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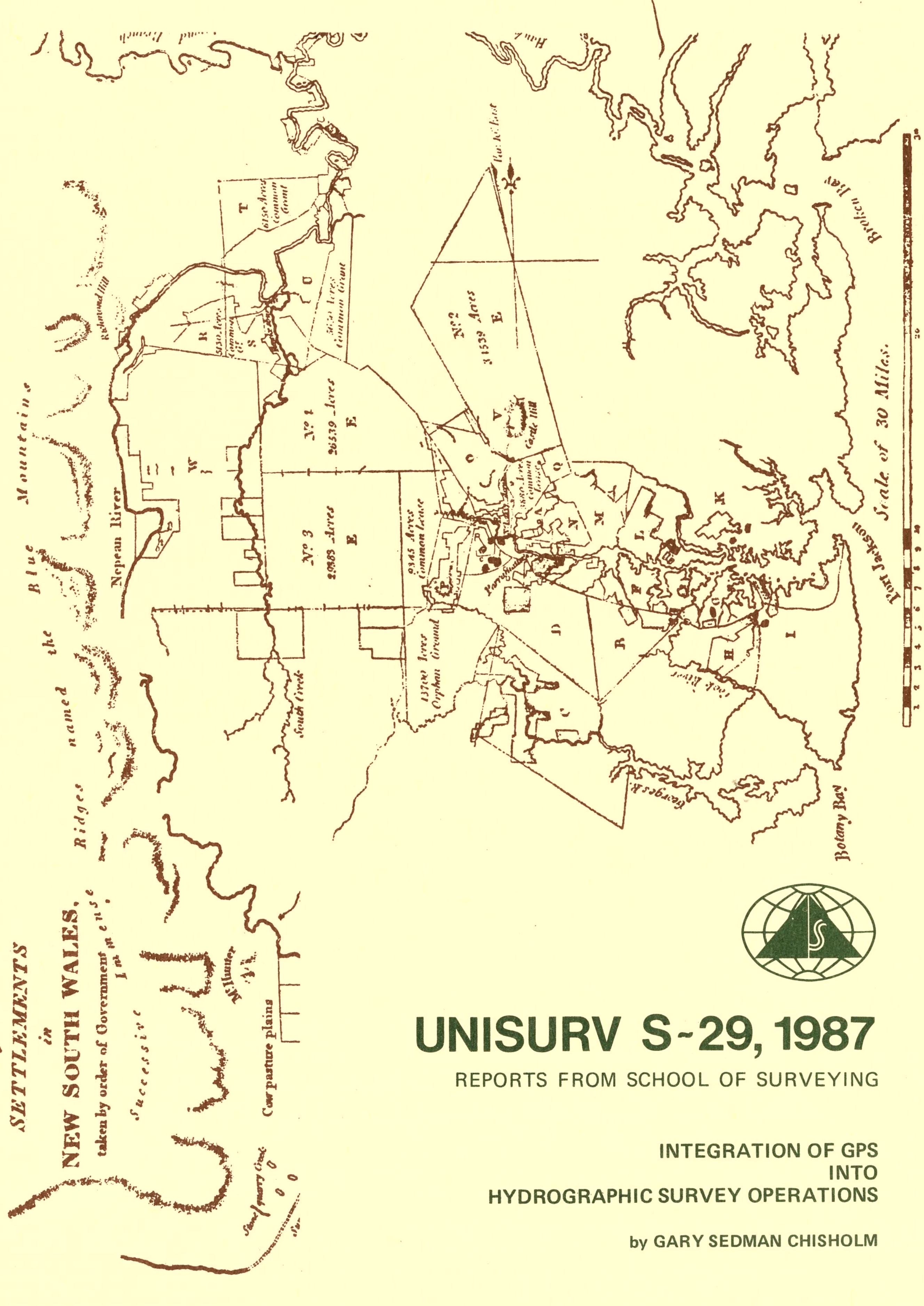

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REPORTS FROM SCHOOL OF SURVEYING

INTEGRATION OF GPS INTO HYDROGRAPHIC SURVEY OPERATIONS

by GARY SEDMAN CHISHOLM

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Abstract

The main aim of this thesis is to determine if the Global Positioning System (GPS) gives sufficiently accurate and reliable horizontal positions to be used as a navigation sensor in hydrographic surveying. An overall description of GPS is presented highlighting the points that must be addressed and understood by the hydrographic survey industry if GPS is to be successfully integrated. The nature of the error sources present in the raw observations are investigated with data taken from Trimble 4000S receivers. The expected range error from a satellite for the present constellation is calculated to be 12m while that of the proposed constellation is 32m. Two methods are investigated to minimise the range error and hence improve position accuracy: the first is a sub-optimal filter which reduces range noise from 2-3m to less than 1m and, the other is differential GPS. Differential GPS is widely believed to be the method that will be implemented to reduce systematic errors and so improve accuracy. Results from processing the GPS data collected showed that the differential technique improved position accuracy from 10m to better than 3m. However if the differential method is going to be at all useful in the hydrographic environment further research needs to be carried out: for example, to monitor how different receiver types perform relative to each other as the filtering techniques may be quite different. Otherwise it is wise to use the same model of receivers when carrying out differential GPS. Integration techniques are discussed because GPS will probably have most impact in hydrographic

surveying as a positioning sensor in an integrated navigation system.

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Acknowledgements

It is a pleasure to thank my supervisor, Associate Professor Art Stolz, for the discussions and guidance to define my topic and direction of study and appreciate his efforts in establishing contacts with both industry for use of GPS equipment, and his colleagues for advice on GPS.

By being forthcoming with GPS receivers, as soon as they were available in Australia, Colin Jones at AWA has been of immense benefit to my study. Moreover, I have been privileged to work with leaders in GPS at UNSW: Dr. Chris Rizos, Dr. Ewan Masters and Bernie Hirsch. I also wish to thank fellow student Don Grant for lending me a sympathetic ear at all times and clear advice on GPS and Least Squares.

I am especially grateful to Dr. Chris Rizos for taking a more than passing interest in my topic and for assistance with developing the processing and simulation software needed for this study.

1. INTRODUCTION.

The determination of the position of an object, such as a river or a mineral deposit, relative to another object has been the basis for exploration and developments for centuries. The techniques for measuring the position of such objects from a kinematic platform (land, air or marine) are carried by out navigators (Rizos et al 1987).

Up until World War II (WWII) the navigator used simple optical ranging means to determine position when in sight of land or else astro-navigation methods with observations to the stars and planets. The resultant accuracy was coarse when compared with accuracies that are achieved today. Since then advances in technology have accelerated considerably along with demands from offshore exploration, resource harvesting, and maintenance of sea passages. The professionals who carried out most of this early work in the marine environment were hydrographic naval officers in the Navy or officers in merchant shipping who had a close relationship with the data they collected as it ensured their safe passage. After WWII the equipment employed gradually became more sophisticated with the use of SHORAN then LORAN radio-navigation.

In 1967 the TRANSIT satellite positioning system was released for civilian use and used to augment sparse land control networks. It was not until the 1970's that the emerging TRANSIT technology was to be utilised for offshore positioning at then unheard of distances offshore with acceptable accuracy, albeit at irregular time intervals. The

TRANSIT receiver used for offshore kinematic operations required design input from both the end user (navigators) and the electronic engineers. TRANSIT was further integrated into many automated position finding suites to act as an input with other sensors or to supplement land-based radio positioning systems all requiring specialised personnel with more scientific knowledge to operate and guarantee the best results. Stirling(1986) states that today the offshore surveyor should be a scientist and not a traditional navigator/hydrographic surveyor responsible for the running of a vessel. Thus the modern hydrographic surveyor's job is to provide information and support services to a wide variety of users such as geophysicists, mariners, or engineers that is sufficiently accurate for their use with as little downtime as possible to minimise expensive offshore costs such as oil rigs and vessel hire.

By the early 1980's the new satellite navigation concept, Global Positioning System, was available for experimentation and in fact many manufacturers had produced commercially available receivers as the market demanded its new capabilities. As with TRANSIT the manufacturers and users have taken a US military system and devised techniques to optimise its performance and prove its suitability as a sole positioning sensor for many hydrographic operations. The operational specifications that the offshore industry has come to expect with conventional land-based navigation systems look to be met and often exceeded with the introduction of the GPS sensor and suitable operating procedures. The radical nature of GPS over TRANSIT is that the fix update is in real-time. This means each update is rapid, absolute and independent so is eminently suitable to kinematic applications like that previously provided by land based radio-navigation. GPS operation is based on a number of visible orbiting satellite 'beacons' that transmit a code at a certain time which is detected by the receiver at an instant later giving rise to a 'pseudo-range'; a distance measurement containing a bias error arising from non-synchronization between satellite and receiver clocks. The receiver software then performs a trilateration to determine the users 3-D position and receiver clock error when pseudo-ranges to four satellites are taken simultaneously. The 'strength of figure' inherent in this trilateration is a factor of the geometric spread of these satellites across the sky and is quantified by the value termed Dilution of Position (DOP). Once again the navigator looks to the skies for the all encompassing network of stations to determine his position.

