	.00	-.01	.00
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121394	-67628.866695	-4472.201789	110.541460	.00	.00	-.02	.00
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121396	-68242.801603	-13027.531334	91.412198	.00	-.01	-.01	.01
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122582	-35848.155377	14011.845943	362.789674	.00	.00	.02	.00
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123601	4894.326962	29387.182280	423.673399	-.01	.04	.00	.04
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123603	4890.854992	21385.264218	461.950639	.00	.05	.00	.05
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123605	5104.131120	12884.262773	479.763066	.03	.04	-.04	.05
123606	4885.202942	8621.114217	490.783910	.04	.02	-.05	.05
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123608	4676.460887	181.406324	495.636150	.03	-.01	-.03	.03
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204123	-78237.684696	25081.789772	-54.463913	.01	.00	.00	.01
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204137	-18588.165584	25052.070330	410.935532	-.01	.01	.00	.02
204138	-14412.351425	25364.013578	421.681155	-.01	.02	-.01	.02
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205179	4145.129987	16535.749471	471.155051	.02	.04	-.02	.05
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 904137   -18626.741624    29918.847359      391.127114  -.02    .01    .00   .02
 904138   -13949.514563    29758.604490      405.616318  -.02    .02   -.01   .03
 904139    -9969.849246    29699.414864      413.789058  -.02    .03   -.02   .03
 904140    -5670.380689    29990.559505      418.508790  -.01    .03   -.01   .03
 904141    -1259.506578    29904.555344      421.922716  -.01    .03    .00   .03
 904142     3028.912368    29674.510796      422.485572  -.01    .04    .00   .04
 904187   -30669.479183    21484.836010      372.223942  -.01   -.01   -.01   .01
 905179     4062.725484    21299.685530      464.551284   .00    .05    .00   .05
 905197   -74839.855368    20894.217231         .165217   .01    .00    .00   .01
 906270   -64792.999900    12294.404273      132.117768   .00    .00    .00   .00
 906271   -60988.449856    12403.493090      170.361002   .01    .01    .02   .01
 906272   -56058.776261    12096.953503      217.815369   .01    .01    .03   .01
 906273   -51935.927583    12630.341794      251.857631   .01   -.01    .00   .01
 906278   -51935.990958    12630.318736      251.044805   .00   -.03    .13   .03
 907321     5553.627033     3952.936764      482.284747   .04   -.01   -.04   .04
 907322     1941.544879     3979.340972      486.175984   .03    .00   -.05   .03
 907335   -52735.737377     4343.833382      253.912490   .01   -.02    .03   .02
 907336   -57955.226425     4452.612829      208.091649   .01   -.01    .01   .01
 907337   -62206.477346     3646.203483      167.826726   .01    .00    .01   .01
 907338   -66627.703750     4060.442004      122.734426   .00    .01    .00   .01
 908354   -25082.199824    -4390.048361      424.658454  -.01    .00   -.02   .01
 922586   -40346.608555    32003.621474      275.044650   .00    .00    .01   .01

                                             MIN      :  -.04   -.04   -.24   .00
                                             MEAN     :   .00    .00   -.01   .02
                                             MAX      :   .04    .05    .17   .06
                                             RANGE    :   .08    .09    .41   .06

                                             STD DEVS:    .01    .01    .04   .02
                                             STD DEV VECTOR:          .04
```

Appendix I

PATB-GPS aerial triangulation results using Differential GPS positions for Run 6.

```
1
   PATB-GPS :                      COPYRIGHT :  H.KLEIN/F.ACKERMANN 1988-1994

   BLOCK ADJUSTMENT WITH BUNDLES                              REVISION Jun-94

   PROJECT  : Range test 1
   USER-ID. : gd

   START OF EXECUTION : 18-FEB-99 11:19:03

   ***************************************************************************
   ***************************************************************************
   **                                                                       **
   ** PROGRAM VERSION  PATB-GPS                                             **
   ** =========================                                             **
   **                                                                       **
   ** DIRECTORY FOR INPUT AND OUTPUT FILES :  PRESENT WORKING DIRECTORY     **
   ** INPUT                                                                 **
   ** BASIC DATA                                         FROM FILE rt3.bas  **
   ** PHOTOGRAPHS                                        FROM FILE rt3.obs  **
   ** CONTROL POINTS                                     FROM FILE gda.ctl  **
   **                                                                       **
   ** INITIAL VALUES FOR EXTERIOR ORIENTATION PARAMETERS ARE CALCULATED     **
   **                                                                       **
   ** WITHOUT AUTOMATIC GROSS ERROR DETECTION                               **
   ** NO CORRECTION OF SYSTEMATIC ERRORS                                    **
   ** ADJUSTMENT WITH GPS-OBSERVATIONS                                      **
   **            WITH DETERMINATION OF GPS-DRIFT PARAMETERS                 **
   **            NO DETERMINATION OF GPS-ANTENNA OFFSET                     **
   ** NO INVERSION OF NORMAL EQUATIONS                                      **
   **                                                                       **
   ** ITERATION SEQUENCE WILL BE TERMINATED :                               **
   ** 1. IF 10 ITERATION STEPS ARE PERFORMED                                **
   ** 2. IF CHANGE OF ADJUSTED TERRAIN COORDINATES                          **
   **    BETWEEN TWO ITERATION STEPS FOR ALL POINTS      <     0.300        **
   **    IN THE TERRAIN SYSTEM                                              **
   ** 3. IF CHANGE OF SIGMA LESS THAN 0.001%                                **
   ** 4. IF SIGMA DOES NOT CONFIRM WITH READ IN STANDARD DEVIATIONS         **
   ** 5. IF THE RMS-VALUE OF OBSERVATIONS DIVERGES                          **
   **                                                                       **
   ** INPUT FORMATS AND INPUT SEQUENCES :                                   **
   ** PHOTOGRAPH NUMBERS          (I10,F10.3,I5)                            **
   ** PHOTOGRAPH POINTS           (I10,2F10.1,i5)                           **
   ** SEQUENCE OF READ IN COORDINATES OF PHOTO POINTS                 = X Y **
   ** HORIZONTAL CONTROL          (I8,2f15.3,15x,i5)                        **
   ** SEQUENCE OF READ IN COORDINATES OF HORIZONTAL CONTROL POINTS    = X Y **
   ** VERTICAL CONTROL            (I8,30x,f15.3,i5)                         **
   ** GPS-OBSERVATIONS            (I8,3f15.3,f8.0,i5)                       **
   **                                                                       **
   ** READ IN IMVK                                         =   25           **
   **                                                                       **
   ** LIMITATIONS                                                           **
   ** NUMBER OF POINTS IN ONE PHOTO          RESTRICTED TO   60             **
   ** NUMBER OF CONTROL POINTS IN ONE LIST   RESTRICTED TO  750             **
   ** NUMBER OF PHOTOS IN ONE PHOTO GROUP    RESTRICTED TO   60             **
   ** DIMENSIONS OF ADDRESS MATRIX           RESTRICTED TO   50,10          **
   ** NUMBER OF PHOTOS/SUBMATRIX             RESTRICTED TO   20             **
   ** NUMBER OF DIFFERENT FOCAL LENGTHS      RESTRICTED TO   30             **
   ** NUMBER OF POINT RECORDS                RESTRICTED TO  165             **
   ** NUMBER OF PHOTO RECORDS                RESTRICTED TO   60             **
   **                                                                       **
   ** REQUIRED WORKING AREA FOR THESE SPECIFICATIONS     =  108670          **
   ** REQUIRED SCRATCH FILE : BLKSZ = 8192 BYTES,  BLOCKS=    8316          **
   **                                                                       **
   ** BREAK UP LIMIT FOR THE SIZE OF PHOTO GROUPS          =   60           **
   **                                                                       **
   ** PHOTO NUMBERS OF THE FIRST PHOTO GROUP :                              **
   **                                      FIRST READ IN PHOTOGRAPH ASSUMED **
   ** NUMBER OF PHOTOS IN THE FIRST PHOTO GROUP            =    1           **
   **                                                                       **
   ** FOCAL LENGTH IN UNITS OF IMAGE SYSTEM AND CORRESPONDING FL-NUMBER     **
   ** NUMBER OF FOCAL LENGTHS                              =    0           **
   **                                                                       **
   ** SIZE OF PHOTOGRAPHS IN UNITS OF IMAGE SYSTEM                          **
   **   IN X :     230000.000   IN Y :     230000.000                       **
   **                                                                       **
   ** STANDARD DEVIATIONS OF OBSERVATIONS :                                 **
   **                                                                       **
   **   FOR IMAGE POINTS IN X AND Y IN UNITS OF IMAGE SYSTEM                **
   **   DEFAULT SET (SDS NO. 0 OR BLANK) :        8.000                     **
   **                                                                       **
   **   FOR CONTROL POINTS IN UNITS OF TERRAIN SYSTEM                       **
   **                                    PLANIMETRY   HEIGHT                **
   **   1.SET FOR CONTROL POINTS         :    0.500    0.500                **
   **                                                                       **
   **   FOR GPS OBSERVATIONS IN UNITS OF TERRAIN SYSTEM                     **
   **                                    PLANIMETRY   AND HEIGHT            **
   **   1.SET FOR GPS OBSERVATIONS         :     0.250                       **
   **   2.SET FOR GPS OBSERVATIONS         :     1.200                       **
   **                                                                       **
   **                                                                       **
   ** COMMON OFFSET FROM CAMERA TO GPS ANTENNA :                             **
   **                        0.105         -0.052         1.000             **
   **                      IN UNITS OF TERRAIN SYSTEM                       **
   **                                                                       **
   ** PRINTOUT                                                              **
   ** COORDINATES OF CONTROL POINTS AND RESIDUALS                           **
   ** COORDINATES AND RESIDUALS OF CRITICAL POINTS IN SEQUENCE              **
```

```
**                                                                          **
** ADDITIONAL OUTPUT                                                        **
** ADJUSTED TERRAIN COORDINATES IN SEQUENCE        ON FILE rta.fvl          **
** EXTERIOR ORIENTATION PARAMETERS                 ON FILE rt3.ori          **
**                                                                          **
******************************************************************************
******************************************************************************


       read in image points ...........................  1718
       stored unsorted point records ..................    33
       read in photographs ............................   134
       stored unsorted photo records ..................     3
       read in horizontal control points ..............    71
       read in vertical control points ................    71
       read in gps antenna points......................   141
       read in gps profiles............................     8
       stored control point records ...................     1



       PHOTO GROUPS AND PHOTO CONNECTIONS
       ----------------------------------
       photo group   1 has   1 photo
       photo group   2 has   9 photos
       photo group   3 has  10 photos
       photo group   4 has  14 photos
       photo group   5 has  18 photos
       photo group   6 has  23 photos
       photo group   7 has  11 photos
       photo group   8 has  10 photos
       photo group   9 has  10 photos
       photo group  10 has  15 photos
       photo group  11 has  13 photos

       COMPUTATION OF INITIAL VALUES OF EXTERIOR ORIENTATION PARAMETERS
       -----------------------------------------------------------------

       dimensions of submatrices     = ( 120 ,120 )
       dimensions of address matrix = (  50 , 11 )
       maximum number of photos/submatrix    =  30

       initial iteration step
       ----------------------

       number of hyperrows     =    8
       number of hypercolumns =    2


       COMPUTATION OF ADJUSTED TERRAIN COORDINATES
       -------------------------------------------

       dimensions of submatrices     = ( 120 ,120 )
       dimensions of address matrix = (  50 , 11 )
       maximum number of photos/submatrix    =  20

       standard deviations for image points in x and y (in image system)
       default set :     8.000

       standard deviations for control points (in terrain system)
                          planimetry    height
       1. set :                0.500      0.500

       iteration step no.   1
       ------------------
       iteration step with gps

       number of hyperrows     =   10
       number of hypercolumns =    3
       plus 1 column border part for gps

       maximum change of exterior orientation parameters :
       da,db,dc = parameters of rodrigues-matrix
       px,py,pz = coordinates of perspective centers (in terrain system)

                   da =0.071662              px =    400.516
                   db =0.056332              py =    610.471
                   dc =0.023221              pz =    321.658

       maximum change of adjusted terrain coordinates (in terrain system) :

             in x at point-no.           8357        174.295
             in y at point-no.           8346        127.844
             in z at point-no.           8359        366.736

       sigma reached =      53.4938  (in image system)


       iteration step no.   2
       ------------------
       iteration step with gps

       number of hyperrows     =   10
       number of hypercolumns =    3
       plus 1 column border part for gps

       maximum change of exterior orientation parameters :
       da,db,dc = parameters of rodrigues-matrix
       px,py,pz = coordinates of perspective centers (in terrain system)
```

```
           da =0.001670              px =      6.893
           db =0.001151              py =     11.532
           dc =0.001022              pz =     16.382

 maximum change of adjusted terrain coordinates (in terrain system) :

       in x at point-no.          805179          5.022
       in y at point-no.            8358         14.026
       in z at point-no.            7320         24.136

 sigma reached =       7.3416  (in image system)


 iteration step no.   3
 ------------------
 iteration step with gps

 number of hyperrows    =   10
 number of hypercolumns =    3
 plus 1 column border part for gps

 maximum change of exterior orientation parameters :
 da,db,dc = parameters of rodrigues-matrix
 px,py,pz = coordinates of perspective centers (in terrain system)

           da =0.000003              px =      0.028
           db =0.000003              py =      0.031
           dc =0.000002              pz =      0.033

 maximum change of adjusted terrain coordinates (in terrain system) :

       in x at point-no.            7320          0.034
       in y at point-no.            7320          0.044
       in z at point-no.            7320          0.103

 end of adjustment  --  due to condition 2


 STATISTICS
 ----------

  1-fold points          =    2
  2-fold points          =   40
  3-fold points          =  102
  4-fold points          =   34
  5-fold points          =   92
  6-fold points          =   64
  7-fold points          =   13
  8-fold points          =   16
  9-fold points          =   10
 number of block points =  373


 number of observations = 3789
 number of unknowns     = 1971
 redundancy             = 1818


 number of outliers for image observations    =    0
 number of outliers for control observations =    0
 number of outliers for gps observations      =    0

 ROOT MEAN SQUARE VALUES AND CHECK VALUES OF RESIDUALS OF PHOTOGRAMMETRIC OBSERVATIONS
 -------------------------------------------------------------------------------------
                    image system     terrain system        image system

 image points
 ------------
 obs x = 1677  rms x =     5.19  rms x =     0.255  chv vx =    15.58
 obs y = 1677  rms y =     5.44  rms y =     0.268  chv vy =    16.31

 ROOT MEAN SQUARE VALUES AND CHECK VALUES OF RESIDUALS OF NON-PHOTOGRAMMETRIC OBSERVATIONS
 -----------------------------------------------------------------------------------------
                    image system     terrain system      terrain system

 control points with sds-no.  1
 ---------------------------
 obs x =    11  rms x =    12.80  rms x =     0.630  chv vx =     1.89
 obs y =    11  rms y =     3.67  rms y =     0.180  chv vy =     0.54
 obs z =    11  rms z =     3.34  rms z =     0.165  chv vz =     0.49

 ROOT MEAN SQUARE VALUES AND CHECK VALUES OF RESIDUALS OF GPS OBSERVATIONS
 -------------------------------------------------------------------------
                                 terrain system      terrain system

 gps observations with sds-no.  1
 -----------------------------
 obs x =  114                   rms x =    0.067  chv vx =     0.20
 obs y =  114                   rms y =    0.064  chv vy =     0.19
 obs z =  114                   rms z =    0.082  chv vz =     0.25

 gps observations with sds-no.  2
 -----------------------------
 obs x =   20                   rms x =    0.661  chv vx =     1.98
 obs y =   20                   rms y =    0.737  chv vy =     2.21
 obs z =   20                   rms z =    1.431  chv vz =     4.29


 SIGMA NAUGHT      7.44         =    0.366
 ------------
```

```
           COORDINATES OF CONTROL POINTS AND RESIDUALS
           -------------------------------------------
           in units of terrain system


           horizontal control points
                                                code of point
           point-no.      x              y      input -> used          rx          ry    sds check

              25    -69873.014   -15726.485      HV 1                -0.126      -0.004   1   .  .
              26    -72653.385    -1847.868      HV 4                -0.358       0.195   1   .  .
              27    -73912.981    20027.308      HV 4                -0.091      -0.109   1   .  .
              28    -71645.884    29937.296      HV 2                 0.301       0.143   1   .  .
              29    -31262.676    29465.355      HV 3                 0.201       0.032   1   .  .
              42    -31772.848    22556.965      HV 3                -1.458       0.018   1   .  .
              43    -35590.100    13370.653      HV 6                 0.650      -0.480   1   .  .
              45    -47988.815    -4332.370      HV 4                 1.086       0.211   1   .  .
              46    -36058.591   -12463.704      HV 4                -0.542      -0.029   1   .  .
              52     -8939.231    -4353.436      HV 2                 0.142       0.081   1   .  .
              53       415.646   -14504.899      HV 1                 0.196      -0.059   1   .  .

>>>>> warning:                                                        <<<<<
>>>>>    60 planimetric control point(s) not in the block             <<<<<


           vertical control points
                                                code of point
           point-no.                     z      input -> used                      rz    sds check

              25                    66.104      HV 1                           -0.045   1      .
              26                    56.264      HV 4                           -0.201   1      .
              27                    14.268      HV 4                            0.176   1      .
              28                     3.531      HV 2                           -0.106   1      .
              29                   339.449      HV 3                           -0.185   1      .
              42                   363.035      HV 3                            0.153   1      .
              43                   366.988      HV 6                            0.198   1      .
              45                   292.006      HV 4                            0.048   1      .
              46                   360.655      HV 4                            0.205   1      .
              52                   468.576      HV 2                           -0.268   1      .
              53                   464.971      HV 1                            0.025   1      .

>>>>> warning:                                                        <<<<<
>>>>>    60 height control point(s) not in the block                  <<<<<


           COORDINATES OF GPS OBSERVATIONS AND RESIDUALS
           ---------------------------------------------
           in units of terrain system

           gps antenna offset    x` =  0.105   y` = -0.052   z` =  1.000


           photo-no.      x            y             z             t                rx         ry         rz    sds check

           profile-no.         1

           drift parameters:

           linear       -0.1558      -0.0162      -0.0775
           constant     -1.431       -1.244       -3.167

             123   -78566.111    25038.407     7456.546      -10.000            -0.021      0.023      0.052    1
             124   -74353.673    24916.133     7520.075       -9.000             0.017     -0.047     -0.183    1
             125   -69985.883    24832.709     7557.203       -8.000            -0.091      0.002      0.028    1
             126   -65685.424    24946.480     7607.234       -7.000             0.076      0.007     -0.002    1
             127   -61386.854    25159.613     7644.897       -6.000            -0.047     -0.017      0.081    1
             128   -57125.875    25294.707     7673.907       -5.000             0.110      0.010     -0.030    1
             129   -52888.708    25391.239     7701.621       -4.000            -0.061     -0.050      0.034    1
             130   -48580.834    25410.517     7747.360       -3.000            -0.013      0.137      0.135    1
             131   -44271.116    25469.274     7776.411       -2.000            -0.040      0.041      0.042    1
             132   -40009.375    25427.552     7801.157       -1.000             0.078     -0.061     -0.028    1
             133   -35721.676    25373.222     7836.417        0.000            -0.104     -0.006      0.017    1
             134   -31423.747    25306.225     7857.810        1.000             0.091      0.037     -0.202    1
             135   -27168.423    25279.063     7872.313        2.000            -0.009     -0.142      0.041    1
             136   -22849.452    25262.154     7875.639        3.000             0.050      0.046     -0.061    1
             137   -18542.687    25226.106     7904.968        4.000             0.007     -0.044      0.134    1
             138   -14310.400    25229.920     7913.109        5.000             0.046     -0.021     -0.084    1
             139   -10017.943    25183.185     7921.034        6.000            -0.040      0.033     -0.045    1
             140    -5730.060    25164.793     7933.169        7.000             0.100      0.099      0.004    1
             141    -1516.628    25110.064     7945.863        8.000            -0.136      0.045      0.142    1
             142     2761.527    25142.603     7950.487        9.000            -0.014     -0.090     -0.076    1
             143     6987.395    25179.953     7940.916       10.000           --  not in the block --

           profile-no.         2

           drift parameters:

           linear        0.1633      -0.0345       0.0312
           constant     -1.198       -0.633       -1.930

             178     8542.957    16694.292     7960.665      -10.000           --  not in the block --
             179     4058.982    16699.417     7952.998       -9.000             0.008      0.011      0.009    1
             180     -560.987    16702.617     7961.401       -8.000             0.082     -0.054     -0.022    1
             181    -4941.149    16696.778     7948.538       -7.000             0.018     -0.007     -0.080    1
             182    -9235.215    16592.700     7952.546       -6.000            -0.039     -0.012     -0.074    1
             183   -13547.741    16501.557     7950.253       -5.000             0.035     -0.016      0.018    1
             184   -17835.623    16382.630     7956.321       -4.000            -0.092     -0.001      0.049    1
             185   -22233.275    16463.409     7924.005       -3.000             0.015      0.036      0.002    1
             186   -26492.014    16630.843     7921.643       -2.000             0.003     -0.038      0.176    1
             187   -30768.889    16786.805     7893.431       -1.000             0.002      0.030     -0.065    1
             188   -35217.072    16700.072     7858.444        0.000            -0.057     -0.017     -0.037    1
             189   -39545.051    16665.161     7844.850        1.000            -0.083      0.041      0.035    1
```

```
   190   -43824.925     16596.843      7811.112        2.000          0.046     -0.007      0.111     1
   191   -48353.308     16554.822      7791.393        3.000          0.014      0.107     -0.007     1
   192   -52995.051     16298.796      7734.857        4.000          0.049      0.000     -0.022     1
   193   -57666.674     16157.905      7702.100        5.000         -0.050      0.040      0.007     1
   194   -62166.439     16266.458      7664.526        6.000          0.000      0.024      0.035     1
   195   -66681.381     16297.039      7617.961        7.000         -0.016     -0.054     -0.029     1
   196   -71130.027     16370.499      7558.406        8.000         -0.038     -0.027     -0.170     1
   197   -75512.291     16427.237      7513.721        9.000          0.127     -0.005     -0.004     1
   198   -79952.673     16375.772      7451.002       10.000         -0.024     -0.053      0.068     1

profile-no.         3

drift parameters:

linear       0.0707       -0.0974       -0.0516
constant     -0.687        -0.359        -1.624

   321     5816.533      -516.030      7958.234      -10.000         -0.056     -0.105     -0.052     1
   322     1634.629      -570.690      7971.098       -9.000         -0.120      0.054     -0.055     1
   323    -2500.010      -566.281      7958.049       -8.000          0.108     -0.096      0.013     1
   324    -6608.423      -489.603      7970.549       -7.000         -0.010      0.107      0.033     1
   325   -10764.081      -417.486      7970.537       -6.000          0.046      0.036      0.053     1
   326   -14902.665      -362.913      7966.720       -5.000          0.083      0.141     -0.003     1
   327   -19061.924      -311.415      7939.852       -4.000         -0.076     -0.068      0.027     1
   328   -23298.377      -160.517      7939.339       -3.000          0.071      0.064      0.027     1
   329   -27660.300       -12.930      7900.292       -2.000          0.081     -0.061     -0.024     1
   330   -31981.169         0.333      7890.292       -1.000          0.069     -0.069      0.064     1
   331   -36105.300       -27.499      7858.404        0.000         -0.038     -0.068      0.027     1
   332   -40184.938      -148.997      7851.675        1.000         -0.080      0.020     -0.010     1
   333   -44515.846      -286.312      7818.031        2.000         -0.076     -0.024     -0.007     1
   334   -48956.442      -441.786      7790.730        3.000          0.032      0.070     -0.047     1
   335   -53487.111      -526.039      7757.972        4.000         -0.019     -0.015      0.018     1
   336   -57721.494      -512.228      7719.063        5.000         -0.014      0.089     -0.121     1
   337   -61979.524      -520.664      7674.847        6.000         -0.056     -0.079     -0.063     1
   338   -66309.331      -498.717      7628.191        7.000          0.019      0.021      0.025     1
   339   -70584.928      -519.359      7574.368        8.000         -0.104     -0.058      0.122     1
   340   -74776.780      -488.591      7549.549        9.000          0.116      0.096     -0.023     1
   341   -79040.206      -467.204      7501.554       10.000          0.026     -0.057     -0.004     1

profile-no.         4

drift parameters:

linear      -0.0905        0.1154        0.1684
constant     -0.236        -1.026        -1.641

   342   -77952.569     -9077.389      7495.037       -9.500          0.017     -0.011     -0.033     1
   343   -73780.116     -9092.953      7544.470       -8.500         -0.049      0.031      0.151     1
   344   -69531.560     -9092.602      7572.117       -7.500          0.015     -0.068     -0.164     1
   345   -65149.798     -9057.443      7618.756       -6.500          0.015      0.044      0.175     1
   346   -60804.561     -9065.439      7670.651       -5.500         -0.029     -0.009     -0.044     1
   347   -56463.747     -9035.933      7710.819       -4.500          0.029      0.001      0.055     1
   348   -52125.690     -9035.293      7747.707       -3.500         -0.019     -0.026     -0.086     1
   349   -47758.001     -9023.012      7770.597       -2.500          0.007      0.035     -0.072     1
   350   -43393.331     -9032.563      7804.821       -1.500         -0.005      0.023      0.043     1
   351   -39039.751     -9024.744      7834.250       -0.500          0.006      0.014     -0.039     1
   352   -34694.241     -8997.542      7861.389        0.500          0.012     -0.095     -0 031     1
   353   -30270.879     -8897.107      7874.673        1.500          0.042      0.041     -0.012     1
   354   -25797.288     -8753.676      7908.418        2.500         -0.030      0.003      0.060     1
   355   -21203.527     -8738.056      7938.354        3.500          0.059      0.049      0.025     1
   356   -16712.785     -8743.692      7948.689        4.500         -0.089     -0.011      0.053     1
   357   -12251.905     -8826.624      7948.415        5.500          0.094      0.104     -0.153     1
   358    -7821.577     -8855.985      7969.574        6.500         -0.122     -0.078      0.031     1
   359    -3490.200     -8884.647      7972.099        7.500          0.041     -0.055     -0.076     1
   360      801.813     -8991.988      7962.023        8.500         -0.007     -0.047     -0.087     1
   361     5116.375     -9031.460      7940.522        9.500          0.012      0.055      0.206     1

profile-no.         5

drift parameters:

linear       0.2197       -0.0415       -0.0503
constant      0.070        -1.018        -1.211

   386   -72923.584     31025.970      7499.505       -5.500         -0.030      0.035      0.061     1
   387   -72966.674     26630.273      7512.127       -4.500          0.092     -0.092     -0.009     1
   388   -72931.616     22165.254      7531.424       -3.500         -0.005      0.098     -0.017     1
   389   -72825.015     17742.329      7536.593       -2.500          0.008     -0.084     -0.098     1
   390   -72661.859     13290.400      7534.537       -1.500         -0.147      0.024      0.008     1
   391   -72504.378      8781.639      7534.534       -0.500          0.146      0.040      0.055     1
   392   -72468.242      4340.551      7554.811        0.500         -0.086      0.039      0.013     1
   393   -72577.208       -18.513      7540.057        1.500         -0.039     -0.071     -0.044     1
   394   -72741.028     -4221.363      7534.707        2.500         -0.018     -0.004      0.012     1
   395   -72692.007     -8455.453      7539.667        3.500          0.113     -0.013      0.022     1
   396   -72663.813    -12678.842      7538.361        4.500         -0.033      0.026     -0.004     1
   397   -72481.429    -16883.169      7550.133        5.500        --  not in the block --

profile-no.         6

drift parameters:

linear      -0.1331       -0.0016       -0.1521
constant     -0.654        -0.604        -2.027

   575   -40320.861    -16840.140      7745.667       -5.500        --  not in the block --
   576   -40338.059    -12720.268      7753.086       -4.500         -0.058      0.079      0.142     1
   577   -40345.906     -8544.840      7759.960       -3.500          0.024     -0.100     -0.173     1
   578   -40330.181     -4141.721      7768.394       -2.500          0.061     -0.063      0.000     1
   579   -40385.004       337.617      7757.438       -1.500          0.030      0.134      0.097     1
   580   -40393.934      4823.264      7759.393       -0.500         -0.026     -0.053     -0.067     1
   581   -40348.316      9304.089      7768.486        0.500          0.024     -0.068     -0.036     1
   582   -40302.763     13800.467      7777.186        1.500         -0.123      0.174      0.073     1
   583   -40318.346     18324.722      7752.589        2.500          0.086     -0.161     -0.062     1
   584   -40378.732     22877.754      7734.377        3.500         -0.072      0.061     -0.089     1
   585   -40460.113     27447.642      7728.188        4.500          0.090      0.009      0.111     1
   586   -40502.572     32049.598      7681.688        5.500         -0.034     -0.011      0.004     1
```

```
profile-no.        7

drift parameters:

linear        0.3391        0.1191        0.3394
constant     -2.008        -0.122        -1.413

  600       162.246     33865.546      7806.288        -6.000        --  not in the block --
  601       140.543     29702.628      7826.778        -5.000         0.012     -0.016      0.122    1
  602       211.752     25471.141      7823.794        -4.000         0.154     -0.090     -0.142    1
  603       197.522     21271.678      7849.121        -3.000        -0.120      0.064     -0.030    1
  604       206.169     17073.930      7836.698        -2.000        -0.064     -0.003      0.062    1
  605       236.849     12789.438      7862.529        -1.000        -0.093      0.077      0.055    1
  606       189.553      8619.453      7891.150         0.000        -0.016     -0.080     -0.106    1
  607       228.942      4459.142      7888.559         1.000         0.057      0.148      0.018    1
  608       232.011       231.474      7891.319         2.000         0.147     -0.074      0.102    1
  609       208.208     -3904.561      7888.795         3.000        -0.076      0.020     -0.054    1
  610       185.361     -8067.475      7880.368         4.000         0.032      0.008     -0.203    1
  611       168.528    -12190.765      7871.571         5.000        -0.033     -0.053      0.177    1
  612       146.795    -16438.839      7832.179         6.000        --  not in the block --
```

```
profile-no.         8            DIFFERENTIAL GPS TRAJECTORY

         drift parameters:

         linear        0.1070        0.0884       -0.0660
         constant     -1.520        -1.529        -6.647

          9038       7974.973      8111.769      8120.516       -10.000        --  not in the block --
          9039       3580.906      8090.986      8118.499        -9.000        -0.143      1.363      0.479    2
          9040       -754.219      8006.073      8125.560        -8.000         1.679     -0.368      0.023    2
          9041      -5063.462      8030.813      8121.551        -7.000         0.007     -1.184      0.523    2
          9042      -9417.440      8068.463      8113.566        -6.000        -0.140     -0.142      1.175    2
          9043     -13760.275      8184.958      8109.537        -5.000        -1.208     -0.473      1.306    2
          9044     -17947.380      8208.753      8095.114        -4.000        -0.112     -0.996      1.571    2
          9045     -22113.825      8299.834      8086.933        -3.000        -0.230      0.468     -0.720    2
          9046     -26548.405      8371.663      8067.951        -2.000        -0.562     -0.197     -0.939    2
          9047     -30998.874      8445.026      8050.802        -1.000        -0.307     -0.440     -1.575    2
          9048     -35240.592      8526.382      8025.707         0.000        -0.773      0.706     -3.063    2
          9049     -39264.396      8564.515      8006.197         1.000         0.004      2.022     -4.077    2
          9050     -43305.885      8619.780      7973.020         2.000         0.857     -0.470      0.392    2
          9051     -47390.034      8524.512      7948.154         3.000         0.240      0.389      1.153    2
          9052     -51723.616      8375.833      7908.734         4.000         0.187      0.132      0.674    2
          9053     -56150.532      8099.894      7875.715         5.000         0.332      0.107      0.716    2
          9054     -60602.696      7928.870      7830.249         6.000         0.510      0.064      1.042    2
          9055     -65017.939      7942.952      7788.824         7.000         1.160      0.189      0.525    2
          9056     -69426.710      7862.615      7739.514         8.000        -0.549     -0.572      0.571    2
          9057     -73830.167      7933.509      7690.089         9.000        -0.649      0.045      0.759    2
          9058     -78333.015      8108.832      7640.257        10.000        -0.304     -0.644     -0.536    2
```

```
>>>>> warning:                                                      <<<<<
>>>>>     7 GPS antenna point(s) not in the block                   <<<<<


          COORDINATES AND RESIDUALS OF CRITICAL POINTS
          --------------------------------------------
          arranged by increasing point numbers

       photo-no.      x             y               rx          ry     sds check

                   point-no.                 1


                   point-no.               3085    TP 4

         124      -77015.1      88432.1           -9.1       -13.6     0    .  .
         387      -55052.6     -96877.2          -16.0        -0.2     0    1  .
         123        7715.0      89135.2            8.9        -4.0     0    .  .
         386       30385.1    -103648.3           -1.7         0.6     0    .  .

                   point-no.               4142    TP 7

         604      -79613.4      52998.5          -11.9        -8.7     0    .  .
         141       90376.2     -80593.7            2.4       -14.9     0    .  .
         179       30339.5     -90144.0           -1.1         3.0     0    .  .
         602       92976.2      56053.3           -8.6       -11.4     0    .  .
         603        3944.4      51530.1           -9.7        -7.6     0    .  .
         180      -65593.6     -86662.3           -6.5         7.2     0    .  .
         142        -557.7     -86168.2           18.4        -5.7     0    2  .

                   point-no.               5188    TP 8

        9048        9837.4     -77754.3           22.6        12.6     0    5  .
         188        6752.7      85927.7          -15.7         1.2     0    1  .
        9049      -72204.4     -77329.1           36.6         3.8     0    9  .
         581       65364.7     -91939.1            9.7       -10.8     0    .  .
         582      -29551.7     -99152.9           19.1        -9.5     0    3  .
         187       98720.0      99928.4           -8.8         5.0     0    .  .
        9047       97948.5     -82219.4            5.7         0.7     0    .  .
         189      -80716.8      87197.8          -17.9         1.8     0    2  .

                   point-no.               6869    TP 8

        9057      -75331.8      94792.1           -4.5         6.2     0    .  .
        9055      101456.5      88543.5          -18.4        15.1     0    2  .
         393      -66204.1      49762.5           -4.0         4.5     0    .  .
         392       22228.5      48620.9           -5.4        -1.5     0    .  .
         339      -14130.4     -81262.8            7.8        -8.0     0    .  .
```

```
  338     71313.4    -77120.0          5.5      -2.1   0  . .
  340   -100253.1    -77395.2         15.3       1.5   0  . .
 9056     18646.5     88517.7         -2.4      -1.9   0  . .