Already certain trends are emerging on how GPS is being used in hydrographic surveys, primarily as a response to the system characteristics (error propagation and present restricted coverage) and the user requirements. From reviewing those trends this study will limit itself to the single frequency, Standard Positioning Service (SPS) C/A code receivers which possess a real-time navigation capability and have facilities for interfacing to an external computing and logging facility.

The main distinguishing feature of hydrographic surveying over other accurate positioning services is primarily the determination of the position of a kinematic marine vessel in real-time on a global reference frame with the secondary feature being the integration of data from multiple sensors. Hydrographic surveying has always attempted to resolve the conflict inherent in trying to achieve a suitably high accuracy in a harsh and turbulent environment that does not lend itself to being easily monitored. While the author recognizes that airborne survey techniques such as laser seabed profiling may eventually be used for the majority of bathymetric surveying it does not address the problem of positioning a vessel on the surface, which also provides a host of differing services. Of course many kinematic positioning techniques utilised, such as filtering, are similar. This thesis regards 'hydrographic surveying' in its broadest sense with respect to the provision of real-time position in a kinematic marine environment - the end use of this service is a factor of the type of sensors that are monitoring the environment from the vessel and spans fundamental coastal charting operations through to the many varied commercial applications. It also studies the techniques available to utilise the GPS observables to attain various degrees of accuracy and precision to aid hydrographic surveying. Much research into GPS error sources and processing techniques has been contributed by land surveyors who make little use of the pseudo-ranges but more of the Doppler observations of the GPS carrier signal in the same way as used in processing Doppler TRANSIT data. Kinematic GPS as used in hydrographic surveying now makes use of these techniques by meshing pseudo-ranges and Doppler frequency observations to increase precision.

1.1 AIMS OF THE STUDY.

The author has seen the interest in GPS generated in hydrographic surveying and considers that GPS will have a massive impact on the industry. The aim of this thesis is to present to the hydrographic survey industry both an introduction to kinematic GPS and raise a number of vital points that have to be considered when implementing GPS as a navigation sensor. The thesis will assess the scope of hydrographic survey operations by presenting an overview of present hydrographic surveying. Chapter 2 will dicuss the type of work that requires positioning, the demands placed, and how they are being met. A summary of costs for navigation equipment points to the fact that the costs to mobilise and maintain any of the present navigation systems are high and ANY innovative alternative has to be investigated and assessed as to its suitabilty before it is used, let alone generally accepted.

The present seven satellite constellation is yielding quite impressive real-time results but drifts and 'jumps' in position do occur. Why do these occur and will they remain in future proposed constellations? Chapter 3 aims to educate the reader as to how GPS is planned and maintained with the emphasis on considerations for real-time navigation. The various phenomena that can, and cannot, be modelled are investigated resulting in an expected error budget of the basic measurements.

What effect does satellite fix geometry (Dilution of Position - DOP) have on limiting position accuracy? The combined effect that the expected range error and DOP has on limiting navigation in the Australian region is studied to show the regional situation. The period of time that a navigation system provides sub-optimal accuracy is termed an outage. Any user of such a system that experiences outages due to uncontrollable effects, or known system weaknesses, needs to have insight into when to expect them. Thus a study of GPS satellite coverage now and in the future is performed with outages analysed. Chapter 4 presents the results of simulations of satellite constellations spanning Australia and its continental shelf showing how both the present (1987) and the operational situations affect navigation accuracy and integrity.

Many operational limitations of GPS are noted. The aim of Chapter 5 is to present a variety of GPS processing techniques that can be used to maintain GPS integrity and accuracy in the light of the problems introduced in the preceeding chapters. Two methods are investigated to overcome these problems:

- real-time filtering of data and,
- the differential technique.

The conclusion reached is that GPS can reliably be employed as a prime navigation sensor as long as real-time filtering and the differential technique is used then.

Limits to continuous GPS usage will always be present. Examples are satellite failure or loss of signal lock. Because of these limitations the author considers GPS will become part of an integrated survey system in which another independent navigation system cross-checks or supports the other one. Chapter 6 discusses the findings of the study with a look at possible integration of GPS into the navigator's arsenal by considering some of the techniques of integration with other likely sensors.

In the conclusion the author advocates the use of GPS in hydrographic survey operations as long as certain operational and processing techniques are adhered to. These are primarily the use of the differential method to minimise systematic errors and real-time filtering to minimise random noise. Recommendations are made so as to ensure that accuracy and integrity are maintained.

2. HYDROGRAPHIC SURVEY OVERVIEW.

Introduction

The aim of this chapter is to assess the magnitude and scope of the hydrographic survey industry. It summarises the main requirements that are demanded to allow execution of a hydrographic survey and addresses the question of whether GPS will meet these requirements as to accuracy, integrity and cost?

2.1 SPHERE OF OPERATIONS.

In the last 20 years there has been a large increase in the demand for hydrographic surveying services which is reflected by the expansion of specialist hydrographic companies and personnel. For example the membership of the Hydrographic Society has increased four-fold from 1980 to 1985 to well over 2000 members. Similarly the burgeoning private hydrographic survey companies that were formed in the mid 1970's now have millions of dollars invested in modern positioning and computing equipment. Many of these same companies are equipped to design and build sophisticated navigation sensors.

The traditional operators, Navy hydrographers, were entrusted to provide charting of the main sea passages for merchant shipping and their own navies. Today the majority of hydrographic surveyors are employed in providing services for the offshore oil industry. The definition and role of hydrographic surveying has therefore changed and can be stated, broadly speaking, as a mixture of determining:

1. a vessel's surface position or an auxiliary sensor's position in the water column,

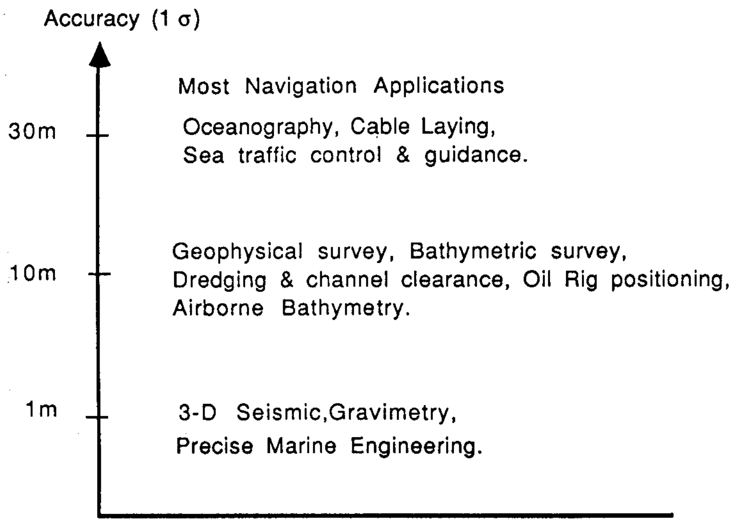
2. the position of points on the sea floor,

3. and recently it may even encompass the determination of position of an airborne sensor(Wells et al, 1981).

The range of marine applications that call upon positioning services is increasing in line with associated technical developments (Figure 2.1). The classification in Figure 2.1 is generalised as the accuracy demanded for a task, such as telecommunication cable laying, can vary from 3m to the 50m level depending on its proximity to other valuable sub-sea structures.

Figure 2.1 **Range of Marine Applications**

(based on Wells D.E. 1986)



In an attempt to classify marine positioning into various zones (Figure 2.3) the classical consideration was to assume that the requirements for accuracy become less stringent in deeper water and thus further from shore. But today that is not always the case even though the volume of precision work in the deep sea is often considerably less. A case study of a precise offshore site survey using acoustic navigation is given in Chapter 6.

Uses the services are regularly put to still include the traditional shipping role, even more so with the supertanker's large drafts and the search for optimum fuel efficient routes. Shipping passages need to be delineated and marked where critical with the seaways requiring regular maintenance in the way of dredging.

Our quest for mineral and food resources has lead to the oceans where the resource has to be remotely sensed and assessed. Like shipping, the fisheries resource, requires a survey input to determine seabed conditions and depth. Similarly aqua-culture needs physical environmental data in the planning stages and then later legal definition for security of tenure.

The role of hydrographic surveying in the search for minerals is an important input along with other allied expert fields. In hydrocarbon exploration the quality of geophysical survey data is a function of the integrity of the relative position updates as well as the absolute position fix. Development of the resource requires even more survey input to aid detailed engineering design and allow construction to proceed in an orderly manner. The entire procedure from exploration until decommissioning is outlined in Table 2.1.

With increasing appreciation of the economic value of the oceanic resource the demand for positioning in a legal cadastral sense is required. Most countries have declared a 200 mile exclusive economic zone that is regularly patrolled and monitored. For mineral resource development the lease boundaries are defined by coordinates but cannot be demarcated by monumentation so this problem is left in the hydrographic surveyor's hands to ensure no encroachment.

The meteoric expansion of hydrographic survey services has been checked recently with the price of oil dropping to below $15US a barrel (1986). This places strain on the survey industry to attempt to reduce operating costs with appropriate technology and hence the interest in GPS as a suitable alternative is very strong.