        point-no.            8350   TP 4

  351    -90180.8    -96143.7          7.3       3.5   0  . .
  576    -16262.6     67208.5         -9.2      17.7   0  . 1
  349     90668.6    -99457.0          2.8       4.0   0  . .
  350      -871.8    -95756.6          7.6       1.9   0  . .

        point-no.           17777

   HO  -37006.381   55440.457        --  not in the block  --
   VE                 139.504        --  not in the block  --
   VE                 139.504        --  not in the block  --

        point-no.           22222

   HO  -28737.520   43464.016        --  not in the block  --
   VE                 275.379        --  not in the block  --
   VE                 275.379        --  not in the block  --

        point-no.           77147

   HO   34923.324   55528.275        --  not in the block  --
   VE                 165.724        --  not in the block  --
   VE                 165.724        --  not in the block  --

        point-no.           77344

   HO  -78219.334   55250.399        --  not in the block  --
   VE                -218.398        --  not in the block  --
   VE                -218.398        --  not in the block  --

        point-no.          122580   TP 9

  579     95407.1    -97658.2         10.6       1.1   0  . .
  330     74188.0    -98284.0          2.5     -10.8   0  . .
 9049    -66307.0     73621.0         -6.6      18.0   0  . 2
  332    -96393.2   -101461.8          2.7       2.4   0  . .
 9048     11584.4     74297.5         -6.2       1.3   0  . .
  331    -11337.1    -98934.0          2.9      11.0   0  . .
 9047     94491.4     70934.3         -4.9      -2.1   0  . .
  580     -1281.6    -96038.2         -1.3      -3.0   0  . .
  581    -90302.0    -98461.7          8.8      12.5   0  . .

        point-no.          123601   TP 3

  602    -82624.5     93681.8         -8.8       2.8   0  . .
  142     41973.6     85235.6        -14.3     -16.7   0  . 1
  601      7351.0     99054.6         -7.4      10.9   0  . .

        point-no.          123602   TP 4

  602      3849.4     93891.0         -4.9       5.7   0  . .
  142     39505.8       341.4        -16.3     -15.2   0  1 .
  603    -83784.7     91197.0         -0.8       7.7   0  . .
  601     94155.3     95079.3         -9.4       2.7   0  . .

        point-no.          123603   TP 4

  602     82459.4     98815.0        -14.6      -0.6   0  . .
  604    -89274.5     95793.3          0.2      -6.1   0  . .
  142     41810.5    -76921.2          2.4     -18.1   0  . 2
  603     -5638.2     93836.3         -3.4       3.9   0  . .

        point-no.          123604   TP 4

  604     -1676.3    100259.3          0.3       1.3   0  . .
  603     80608.9     96981.0          8.6      -9.9   0  . .
  179    -20514.8    -14551.2        -16.1      -3.6   0  1 .
  605    -94713.1     92605.6         -6.0      -8.0   0  . .

        point-no.          122580   TP 9

  580     -1281.6    -96038.2         -1.3      -3.0   0  . .
  581    -90302.0    -98461.7          8.8      12.5   0  . .
  332    -96393.2   -101461.8          2.7       2.4   0  . .
  331    -11337.1    -98934.0          2.9      11.0   0  . .
 9049    -66307.0     73621.0         -6.6      18.0   0  . 2
 9048     11584.4     74297.5         -6.2       1.3   0  . .
  330     74188.0    -98284.0          2.5     -10.8   0  . .
 9047     94491.4     70934.3         -4.9      -2.1   0  . .
  579     95407.1    -97658.2         10.6       1.1   0  . .

        point-no.          204142   TP 5

  141     84856.8      4882.2         20.9     -12.3   0  4 .
  602      5630.6     49335.8         -3.4     -12.8   0  . .
  603    -83164.1     46886.7        -10.0     -11.9   0  . .
  601     93895.5     50312.8         -0.9     -22.5   0  . 4
  142     -4433.4      -128.6         27.0      -2.2   0  8 .

        point-no.          205179   TP 5

  180    -96832.9      1424.2         18.4       5.6   0  2 .
  604     11003.0     81842.7          0.9      11.6   0  . .
  603     93073.1     78921.4         -6.6       2.5   0  . .
  179     -3026.5     -1090.9         11.7       0.8   0  . .
  605    -81899.8     74643.8          0.2      16.1   0  . .

        point-no.          222582   TP 9

 9048    101087.2   -111115.5        -19.0     -25.4   0  3 6
  582       863.5     -3922.4         -7.6       6.4   0  . .
```

```
  9050    -64389.7    -96663.1          16.9      -7.3   0   1  .
   188    100317.8     59685.7         -14.0       1.9   0   .  .
   583    -91703.1       719.1          -1.1      13.1   0   .  .
  9049     18270.4   -112759.2           2.3     -12.7   0   .  .
   190    -72916.2     53253.1           1.4      12.7   0   .  .
   581     93948.6      2175.3         -16.0      -8.4   0   1  .
   189     13136.4     58502.7          -1.3       8.0   0   .  .

            point-no.           223605   TP 9

   180    -15633.2     83292.2          -9.2      -2.7   0   .  .
   606    -84760.2     -5020.5           7.1      -5.8   0   .  .
   604     91684.9     -2816.3           6.6     -12.8   0   .  .
   181   -102258.4     80108.4          -2.5      -0.8   0   .  .
  9041    -97442.8    -95955.8          -5.1      -4.4   0   .  .
  9040    -16578.7    -93351.2          -7.4      -0.2   0   .  .
   605      -404.8     -7856.0          -1.9     -17.7   0   .  1
  9039     70915.5    -93709.4         -11.7       0.8   0   .  .
   179     74558.8     80841.5          -1.2      -4.1   0   .  .

            point-no.           223606   TP 6

  9040     -8457.9    -11926.3          15.9      -8.0   0   1  .
  9039     79027.8    -11878.7           8.6      -6.1   0   .  .
   606      -292.8     -9221.2           5.2      15.8   0   .  .
   607    -85593.3    -12778.4           1.3       8.6   0   .  .
  9041    -92854.7    -14413.1          10.5      -2.3   0   .  .
   605     83744.6    -11263.7           8.3      10.3   0   .  .

            point-no.           321391   TP 5

   392    -90185.2   -101724.7           4.4      13.3   0   .  .
   391     -2328.1    -96591.5           5.8       2.1   0   .  .
  9057     64473.9    -22182.0          22.6     -10.4   0   5  .
  9058    -25585.9    -16285.5          -4.3      -4.8   0   .  .
   390     88491.7    -91386.5           4.0       2.6   0   .  .

            point-no.           321392   TP 5

  9057     69314.6     60703.9         -17.7      -5.7   0   2  .
  9058    -20122.1     65984.7          -4.0      -4.2   0   .  .
   391     83925.3   -100784.2           1.3      -5.5   0   .  .
   393    -91658.2    -99858.6           3.9      -8.4   0   .  .
   392     -4729.7   -102411.1           5.3      -6.4   0   .  .

            point-no.           322581   TP 5

   581    -11407.6    100969.5          -5.7       3.0   0   .  .
  9050     38863.8     -4437.2          -2.5     -12.4   0   .  .
  9051    -41292.9     -4654.5          -5.2     -13.0   0   .  .
   580     82076.2    101879.1         -15.6      -7.8   0   1  .
   582   -101376.0     95014.2          -4.0      10.8   0   .  .

            point-no.           322583   TP 5

   583     13822.5     98894.5          -2.2       0.2   0   .  .
   191    -68691.6    -49182.0          -2.2      -4.5   0   .  .
   584    -75564.7     89371.0          -5.4       8.5   0   .  .
   190     27001.4    -47416.8          10.7      -8.8   0   .  .
   582    103202.0     92324.2          -6.2     -17.2   0   .  1

            point-no.           323605   TP 9

  9040     73597.0    -90382.4          -3.4     -14.4   0   .  .
   180     76027.7     92789.2          -7.7       0.3   0   .  .
   605      8760.0   -101702.4           8.6      -3.6   0   .  .
  9041     -8207.4    -89064.8           1.1      -2.6   0   .  .
   181    -10619.5     86835.6          -0.9      -3.8   0   .  .
   606    -76403.6    -97309.6          15.8      -6.4   0   1  .
   604     98924.5    -96067.7          -1.4       1.2   0   .  .
   182    -97761.6     79261.0           0.0      -0.8   0   .  .
  9042   -100462.7    -86851.1           1.0      -2.3   0   .  .

            point-no.           907322   TP 7

   608    -79848.8     39331.4         -18.4       9.9   0   2  .
  9040    -49868.8     81596.0           0.0       4.0   0   .  .
  9039     36637.8     82236.5          -1.7       6.3   0   .  .
   322     -4430.3    -97361.9          11.4      15.4   0   .  .
   607      9417.2     33942.7         -23.8       8.4   0   6  .
   323    -89653.6    -98052.3           1.4      11.6   0   .  .