Operation	Professional Personnel (The Surveyor's Role)
1. **Seismic Exploration**	Geologist, Geophysicist, Surveyor (shore control, positioning systems, QC and post processing of positioning data etc.)
2. **Exploration Drilling** a) Rig Site Surveys	Mariner, Driller, Geophysicist, Geotechnical engineer, Surveyor (as 1 plus mapping of seabed features and immediate sub-seabed features)
(b) Rig Positioning	Mariner, Driller, Surveyor (positioning of rig)
3. **Pre-Development Surveys** (Pipeline route surveys, Platform foundation surveys, etc.)	Civil/Structural/Geotechnical Engineer, Naval Architect, Geophysicist, Surveyor—(desk studies, positioning, survey planning, processing of depth and positioning data, mapping of seabed and immediate sub-seabed features)
4. **Pre Installation Surveys** (Pre-pipelay surveys, pre-platform installation surveys)	Civil/Structural/Engineer, Diver or ROV operator, Surveyor (vessel and ROV positioning, planning/installation/calibration of specialist installation acoustic aids, debris clearance.)
5. **Platform Construction**	Structural Engineer, Naval Architect, Surveyor (dimensional control, as-built surveys (traditional/photogrammetry), float out, etc.)
6. **Installation Operations** (Pipelay, jacket installation, hook-up etc)	Mariner, Civil/Structural/Engineer, Naval Architect, Diver or ROV operator, Surveyor (positioning, platform level, etc.)
7. **Post Installation Inspection Surveys** (Initial and Annual)	Relevant QC Engineer, Diver or ROV operator, Surveyor (positioning of vessel and/or ROV underwater photogrammetry, etc.)
8. **Installation Removal** (Field Exhausted)	Mariner, Engineer, Diver or ROV Operator, Surveyor. (this stage not yet reached in North Sea.)

Table 2.1 The Surveyors Role - Stages in an Offshore Development (Stirling,1986).

2.2 USER REQUIREMENTS.

Who uses hydrographic survey services? For the last 20 years the majority of this service was supplied by the Navy which was entrusted to produce mariner's charts. Their product was also utilised by the merchant navies and fishing industry. While the Navy was thorough in the execution of its service the production of its charts suffered the problems of long periods between revisions and limited coverage since the primary reason was of course for delineation and maintenance of the sea-ways for trade and security.

Today the user of a large proportion of hydrographic survey services is the oil industry (**the client**) which has far different needs than can be supplied by the published charts. Their needs demand **real-time navigation with near real-time interpretation of the data** gathered by the company that supplies the hydrographic surveyors and geophysicists (**the contractor**). The area surveyed is normally only of interest to the client rather than the public in general.

Basic to any navigation system is the fact that the user must have confidence in its operation, in that it should be free from 'down time' giving literally 24 hours service and be reliable, that is, remain calibrated. Braff et al(1983) described the INTEGRITY of a navigation system which can be measured by:

a) its ability to detect malfunctions affecting the level of performance ,

b) the time delay from initial occurrence of the malfunction to notification of the navigator.

Systems are built with this concept being maintained by either having 100% redundancy in the hardware or independent systems that cross-check each other.

Users requiring positioning services usually have a well defined AREA OF OPERATION in which they require accurate positioning ,for example a seismic survey covering 50 x 50km or dredging control for a harbour entrance being 100m wide and 2km long. Due to operational and geometrical constraints inherent with radio-positioning systems the end user had to optimise location of the land-based beacons to meet the accuracies shown in Figure 2.3. Also due to financial constraints the positioning is usually not available outside the area of immediate interest but would definitely be used if a cheap global system were available. The stand alone GPS unit would neatly 'fill in those gaps' in which precise, but expensive, positioning does not extend to.

The user onboard a vessel carrying out continuous seismic profiling or other profiling operations is primarly interested with determining the vessel's TRACK along a predefined series of lines. Raw positioning data is collected and processed by computer before it can be displayed to the navigator in a straight forward manner on a visual display unit. This data can be arranged so that the dynamics of the vessel, with respect to the predefined line, is readily available and so necessary helm corrections are made to maintain the vessel within a specified corridor of the track. This places demands on UPDATE RATES to a level less than every 5-10 seconds. For QUALITY CONTROL in the radio-navigation solution the user requires that in the minimum case, a least squares solution is continuously carried out with the data, and range residuals displayed along with the single mean square error of those residuals to give confidence in the positioning (McDermott International SEA 1983). With the increased awareness of the need for redundancy through over-determination, minimum requirements today are three ranges so that those statistical tests can be performed and the primary system can be supplemented with a secondary system that does not suffer from the same measurement errors and therefore provides an independent check on position.

At this stage in the process raw measurements and processed data can be logged on a permanent medium along with any auxiliary data like echosounder depth if it is available in digital form from the sensor. Advanced post-processing techniques such as smoothing, a special case of Kalman Filtering discussed in Chapter 5, can be carried out at a more convenient stage by re-reading the navigation and sensor data. Any poor data that has become evident such as 'range spikes' or excessive noise can be edited and so the best estimate of the vessel is determined from a full analysis of all data.

A requirement for many surveys, and one which the user has accepted unwillingly is the MOBILISATION and LOGISTICS necessary to establish and maintain land-based radio positioning services. Permits for residence at the shore stations along with transmitting frequency allocation have to be gained well in advance of any operation and even then re-siting to less optimum locations is often required to meet government conditions. Time must be budgeted for mobilising the navigation gear onboard the vessel of opportunity and calibrating it. A typical navigation budget may be less than 10% of total project cost for a 2D seismic survey but the case may arise where in fact more money is spent on establishment, calibration and navigation data acquisition than on the seismic data acquisition (pers. comm. Esso 1985). Any proposal that does away with the land based mobilisation, does not require powerful transmission methods yet provides the desired service is readily accepted by the user, for example the rapid rise in use of Satellite

Integrated Acoustic Navigation. The mobilisation requirements for a single GPS base station to transmit the differential message are much less stringent than those for most land based radio-navigation systems, especially ARGO which must be close to the coastline.

The user requirements when selecting PERSONNEL to carry out a hydrographic survey vary considerably with present day radio-positioning systems. Lesser qualified personnel are used on surveys in which little interpretation of the data collected is going to be carried out and so the monitoring software is given the task of quality control. Whenever new techniques or innovative projects are executed then the most skilled surveyors are on site to ensure that the system runs efficiently, program 'bugs' are removed, and the client is obtaining the service required. The integration of a GPS sensor into any of the applications places vastly different demands on the GPS knowledge of the operator of the receiver - from a 'button pusher' in the case of routing an oil rig through to a thorough surveying background so that it is possible to quality control a precise marine engineering project using GPS. It is envisaged that the commissioned GPS system (post 1989) will give single receivers an accuracy of 30-100m and for users who regard that as sufficient the operators will require little knowledge of GPS. But as operations demand increasing accuracy then both techniques and personnel in charge will have to have an in-depth knowledge of GPS. The development in this field of personnel will have a bearing on how well GPS is integrated into hydrographic survey operations.

Two uses for accurate positioning that are representative of the various applications shown in Figure 2.3, seismic surveying and bathymetry, are described to highlight both the similar and the differing constraints that users demand.

2.2.1 Seismic Surveying.

Hydrographic surveyors are often called to provide the position services for geophysical surveys to delineate sedimentary bedding structures for engineering operations or hydrocarbon bearing structures. This can be the most demanding use of positioning service in some ways and is explained to show total demand on positioning and automated data processing .

The geophysical process for deep seismic data acquisition starts with the triggering of an acoustic source which is towed in the water directly behind the vessel. The acoustic pulse generated, travels through the water column and is reflected firstly from the seabed then at sub-seabed reflectors whenever the density of the material changes significantly (a discontinuity). The returned pulses of signal plus noise, which by now have become heavily attenuated are sensed by a series of hydrophones in the trailing streamer and recorded; the triggering of one acoustic pulse is commonly called a shot point (Figure 2.2).

The next shot point position occurs at the nominal hydrophone spacing (eg. 25m) and this continues repeatedly til the end of the survey line which can be from 3km to 30km. By using such a method points on the geological structure are monitored from a large number of evenly spaced sensors along the trailing streamer and later post-processing stacks this data, removing noise, and produces a model of the subsurface geology. The quality of signal enhancement and structure position is dependent on the accuracy of shot point relative positioning and so is only allowed to vary by a small percentage from the nominal spacing. Meanwhile the positioning also needs to be updating at faster than every five seconds to aid the helmsman to keep inside a corridor of ±10-20m either side of the desired track.

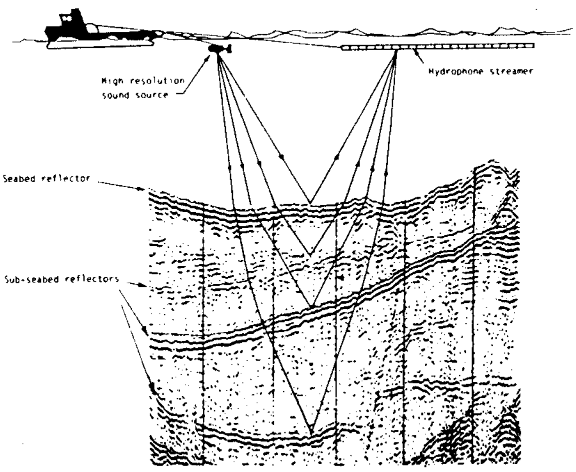


Fig 2.2 Seismic Surveying (Ingham 1984)

Often seismic profiling is carried out using measured ranges in the hundreds of kilometres with noise present in them principally due to short term atmospheric effects. This data is numerically filtered in the navigation computer by a Kalman Filter (Gelb 1974), making use of previous recent updates and tracking information, to yield the optimum solution for the vessel state (position and speed) in a random noise environment. This method consistently gives more precise results when compared with a single epoch least squares technique and is explained further in Chapter 5.

If more intensive survey is to be carried out at a later stage or drilling is to be commenced then the positioning data must be related to some control network that allows for the previous defined structure's position to be relocated with sufficient accuracy, typically quoted as 10m (1σ) (Johnson and Ward 1978).

2.2.2 Bathymetric Survey.

The determination of the depth and nature of the seabed surface in ports and harbours is probably the most routinely carried out hydrographic task of all to which many authorities have set down and maintain high standards and demand continual quality control.

A succession of parallel lines is sailed across the area (spaced every 5-10m) and contours derived from the resulting profiles as measured by sonar methods. The demands on a suitable positioning system are:

- Position fixes must be obtained at a rate compatible with the sounding rate (can be several a second, up to several seconds) to give a reasonable sounding density.
- Position fix rate must be such that the helmsman gets precise boat performance to ensure suitable rudder corrections to maintain a tight corridor along the desired track; usually within 50% of line spacing.
- Before use, the equipment must be calibrated and error ellipses continually monitored to ensure they are within accepted limits.
- Positions calculated must not include the spurious range data that come about due to reflections from port facilities or vessels. This can be minimised by processing the data through a Kalman Filter algorithim to "filter" out spurious

noise, or even "gate" the noise rather than using a straightforward Least Squares solution with no rejection or editing at all. The use of Kalman filtering, as discussed in Chapter 5, is even more evident when some ranges are randomly being shadowed by islands or vessels.

2.3 ACCURACIES.

What are the accuracies demanded in the hydrographic survey environment? A knowledge of the accuracies dictates the degree of refinement needed to model and process GPS data. As for all survey tasks the cost benefit of any operation is weighed up against the desired accuracy which is determined by the end use of the project. The final accuracy specifications for a given operation vary widely both in approach and in numeric value.

The main dictates for accuracy specification in the hydrographic sense are:

a) Legislative requirements which are legally imposed and usually stated with respect to offshore legal boundaries such as international offshore zones and boundaries (defined under bilateral declarations between countries) or for resource exploration delineation and confirmation. For example the Canadian Government has proposed that the allowable maximum semi-axis in the 95% confidence ellipse of the position measurement be within

$$r(cm) = 30 \times d$$

where d is the distance in kilometres from the nearest shore control, and that positions also shall be confirmed via two independent surveying measurement techniques (EMR 1975).

b) The scale of the survey plan can dictate accuracy tolerances. For example typical international standards state that for harbours and channels plotted at 1:10 000 or larger then position accuracy be 1mm at survey scale (for 1 sigma). Similarly the line spacing for survey lines should be every 6mm at survey scale.

c) Client requirements:

1) The client often specifies the accuracy to be attained regardless of the operation and the contactor is left to propose a system that satisfies those requirements and maintains the desired specifications.

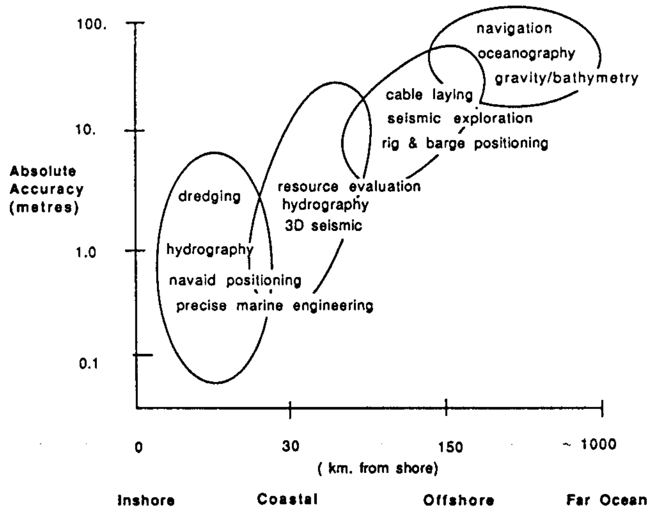
2) The client could similarly specify the equipment and procedures to be followed, thus indirectly dictating the accuracy. A bare minimum case could state that 'positioning is to be by a microwave system, calibrated monthly and supplying no less than three ranges simultaneously to a dedicated computer that carries out a least squares solution and presents the position data along with its residuals and mean square error' (McDermott International SEA 1983). This usually results in a position fix accuracy of 2-3m; less if filtering is applied.

d) An expression of relative accuracy that is often quoted in hydrographic surveying is 'repeatability'. Although not formally defined it means that for a given positioning system installation the position determined at one epoch will be the same when the vessel returns to the same position at a later epoch. The interval between epochs may be hours, days or even months. As the coordinates of the base stations may be in a unique local datum then 'repeatability' is also a function of the actual ground marks.

A graphical figure, Figure 2.3, shows the most common uses for marine positioning versus the demands on the position accuracy.

Basically GPS accuracy is dependent on receiver sophistication, quality control during operation and use of suitable processing algorithims.

FIGURE 2.3 Typical Positioning Uses and Accuracies.



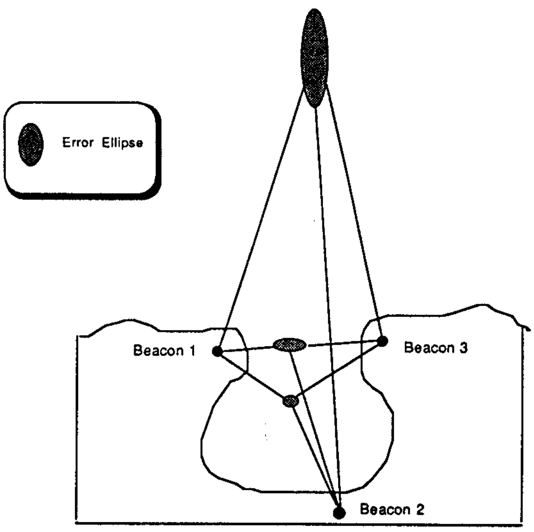
2.4 PRESENT DAY RADIO-POSITIONING SYSTEMS.

The method for determining the position of a vessel undertaking a hydrographic survey has in most cases been by radio-positioning systems in which ranges, or lanes, are measured to land-based stations and sent directly into a dedicated computer solving for 2-D coordinates and giving some indication of the confidence in the update.

As can be seen from Table 2.2 systems in current use reveal that as range is extended accuracy obtainable and reliabilty is sacrificed. High accuracy at very short ranges is possible and poor accuracy at very long ranges is available; but high accuracy at long ranges is beyond the capabilities of most land-based systems except for the very expensive ones. The limits are due to the fact that the long ranges propagating over a spherical earth dictates that the radio frequency used must be capable of following the curved surface. Medium and low frequency ground waves do this to some extent but changes in ground conductivity (eg. land path) have a perturbing effect that limits accuracy. Higher frequency ionospherically reflected sky-waves can follow the curve but the rapid variations, both hourly and diurnally, in the reflecting surface (ionosphere) limits operations.

Figure 2.4 Configurations for Radio Navigation

Optimum Position fixing occurs in well defined areas only



The highest accuracies are obtainable by the use of very high frequencies (eg. laser) which by definition cannot follow the earths curvature and become heavily attenuated so operation is restricted to a very limited range. Even over short ranges typical land-based systems require a suitable geometric configuration that the three (or more) transmitting beacons be configured so to maintain a strong "fix geometry " over the entire survey area. Figure 2.4 shows that an optimum siting of three beacons for an inshore operation rapidly weakens whenever a baseline is intersected and may not be suitable for an offshore operation at all. To improve the offshore position fix the beacons would have to be re-sited along the coastline and may even have to be replaced with units capable of achieving the longer range. This problem in short range operations is partially solved by polar systems (eg. Polarfix) which continuously measures bearing and distance from land to a mobile vessel.

The three main radio positioning systems operate on the microwave, ultra-high or 2MHz frequencies.

Microwave systems are the most popular by shear numbers in use due to small size and portability with high accuracy over the line-of-sight ranges. The advantage of the signal travelling in straight lines with constant velocity can unfortunately lead to severe multipath problems of 'range-holes' and nulling in harbours.

UHF systems operate at 400MHz. and perform much as microwave systems when within line-of-sight of the transmitting beacons. Beyond line-of-sight a reflective temperature inversion layer forms a duct in which the signal can travel over 2 x line-of-sight. Inherent in the ducting concept is signal wandering which causes path length to exceed true distance by a few metres and so UHF measurement errors grow gradually with distance. Larger antennas and power supplies are required for UHF systems often resulting in manned stations, but still UHF is commonly used for surveys at line-of-sight to 100kms.