END OF EXECUTION : 18-FEB-99 11:22:20

PATB-GPS END
```

Appendix J

Comparison of adjusted image point coordinates derived from aerial triangulation using Differential GPS trajectory for run 6 (Appendix H) and adjusted image points derived from aerial triangulation using the Lightning Ridge base station trajectory (Appendix C).

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PROGRAM: COMPARE                 COMPARES DATA SETS                    18-Feb-99
                               COMPARISON OF COMMON POINTS
                                                            DIFFERENCES
 LABEL         X                 Y                   Z          X     Y     Z      XY
   25   -69873.124284   -15726.477652        66.059812  -.02  -.01   .00    .02
   26   -72653.700016    -1847.753551        56.063601  -.04   .08   .00    .09
   27   -73913.110772    20027.194040        14.450727   .04   .01  -.01    .04
   28   -71645.583325    29937.452956         3.428724   .00  -.01   .00    .01
   29   -31262.453952    29465.460461       339.298610  -.02  -.07  -.03    .08
   42   -31774.286079    22556.991965       363.187351  -.02  -.01   .00    .02
   43   -35589.438678    13370.198924       367.080352  -.01  -.03   .11    .03
   45   -47987.720585    -4332.164885       292.065776  -.01   .01  -.01    .01
   46   -36059.137465   -12463.723057       360.859667   .00  -.01   .00    .01
   52    -8939.109716    -4353.400247       468.356407   .02   .05  -.05    .05
   53      415.785873   -14504.963955       464.995974   .06   .01   .00    .06
 3085   -78011.689277    29609.425817       -70.523770   .05  -.03  -.04    .06
 3086   -74203.341329    29440.211143       -24.788811   .03  -.03   .00    .04
 3087   -70885.344780    29432.840857        13.867487   .01  -.01  -.01    .02
 3088   -66156.191517    29127.111660        66.532419   .02   .01  -.03    .02
 3089   -61814.034217    28824.606290       111.140260   .03   .02  -.06    .03
 3091   -54279.104560    29579.276048       179.677035   .04   .00  -.07    .04
 3092   -50149.566340    29272.976887       216.127970   .04  -.01  -.07    .04
 3093   -46578.792269    29262.579440       243.819199   .04  -.02  -.09    .04
 3094   -41811.180098    29050.378195       279.149560   .03  -.02  -.07    .03
 3095   -37431.087168    29420.408075       304.809253   .04  -.03  -.05    .05
 3096   -32961.620498    29440.069246       330.093366   .00  -.07  -.05    .07
 3097   -29150.250320    29884.507145       346.562679  -.06  -.11  -.02    .12
 3098   -24484.624427    29097.963781       370.723261  -.14  -.09  -.02    .17
 3099   -20203.733303    29713.357370       385.330478  -.21  -.05  -.08    .21
 3100   -15653.647923    28909.265865       405.028637  -.23   .03  -.15    .23
 3101   -11507.438581    29022.842523       413.364360  -.23   .09  -.19    .25
 3102    -7519.266762    29046.400027       420.804065  -.22   .13  -.20    .25
 3103    -2529.962423    28665.430317       426.256831  -.19   .15  -.20    .24
 3104     1197.350588    28448.126133       428.030619  -.18   .16  -.23    .24
 4123   -79244.666966    21208.957353       -55.052899   .06  -.01   .00    .06
 4125   -70661.213522    20475.758262        49.703032   .04   .02   .01    .04
 4126   -65995.025755    20801.921831        99.406429   .03   .04   .00    .05
 4127   -61469.464124    20384.661088       147.232672   .03   .03  -.03    .04
 4128   -57182.817739    20810.182374       187.314531   .03   .01  -.06    .03
 4129   -52564.947834    20706.611516       227.956414   .03   .00  -.07    .03
 4130   -48180.473523    20741.522695       264.200841   .04  -.02  -.08    .04
 4131   -43847.695081    21244.749154       294.124602   .03  -.03  -.07    .04
 4132   -39665.451025    20850.604071       323.092250   .02  -.04  -.06    .04
 4133   -35491.186050    20976.792982       348.431059   .00  -.05  -.06    .05
 4134   -31762.441593    20810.889634       368.454547  -.02  -.03  -.04    .04
 4135   -26582.851022    20802.721000       393.567869  -.08  -.02  -.03    .08
 4136   -22645.039009    21009.286300       408.864913  -.12  -.01  -.06    .12
 4137   -18215.029379    20593.497191       426.154958  -.15   .02  -.11    .15
 4138   -13788.861900    20594.280379       439.004624  -.17   .06  -.16    .18
 4139    -9824.262829    20673.131909       446.723121  -.17   .10  -.18    .20
 4140    -5257.072676    20611.920818       453.156518  -.17   .14  -.19    .22
 4141    -1465.850204    20190.432707       458.137303  -.15   .16  -.21    .22
 4142     2810.572910    20938.473728       464.578792  -.17   .17  -.24    .24
 5125   -71010.743060    11940.462830        66.330167   .04   .04   .03    .06
 5141   -48270.922303    12896.572279       280.515984  -.13  -.04   .26    .14
 5179     4060.611575    12664.124393       472.621883  -.13  -.03  -.49    .14
 5182    -9353.460082    12073.562112       466.217668  -.17   .09  -.03    .19
 5183   -13586.488615    11912.679240       458.425030  -.17  -.02  -.10    .17
 5184   -18070.481478    11899.929666       446.224975  -.14   .07   .10    .16
 5185   -22276.645679    12249.368690       432.101779  -.11   .08   .18    .13
 5186   -26720.029989    12006.915435       413.476418   .08   .18   .53    .19
 5187   -30679.645813    12631.850109       393.233176   .01   .18   .55    .18
 5188   -35689.249589    12354.782815       367.028407  -.11   .04   .31    .12
 5189   -39321.569406    12629.038061       346.766589   .01   .01   .20    .01
 5190   -43843.768011    11897.132560       315.729889   .02   .04   .15    .05
 5191   -48271.325856    12896.263247       281.739044   .02  -.03   .01    .03
 5192   -53211.383241    12158.187991       242.297020  -.02  -.03  -.03    .04
 5193   -57722.714692    11582.948471       203.804710  -.02   .01  -.02    .03
 5194   -62703.272553    12145.169851       153.479387   .01   .00  -.02    .01
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5195	-67356.509897	11830.051142	106.406148	.04	.11	.10	.12
5196	-71010.453907	11940.360417	66.257031	.01	.04	.02	.04
5197	-76153.808832	12334.448116	6.742408	.06	-.09	-.18	.11
5198	-78230.744274	12362.329890	-19.710719	.14	-.25	-.44	.28
5784	-18071.840689	11898.610172	446.173109	.11	-.30	.30	.32
6267	-79017.099647	3933.921874	-20.205611	-.17	.28	-.05	.33
6268	-73925.344602	12257.999741	33.009241	.05	-.03	-.12	.05
6269	-68450.689870	11916.525679	94.915351	.02	.10	.12	.10
6270	-64602.615747	3067.214053	144.737189	.00	.00	.27	.00
6271	-60400.096045	3490.129003	185.061424	-.04	.07	.08	.08
6272	-56474.264991	3404.481232	222.333092	.01	.06	.01	.06
6273	-51582.408379	3406.703470	263.432322	-.02	.04	.05	.05
6274	-48531.654972	3949.388595	289.765698	.00	-.01	.07	.01
6275	-44206.390827	3923.135301	322.070633	.02	-.03	.15	.04
6278	-31757.131530	4069.831583	397.385692	.05	-.09	.13	.11
6279	-27207.810065	4457.585214	418.343594	-.03	-.16	.19	.17
6280	-22706.398103	3782.305715	438.132715	.02	-.11	.05	.11
6281	-18534.009338	3878.587271	452.460935	-.02	.01	-.10	.03
6282	-14139.370880	3540.478702	468.909482	-.14	.01	-.08	.14
6283	-10069.516656	4278.049909	480.487161	-.05	-.03	-.07	.05
6284	-5612.218360	3736.875230	480.519346	-.01	-.03	-.03	.03
6285	-1465.764941	3397.576321	482.003455	.05	.12	-.28	.13
6286	3724.094771	3815.809962	484.458651	.11	.29	-.60	.31
6287	7858.727889	3494.950128	481.001880	.36	.25	-.48	.44
6868	-74215.079772	3755.722330	37.974022	-.02	.23	-.10	.23
6869	-69745.484910	3236.608424	88.485004	-.07	.03	.30	.08
7320	9519.870309	-5175.456176	474.081352	.23	-.01	-.30	.23
7321	5473.893875	-4437.417001	478.884992	.17	.03	-.35	.17
7322	1071.573438	-4868.807181	480.340033	.11	.03	-.34	.11
7323	-3267.866167	-5002.641775	480.163443	.06	.01	-.24	.06
7324	-7776.490622	-4865.260794	469.091563	.03	.00	-.18	.03
7325	-11527.243541	-5119.794169	462.537225	.01	-.01	-.15	.02
7326	-16076.619898	-4357.810316	453.788196	.00	-.01	-.11	.01
7327	-20293.250575	-3973.450714	443.645003	.00	-.02	-.08	.02
7328	-23254.430219	-4525.736541	431.958143	.00	-.04	-.05	.04
7329	-27113.483766	-4735.769197	416.399379	.00	-.04	-.03	.04
7330	-30714.878483	-4072.082516	401.158614	.01	-.03	-.03	.04
7331	-35288.388065	-5298.895415	375.676100	.01	-.01	-.03	.02
7332	-39153.128641	-4302.542388	353.593814	.01	.00	-.03	.01
7333	-44086.549340	-4150.299942	320.292582	-.01	.00	-.01	.01
7334	-48254.388431	-4938.602322	288.754804	-.02	.01	-.02	.02
7335	-52606.505287	-4355.983019	252.593074	-.03	.02	-.02	.03
7336	-57103.868674	-4784.007177	213.376842	-.04	.03	-.01	.05
7337	-61678.774911	-4813.718276	170.719297	-.06	.04	.02	.07
7338	-65592.151147	-5166.434152	130.470694	-.06	.05	.04	.08
7339	-70083.670022	-5319.281176	83.436408	-.07	.07	.03	.10
7340	-74411.362710	-4407.594434	34.578321	-.09	.10	-.04	.13
7341	-78507.065824	-4677.070059	-15.328569	-.12	.10	-.03	.16
7727	-73915.970259	20024.008365	14.023461	.05	-.01	-.03	.05
7728	-71649.657164	29937.634406	2.474307	.02	-.03	.01	.04
7751	-14225.226732	4535.142056	464.926029	-.05	.03	-.13	.06
7752	-8941.278760	-4353.925210	466.744562	.03	.00	-.17	.03
8343	-73608.646153	-13038.928470	32.142221	-.09	.04	.08	.10
8344	-69517.298495	-13524.511173	76.974131	-.08	.05	.13	.10
8345	-65025.349221	-13030.815466	126.310375	-.09	.06	.15	.11
8346	-60975.117651	-13366.332395	166.668420	-.08	.02	.07	.08
8347	-56593.660107	-13258.195502	204.864220	-.06	.00	.04	.06
8348	-52137.888735	-13217.790520	243.506995	-.04	-.01	.01	.04
8349	-48661.689291	-13416.369375	271.659742	-.03	-.01	.01	.03
8350	-43406.500642	-13554.284018	310.176087	-.01	-.02	.01	.02
8351	-39457.349384	-12425.772808	339.717503	.00	-.02	-.01	.02
8353	-30474.937694	-12869.081607	391.557658	.01	-.02	-.05	.02
8354	-25609.778418	-12810.586348	420.623667	.01	-.02	-.07	.03
8355	-21492.696496	-12785.044607	433.120381	.01	-.02	-.09	.02
8356	-17438.674602	-12430.723998	438.327358	.01	-.02	-.11	.02
8357	-12951.848153	-13345.340711	447.534402	.02	-.02	-.14	.03
8358	-8481.141965	-12885.927016	456.256572	.02	-.03	-.18	.04
8359	-4120.008713	-13525.645459	478.325852	.04	-.05	-.23	.06
8360	240.902648	-12982.247961	464.592213	.09	-.07	-.32	.11
8361	5021.232573	-12976.554002	465.123044	.12	-.09	-.37	.15
41342	-48788.312914	-3636.615417	287.029239	-.01	.01	-.01	.02
41357	-33494.886183	15680.800260	372.705594	.00	-.03	.10	.03
101326	-6642.841495	-8199.383259	472.041139	.03	-.02	-.18	.04
104128	-57508.339029	29504.539760	149.992995	.04	.01	-.07	.04
106045	-22382.577672	13197.144110	429.580951	.34	-.24	.80	.42
121386	-68488.396275	31043.227210	32.998117	-.03	-.01	.03	.03
121387	-68532.155722	26909.661100	50.420884	.02	.01	.00	.02
121388	-68312.629461	22341.861267	69.217454	.03	.02	.03	.04
121389	-67803.712167	18167.152880	87.725853	.03	.03	.06	.04

121390	-67501.924236	13108.772117	102.604809	.04	.06	.08	.07
121391	-67558.869223	9228.455859	108.982678	.02	.08	.11	.08
121392	-67408.775503	4255.818665	113.960210	-.05	.04	.17	.06
121393	-67597.830160	-173.982084	113.784471	-.04	.06	.12	.07
121394	-67628.866695	-4472.201789	110.541460	-.05	.05	.06	.08
121395	-67931.434078	-8467.917646	102.812729	-.07	.05	.10	.09
121396	-68242.801603	-13027.531334	91.412198	-.08	.05	.14	.09
122576	-35450.405878	-12551.820841	363.581965	.01	-.01	-.01	.02
122577	-35411.123782	-8029.532744	371.479526	.01	-.01	-.01	.01
122578	-35399.646875	-3958.315350	376.367780	.02	-.01	-.03	.02
122579	-35577.185017	809.174036	377.553191	.04	.00	-.01	.04
122580	-35594.842686	4750.578825	377.398634	.07	-.01	.02	.07
122581	-35711.891760	9460.142996	372.579880	-.08	.00	.23	.08
122582	-35848.155377	14011.845943	362.789674	-.02	-.02	.12	.03
122583	-35701.245858	18074.875629	355.320480	.01	-.04	.03	.04
122584	-35739.430384	22977.229620	339.829061	.02	-.03	-.02	.03
122585	-36048.862563	27369.602857	321.435755	.03	-.04	-.04	.05
123601	4894.326962	29387.182280	423.673399	-.18	.18	-.33	.25
123602	4775.494066	25182.284184	438.890667	-.16	.16	-.34	.23
123603	4890.854992	21385.264218	461.950639	-.17	.17	-.30	.24
123604	5041.664293	17137.790649	470.827153	-.11	.21	-.36	.23
123605	5104.131120	12884.262773	479.763066	-.11	.19	-.33	.22
123606	4885.202942	8621.114217	490.783910	-.16	.28	-.39	.32
123607	4506.208058	4411.836651	489.887218	.11	.31	-.61	.33
123608	4676.460887	181.406324	495.636150	.19	.14	-.57	.23
123609	4380.486602	-3698.885302	492.669885	.15	.03	-.45	.15
123610	4244.020378	-8104.752013	474.824159	.15	-.02	-.44	.15
123611	4756.066423	-12162.535654	466.815705	.13	-.08	-.39	.15
204123	-78237.684696	25081.789772	-54.463913	.04	-.03	-.09	.05
204124	-74275.756061	24831.988723	-6.634030	.04	-.01	-.02	.04
204125	-69742.859870	24527.697296	45.879649	.03	.00	-.01	.03
204126	-65603.105149	24865.447480	89.449849	.03	.01	-.03	.03
204127	-61504.052641	25385.633501	128.871162	.03	.01	-.05	.03
204128	-57045.267112	24962.137652	174.124682	.03	.00	-.07	.03
204129	-53484.543505	25226.563183	204.736174	.03	.00	-.08	.03
204130	-48781.049533	25256.384515	243.555428	.03	-.01	-.08	.04
204131	-43977.342343	25709.070377	278.490103	.02	-.02	-.06	.03
204132	-39998.372966	25262.063122	306.544193	.03	-.03	-.06	.04
204133	-35225.925947	25481.659220	333.934009	.01	-.04	-.02	.04
204134	-31342.951583	25569.120089	355.031928	-.03	-.04	-.01	.05
204135	-27373.573426	25340.354814	373.678339	-.08	-.04	.01	.09
204136	-22643.548065	25318.742848	396.082645	-.14	-.02	-.03	.14
204137	-18588.165584	25052.070330	410.935532	-.18	.01	-.09	.18
204138	-14412.351425	25364.013578	421.681155	-.20	.05	-.15	.21
204139	-9745.422344	24937.010958	433.464231	-.20	.09	-.20	.22
204140	-5837.186709	25363.435583	436.963096	-.19	.12	-.20	.23
204141	-1925.117764	25111.715981	440.831156	-.17	.14	-.20	.22
204142	2609.797609	25154.255696	443.882256	-.17	.16	-.28	.23
205179	4145.129987	16535.749471	471.155051	-.11	.19	-.32	.22
205181	-5568.602932	16342.515240	463.909302	-.15	.15	-.10	.21
205182	-9371.648358	16780.799317	458.210090	-.16	.11	-.12	.19
205183	-13585.172719	16675.287221	449.432067	-.17	.07	-.11	.18
205184	-18086.381224	16399.815923	437.701804	-.16	.05	-.01	.16
205185	-22055.543495	16076.106141	424.851993	-.12	.03	.07	.13
205186	-26549.648174	16501.633329	405.325492	-.06	.00	.15	.06
205187	-30761.584615	16953.882711	384.405149	-.02	-.02	.11	.03
205188	-35426.733855	16485.361147	360.979473	.00	-.04	.06	.04
205189	-39444.307161	16637.126400	336.573174	.02	-.03	.05	.04
205190	-44145.961457	16515.622125	304.534860	.03	-.02	.03	.04
205191	-48343.858511	16600.400652	274.148593	.03	-.01	-.04	.03
205192	-52958.759523	16544.977071	236.032707	.02	.00	-.05	.02
205193	-57583.117860	16290.317144	195.964120	.01	.02	-.03	.02
205194	-62231.665335	16165.037185	150.823542	.02	.03	.01	.04
205195	-66846.687951	16007.732243	103.401550	.03	.04	.05	.06
205196	-71056.138203	16328.598517	56.754671	.04	.03	.02	.05
205197	-75057.480970	16339.263303	10.500627	.06	.00	-.05	.06
205198	-79785.030372	16329.817270	-46.764055	.03	-.01	-.10	.03
206267	-78515.409132	8524.286965	-16.572621	.39	.01	-.05	.39
206268	-74133.481202	8407.332630	35.800635	.03	.07	-.07	.08
206269	-69468.974822	7574.775527	89.341887	-.06	.08	.23	.10
206270	-64813.278868	7705.080857	138.804597	.08	.09	.17	.13
206271	-60540.361628	7798.881080	182.065916	-.03	.09	-.08	.09
206272	-55679.566554	7802.202812	227.504205	.00	.05	-.06	.05
206273	-52121.321805	7587.866513	256.951438	-.05	.03	.00	.06
206274	-47114.970864	8216.926117	296.536763	-.05	-.01	.06	.06
206275	-43223.409328	8439.079602	326.462276	.01	.02	.07	.02
206276	-39133.266926	8324.733567	352.764038	.02	.02	.10	.02
206277	-34872.689531	8033.818081	378.855161	-.03	-.02	.23	.04
206278	-30904.546018	7901.977677	399.875924	.04	-.11	.54	.12

206279	-26747.730263	8200.968433	418.804769	.07	-.14	.61	.16
206280	-22377.741247	7417.959040	438.448692	.17	-.13	.33	.22
206281	-18305.740533	7519.681581	451.738059	.05	-.05	.11	.08
206282	-13887.201935	7748.021200	463.602566	-.21	.02	-.09	.21
206283	-9294.924735	7421.622063	478.004135	-.09	.04	-.05	.10
206284	-4913.561755	7805.150602	479.176990	-.02	.09	-.12	.09
206286	3769.187853	7855.807309	480.250956	-.07	.30	-.42	.31
207321	5546.292868	-642.909436	481.079391	.19	.08	-.46	.20
207322	1649.339014	-462.604066	498.870193	.10	.08	-.40	.13
207323	-2691.123640	-592.436073	481.076483	.04	.05	-.25	.06
207324	-6814.057023	-437.196569	485.354555	.01	.02	-.15	.03
207325	-10499.438463	-159.099055	467.627671	-.01	.02	-.14	.02
207326	-15090.360604	-427.492362	459.122488	-.02	.00	-.11	.02
207327	-18877.374926	-278.396834	450.312517	-.02	-.01	-.08	.03
207328	-23484.124373	-20.541401	434.856711	-.01	-.03	-.02	.04
207329	-27567.419639	-56.601033	417.958002	.01	-.04	.04	.04
207330	-31792.961517	-2.393644	397.265686	.03	-.02	.02	.04
207331	-35654.474874	216.556284	376.716384	.04	.00	-.02	.04
207332	-40007.490711	-481.588580	349.855525	.02	.01	-.03	.02
207333	-44430.443960	-94.113798	320.513846	.00	.02	.03	.02
207335	-53565.709446	-275.906969	247.865852	-.02	.03	.01	.04
207336	-57991.484735	-188.237717	208.823314	-.03	.05	.03	.06
207337	-61726.222555	-628.161605	172.697440	-.04	.05	.07	.07
207338	-66594.926889	-335.496623	124.294392	-.04	.06	.14	.07
207339	-70281.684011	-403.142346	83.944405	-.05	.08	.08	.09
207340	-74731.042302	-173.240245	32.243002	-.06	.13	-.06	.14
207341	-79287.660513	-45.895611	-23.086802	-.16	.14	-.06	.21
207384	-48902.363476	-506.376671	286.755473	-.01	.02	.01	.02
208342	-77981.803093	-8939.180287	-13.691964	-.12	.06	-.01	.14
208343	-74366.680793	-8798.583468	30.021511	-.09	.06	.01	.11
208344	-69953.868988	-9011.362044	80.158579	-.08	.05	.08	.10
208345	-65018.454002	-9020.135418	133.439286	-.08	.04	.11	.09
208346	-60885.863249	-9133.029309	173.850087	-.06	.03	.04	.07
208347	-56321.913392	-8769.663544	216.357914	-.05	.02	.01	.05
208348	-52215.494879	-8825.715565	251.347444	-.04	.01	-.01	.04
208349	-47785.915416	-8690.051242	287.532772	-.02	.00	-.01	.02
208350	-43232.743757	-9040.010540	320.388820	-.01	.00	.01	.01
208351	-39356.934742	-8926.131113	346.382307	.00	-.01	-.01	.01
208352	-34766.376808	-8829.066566	374.550433	.01	-.01	-.03	.01
208353	-30369.107846	-8927.871279	396.889433	.01	-.02	-.05	.02
208354	-25706.407206	-8565.009018	424.410652	.01	-.02	-.07	.02
208355	-21253.665551	-8521.372982	433.841476	.01	-.02	-.09	.02
208356	-16778.754948	-8335.548374	447.052047	.01	-.02	-.12	.02
208357	-12025.186301	-8558.242489	457.748072	.02	-.02	-.15	.02
208358	-7589.477446	-9097.349849	469.236803	.03	-.02	-.18	.04
208359	-3603.873171	-8492.902574	473.932183	.05	-.02	-.23	.06
208360	721.721273	-9159.061369	473.382748	.10	-.03	-.32	.10
208361	4980.018845	-8260.514596	474.501110	.17	-.03	-.47	.17
221386	-72924.772734	31113.690494	-17.650935	.00	-.03	-.02	.03
221387	-73095.202879	26649.631865	-.121985	.03	-.01	-.03	.03
221388	-72959.639665	22380.886178	17.513570	.04	.00	-.02	.04
221389	-72678.444034	17713.707647	34.667229	.04	.02	-.01	.05
221390	-72493.875162	13480.956358	46.759603	.06	.03	.00	.07
221391	-72300.662392	9113.398260	56.371670	.02	.06	.03	.06
221392	-72345.247403	4457.446761	59.167048	-.01	.12	.02	.12
221393	-72151.185118	-13.239439	62.442026	-.03	.10	.01	.11
221394	-72786.095275	-3963.270520	54.026088	-.07	.08	-.01	.11
221395	-72522.702937	-8275.562654	52.586371	-.08	.06	.02	.10
221396	-72813.636744	-12303.397390	42.900116	-.08	.05	.08	.10
222576	-40016.910575	-12866.077489	334.772498	.00	-.02	.00	.02
222577	-39778.057813	-8748.891433	344.290892	.00	-.01	.00	.01
222578	-40294.606105	-3369.665599	346.995128	.01	.01	-.02	.01
222579	-40582.334935	196.673823	346.555742	.01	.01	.01	.02
222580	-40137.458070	4365.214272	349.263792	.04	.02	.00	.04
222581	-40227.125323	9169.483983	345.306005	.02	.01	.12	.03
222582	-40240.993870	13870.351039	336.521361	.02	.01	.20	.02
222583	-39895.397231	18268.211913	329.184995	.02	-.03	.01	.04
222584	-40564.991071	22754.057673	311.700203	.02	-.03	-.06	.03
222585	-40387.040902	27468.970493	294.858389	.03	-.03	-.07	.04
223601	173.778180	30160.296047	421.333408	-.18	.15	-.20	.24
223602	194.675383	25670.585878	438.977489	-.17	.15	-.23	.23
223603	4.220397	21377.730421	455.101587	-.16	.16	-.22	.22
223604	69.499822	17233.567712	462.783641	-.12	.17	-.20	.21
223605	17.387814	12700.140024	475.656996	-.01	.08	-.27	.08
223606	-273.799043	8609.681394	490.071299	.04	.17	-.27	.18
223607	-129.545271	4186.650175	483.552288	.06	.16	-.33	.17
223608	-123.241701	153.163630	483.129965	.07	.09	-.39	.11
223609	-481.027487	-3928.455411	480.041878	.08	.03	-.30	.09
223610	78.547358	-8056.144086	474.919198	.09	-.02	-.32	.10

```
223611      323.498836  -11845.534604     467.398483   .09  -.06  -.30   .10
305198   -80307.220497   11575.597955     -43.870397   .01  -.12  -.18   .12
306270   -63878.156135    2768.372729     150.980843   .03   .11   .34   .11
306271   -61094.853910    3285.185697     178.867381  -.01   .10   .09   .11
306869   -68961.124604    2714.460883      97.148733  -.09   .15   .52   .17
321386   -77616.203799   31084.244064     -74.112153   .03  -.05  -.08   .06
321387   -78058.605075   26499.581096     -58.303765   .04  -.02  -.08   .05
321388   -77942.139107   22017.780253     -40.667543   .05  -.03  -.08   .06
321389   -77757.748614   17759.790520     -24.986243   .05   .00  -.11   .05
321390   -77318.656767   13279.868546      -8.927198   .08  -.01  -.10   .08
321391   -76898.808077    8947.848556       3.110225   .14   .04  -.01   .15
321392   -77038.401132    4810.409888       4.162755   .06   .27  -.12   .27
321393   -77270.988135      95.067128       2.034808  -.10   .16  -.15   .18
321394   -77499.811518   -3751.666409      -1.748753  -.11   .11  -.07   .15
321395   -77034.028034   -8760.066327      -1.937667  -.12   .06  -.06   .14
321396   -77151.699554  -12942.848177     -10.541006  -.10   .03   .03   .11
322576   -45060.359156  -12903.839623     299.032769  -.02  -.01   .02   .02
322577   -44951.293163   -8031.530238     309.815384  -.02   .00   .02   .02
322578   -44811.668465   -3970.508132     315.815064  -.01   .01   .00   .01
322579   -44968.836477     847.120813     316.141740   .01   .02   .04   .02
322580   -44650.110735    5225.321013     318.866686   .03  -.01   .16   .03
322581   -45184.798606    8885.309423     310.765379   .00   .00   .08   .01
322582   -44129.378645   14250.633972     309.670002   .03   .00   .09   .03
322583   -44960.398520   19018.493675     292.876740   .03  -.03   .00   .04
322584   -44955.366619   23048.932183     279.986588   .02  -.02  -.06   .03
322585   -45149.956491   27267.949032     263.386334   .03  -.02  -.07   .03
323601    -4548.809447   29259.254576     421.724401  -.21   .15  -.17   .25
323602    -4517.833822   25296.093933     437.214035  -.18   .13  -.13   .22
323603    -4370.063698   21468.564768     451.773530  -.17   .14  -.15   .22
323604    -3925.150185   17563.359916     461.408833  -.13   .14  -.11   .19
323605    -4474.615818   12398.520928     472.474858  -.09   .15  -.08   .17
323606    -4525.491116    9010.365096     478.724316  -.04   .12  -.14   .13
323607    -4657.547594    4773.108808     481.085094   .03   .04  -.11   .05
323608    -4422.711345     715.738431     482.268054   .02   .05  -.22   .06
323609    -4567.388762   -3501.341555     488.414284   .05   .02  -.21   .05
323610    -4501.840849   -7805.814434     472.778304   .05  -.02  -.20   .05
323611    -4685.679892  -12107.438093     469.214542   .03  -.04  -.18   .05
606270   -64817.613553   10766.701194     133.926922   .12   .08   .12   .15
706275   -42505.587508    9096.225378     330.516289   .05   .04   .14   .06
722586   -44489.610345   32027.668635     246.856495   .02   .00  -.10   .02
805179     4061.085231   12664.631591     472.169050  -.11   .21  -.31   .24
822586   -35980.486204   32087.113442     301.270910   .06  -.02  -.07   .06
904129   -52949.652115   30114.385116     188.219164   .04   .00  -.08   .04
904130   -48975.764266   29169.451876     226.000821   .04  -.01  -.09   .04
904131   -44078.948780   29881.122126     259.481793   .03  -.02  -.08   .04
904132   -39640.250458   30100.640446     287.895479   .04  -.03  -.09   .05
904133   -35138.621108   29879.520846     315.822605   .03  -.05  -.05   .06
904135   -26884.213563   30006.804497     356.164653  -.10  -.13   .00   .16
904136   -22471.816480   30218.426923     374.257118  -.18  -.10  -.03   .21
904137   -18626.741624   29918.847359     391.127114  -.23  -.03  -.10   .23
904138   -13949.514563   29758.604490     405.616318  -.25   .06  -.17   .25
904139    -9969.849246   29699.414864     413.789058  -.24   .11  -.20   .26
904140    -5670.380689   29990.559505     418.508790  -.22   .14  -.20   .27
904141    -1259.506578   29904.555344     421.922716  -.19   .16  -.21   .25
904142     3028.912368   29674.510796     422.485572  -.19   .16  -.24   .25
904187   -30669.479183   21484.836010     372.223942  -.04  -.04  -.05   .06
905179     4062.725484   21299.685530     464.551284  -.18   .18  -.26   .25
905197   -74839.855368   20894.217231        .165217   .05   .00  -.01   .05
906270   -64792.999900   12294.404273     132.117768   .09   .07   .08   .11
906271   -60988.449856   12403.493090     170.361002  -.02  -.02  -.12   .03
906272   -56058.776261   12096.953503     217.815369  -.02  -.02  -.08   .03
906273   -51935.927583   12630.341794     251.857631   .01  -.02  -.01   .03
906278   -51935.990958   12630.318736     251.044805  -.07   .01  -.07   .07
907321     5553.627033    3952.936764     482.284747   .20   .27  -.51   .33
907322     1941.544879    3979.340972     486.175984   .08   .24  -.45   .25
907335   -52735.737377    4343.833382     253.912490  -.01   .06   .04   .06
907336   -57955.226425    4452.612829     208.091649  -.02   .07   .06   .07
907337   -62206.477346    3646.203483     167.826726  -.02   .09   .10   .09
907338   -66627.703750    4060.442004     122.734426  -.03   .02   .22   .03
908354   -25082.199824   -4390.048361     424.658454   .00  -.04  -.05   .04
922586   -40346.608555   32003.621474     275.044650   .04  -.01  -.08   .04

                                          MIN      :  -.25  -.30  -.61   .00
                                          MEAN     :  -.02   .03  -.05   .09
                                          MAX      :   .39   .31   .80   .44
                                          RANGE    :   .63   .61  1.41   .44

                                          STD DEVS:    .09   .09   .18   .13
                                          STD DEV VECTOR:          .221
```

Appendix K

PATB-GPS aerial triangulation adjustment results using ***no ground control*** *and the Hobart base station trajectory solution for run 6. Only 5 east-west flight runs used, no tie runs.*

```
PATB-GPS :                      COPYRIGHT :  H.KLEIN/F.ACKERMANN 1988-1994

BLOCK ADJUSTMENT WITH BUNDLES                              REVISION Jun-94

PROJECT  : Range test 1
USER-ID. : gd

START OF EXECUTION : 09-FEB-99 10:19:57

***************************************************************************
***************************************************************************
**                                                                       **
** PROGRAM VERSION  PATB-GPS                                              **
** ========================                                              **
**                                                                       **
** DIRECTORY FOR INPUT AND OUTPUT FILES :  PRESENT WORKING DIRECTORY     **
** INPUT                                                                 **
** BASIC DATA                                       FROM FILE rt9.bas    **
** PHOTOGRAPHS                                      FROM FILE rt9.obs    **
** CONTROL POINTS                                   FROM FILE gd9.ctl    **
**                                                                       **
** INITIAL VALUES FOR EXTERIOR ORIENTATION PARAMETERS ARE CALCULATED     **
**                                                                       **
** WITHOUT AUTOMATIC GROSS ERROR DETECTION                               **
** NO CORRECTION OF SYSTEMATIC ERRORS                                    **
** ADJUSTMENT WITH GPS-OBSERVATIONS                                      **
**            NO DETERMINATION OF GPS-DRIFT PARAMETERS                   **
**            NO DETERMINATION OF GPS-ANTENNA OFFSET                     **
** NO INVERSION OF NORMAL EQUATIONS                                      **
**                                                                       **
** ITERATION SEQUENCE WILL BE TERMINATED :                               **
** 1. IF 10 ITERATION STEPS ARE PERFORMED                                **
** 2. IF CHANGE OF ADJUSTED TERRAIN COORDINATES                          **
**    BETWEEN TWO ITERATION STEPS FOR ALL POINTS      <    0.300         **
**    IN THE TERRAIN SYSTEM                                              **
** 3. IF CHANGE OF SIGMA LESS THAN 0.001%                                **
** 4. IF SIGMA DOES NOT CONFIRM WITH READ IN STANDARD DEVIATIONS         **
** 5. IF THE RMS-VALUE OF OBSERVATIONS DIVERGES                          **
**                                                                       **
** INPUT FORMATS AND INPUT SEQUENCES :                                   **
** PHOTOGRAPH NUMBERS          (I10,F10.3,I5)                            **
** PHOTOGRAPH POINTS           (I10,2F10.1,i5)                           **
** SEQUENCE OF READ IN COORDINATES OF PHOTO POINTS                 = X Y **
** HORIZONTAL CONTROL          (I8,2f15.3,15x,i5)                        **
** SEQUENCE OF READ IN COORDINATES OF HORIZONTAL CONTROL POINTS    = X Y **
** VERTICAL CONTROL            (I8,30x,f15.3,i5)                         **
** GPS-OBSERVATIONS            (I8,3f15.3,f8.0,i5)                       **
**                                                                       **
** READ IN IMVK                                      =   10              **
**                                                                       **
** LIMITATIONS                                                           **
** NUMBER OF POINTS IN ONE PHOTO         RESTRICTED TO   60              **
** NUMBER OF CONTROL POINTS IN ONE LIST  RESTRICTED TO  750              **
** NUMBER OF PHOTOS IN ONE PHOTO GROUP   RESTRICTED TO   60              **
** DIMENSIONS OF ADDRESS MATRIX          RESTRICTED TO   50,10           **
** NUMBER OF PHOTOS/SUBMATRIX            RESTRICTED TO   20              **
** NUMBER OF DIFFERENT FOCAL LENGTHS     RESTRICTED TO   30              **
** NUMBER OF POINT RECORDS               RESTRICTED TO  165              **
** NUMBER OF PHOTO RECORDS               RESTRICTED TO   60              **
**                                                                       **
** REQUIRED WORKING AREA FOR THESE SPECIFICATIONS     =  108670          **
** REQUIRED SCRATCH FILE : BLKSZ = 8192 BYTES,  BLOCKS=    8256          **
**                                                                       **
** BREAK UP LIMIT FOR THE SIZE OF PHOTO GROUPS        =   60             **
**                                                                       **
** PHOTO NUMBERS OF THE FIRST PHOTO GROUP :                              **
**                                        FIRST READ IN PHOTOGRAPH ASSUMED **
** NUMBER OF PHOTOS IN THE FIRST PHOTO GROUP          =    1             **
**                                                                       **
** FOCAL LENGTH IN UNITS OF IMAGE SYSTEM AND CORRESPONDING FL-NUMBER     **
** NUMBER OF FOCAL LENGTHS                            =    0             **
**                                                                       **
** SIZE OF PHOTOGRAPHS IN UNITS OF IMAGE SYSTEM                          **
**   IN X :      230000.000    IN Y :      230000.000                    **
**                                                                       **
** STANDARD DEVIATIONS OF OBSERVATIONS :                                 **
**                                                                       **
**   FOR IMAGE POINTS IN X AND Y IN UNITS OF IMAGE SYSTEM                **
**   DEFAULT SET (SDS NO. 0 OR BLANK) :          8.000                   **
**                                                                       **
**   FOR CONTROL POINTS IN UNITS OF TERRAIN SYSTEM                       **
**                                       PLANIMETRY   HEIGHT             **
**   1.SET FOR CONTROL POINTS          :   1000.000 1000.000             **
**                                                                       **
**   FOR GPS OBSERVATIONS IN UNITS OF TERRAIN SYSTEM                     **
**                                       PLANIMETRY   AND HEIGHT         **
**   1.SET FOR GPS OBSERVATIONS          :     0.100                     **
**   2.SET FOR GPS OBSERVATIONS          :     0.100                     **
**                                                                       **
**                                                                       **
** COMMON OFFSET FROM CAMERA TO GPS ANTENNA :                             **
**                        0.105          -0.052          1.000           **
**                      IN UNITS OF TERRAIN SYSTEM                       **
```

```
**                                                                      **
** PRINTOUT                                                             **
** COORDINATES OF CONTROL POINTS AND RESIDUALS                          **
** COORDINATES AND RESIDUALS OF CRITICAL POINTS IN SEQUENCE             **
**                                                                      **
** ADDITIONAL OUTPUT                                                    **
** ADJUSTED TERRAIN COORDINATES IN SEQUENCE       ON FILE rt9.fvl       **
** EXTERIOR ORIENTATION PARAMETERS                ON FILE rt9.ori       **
**                                                                      **
**************************************************************************
**************************************************************************


      read in image points ...........................  1223
      stored unsorted point records ..................    23
      read in photographs ............................   101
      stored unsorted photo records ..................     2
      read in horizontal control points ..............    71
      read in vertical control points ................    71
      read in gps antenna points......................   104
      read in gps profiles............................     5
      stored control point records ...................     1



      PHOTO GROUPS AND PHOTO CONNECTIONS
      ----------------------------------
      photo group   1 has   1 photo
      photo group   2 has   5 photos
      photo group   3 has   8 photos
      photo group   4 has  12 photos
      photo group   5 has  16 photos
      photo group   6 has  11 photos
      photo group   7 has  11 photos
      photo group   8 has  10 photos
      photo group   9 has  10 photos
      photo group  10 has  10 photos
      photo group  11 has   7 photos

      COMPUTATION OF INITIAL VALUES OF EXTERIOR ORIENTATION PARAMETERS
      ----------------------------------------------------------------

      dimensions of submatrices     = ( 120 ,120 )
      dimensions of address matrix = (  50 , 11 )
      maximum number of photos/submatrix    =  30

      initial iteration step
      ----------------------

      number of hyperrows     =    5
      number of hypercolumns =    2
>>>>> warning:                                                    <<<<<
>>>>> Single point:             8362 in photo:        361 -- not used <<<<<

>>>>> warning:                                                    <<<<<
>>>>> Single point:           207320 in photo:        321 -- not used <<<<<

>>>>> warning:                                                    <<<<<
>>>>> Single point:           907320 in photo:        321 -- not used <<<<<

>>>>> warning:                                                    <<<<<
>>>>> Single point:           206287 in photo:       6039 -- not used <<<<<

>>>>> warning:                                                    <<<<<
>>>>> Single point:             5178 in photo:        179 -- not used <<<<<

>>>>> warning:                                                    <<<<<
>>>>> Single point:           105178 in photo:        179 -- not used <<<<<

>>>>> warning:                                                    <<<<<
>>>>> Single point:           123604 in photo:        179 -- not used <<<<<

>>>>> warning:                                                    <<<<<
>>>>> Single point:           123605 in photo:        179 -- not used <<<<<

>>>>> warning:                                                    <<<<<
>>>>> Single point:           205178 in photo:        179 -- not used <<<<<

>>>>> warning:                                                    <<<<<
>>>>> Single point:           905178 in photo:        179 -- not used <<<<<

>>>>> warning:                                                    <<<<<
>>>>> Single point:             4143 in photo:        142 -- not used <<<<<

>>>>> warning:                                                    <<<<<
>>>>> Single point:           123601 in photo:        142 -- not used <<<<<

>>>>> warning:                                                    <<<<<
>>>>> Single point:           123602 in photo:        142 -- not used <<<<<

>>>>> warning:                                                    <<<<<
>>>>> Single point:           123603 in photo:        142 -- not used <<<<<

>>>>> warning:                                                    <<<<<
>>>>> Single point:           204143 in photo:        142 -- not used <<<<<

>>>>> warning:                                                    <<<<<
>>>>> Single point:           904143 in photo:        142 -- not used <<<<<
```

```
COMPUTATION OF ADJUSTED TERRAIN COORDINATES

dimensions of submatrices     = ( 120 ,120 )
dimensions of address matrix = (  50  , 11 )
maximum number of photos/submatrix    =  20

standard deviations for image points in x and y (in image system)
default set :     8.000

standard deviations for control points (in terrain system)
                   planimetry    height
1. set :             1000.000  1000.000


iteration step no.   1
------------------
iteration step with gps

number of hyperrows     =    8
number of hypercolumns =    2
plus 1 column border part for gps

maximum change of exterior orientation parameters :
da,db,dc = parameters of rodrigues-matrix
px,py,pz = coordinates of perspective centers (in terrain system)

            da =0.220110                px = 36240.638
            db =0.092819                py = 13286.344
            dc =0.075199                pz =  6032.771

maximum change of adjusted terrain coordinates (in terrain system) :

      in x at point-no.           7320       39204.693
      in y at point-no.         904136       16896.080
      in z at point-no.           8359         423.702

sigma reached =  11178.6761  (in image system)


iteration step no.   2
------------------
iteration step with gps

number of hyperrows     =    8
number of hypercolumns =    2
plus 1 column border part for gps

maximum change of exterior orientation parameters :
da,db,dc = parameters of rodrigues-matrix
px,py,pz = coordinates of perspective centers (in terrain system)

            da =0.155114                px =     32.064
            db =0.082886                py =     70.585
            dc =0.087465                pz =     26.092

maximum change of adjusted terrain coordinates (in terrain system) :

      in x at point-no.           8361         346.303
      in y at point-no.           8359         247.597
      in z at point-no.           7320         280.003

sigma reached =     492.3053  (in image system)


iteration step no.   3
------------------
iteration step with gps

number of hyperrows     =    8
number of hypercolumns =    2
plus 1 column border part for gps

maximum change of exterior orientation parameters :
da,db,dc = parameters of rodrigues-matrix
px,py,pz = coordinates of perspective centers (in terrain system)

            da =0.013901                px =      2.503
            db =0.008078                py =      1.146
            dc =0.008757                pz =     19.104

maximum change of adjusted terrain coordinates (in terrain system) :

      in x at point-no.           8361         175.598
      in y at point-no.           8361         285.350
      in z at point-no.           8357         133.631

sigma reached =      12.0237  (in image system)


iteration step no.   4
------------------
iteration step with gps

number of hyperrows     =    8
number of hypercolumns =    2
plus 1 column border part for gps

maximum change of exterior orientation parameters :
da,db,dc = parameters of rodrigues-matrix
px,py,pz = coordinates of perspective centers (in terrain system)

            da =0.000079                px =      0.011
            db =0.000046                py =      0.031
            dc =0.000065                pz =      0.126
```