2MHz systems is a suitable frequency for ranges up to, and over 300km. (with more during daylight) since the frequency is low enough to follow the curvature of the earth without

Table 2.2

Main Present Day Radio-Navigation Systems

System	Coverage	Method	Frequency	Accuracy	Comments
Omega	World-wide	Phase comparisons	12KHz	2km. day 4km. night	Low accuracy
Loran C	Some large chains	Pulsed arrival time differences	100KHz	100-200m.	Only partial world coverage. None in SW Pacific.
Geoloc	1000km.	Spread-spectrum technique	2MHz	2m. + 15ppm	Expensive , needs satellite receivers and cesium clocks for time keeping
SPOT	740km.	Moving frequency phase comparison	2MHz.	3-12m.	Eliminates sky wave effects , calibrated with GPS , needs cesium clocks.
Argo	300km. at night 600km in day	Phase comparison	2MHz	3-12m.	Can skip lanes of 80m. due to ionospheric sky wave effects. Needs good independent calibration
Syledis	150km.	Pulse measured pseudo-ranges	420MHz.	3m.+15ppm	
Maxiran	300km.	"	"	"	Needs amplifiers for longer ranges
Miniranger	Line of sight 70km	Microwave	9GHz	3m.	Line of sight , Miniranges can suffer from "range-holes"
Microfix	"	"	5GHz	1-3m.	
Polarfix	up to 10km .	Laser range & digital azimuth		.2m/km.	Outputs range & bearing, high accuracy

ducting, yet still allow one metre resolution of the carrier phase measurements. Skywave interference at sunrise and sunset plus large ground antennas and range ambiguity of 90m are the main problems with the 2MHz frequency. The new spread-spectrum technique can combat skywave but the more sophisticated electronics demand semi-permanent installations and thus higher costs.

World-wide high accuracy positioning systems face certain physical limitations that only satellite based technology can overcome efficiently.

2.5 SATELLITE NAVIGATION SYSTEMS.

Even though the TRANSIT satellite system has been used since the mid-70's what are the limitations to its use? What does GPS attempt to solve that makes it look so attractive to hydrographic surveying?

With the advent of satellite technology it was possible to place high frequency transmitters up in space where they could cover a large proportion of the earths surface at one time and send their signals through the atmosphere at a steep angle thus allowing accurate measurements.

Since 1967 the US Navy Satellite System, TRANSIT, has been used as a method to determine absolute global position in both static and kinematic modes. It was not until the mid-70's that newer techniques developed both the system and receivers to a product that was portable and accurate enough for more widespread use offshore. Now receivers are more reliable, portable and positions are based on a well defined global geodetic datum based on the Broadcast Ephemeris, approximated by the NWL-9D Datum.

At the equator a TRANSIT satellite is available for position updates every 100 minutes on average, while at high latitudes it is more likely every 35 minutes. The Doppler shift of the satellites transmitted frequency, as monitored by the receiver, is caused by the motion of the satellite relative to the receiver with integration over a known time period giving a change of range measurement - the fundamental observable. This integrated Doppler count observable is used to derive slant ranges which are compared with values computed from estimates of the vessels position. This initial position data is iteratively adjusted along with the vessels historical course and speed until the estimated range changes agree with the observed values to a specified tolerance and so an updated position can be output.

The nature of the position update by TRANSIT is shown in Figure 2.5 with the successive observations R_1, R_2, etc. requiring tags to the vessels speed and heading before a fix update can be computed whereas the GPS fix is instantaneous and independent of vessel dynamics as pseudo-ranges are measured simultaneously.

The accuracy of a TRANSIT fix on a moving vessel depends to a large degree on the validity of the input speed and heading across the ground. For example a one knot error will introduce a position error of about 400m. As the motion of a vessel is difficult to assess precisely from sensing its passage through a moving water body a single pass fix onboard a vessel, using a dual frequency receiver may be typically ±100m. One manufacturer quotes a single position fix to be ±35-40m + 400m/knot of velocity error (see Ingham

1984). The nature of this error appears in a random nature such that if a large group were taken then the variance would decrease substantially and the mean would be unbiased.

In summary the nature of TRANSIT updates are :

- irregular position updates; hourly.
- large single fix error of ±35-40m + 400m for every knot of velocity error.
- error for a single pass on a stationary platform ±20m.
- requires accurate speed and heading inputs while acquiring signals in dynamic mode.
- position is referenced to a global datum, Broadcast Ephemeris.

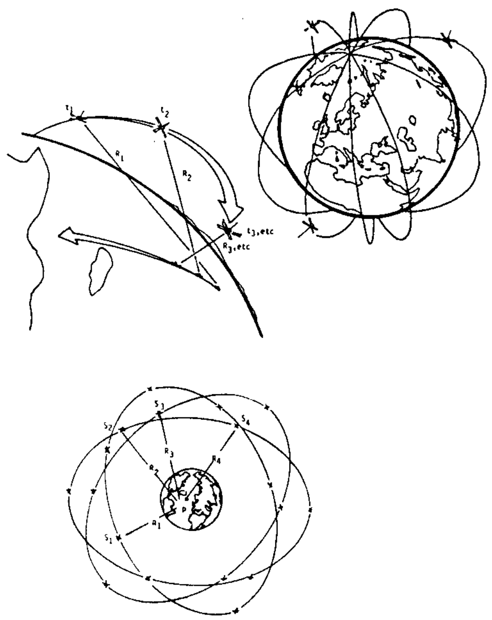


Fig. 2.5 The nature of a fix by artificial satellite : Transit (top) and GPS(bottom) (Ingham 1984)

Even though it has severe operating limitations TRANSIT is often integrated to the hydrographers position finding suite acting as a quality control device (eg. monitor cycle slips of 2MHz radio navigation), or as a position update sensor with sonar doppler systems, or as a method of calibrating acoustic arrays . In remote locations where relative and absolute positions over a 20km^2 site is essential an acoustic transponder array is deployed. Once calibrated in a relative sense the internal precision is typically better than ±2-3m which allows for precise velocity over ground to be determined, from sensing the acoustic array, which can then be input to a TRANSIT satellite receiver. By obtaining 25-30 valid TRANSIT updates throughout the array the absolute calibration can be calculated with confidence of better than ±20m. (Geomex 1984).

With the advent of GPS all the advantages of satellite-to-earth position determination are maintained as well as introducing real-time capabilities and major improvements in accuracy.

GPS was designed from the outset as a **real-time navigation system**, which calculates position by measuring the time taken for a coded pulse to travel from the satellite vehicle(SV) to the receiver. This time of transit is biased by a non-synchronization of SV and receiver clocks and once scaled by the speed of light is termed the '**pseudo-range**'. Simultaneous observations to 4 or more SV's allows for the receiver's 3-D coordinates and the receiver clock bias to be determined. The height component from the solution is seldom of use in hydrographic surveying as the vessel is travelling on the sea surface which, to the level of precision required, approximates the geoid. The height parameter can be constrained in most receivers by inputting the near constant height of receiver above the ellipsoid so reducing the number of parameters to three and subsequently a minimum of only three SV's need be visible. The geometric configuration (**Dilution of Position**) of the SV's above the receiver, along with errors due to unmodelled atmospheric effects and ephemeris errors (**User Expected Range Error**) has a bearing on the precision of the calculated position.

GPS has the potential of allowing continuous 24 hour navigation if sufficient SV's are in orbit but due to possible SV faults on a minimal, but cost effective, constellation then periods of sub-optimal navigation, termed outages, may well exist. On top of that the organization operating the system will probably limit single point positioning accuracy from 30m-100m and so a shore based static GPS receiver will have to monitor performance then transmit corrections to the kinematic receiver - a technique termed **Differential GPS**.

2.6 COSTS.

When the cost of a hydrographic survey is considered in total the navigation equipment, base station operators and navigators are a major proportion of total survey costs. If the use of GPS can either speed up the survey or be carried out with fewer personnel then savings are already made without considering lower hardware costs. Already some hydrographic survey companies are able to obtain cost benefits from using the expensive TI4100 GPS receiver in their navigation suite.

When comparing the costs of differing navigation equipment and techniques then factors such as the operational constraints, like range limits, accuracy obtainable and equipment size amongst others has to be evaluated along with the end use specifications. The equipment mentioned in Table 2.3 spans the extremes of present day radio-navigation range capabilities but GPS has the potential of being substituted for all of them, excepting the very precise Polarfix operating in built-up environs that limit sky visibilty.

Table 2.3 shows the 'turn key' capital cost for the hardware excluding auxiliary computers with the daily hire rate covering hardware and personnel needed for system maintenance, that is technicians and base station operators. In both cases the costs are for a complete system to satisfy positioning of one vessel. Although single GPS receivers are presently (1987) being used by hydrographic surveyors to augment positioning it is envisaged that the fully commissioned GPS system will require that a differential mode be used to maintain accuracy and so a second land based receiver will be required.

Table 2.3 Equipment and Hire Costs

(in Australian $ = 0.65 US$)

Equipment	Capital Equipment Cost	Daily Hire Rate
SPOT(2+4)	N/A	5800
Argo(2+4)	461000	1000
Syledis(2+4)	261000	600
Maxiran(2+4)	308000	700
Polarfix	134000	900
OCEANO Acoustic c/w Transit Receiver suit small site survey	277000	1000
Transit Receiver eg.MX1107	56900	250
Trimble 4000A GPS	50000	300
2 Units needed for Differential GPS		

Table 2.3 shows that even at present costs two GPS receivers are much cheaper than the other options. The cost of a communication link must be added to allow the differential GPS technique to be carried out.

2.7 GOVERNMENT POLICY.

The staging of GPS implementation is such that the present system allows all users to access the two codes transmitted.

These codes are the Precise code (P) and the Coarse/Acquisition code (C/A). The use of both codes allows for the highest accuracy to be attained in real-time but are civilian users going to get access to them both? Similarly the organization operating GPS has the power to degrade the system accuracy at will by implementing Selective Availability (SA). Policy decisions made now will directly influence how GPS is integrated into hydrographic survey operations.

As was the case with the TRANSIT system, GPS is conceived and operated by the U.S. Department of Defense (DoD) and is being utilised by the civilian market presently without paying any user fees. Its future operational specifications, as concerns the civilian user, is of prime importance to the method of operation and degree of software and hardware development that needs to be initiated today. Information on the intended future service of all American Government radio-positioning systems is published yearly in the U.S. Federal Radionavigation Plan (FRP) issued by the DoD/DoT and although no definitive statements have been released it looks like the following conclusions can be drawn:

* Quote from the November 1985 FRP (Scull 1986) : "It is the goal of the DoD to phase out use of TACAN, VOR/DME, OMEGA, LORAN C, and TRANSIT in the military. Civil user phase out of LORAN C and OMEGA would be keyed to:

(a) resolution of GPS accuracy, coverage, integrity, and financial issues.

(b) GPS meeting civil air, marine, and land needs currently met by LORAN C and OMEGA.

(c) GPS civil user equipment being available at prices that would be economically acceptable to LORAN C and OMEGA users.

(d) a transition period of 15 years."

From present worldwide GPS usage of the Block I satellites by the civilian community it is noted that GPS has been accepted very favourably and there appears no reason for the FRP to be altered due to positioning non-performance. The Shuttle disaster in 1986 has seriously affected the scheduling for the deployment of the Block II satellites which implies that TRANSIT and LORAN C are to remain the prime navigation systems for the military, and many civilian users, for at least two years more than expected.

The report further states that:

* TRANSIT will not be operated by or transferred to a civilian agency of the U.S. Government beyond 1994.

* DoD will phase out its use of LORAN C by 1992. The U.S. will cease LORAN C operations outside the geographic limits of the U.S. once its military users are GPS equipped in 1992.

* Selective Availability policy will degrade real-time point positioning by GPS to ±100m (2drms) by dithering the broadcast signal. Note that 2drms is the square root of the sum of the squares of the two sigma error components along the major and minor axis of a probability ellipse.

* Unless specifically authorised civilians will not be able to access the higher accuracy P code in the Precise Positioning Service. The policy enables U.S. companies working in the "national interest" to have controlled access to this P code.

* The FRP regards that most marine requirements are met

with the proposed GPS Standard Positioning Service except for harbour navigation and precise offshore survey. The DoT has supported research in the field of differential GPS to obtain the higher accuracies and assumes the differential technique will be used by those users who require improved accuracy.

* Civilian users will not be charged a yearly user fee to gain access to the C/A code.

Since most hydrographic surveyors will be operating GPS with the **Standard Positioning Service under Selective Availability** then an accuracy of 30m-100m will be of limited use. The differential method that is already used with other long range positioning systems such as LORAN C, OMEGA, and translocation with TRANSIT, will be used to improve the degraded accuracy. It involves a monitor receiver in the vicinity of the area of operation which transmits corrections to other users, be they time in the case of LORAN C (Blanchard 1986) or orbital corrections in TRANSIT, to minimise systematic errors. The Radio Technical Commission for Maritime Services in the U.S.A. has already produced specific message formats that they suggest are the most suitable for transmission of these differential corrections. Commercial receivers are already being sold which accept these differential messages in real-time.

2.8 IMPACT OF GPS ON THE HYDROGRAPHIC SURVEY INDUSTRY.

From this overview of present hydrographic survey operations it is apparent GPS can meet the usual requirements and so is poised to have a massive impression on the industry. Since GPS is a satellite based system it can operate worldwide. The physical limitations inherent with land based radio-navigation systems are overcome efficiently with satellite based systems. Real-time multi-range solutions from GPS allows for continuous positioning with quality control from overdetermination of the fix solution. GPS hardware to date has been more compact and easier to mobilise than other land based radio-navigation systems. Apart from GPS meeting the operational requirements the cost benefit ratio shows GPS to be very competitive (see Section 2.6).

GPS is already being used in hydrographic surveying and accuracies of 1-2m (Seeber 1985) have been achieved in limited sea trials. Concern about system integrity, accuracy and satellite coverage in the future shows a need for research into methods to maintain accuracy. The following chapters address those problems and introduce methods to solve them. If GPS can be shown to give acceptable results then can GPS be considered as **the prime navigation system** onboard a survey vessel? Certainly it can be used as part of a mutli-sensor navigation system today.

3. GPS OPERATION

3.1 THE GPS SYSTEM.

3.1.1 Introduction.

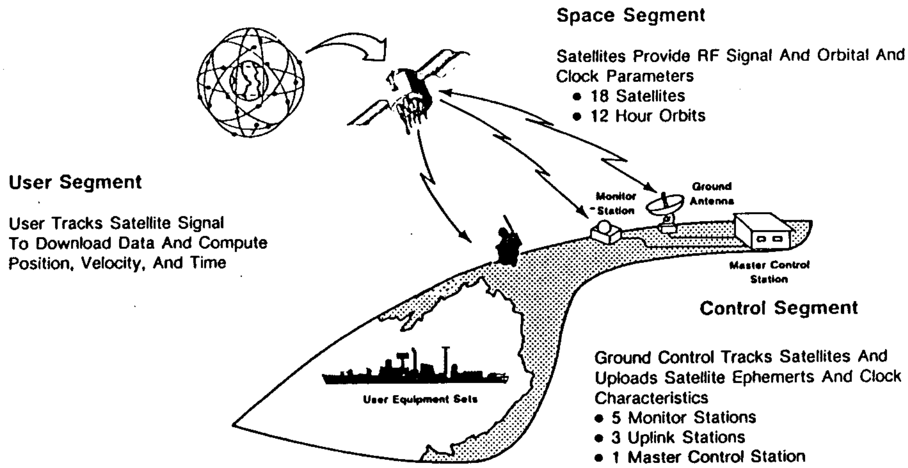
For a full understanding of kinematic GPS performance the main GPS system components need to be defined. The signal structure is explained to highlight the limits inherent in the system, independent of propagation effects. The transmitted satellite message is detailed with the orbital motion of the satellites defined.

Like its predecessor, TRANSIT, the Navstar GPS is a worldwide, all-weather satellite navigation and timing service conceived and maintained by the U.S. Department of Defense. GPS has the added advantage of allowing 24 hour real-time positioning.

The Joint Program Office (JPO), under the DoD is responsible for the development of GPS which is being implemented in three phases. From December 1973 to June 1979 **Phase I** validated the system concept and identified preferred designs of user equipment. **Phase II** began in August 1979 with the DoD approved transition into full scale engineering development. This phase has verified the operational effectiveness of the GPS concept for both military and civilian users. These two initial phases have resulted in seven satellite vehicles (SV's) being maintained in orbit and used by a rapidly growing User Segment even though they are all of the Block I type SV's. The transition from Phase II to **Phase III** (being the implementation of the operational system) is continually being re-scheduled to coincide with resumption of the Space

Shuttle flights. Priority has been given for Space Shuttle payloads to carry the Block II SV's into orbit so as to effect worldwide, 24 hour, 2-D coverage as soon as possible.

Figure 3.1 3 Segment System Concept
(Rockwell International Corp.)



The Global Positioning System has three main segments (Figure 3.1) that constitute its operation :

Space Segment (SS)

Consists of the satellite Space Vehicles (SV). When fully operational it will consist of 18SV in six orbital planes with three SV's spaced equally in each plane plus three equally distributed spare SV's. Chapter 4 discusses orbit configurations in more detail. Presently there are seven SV's in orbits inclined at 63^{o} to the equator at a radius of 26,000 kms and a 12 sidereal hour period. The Block II SV's will be in similar orbits but with an inclination angle of 55^{o} and spacing such that a minimum of 4 satellites above 5^{o} elevation will be in view to a user at any one time.

Each SV transmits synchronous time signals on two L-band frequencies, L1 and L2, with the navigation message being modulated onto those carriers. All SV have a mean mission duration of six years and a design life of seven and a half years. Electrical power is from two solar energy converting panels that charge batteries for use whenever the earth eclipses the sun. When on-station, the SV's operate in an earth-pointing, three axis stabilised mode with each SV having its own on-board propulsion system for maintaining orbit position and stability control.