```
maximum change of adjusted terrain coordinates (in terrain system) :

      in x at point-no.          8361          3.719
      in y at point-no.          8361          6.111
      in z at point-no.          8348          2.229

sigma reached =      7.9215  (in image system)


iteration step no.   5
------------------
iteration step with gps

number of hyperrows    =    8
number of hypercolumns =    2
plus 1 column border part for gps

maximum change of exterior orientation parameters :
da,db,dc = parameters of rodrigues-matrix
px,py,pz = coordinates of perspective centers (in terrain system)

           da =0.000000               px =     0.000
           db =0.000000               py =     0.000
           dc =0.000000               pz =     0.000

maximum change of adjusted terrain coordinates (in terrain system) :

      in x at point-no.          7320          0.001
      in y at point-no.          8361          0.002
      in z at point-no.          7320          0.001


end of adjustment  --  due to condition 2



STATISTICS
----------

 2-fold points         =   95
 3-fold points         =  159
 4-fold points         =   15
 5-fold points         =   30
 6-fold points         =   55
number of block points =  354


number of observations = 2741
number of unknowns     = 1668
redundancy             = 1073


number of outliers for image observations   =    0
number of outliers for control observations =    0
number of outliers for gps observations     =    0

ROOT MEAN SQUARE VALUES AND CHECK VALUES OF RESIDUALS OF PHOTOGRAMMETRIC OBSERVATIONS
-------------------------------------------------------------------------------------
                  image system     terrain system        image system

image points
------------
obs x = 1207  rms x =      5.88   rms x =     0.290   chv vx =    17.63
obs y = 1207  rms y =      4.40   rms y =     0.217   chv vy =    13.20

ROOT MEAN SQUARE VALUES AND CHECK VALUES OF RESIDUALS OF NON-PHOTOGRAMMETRIC OBSERVATIONS
-----------------------------------------------------------------------------------------
                  image system     terrain system      terrain system

control points with sds-no.  1
--------------------------
obs x =    8  rms x =     29.15   rms x =     1.438   chv vx =     4.31
obs y =    8  rms y =     33.00   rms y =     1.628   chv vy =     4.88
obs z =    8  rms z =     44.09   rms z =     2.175   chv vz =     6.53

ROOT MEAN SQUARE VALUES AND CHECK VALUES OF RESIDUALS OF GPS OBSERVATIONS
-------------------------------------------------------------------------
                                   terrain system      terrain system

gps observations with sds-no.  1
-----------------------------
obs x =   81                      rms x =     0.013   chv vx =      0.04
obs y =   81                      rms y =     0.018   chv vy =      0.05
obs z =   81                      rms z =     0.044   chv vz =      0.13

gps observations with sds-no.  2
-----------------------------
obs x =   20                      rms x =     0.019   chv vx =      0.06
obs y =   20                      rms y =     0.018   chv vy =      0.06
obs z =   20                      rms z =     0.085   chv vz =      0.26


SIGMA NAUGHT      7.92          =     0.391
------------


COORDINATES OF CONTROL POINTS AND RESIDUALS
-------------------------------------------
in units of terrain system
```

```
           horizontal control points
                                                 code of point
           point-no.      x                y     input -> used          rx         ry     sds check

             26    -72653.385     -1847.868      HV 2                0.211     -0.408     1   .  .
             27    -73912.981     20027.308      HV 2                0.090     -2.063     1   .  .
             29    -31262.676     29465.355      HV 3               -1.385     -2.603     1   .  .
             42    -31772.848     22556.965      HV 3               -3.218     -2.065     1   .  .
             43    -35590.100     13370.653      HV 3               -0.170     -2.187     1   .  .
             45    -47988.815     -4332.370      HV 4                0.992     -0.509     1   .  .
             46    -36058.591    -12463.704      HV 2               -1.566     -0.753     1   .  .
             52     -8939.231     -4353.436      HV 2               -0.868     -0.377     1   .  .

>>>>> warning:                                                          <<<<<
>>>>>    63 planimetric control point(s) not in the block               <<<<<


           vertical control points
                                                 code of point
           point-no.                    z        input -> used                     rz     sds check

             26                    56.264        HV 2                          -2.258     1      .
             27                    14.268        HV 2                          -1.952     1      .
             29                   339.449        HV 3                          -3.459     1      .
             42                   363.035        HV 3                          -1.734     1      .
             43                   366.988        HV 3                          -0.863     1      .
             45                   292.006        HV 4                          -1.031     1      .
             46                   360.655        HV 2                          -2.621     1      .
             52                   468.576        HV 2                          -2.301     1      .

>>>>> warning:                                                          <<<<<
>>>>>    63 height control point(s) not in the block                    <<<<<


           COORDINATES OF GPS OBSERVATIONS AND RESIDUALS
           ---------------------------------------------
           in units of terrain system

           gps antenna offset    x` =  0.105    y` = -0.052    z` =  1.000

          photo-no.      x            y             z             t                rx         ry         rz    sds check

          profile-no.          1

          drift parameters:

          linear      0.0000        0.0000        0.0000
          constant     0.000         0.000         0.000

            123    -78565.984      25037.325      7454.155       -10.000          -0.009      0.002      0.026     1
            124    -74353.702      24915.035      7517.606        -9.000           0.005     -0.008     -0.076     1
            125    -69986.068      24831.595      7554.657        -8.000           0.001     -0.010      0.004     1
            126    -65685.765      24945.350      7604.610        -7.000           0.019     -0.005     -0.011     1
            127    -61387.351      25158.467      7642.196        -6.000          -0.008     -0.008      0.005     1
            128    -57126.527      25293.544      7671.128        -5.000           0.024     -0.004     -0.030     1
            129    -52889.516      25390.060      7698.764        -4.000          -0.001     -0.016     -0.019     1
            130    -48581.798      25409.322      7744.426        -3.000           0.016      0.011     -0.003     1
            131    -44272.236      25468.063      7773.399        -2.000           0.012     -0.011     -0.016     1
            132    -40010.651      25426.325      7798.068        -1.000           0.017     -0.015     -0.013     1
            133    -35723.107      25371.978      7833.250         0.000          -0.001      0.001      0.003     1
            134    -31425.334      25304.965      7854.566         1.000           0.030      0.009     -0.037     1
            135    -27170.166      25277.787      7868.991         2.000           0.012     -0.019      0.025     1
            136    -22851.351      25260.862      7872.240         3.000           0.019      0.008     -0.024     1
            137    -18544.741      25224.798      7901.491         4.000           0.010     -0.006      0.028     1
            138    -14312.610      25228.595      7909.555         5.000           0.023     -0.004     -0.034     1
            139    -10020.309      25181.844      7917.402         6.000           0.012      0.006     -0.011     1
            140     -5732.582      25163.436      7929.460         7.000           0.039      0.007      0.011     1
            141     -1519.306      25108.691      7942.076         8.000          -0.001     -0.017      0.043     1
            142      2758.694      25141.214      7946.623         9.000           0.005      0.004      0.009     1
            143      6984.406      25178.547      7936.974        10.000         --  not in the block --

          profile-no.          2

          drift parameters:

          linear      0.0000        0.0000        0.0000
          constant     0.000         0.000         0.000

            178      8540.126      16694.004      7958.422       -10.000         --  not in the block --
            179      4056.314      16699.095      7950.787        -9.000           0.004      0.014     -0.002     1
            180      -563.491      16702.260      7959.221        -8.000          -0.013      0.043      0.118     1
            181     -4943.490      16696.387      7946.389        -7.000           0.002      0.035      0.062     1
            182     -9237.393      16592.274      7950.428        -6.000          -0.002      0.033      0.044     1
            183    -13549.755      16501.097      7948.167        -5.000           0.010      0.003      0.010     1
            184    -17837.474      16382.135      7954.266        -4.000          -0.010      0.014      0.045     1
            185    -22234.963      16462.879      7921.981        -3.000           0.007      0.010      0.000     1
            186    -26493.538      16630.279      7919.650        -2.000           0.010     -0.013      0.026     1
            187    -30770.250      16786.206      7891.470        -1.000           0.002      0.024      0.004     1
            188    -35218.270      16699.439      7856.514         0.000           0.016      0.037      0.076     1
            189    -39546.085      16664.493      7842.951         1.000          -0.006      0.036      0.106     1
            190    -43825.796      16596.141      7809.244         2.000           0.001     -0.008      0.055     1
            191    -48354.016      16554.085      7789.557         3.000           0.007      0.031      0.026     1
            192    -52995.595      16298.025      7733.052         4.000           0.011     -0.004      0.003     1
            193    -57667.055      16157.099      7700.326         5.000          -0.007      0.031      0.073     1
            194    -62166.657      16265.618      7662.783         6.000          -0.002      0.024      0.072     1
            195    -66681.435      16296.164      7616.250         7.000          -0.002      0.006      0.044     1
            196    -71129.918      16369.590      7556.726         8.000           0.003      0.017      0.034     1
            197    -75512.019      16426.293      7512.072         9.000           0.005      0.005      0.032     1
            198    -79952.237      16374.794      7449.384        10.000          -0.009     -0.010      0.011     1

          profile-no.          3

          drift parameters:
```

```
linear        0.0000        0.0000        0.0000
constant       0.000         0.000         0.000

  321      5815.139      -515.415      7957.126       -10.000         0.004     -0.003      0.033    1
  322      1633.306      -570.173      7969.938        -9.000        -0.014     -0.001      0.059    1
  323     -2501.262      -565.861      7956.838        -8.000        -0.002     -0.045      0.096    1
  324     -6609.605      -489.280      7969.286        -7.000        -0.012     -0.009      0.051    1
  325    -10765.192      -417.261      7969.222        -6.000         0.006     -0.006      0.058    1
  326    -14903.705      -362.785      7965.354        -5.000         0.015      0.010      0.046    1
  327    -19062.894      -311.384      7938.434        -4.000        -0.015     -0.029      0.055    1
  328    -23299.276      -160.584      7937.870        -3.000         0.012     -0.003      0.049    1
  329    -27661.128       -13.094      7898.771        -2.000         0.012     -0.025      0.039    1
  330    -31981.926         0.072      7888.719        -1.000         0.008     -0.018      0.054    1
  331    -36105.987       -27.858      7856.780         0.000        -0.010     -0.020      0.053    1
  332    -40185.554      -149.453      7849.999         1.000        -0.014     -0.006      0.056    1
  333    -44516.391      -286.866      7816.304         2.000        -0.018     -0.029      0.059    1
  334    -48956.917      -442.437      7788.951         3.000         0.001     -0.011      0.055    1
  335    -53487.515      -526.787      7756.142         4.000        -0.001     -0.043      0.091    1
  336    -57721.827      -513.074      7717.181         5.000         0.005     -0.010      0.022    1
  337    -61979.787      -521.607      7672.913         6.000         0.001     -0.037      0.024    1
  338    -66309.523      -499.757      7626.206         7.000         0.016     -0.023      0.049    1
  339    -70585.049      -520.497      7572.331         8.000         0.005     -0.036      0.084    1
  340    -74776.830      -489.826      7547.461         9.000         0.029      0.012     -0.015    1
  341    -79040.186      -468.536      7499.414        10.000         0.016     -0.005     -0.041    1

profile-no.          4

drift parameters:

linear        0.0000        0.0000        0.0000
constant       0.000         0.000         0.000

  342    -77951.945     -9079.512      7491.796        -9.500        -0.010     -0.003      0.038    1
  343    -73779.583     -9094.960      7541.397        -8.500        -0.014      0.004      0.008    1
  344    -69531.117     -9094.494      7569.213        -7.500        -0.014     -0.009     -0.057    1
  345    -65149.446     -9069.220      7616.020        -6.500         0.001      0.000      0.045    1
  346    -60804.299     -9067.100      7668.083        -5.500        -0.009     -0.001      0.001    1
  347    -56463.576     -9037.479      7708.420        -4.500        -0.007     -0.001      0.028    1
  348    -52125.609     -9036.723      7745.476        -3.500        -0.018     -0.005     -0.014    1
  349    -47758.011     -9024.327      7768.535        -2.500        -0.018      0.000     -0.005    1
  350    -43393.431     -9033.762      7802.927        -1.500        -0.020      0.006      0.013    1
  351    -39039.942     -9025.828      7832.525        -0.500        -0.015      0.019     -0.043    1
  352    -34694.522     -8998.511      7859.832         0.500        -0.020      0.007     -0.034    1
  353    -30271.251     -8897.960      7873.285         1.500        -0.010      0.017     -0.027    1
  354    -25797.750     -8754.414      7907.198         2.500        -0.017      0.010     -0.003    1
  355    -21204.080     -8738.678      7937.302         3.500         0.003      0.015     -0.012    1
  356    -16713.428     -8744.199      7947.806         4.500        -0.023      0.005      0.001    1
  357    -12252.639     -8827.016      7947.700         5.500         0.009      0.027     -0.051    1
  358     -7822.402     -8856.261      7969.028         6.500        -0.036     -0.008      0.011    1
  359     -3491.115     -8884.808      7971.721         7.500         0.004      0.001     -0.041    1
  360       800.807     -8992.033      7961.814         8.500         0.002      0.009     -0.075    1
  361      5115.279     -9031.390      7940.481         9.500         0.008      0.024      0.014    1
```

```
profile-no.          5          HOBART BASE STATION TRAJECTORY - NO GROUND CONTROL

      drift parameters:

    linear        0.0000        0.0000        0.0000
    constant       0.000         0.000         0.000

    6038      7973.024      8109.544      8121.818       -10.000        --  not in the block --
    6039      3579.648      8089.112      8120.645        -9.000        -0.031      0.018     -0.065     2
    6040      -755.874      8003.876      8127.221        -8.000         0.040      0.003     -0.195     2
    6041     -5064.746      8028.299      8123.078        -7.000        -0.026     -0.009     -0.084     2
    6042     -9418.652      8066.147      8115.626        -6.000         0.003      0.018     -0.080     2
    6043    -13761.585      8182.617      8112.072        -5.000        -0.024     -0.010     -0.072     2
    6044    -17948.549      8206.412      8098.094        -4.000        -0.021     -0.018     -0.100     2
    6045    -22115.744      8299.158      8086.712        -3.000        -0.017     -0.012      0.004     2
    6046    -26549.763      8371.004      8067.226        -2.000        -0.028     -0.023     -0.012     2
    6047    -30999.915      8444.555      8049.533        -1.000         0.001     -0.019     -0.062     2
    6048    -35241.626      8525.915      8023.352         0.000        -0.021      0.023     -0.125     2
    6049    -39265.593      8564.264      8003.124         1.000         0.006      0.039     -0.116     2
    6050    -43305.896      8618.315      7974.371         2.000         0.007     -0.032     -0.079     2
    6051    -47389.941      8523.090      7950.220         3.000         0.002     -0.014     -0.053     2
    6052    -51723.448      8374.358      7910.715         4.000        -0.014     -0.021     -0.088     2
    6053    -56150.348      8098.177      7877.611         5.000         0.002      0.001     -0.064     2
    6054    -60602.109      7926.933      7832.372         6.000        -0.003      0.009     -0.073     2
    6055    -65017.690      7940.906      7790.338         7.000         0.023      0.006     -0.074     2
    6056    -69428.261      7860.486      7741.184         8.000        -0.011     -0.013     -0.091     2
    6057    -73829.681      7931.528      7692.103         9.000         0.013      0.023     -0.028     2
    6058    -78332.236      8106.939      7642.589        10.000         0.005     -0.007     -0.032     2
```

```
>>>>> warning:                                                      <<<<<
>>>>>     3 GPS antenna point(s) not in the block                   <<<<<


              COORDINATES AND RESIDUALS OF CRITICAL POINTS
              --------------------------------------------
              arranged by increasing point numbers


          photo-no.       x              y              rx          ry     sds check


                    point-no.                5179    TP 4

           6040     -96691.2       -89811.8          20.7         8.2     0    2  .
           6039     -10076.6       -90445.7          20.9        -4.0     0    2  .
            179      -6293.3        76681.1          -8.0        -8.8     0    .  .
```

```
 180     -98698.3      80988.8          -31.5        1.4    0   8  .