Control Segment (CS)

This comprises five Monitor Stations (MS), located nearly equatorial, at Diego Garcia, Ascension Island, Hawaii, Kwajalein, and Falcon Air Force Base (Colorado Springs). They are equipped with a Navstar receiver and cesium clock (hydrogen masers in future) so to passively track all SV's in view. The observations are combined with environmental data and transmitted to the Master Control Station (MCS) presently located at Falcon Air Force Station where they are processed and used for orbit determination and determination of clock biases. Each MS combines one and a half seconds psuedo-range measurement data with ionospheric and meteorological data to compute a smoothed data measurement every 15 minutes. The MS transmits this data to the MCS which processes the 15 minute smoothed data in a Kalman filter to generate ephemeris and clock state predictions for each satellite (Stein 1986). The resulting orbit is used to generate an ephemeris, represented by a modified set of Keplerian elements that are actually a best fit of the corrected ellipse to the true orbit which meets the desired accuracy over one hour. The MCS maintains GPS system time, with a set of cesium clocks (also connected with the time standard of US Naval Observatory in Washington D.C.) and is capable of adjusting the time phase and frequency of the SV clocks as required.

This data is transmitted to each SV by an upload message, presently about every eight to ten hours during Phase II, consisting of SV ephemerides, clock correction coefficients and coefficients to correct for atmospheric delays (as calculated by the MSC). The upload is carried on an S-band frequency from the three Ground Control Stations at either Ascension Island, Diego Garcia or Kwajalein. This data is loaded into the satellites memory and the pre-stored navigation messages are available to support a 14 day prediction span in which user range errors degrade 'gracefully' from 16 to 200 metres. Every hour the SV transmits a (refreshed) new navigation message from its stored data.

User Segment (US)

The user segment is the receiver and end user with the typical Navstar set consisting of an antenna, receiver, data processor with software and a control display unit. The receiver can be manufactured by any number of private manufacturers with decoding of the codes carried out as defined in the ICD-GPS-200 document. The raw measurements are pseudo-range, the Doppler frequency shift of the carrier signal and the carrier beat phase on the C/A code sampled either sequentially or with mutliplex techniques. The US then has the capability to convert these measurements to geocentric cartesian or geographic coordinates, velocity and a receiver clock bias.

3.1.2 Signals and Message.

Each satellite transmits 2 L-band spread-spectrum signals whose carrier frequencies and code epochs are synchronised with the satellite clocks. The GPS signal properties are designed to satisfy the following operational specifications (Spilker 1978):

- allow accurate time-of-arrival measurement without ambiguity, in real-time.
- allow accurate Doppler shift measurement .
- provide an efficient data channel.
- provide rapid acquisition for navigation with a capability for high accuracy for more demanding but specified users.
- good interference rejection properties.

The use of the dual L-band frequencies allows for the highest accuracy positioning by being able to minimise ionospheric effects. Unfortunately the L2 (1227.6 MHz) frequency will only be accessible to selected users whereas the L1 (1575.42 MHz) will be generally available to civilian users (King et al 1985). The construction of the transmitted signals is quite complex but satisfies the demands required for an accurate real-time navigation system as outlined above (King et al, 1985).

The transmission of the timing, or ranging, pulse is achieved by making use of Pseudo-Random Noise (PRN) code techniques as employed in various other navigation systems, for example Syledis. The PRN code is a binary code (±1's) generated by a mathematical algorithim which is added to the carrier signals as binary phase modulations. They in effect produce a wide-band spectrum which is inherently difficult to interfere and jam as the receiver produces exactly the same PRN code and signal de-spreading (see Section 3.2) is carried out by obtaining maximum correlation of internal and external signals. Large increases in signal to noise ratios are experienced due to de-spreading.

As shown in Figure 3.2 two PRN codes are transmitted. The P-code (Precise) is a **PRN** code with a data rate of 10.23Mbps and a period of one week, being reset weekly. Each satellite transmits a unique P-code which is really a one week segment of a 38 week long code, so if a P-code was allowed to continue without being reset weekly there would be overlapping of codes with other satellites, before repeating itself after week 38. The nature of this code is such that it is difficult for a receiver to lock onto such a long and rapid code without prior knowledge of the exact code sequence.

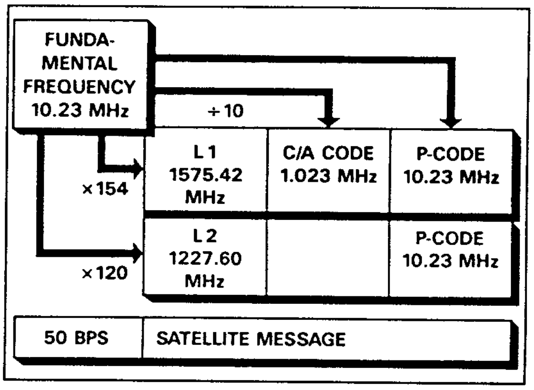


Figure 3.2 GPS Satellite Signals.
(Scherrer 1985)

The C/A code is a much simpler code, again a pseudo-random binary sequence, but only one millisecond in duration and transmitting at 1.023Mbps to allow easier access properties. This code is termed a **Gold code** formed by the product of two finite series resulting in a possible 1023 unique codes. The

C/A code is only modulated onto the L1 carrier whereas the P-code is on both L1 and L2. Thus without knowledge of how to access the P-code, then the L2 frequency is also unattainable (Spilker 1978).

The rationale behind the selection of the various frequencies can be highlighted by reference to Table 3.1. The selected frequencies allows for typical receiver resolutions of 6m for C/A code chip (time of one binary pulse code) and 3mm for the L1 carrier.

Table 3.1 Resolution of GPS C/A Code

Frequency	Length of 1 element	Resolution	Range Resolution
C/A code 1KHz	1 msec = 300km.	1 chip	300m.
C/A code chip 1.023MHz	293.3m.	<1/50	< 6m.
L1 carrier 1575.42MHz	19cm.	<1/60	< 3mm

Further to each SV's signal is added a 1500 bit binary navigation message at a rate of 50bps providing the user segment with information on system status, system time, ionospheric data and orbital data for the particular satellite. The C/A code epochs are used to provide the 50Hz clock for encoding the navigation message. The data format is illustrated in Figure 3.3. Each 1500 bit frame is divided into five subframes of 300 bits, which are further subdivided into ten 30 bit words. Each word comprises 24 information bits and six parity bits.

The first word of each subframe is a synchronization/telemetry (TLM) word, and comprises a fixed 8 bit preamble for synchronization, followed by information on the message status. The second word of each subframe is a handover word (HOW) which gives system time in terms of the number of 1.5 second units since the start of the week, termed the Z count (ICD-GPS-200). P-code receivers use the Z count to determine the approximate phase of the P-code, and may then measure range and time to better than one P-code chip length by correlation with the received P signal. C/A code receivers use the Z count, in conjunction with the data bit transitions and the 1ms C/A code epochs to determine system time to within 1ms. Greater precision, to within one C/A code chip length is then obtainable by correlation with the received satellite C/A signal.

The remaining eight words in the first subframe convey data which include ionospheric coefficients, the satellite delay calibration and the satellite time correction coefficients. The second and third subframes contain the ephemeris data, the fourth subframe is for special messages, providing space for 192 bits every 30s. The fifth subframe contains cyclically one page of a 25 page almanac, which provides 25 sets of Keplerian elements to assist in the selection and acquisition of other satellites.

DETAILS OF THE NAVIGATION MESSAGE.

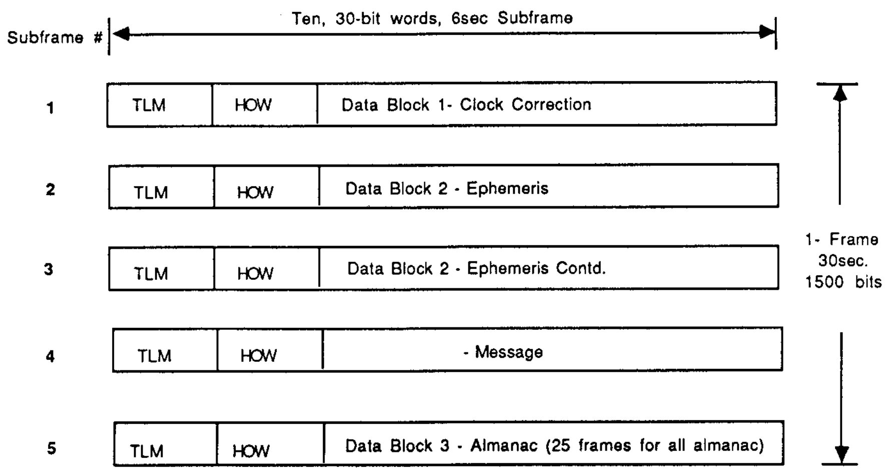
DATA BLOCK I occupies the first sub-frame and supplies the eight coefficients that are required for the Klobuchar ionospheric correction model as presented in the ICD-GPS-200. The calibrated Group Delay (Tgd) term for single frequency users and three coefficients that define the satellite clock offset with respect to the GPS system time are also transmitted in this Data Block. Control Segment will maintain all SV times to better than one millisecond of

GPS time to insure that all SV transmit the same subframe. These corrections are discussed further in Chapter 3.3.

DATA BLOCK II appears in the second and third subframes and presents the parameters needed to determine the exact position of a satellite for a given time.

Figure 3.3

GPS Message Structure



Orbital Motion of GPS Satellites.