           point-no.            5183   TP 6

6044     -85415.2     -78146.0           14.8        2.3    0   .  .
6042      83055.7     -81716.5           -9.6       -3.0    0   .  .
6043      -2954.3     -74206.7           -1.7        9.6    0   .  .
 183      -1789.5      94234.4            3.1        1.7    0   .  .
 184     -88619.5      83928.9          -23.3       -4.4    0   4  .
 182      85530.6      93330.4           17.0       -6.3    0   .  .

           point-no.            5187   TP 6

6048     -89877.9     -80227.3           15.8       -4.9    0   .  .
 186      76779.1      81250.3           -1.9        6.0    0   .  .
 187      -4578.7      89611.5           -0.1       -4.8    0   .  .
 188     -94061.5      75715.8          -19.0       -2.8    0   1  .
6047      -3727.7     -87152.6            5.5        7.9    0   .  .
6046      80955.9     -86237.5           -0.2       -2.6    0   .  .

           point-no.            5188   TP 6

6047      97948.5     -82219.4            4.0       -6.8    0   .  .
6049     -72204.4     -77329.1           36.5        3.3    0   9  .
6048       9837.4     -77754.3           18.4        7.1    0   1  .
 189     -80716.8      87197.8          -36.6       -5.9    0   9  .
 188       6752.7      85927.7          -23.0       -4.2    0   4  .
 187      98720.0      99928.4            2.3        2.2    0   .  .

           point-no.            5189   TP 6

 188      80383.1      83823.6           30.5      -12.2    0   8  .
6049        585.5     -86345.7           -5.8        7.9    0   .  .
6048      82984.7     -85498.4          -11.6        6.0    0   .  .
6050     -81297.0     -71530.0           -9.2        8.7    0   .  .
 190     -92612.8      77764.0          -13.7       -8.0    0   .  .
 189      -6300.7      83478.8           11.5        0.0    0   .  .

           point-no.            5190   TP 6

6051     -71779.3     -62539.6            7.8        7.9    0   .  .
6049      93091.9     -75495.4          -18.3       -7.6    0   1  .
6050       8611.2     -62415.2            0.2        4.4    0   .  .
 191     -97403.3      96704.1          -12.6       -2.9    0   .  .
 190      -1363.1      96692.6            5.3       -2.4    0   .  .
 189      85544.3     100787.5           18.8        1.2    0   1  .

           point-no.            5192   TP 5

 193     -93631.8      74659.8          -18.1       -8.3    0   1  .
6053     -60977.2     -75073.3           13.1        2.9    0   .  .
 192       1532.7      85436.8          -14.2       -4.7    0   .  .
 191      95006.2      94780.2           10.6       -2.4    0   .  .
6052      25411.9     -77422.8           11.3        9.1    0   .  .

           point-no.            6272   TP 5

6052     107881.8      91380.3           -9.9       -5.0    0   .  .
 336     -25269.8     -79571.0           -1.2        3.9    0   .  .
6053      17888.1      93411.5           -8.7       -6.0    0   .  .
 335      61791.2     -78821.4           24.5        1.7    0   4  .
6054     -72835.5      97338.0           -5.3        7.4    0   .  .

           point-no.            6274   TP 6

 335     -99168.2     -90268.5          -17.7        3.6    0   1  .
6052     -52135.5      94442.4            6.7       -2.7    0   .  .
 333      82644.9     -92104.8           16.3       -1.9    0   .  .
6051      31855.1      89277.6            4.5       -7.0    0   .  .
 334      -9956.8     -91466.1           -1.1        8.3    0   .  .
6050     112868.0      91500.0           -9.3       -1.0    0   .  .

           point-no.            6278   TP 6

6048     -64203.6      89100.7           12.9        4.0    0   .  .
6047      17755.5      83875.3           -2.0       -0.1    0   .  .
 329      85446.8     -83286.2           14.8       -7.6    0   .  .
 330      -4303.6     -85003.4           -3.4       17.1    0   .  3
6046     108241.5      84363.2           -5.5      -12.1    0   .  .
 331     -89683.6     -83653.4          -16.8       -1.2    0   .  .

           point-no.            6280   TP 6

6044      94392.8      86605.3          -14.6       -9.9    0   .  .
6046     -73146.2      95060.0            1.8        3.1    0   .  .
 329     -99148.8     -77936.6           -8.9       -0.5    0   .  .
6045      13990.8      86045.2            1.9        1.8    0   .  .
 328      -9638.6     -78610.7            1.7        9.0    0   .  .
 327      82945.4     -81400.8           17.8       -2.4    0   1  .

           point-no.            6284   TP 6

 323      64810.1     -85305.1           20.6        1.4    0   2  .
 325    -103996.5     -87214.5           -2.7       -3.3    0   .  .
 324     -18509.3     -85932.0            5.2        6.7    0   .  .
6042     -72472.9      85275.7           -5.8       -4.7    0   .  .
6040     101615.5      82811.8          -11.9       10.9    0   .  .
6041      11566.0      84423.4           -5.5       -9.9    0   .  .

           point-no.            6868   TP 6

6058     -75309.8      88393.1            3.2       -4.7    0   .  .
 341     -96060.8     -84795.7           -5.9        7.8    0   .  .
6056     106578.4      69796.5           -4.6       -5.3    0   .  .
 340      -9103.2     -86816.4           -9.0        4.6    0   .  .
 339      78287.1     -90534.1           19.3       -3.4    0   1  .
```

```
 6057      13145.7      82887.4          -4.0        1.8    0  .  .

          point-no.          6869   TP 6

  338      71313.4     -77120.0          22.2       -5.1    0  3  .
  340    -100253.1     -77395.2           8.6        3.8    0  .  .
  339     -14130.4     -81262.8          -1.8       -7.2    0  .  .
 6057     -75331.8      94792.1           0.1        0.2    0  .  .
 6056      18646.5      88517.7          -6.7       -7.6    0  .  .
 6055     101456.5      88543.5         -23.0       17.8    0  4  4

          point-no.          8344   TP 3

  345     -90352.0     -94108.3          -0.3       -6.6    0  .  .
  344      -1389.5     -89300.9           1.0       14.0    0  .  1
  343      85967.3     -90489.4          -0.5       -7.3    0  .  .


          point-no.        222580   TP 6

  331      81747.5     -92416.6          19.3       -2.7    0  1  .
 6050     -57262.0      92401.3           3.5       -8.0    0  .  .
  332      -2610.1     -95886.0           3.2        8.9    0  .  .
  333     -90514.0     -97694.1         -13.9        1.3    0  .  .
 6049      23171.4      78118.5           0.7       -1.6    0  .  .
 6048     103064.0      80350.0         -13.0        2.1    0  .  .

          point-no.        222582   TP 6

 6049      18270.4    -112759.2          -3.0        1.1    0  .  .
  190     -72916.2      53253.1          -5.2        6.9    0  .  .
  189      13136.4      58502.7           7.6        5.1    0  .  .
 6048     101087.2    -111115.5         -23.6      -12.5    0  4  .
 6050     -64389.7     -96663.1          14.7       -0.1    0  .  .
  188     100317.8      59685.7           9.2       -0.3    0  .  .

          point-no.        223605   TP 6

 6040     -16578.7     -93351.2           3.1        5.6    0  .  .
  180     -15633.2      83292.2           7.2       -2.0    0  .  .
 6041     -97442.8     -95955.8          10.6      -14.8    0  .  2
  179      74558.8      80841.5          13.4        3.3    0  .  .
 6039      70915.5     -93709.4         -14.5       14.3    0  .  1
  181    -102258.4      80108.4         -18.6       -4.5    0  1  .

          point-no.        306869   TP 3

 6056       4195.3     100214.2           0.4      -12.1    0  .  .
 6057     -90525.5     105398.8          -0.7       -1.7    0  .  .
 6055      85929.8      99282.1          -0.5       13.7    0  .  1

          point-no.        323605   TP 6

  182     -97761.6      79261.0         -18.9       -2.4    0  1  .
 6040      73597.0     -90382.4         -21.0       -5.9    0  2  .
  180      76027.7      92789.2          18.8        3.7    0  1  .
 6041      -8207.4     -89064.8           5.8        6.3    0  .  .
 6042    -100462.7     -86851.1          15.4        1.3    0  .  .
  181     -10619.5      86835.6          -0.4       -2.5    0  .  .

          point-no.        323607   TP 5

  324     -37217.3    -107682.5           3.6       -0.5    0  .  .
 6040      81746.3      62486.6         -17.9        4.9    0  1  .
 6041      -7091.1      63426.9          -4.2        0.0    0  .  .
 6042     -91974.0      65295.3           2.6        1.5    0  .  .
  323      46407.4    -107388.0          16.3       -4.6    0  .  .

          point-no.        907338   TP 5

  339     -78249.4     -99583.8         -18.1        4.2    0  1  .
 6056     -44430.8      78262.5           8.2       -8.2    0  .  .

END OF EXECUTION : 09-FEB-99 10:22:53

PATB-GPS END
```

Appendix L

Comparison of adjusted image points derived from aerial triangulation without ground control and using only 5 east-west runs (Appendix K) and adjusted image points derived from aerial triangulation using the Lightning Ridge trajectory (Appendix C).

```
PROGRAM: COMPARE                  COMPARES DATA SETS                  9-Feb-99
                              COMPARISON OF COMMON POINTS
                                                         DIFFERENCES
  LABEL         X                Y                  Z         X     Y     Z      XY
     26   -72653.628543     -1847.959969         56.027574   .45  -.32 -2.02    .55
     27   -73912.796973     20027.373631         14.399656  -.09 -2.13 -2.08   2.13
     29   -31262.166368     29465.464108        339.364990 -1.90 -2.71 -3.37   3.31
     42   -31773.999051     22557.019281        363.232425 -2.07 -2.12 -1.93   2.96
     43   -35589.266177     13370.365738        367.217248 -1.00 -1.90 -1.09   2.15
     45   -47987.462573     -4332.365880        292.014753  -.36  -.51 -1.04    .63
     46   -36058.966495    -12463.992370        360.915363 -1.19  -.46 -2.88   1.28
     52    -8938.641382     -4353.609741        468.445810 -1.46  -.20 -2.17   1.47
   3085   -78011.417944     29609.542507        -70.636316  -.19  -.83 -5.80    .85
   3086   -74203.131025     29440.409432        -24.931152   .08 -3.12 -2.96   3.12
   3087   -70885.135376     29433.110468         13.762367   .14 -3.38 -2.58   3.38
   3088   -66155.951461     29127.545400         66.321605  -.55 -3.57 -2.51   3.61
   3089   -61813.697808     28825.133752        110.880923 -1.00 -3.38 -2.68   3.53
   3091   -54278.557112     29579.797010        179.485676 -1.38 -2.79 -3.71   3.12
   3092   -50148.925273     29273.398103        216.012100 -1.24 -2.68 -4.07   2.96
   3093   -46578.118978     29262.859265        243.822536 -1.09 -2.76 -4.21   2.96
   3096   -32961.256030     29440.008937        330.285467 -1.91 -2.91 -3.07   3.48
   3097   -29149.942012     29884.539006        346.593129 -2.21 -2.81 -3.37   3.57
   3098   -24484.279595     29098.079844        370.636337 -2.55 -2.54 -3.75   3.61
   3099   -20203.314950     29713.492574        385.248233 -2.62 -2.31 -4.23   3.49
   3100   -15653.190811     28909.305749        405.099657 -2.59 -2.11 -4.34   3.34
   3101   -11507.011903     29022.779337        413.591329 -2.42 -1.94 -4.56   3.11
   3102    -7518.924266     29046.256519        421.127248 -2.28 -2.07 -4.55   3.08
   3103    -2529.736976     28665.278254        426.506670 -2.32 -2.79 -3.71   3.63
   3104     1197.528629     28447.904819        428.168259 -2.69 -2.58 -3.27   3.72
   4123   -79244.259347     21209.133472        -55.049362   .07 -2.81 -1.88   2.81
   4125   -70660.836609     20476.016012         49.586400  -.11 -3.06 -1.27   3.07
   4126   -65994.625290     20802.313793         99.319871  -.54 -3.02 -1.58   3.07
   4127   -61469.030138     20385.153395        147.176933  -.81 -3.02 -1.69   3.13
   4128   -57182.363490     20810.670641        187.235209 -1.05 -2.93 -2.02   3.12
   4129   -52564.467277     20707.060159        227.909814 -1.19 -2.93 -2.32   3.16
   4130   -48179.965522     20741.915107        264.233183 -1.21 -3.06 -2.69   3.29
   4131   -43847.183770     21245.030866        294.225034 -1.30 -3.08 -2.60   3.34
   4132   -39664.984941     20850.792728        323.247132 -1.31 -2.42 -2.09   2.75
   4133   -35490.780294     20976.880480        348.571734 -1.48 -2.36 -1.93   2.78
   4134   -31762.079290     20810.928986        368.547048 -1.82 -2.14 -2.00   2.81
   4135   -26582.473318     20802.692237        393.534149 -2.11 -2.09 -2.31   2.97
   4136   -22644.657320     21009.283642        408.826488 -2.22 -2.30 -3.09   3.19
   4137   -18214.640333     20593.538917        426.241427 -2.23 -2.30 -3.33   3.20
   4138   -13788.511301     20594.338303        439.234494 -2.24 -2.01 -3.24   3.01
   4139    -9823.987468     20673.212509        447.111768 -2.27 -1.95 -3.25   3.00
   4140    -5256.925960     20612.010254        453.669207 -2.43 -1.99 -3.23   3.14
   4141    -1465.816597     20190.463255        458.655973 -2.76 -1.80 -3.00   3.30
   4142     2810.469051     20938.360712        465.007284 -3.34 -1.15 -3.08   3.53
   5179     4060.314767     12663.615788        471.975165 -3.26  1.20  3.07   3.47
   5182    -9353.207153     12074.166014        467.269700 -1.87 -1.02   .05   2.13
   5183   -13586.131285     11912.671184        458.661322 -1.69  -.42   .85   1.74
   5184   -18069.879002     11900.069689        446.562980 -2.09 -3.04 -2.68   3.69
   5185   -22276.207076     12249.108501        431.879627 -2.37 -2.48 -2.03   3.43
   5186   -26719.345382     12006.758305        413.688988 -2.18  -.31   .79   2.20
   5187   -30679.371136     12632.024463        393.648096 -1.54  -.68   .65   1.68
   5188   -35689.701039     12354.949636        367.394417  -.23  -.57   .76    .62
   5189   -39320.922405     12628.968022        346.243985 -1.62  -.79  1.36   1.80
   5190   -43843.332815     11897.423560        315.472297 -1.28 -1.69   .84   2.12
   5191   -48270.683301     12896.947422        281.811284 -1.32 -3.48 -1.95   3.73
   5192   -53210.948220     12158.329349        241.695625 -1.09 -1.51   .93   1.86
   5193   -57722.288477     11583.233169        203.309619  -.98 -1.58   .90   1.86
   5194   -62702.536180     12145.998806        153.809245  -.96 -2.17   .05   2.38
   5195   -67355.906095     11830.487072        106.278694  -.63 -1.94   .31   2.04
   5196   -71010.113208     11940.618735         66.027579  -.24 -1.91   .24   1.93
   5197   -76153.527722     12334.473170          6.174094  -.34 -1.93   .41   1.96
   5198   -78230.279988     12362.944367        -19.499795  -.47 -2.53  -.50   2.57
   6267   -79017.550620      3934.051799        -20.930171  2.68  -.28   .10   2.70
   6268   -73924.972793     12257.899859         32.547027  -.16 -1.46   .65   1.47
   6269   -68449.788849     11916.858065         94.704576  -.96 -1.90   .60   2.13
```

6270	-64602.658792	3067.370479	144.418446	.60	-2.19	.79	2.27
6271	-60399.744148	3490.072064	185.055367	-.37	-.93	-1.61	1.00
6272	-56473.632156	3404.594609	222.249640	-.78	-2.02	.45	2.16
6273	-51582.346187	3405.624071	264.820568	-.41	-.85	-1.04	.94
6274	-48531.372296	3949.336447	289.861775	-.80	-1.93	-.11	2.09
6275	-44205.692236	3922.848585	322.231121	-1.32	-1.62	-.45	2.09
6278	-31756.619680	4069.577374	397.223417	-1.23	-.69	-.12	1.41
6279	-27207.425841	4456.324369	419.114670	-1.21	.40	-1.16	1.28
6280	-22705.901723	3782.012197	437.841457	-1.44	-.47	.01	1.51
6281	-18533.279368	3878.018373	452.430394	-1.82	-.23	-.18	1.83
6282	-14139.014939	3540.064462	468.736861	-1.57	-.37	.01	1.61
6283	-10069.152758	4277.870454	480.239318	-1.68	-.67	.00	1.80
6284	-5611.278132	3736.592280	480.401351	-2.27	-.40	-.29	2.31
6285	-1465.370084	3397.201642	482.079956	-1.55	.19	-.61	1.57
6286	3725.028950	3816.056713	483.543052	-1.69	.07	.20	1.69
6287	7860.473148	3495.665743	479.009558	-2.31	.07	.22	2.31
6868	-74215.295475	3756.044682	37.248344	1.38	-2.79	2.08	3.11
6869	-69745.322123	3236.186358	88.821095	.55	-1.67	.32	1.75
7320	9520.725289	-5176.030635	473.930437	-2.27	1.42	-.15	2.67
7321	5474.663027	-4437.804892	478.715761	-2.00	1.30	-.31	2.38
7322	1072.233055	-4869.116742	480.249684	-2.00	1.18	-.48	2.33
7323	-3267.243734	-5002.925603	480.216689	-1.69	.99	-.54	1.96
7324	-7775.884541	-4865.543428	469.154668	-1.51	.62	-.76	1.64
7325	-11526.650599	-5120.121340	462.567857	-1.47	.54	-.90	1.56
7326	-16076.053616	-4358.243315	453.761655	-1.35	.58	-.87	1.47
7327	-20292.717667	-3973.968030	443.594430	-1.22	.57	-1.01	1.34
7328	-23253.924712	-4526.288820	431.951975	-1.13	.55	-1.23	1.26
7329	-27113.021800	-4736.368143	416.468200	-1.01	.52	-1.47	1.14
7330	-30714.425136	-4072.610544	401.145154	-1.01	.43	-1.36	1.10
7331	-35288.007551	-5299.285313	375.602723	-.98	.18	-1.51	.99
7332	-39152.747928	-4302.851440	353.525082	-.80	-.25	-1.30	.84
7333	-44086.197175	-4150.534803	320.214876	-.88	-.67	-1.13	1.10
7334	-48254.089693	-4938.842104	288.709800	-.63	-.51	-1.28	.81
7335	-52606.219484	-4356.244660	252.577895	-.47	-.47	-1.26	.67
7336	-57103.617746	-4784.238948	213.228855	-.25	-.48	-1.23	.54
7337	-61678.575055	-4813.961778	170.537840	.00	-.59	-1.34	.59
7338	-65592.007014	-5166.689844	130.349544	.09	-.80	-1.84	.80
7339	-70083.568504	-5319.537908	83.332467	.14	-.90	-2.38	.91
7340	-74411.302794	-4407.833316	34.396263	.15	-.69	-2.26	.70
7341	-78507.001050	-4677.409578	-15.432216	-.02	.68	-2.62	.68
7727	-73915.568288	20024.229635	13.977455	-.11	-2.81	-1.23	2.82
7728	-71649.447669	29937.886718	2.323093	.15	-3.77	-2.24	3.77
7751	-14224.759431	4534.750311	464.784355	-1.52	.25	-1.19	1.54
7752	-8940.693526	-4354.226318	466.801117	-1.44	.36	-.33	1.49
8343	-73608.543678	-13039.221478	31.980886	-.94	-1.51	-5.03	1.78
8344	-69517.187069	-13524.792447	76.857248	-.41	-1.96	-5.71	2.01
8345	-65025.247080	-13031.087923	126.213161	.83	-1.19	-4.31	1.45
8346	-60974.907850	-13366.732522	166.338548	.28	.26	-1.99	.38
8347	-56593.377067	-13258.524278	204.646737	-.23	.21	-1.89	.31
8348	-52137.587485	-13218.053025	243.403344	-.62	.02	-1.97	.62
8349	-48661.399912	-13416.612354	271.585100	-.72	-.23	-2.11	.76
8350	-43406.229975	-13554.560325	310.083682	-1.10	-.29	-1.98	1.14
8351	-39457.088795	-12426.069913	339.689626	-1.19	.23	-1.84	1.22
8353	-30474.633408	-12869.672543	391.349792	-.82	.18	-1.79	.84
8354	-25609.319052	-12811.258816	420.385978	-.90	.42	-1.47	.99
8355	-21492.098179	-12785.692610	432.895484	-1.07	.60	-1.08	1.23
8356	-17437.984022	-12431.245598	438.205870	-1.23	.55	-.93	1.35
8357	-12951.112357	-13345.688010	447.577738	-1.33	.38	-1.17	1.38
8358	-8480.480646	-12886.130330	456.445733	-1.27	.40	-1.02	1.33
8359	-4119.471041	-13525.797768	478.569354	-1.42	.93	-.36	1.70
8360	241.356497	-12982.560057	464.683985	-1.43	1.35	-.29	1.97
8361	5021.674261	-12977.043867	465.095242	-1.37	.53	-1.90	1.47
41342	-48788.026371	-3636.864810	286.963589	-.66	-.64	-1.38	.92
41357	-33494.644531	15680.911729	372.915677	-1.46	-1.85	-1.36	2.36
101326	-6642.232626	-8199.694031	472.174199	-1.40	.51	-.38	1.49
104128	-57507.879494	29505.105761	149.736564	-1.31	-3.01	-3.41	3.28
121387	-68531.879450	26909.982857	50.412110	-.36	-3.46	-2.57	3.48
121388	-68312.262299	22342.205498	69.215730	-.61	-2.67	-1.61	2.74
121389	-67803.280334	18167.464241	87.724454	-.19	-2.22	-1.64	2.23
121390	-67501.300927	13109.000389	102.377541	-.61	-2.02	-.26	2.11
121391	-67557.867032	9228.332909	108.213193	-1.03	-1.82	2.09	2.09
121392	-67408.688094	4255.375432	114.159502	.44	-1.04	.98	1.13
121393	-67597.755496	-174.250454	113.861449	.21	-.79	-2.10	.82
121394	-67628.741550	-4472.461265	110.492665	.28	-.73	-1.92	.79
121395	-67931.316850	-8468.186767	102.789879	.21	-.38	-4.05	.44
121396	-68242.683241	-13027.807164	91.329740	.52	-1.33	-4.36	1.43
122576	-35450.166916	-12552.195301	363.507883	-.94	.30	-1.93	.98
122577	-35410.805577	-8029.915202	371.407862	-.35	.67	-1.93	.76
122578	-35399.247136	-3958.707533	376.306508	-.85	.32	-1.42	.91

122579	-35576.646876	808.814181	377.403008	-1.08	.28	-1.43	1.12
122580	-35594.005255	4750.455220	376.829460	-1.65	-.80	.02	1.84
122581	-35711.151151	9460.045955	371.811372	-1.35	-.52	1.87	1.45
122582	-35847.949677	14012.031638	362.958745	-1.24	-1.72	-1.07	2.12
122583	-35700.906501	18075.020161	355.450376	-1.13	-1.98	-1.33	2.28
122584	-35739.020892	22977.318041	340.011494	-1.32	-2.01	-1.69	2.40
122585	-36048.407549	27369.604610	321.684662	-1.38	-2.68	-2.42	3.01
123606	4885.797402	8621.936432	490.040919	-2.45	-.13	2.39	2.45
123607	4507.108689	4411.881004	489.278694	-1.77	.18	-.57	1.78
123608	4677.364623	181.222768	495.172080	-2.01	1.29	-2.50	2.39
123609	4381.239822	-3699.250331	492.487919	-2.03	1.15	-1.08	2.33
123610	4244.628937	-8105.206511	474.768207	-1.32	1.17	-.75	1.76
123611	4756.537779	-12163.010996	466.815383	-1.48	1.46	-.58	2.08
204123	-78237.367086	25081.956356	-54.623180	.16	-2.77	-3.53	2.77
204124	-74275.459117	24832.217398	-6.727400	.09	-2.70	-2.05	2.70
204125	-69742.542484	24528.005692	45.792328	-.19	-3.05	-1.48	3.06
204126	-65602.770578	24865.829764	89.277598	-.60	-3.08	-1.85	3.14
204127	-61503.670698	25386.072931	128.656875	-.95	-3.05	-2.11	3.19
204128	-57044.804265	24962.572982	173.915417	-1.21	-2.87	-2.48	3.11
204129	-53484.017058	25226.971705	204.544784	-1.26	-2.79	-2.93	3.06
204130	-48780.469498	25256.715628	243.481225	-1.20	-2.84	-3.38	3.08
204131	-43976.762198	25709.289360	278.573386	-.99	-3.14	-3.88	3.29
204132	-39997.856477	25262.201430	306.712377	-1.01	-2.95	-2.66	3.12
204133	-35225.512432	25481.707225	334.151427	-1.43	-2.42	-1.87	2.81
204134	-31342.604437	25569.160817	355.145068	-1.93	-2.48	-2.58	3.14
204135	-27373.230716	25340.408868	373.672120	-2.23	-2.42	-2.92	3.29
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204138	-14411.941790	25364.032977	421.859170	-2.40	-2.11	-4.06	3.20
204139	-9745.088666	24936.991059	433.803256	-2.29	-2.08	-4.01	3.09
204140	-5836.945636	25363.369280	437.375646	-2.35	-2.14	-3.90	3.18
204141	-1924.974093	25111.607339	441.212785	-2.58	-2.28	-3.15	3.45
204142	2609.868606	25154.015473	444.122218	-4.34	-1.57	-2.90	4.62
205179	4144.701639	16535.880982	471.863444	-2.83	-1.35	-.13	3.14
205181	-5568.442928	16342.738251	464.599203	-2.23	-2.01	-2.27	3.00
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205183	-13584.776691	16675.392411	449.750300	-1.99	-2.00	-2.15	2.82
205184	-18085.920762	16399.877885	437.888914	-2.11	-2.29	-3.04	3.11
205185	-22055.107468	16076.095751	424.846145	-2.29	-2.21	-2.71	3.19
205186	-26549.264066	16501.580525	405.296410	-2.18	-1.76	-1.24	2.80
205187	-30761.274987	16953.911103	384.472063	-1.80	-1.79	-1.23	2.54
205188	-35426.461440	16485.507326	361.145686	-1.14	-1.76	-.72	2.10
205189	-39443.911558	16637.372527	336.724449	-1.03	-2.33	-1.18	2.54
205190	-44145.511717	16515.962597	304.555614	-1.13	-2.93	-1.84	3.14
205191	-48343.359454	16600.818777	274.088082	-1.15	-2.88	-2.35	3.10
205192	-52958.299744	16545.412224	235.863399	-1.21	-2.70	-1.56	2.96
205193	-57582.659859	16290.775744	195.816991	-1.08	-2.59	-1.12	2.81
205194	-62231.168549	16165.503373	150.837214	-.80	-2.62	-1.19	2.74
205195	-66846.176647	16008.084088	103.265865	-.56	-2.50	-1.03	2.56
205196	-71055.704636	16328.845832	56.479525	-.10	-2.48	-.71	2.48
205197	-75057.118603	16339.471763	10.238001	-.27	-2.23	-.63	2.24
205198	-79784.647215	16330.086313	-46.876588	.06	-2.48	-1.38	2.48
206267	-78515.246288	8522.674005	-17.462443	-.01	-.94	1.64	.94
206268	-74133.444920	8407.206366	35.204137	.30	-1.70	1.81	1.73
206269	-69468.811387	7574.834230	89.275234	.09	-2.23	1.02	2.23
206270	-64812.995294	7705.016870	138.843470	-.23	-1.53	1.43	1.55
206271	-60540.186355	7799.327510	181.360223	-.33	-1.89	2.31	1.92
206272	-55679.610010	7801.953076	226.240705	-.33	-1.21	2.39	1.26
206273	-52121.100510	7587.224019	256.794211	-.70	-.84	1.42	1.09
206274	-47113.571738	8218.177097	296.594572	-1.97	-2.68	1.34	3.33
206276	-39132.452479	8324.478077	352.252017	-1.38	-.41	1.53	1.44
206277	-34871.539344	8034.360362	377.928472	-1.81	-1.22	2.10	2.18
206278	-30903.311687	7900.698151	399.463190	-2.01	.68	1.55	2.13
206279	-26745.408456	8200.992282	418.531993	-3.25	-.54	1.21	3.29
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206282	-13886.349502	7747.572747	463.074294	-2.16	-.07	1.85	2.16
206283	-9295.306523	7421.527099	477.601538	-1.12	-.45	1.49	1.21
206284	-4913.410678	7805.591723	478.828879	-1.86	-.87	1.39	2.06
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207324	-6813.432520	-437.488681	485.284187	-1.70	.32	-1.29	1.73
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207327	-18876.842605	-278.842900	450.234678	-1.37	.37	-1.15	1.42
207328	-23483.642022	-21.027286	434.773779	-1.21	.36	-1.23	1.26
207329	-27566.920632	-57.159114	418.147923	-1.16	.39	-1.62	1.22

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207331	-35653.927223	216.199049	376.547114	-1.00	.62	-1.51	1.18
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207335	-53565.408756	-276.160248	248.076831	-.49	-.67	-1.52	.84
207336	-57991.203479	-188.417121	208.713092	-.31	-.72	-1.35	.79
207337	-61726.001797	-628.353977	172.586117	-.06	-.77	-1.21	.78
207338	-66594.773720	-335.722908	124.324407	.18	-.78	-1.56	.80
207339	-70281.608382	-403.382483	83.928692	.56	-.84	-1.32	1.01
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207341	-79287.926808	-46.212168	-23.547337	1.46	.71	-1.41	1.62
207384	-48902.050656	-506.602626	286.778216	-.70	-.67	-1.41	.97
208342	-77981.734576	-8939.491876	-13.897779	-.57	.11	-2.85	.58
208343	-74366.598457	-8798.870884	29.862394	-.43	-.65	-3.22	.77
208344	-69953.764212	-9011.636790	80.077168	-.39	-.66	-4.40	.77
208345	-65018.338131	-9020.422976	133.353085	.55	-.55	-3.36	.78
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208348	-52215.203001	-8825.986775	251.282478	-.53	-.26	-1.65	.59
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208350	-43232.436953	-9040.289590	320.315828	-.80	-.28	-1.72	.85
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208353	-30368.731860	-8928.360660	396.722483	-.89	.18	-1.40	.91
208354	-25705.932805	-8565.543634	424.240993	-.99	.30	-1.14	1.03
208355	-21253.105799	-8521.889631	433.677960	-1.14	.38	-.88	1.20
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208357	-12024.543212	-8558.601959	457.790828	-1.39	.40	-.83	1.44
208358	-7588.856702	-9097.644921	469.378308	-1.40	.48	-.64	1.48
208359	-3603.283509	-8493.184525	474.066843	-1.43	.91	-.37	1.70
208360	722.271496	-9159.420208	473.401573	-1.45	.92	-.15	1.72
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221390	-72493.444566	13481.121146	46.414701	-.29	-2.07	-.18	2.09
221391	-72300.264793	9113.293539	55.740004	-.55	-1.63	1.57	1.72
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221393	-72151.110317	-13.459752	62.323527	.46	-.26	-1.42	.53
221394	-72786.018032	-3963.525429	53.901386	.11	-.76	-2.70	.77
221395	-72522.613974	-8275.841610	52.465147	-.18	-.24	-4.30	.30
221396	-72813.537873	-12303.691926	42.740653	-.64	-1.30	-4.41	1.45
222576	-40016.637927	-12866.384954	334.693195	-.77	-.05	-2.00	.78
222577	-39777.739525	-8749.212342	344.227806	-.17	.16	-2.08	.24
222578	-40294.210948	-3369.964637	346.892995	-.81	-.19	-1.37	.83
222579	-40581.873219	196.377511	346.491022	-1.29	-.62	-1.22	1.43
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223603	4.230179	21377.694697	455.620845	-2.91	-1.72	-2.92	3.38
223604	69.411813	17233.710601	463.537833	-2.67	-1.59	-1.53	3.11
223605	17.408214	12700.671354	476.613734	-3.21	-.39	.90	3.23
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321389	-77757.371424	17759.994221	-25.234698	.08	-2.78	-2.16	2.78
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 904136    -22471.438215    30218.584074     374.136635 -2.58 -2.44 -4.20  3.55
 904137    -18626.307516    29918.960737     391.086584 -2.60 -2.24 -4.36  3.43
 904138    -13949.065960    29758.599989     405.754934 -2.49 -1.92 -4.71  3.15
 904139     -9969.452967    29699.301069     414.079206 -2.28 -1.88 -4.81  2.96
 904140     -5670.065361    29990.391098     418.823055 -2.29 -2.27 -4.38  3.22
 904141     -1259.264272    29904.373423     422.115303 -2.40 -2.19 -4.11  3.25
 904142      3029.122954    29674.248969     422.519523 -2.96 -3.27 -2.76  4.41
 904187    -30669.100076    21484.843484     372.269953 -1.92 -2.13 -2.24  2.87
 905179      4062.581369    21299.516360     464.939129 -2.95 -1.37 -3.16  3.25
 905197    -74839.491305    20894.412929        .060965  -.18 -3.12 -1.52  3.13
 906270    -64792.388002    12294.904207     132.311428  -.76 -1.87   .48  2.02
 906271    -60987.807372    12404.127717     170.439533  -.92 -1.91   .77  2.12
 906272    -56058.380004    12097.577176     217.658640  -.92 -1.90   .94  2.12
 906273    -51935.674334    12630.907394     251.871109 -1.24 -3.04 -1.28  3.28
 907321      5554.439593     3952.832943     481.823194 -1.77   .68  -.96  1.89
 907322      1942.295424     3979.381528     485.543577 -1.67   .50  -.16  1.75
 907335    -52735.490916     4343.226599     254.605776  -.51 -1.31 -1.00  1.40
 907336    -57955.097538     4452.678138     207.884729  -.23 -1.96  -.18  1.98
 907337    -62206.191851     3645.895409     168.049416  -.06 -1.66  -.33  1.66
 907338    -66627.422560     4060.312655     122.885539   .23 -1.98  -.29  2.00
 908354    -25081.711507    -4390.625719     424.632278 -1.08   .52 -1.19  1.19

                                              MIN      : -4.34 -3.77 -5.80   .24
                                              MEAN     : -1.13 -1.21 -1.44  2.11
                                              MAX      :  2.68  1.46  3.25  4.62
                                              RANGE    :  7.03  5.23  9.05  4.38

                                              STD DEVS:  1.47  1.79  2.24  2.32
                                              STD DEV VECTOR:       3.22
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