The satellites orbit is defined in an inertial reference frame which by definition has a non-accelerating origin point, being accepted as the geocentre of the earth. The earth also rotates with respect to this inertial reference frame with a different character from the satellites orbit. The motion of the satellite with respect to an Earth Centred Earth Fixed (ECEF) coordinate system is most clearly explained by considering firstly the dynamics of the satellite in its own orbit then the relationship (transformation) between this orbit and the ECEF system. To actually compute the instantaneous position of a SV with respect to this ECEF terrestrial system the same approach is taken. That is first compute the SV position in its orbit, then relate the orbit to the terrestial system (King et al

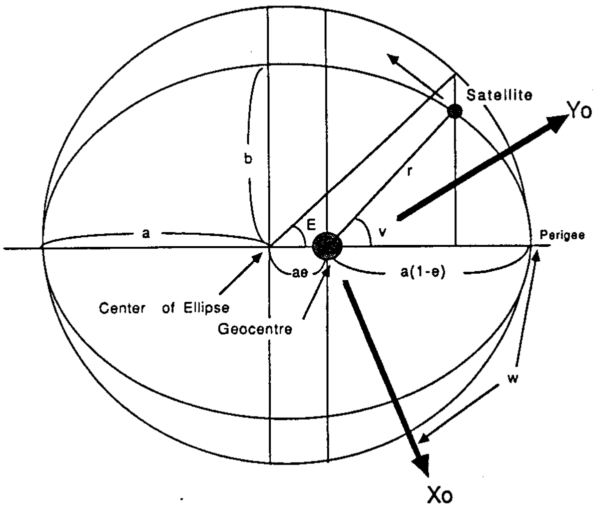
1985).

Orbital Ellipse.

For a given time t, one wants to know the X,Y coordinates of the SV in the orbital ellipse.

The definition of the orbital coordinate system specifies that the origin of the orbit is the geocentre with the Z axis perpendicular to the plane scribed out by the orbital ellipse. The X axis then passes from the geocentre to the ascending node with the Y axis completing a right hand coordinate system as shown on Figure 3.4.

Figure 3.4 Elliptical Orbit.



Due to the eccentricity of the SV orbit the earth's geocentre does not occupy the centre of the ellipse but instead one of the foci points as defined by Kepler's empirical laws. Kepler's third law states also that the ratio between the cube of the semi-major axis of a SV orbit and the square of its period is a constant for all SV's about a mass. This gives the value of Mean Motion;

$$n_0 = \sqrt{(\mu/a^3)}$$

Calculation of the true anomaly, ν, (the angle from the geocentre/perigee line to the satellite), the argument of latitude, u, (being the angle from the X axis to the SV) and the orbital radius, r is carried out by equations in Table 3.2.

To yield rectangular coordinates:

$X_0 = r.\cos.u$

$Y_0 = r.\sin.u$

Terrestial (Earth Centred Earth Fixed) System.

The calculations for this second transformation from SV orbit to an ECEF system takes the SV orbital position and rotates it about the ascending node. This rotation is equal to the inclination angle, and rotates the orbital plane by the instantaneous longitude of the ascending node (Scherrer 1985).

The origin of this system is at the geocentre with the Z axis being the true rotation axis of the earth and the X axis the intersection of the plane perpendicular to this Z axis (equator) and the Greenwich meridian. The Y axis completes the right handed coordinate system as shown on Figure 3.5.

Both the inclination angle and the right ascension of the ascending node are projected by equations in Table 3.2. Primarily secular drift in right ascension ($\dot{i}$) is due to the second zonal harmonic but also includes the smaller affect of earth wobble and polar wander. The final result are the X,Y,Z coordinates of the SV in an ECEF system at time t.

Thus the data in the navigation message plus a given instantaneous GPS time are input to the equations in Table 3.5 and result in the X,Y,Z in the ECEF system of any SV. These routines are installed in all code correlating real-

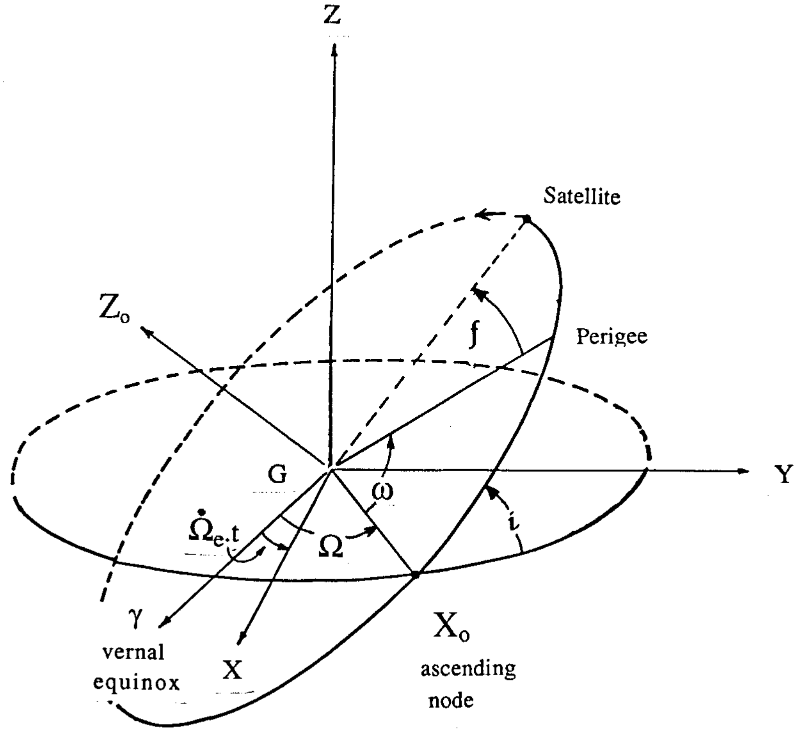


Figure 3.5
Keplerian Orbital Elements

Table 3.2 Ephemeris Representation Definitions

(Van Dierendonck et al 1978)

$\mu = 3.986008 \times 10^{14}$ meters^3/sec^2	WGS 72 value of the earth's universal gravitational parameter	
$\dot{\Omega}_e = 7.292115147 \times 10^{-5}$ rad/sec	WGS 72 value of the earth's rotation rate	
$A = (\sqrt{A})^2$	Semi-major axis	
$n_o = \sqrt{\dfrac{\mu}{A^3}}$	Computed mean motion	
$t_k = t - t_{oe}$*	Time from epoch	
$n = n_o + \Delta n$	Corrected mean motion	
$M_k = M_o + nt_k$	Mean anomaly	
$M_k = E_k - e \sin E_k$	Kepler's equation for eccentric anomaly	
$\cos v_k = (\cos E_k - e)/(1 - e \cos E_k)$	True anomaly	
$\sin v_k = \sqrt{1 - e^2} \sin E_k/(1 - e \cos E_k)$		
$\phi_k = v_k + \omega$	Argument of latitude	
$\delta u_k = C_{us} \sin 2\phi_k + C_{uc} \cos 2\phi_k$	Argument of latitude correction	2nd harmonic perturbations
$\delta r_k = C_{rc} \cos 2\phi_k + C_{rs} \sin 2\phi_k$	Radius correction	
$\delta i_k = C_{ic} \cos 2\phi_k + C_{is} \sin 2\phi_k$	Correction to inclination	
$u_k = \phi_k + \delta u_k$	Corrected argument of latitude	
$r_k = A(1 - e \cos E_k) + \delta r_k$	Corrected radius	
$i_k = i_o + \delta i_k$	Corrected inclination	
$x_k' = r_k \cos u_k$	Positions in orbital plane	
$y_k' = r_k \sin u$		
$\Omega_k = \Omega_o + (\dot{\Omega} - \dot{\Omega}_e)t_k - \dot{\Omega}_e t_{oe}$	Corrected longitude of ascending node	
$x_k = x_k' \cos \Omega_k - y_k' \cos i_k \sin \Omega_k$	Earth fixed coordinates	
$y_k = x_k' \sin \Omega_k + y_k' \cos i_k \cos \Omega_k$		
$z_k = y_k' \sin i_k$		

* t is GPS system time at time of transmission, i.e., GPS time of reception corrected for transit time (range/speed of light). Furthermore, t_k must be the actual total time difference between the time t and the epoch time t_{oe}, and must account for beginning or end of week crossovers. That is, if t_k is greater than 302,400, subtract 604,800 from t_k. If t_k is less than −302,400 add 604,800 to t_k.

time positioning receivers and carried out at each epoch.

The MESSAGE BLOCK occupies the fourth sub-frame and provides for the transmission of 23, 8 bit ANSC II characters (plus 8 non-information bearing bits) which are generated by the Control Segment to convey alpha-numeric information. As at June 1986 the following message was being transmitted :

"FOR INFO 303-554-2470"

DATA BLOCK III The ALMANAC MESSAGE BLOCK is sent in this block, the fifth sub-frame and is a subset of the full navigation message to allow prediction and searching for other suitable SV's.

The SV clock offset and its first order drift term is transmitted along with seven Keplerian parameters and one perturbation parameter.

This data block cycles repeatedly transmitting information on 25 different SV's; one every 30 seconds so that each SV provides the user an almanac for other SV's to aid acquisition.

The almanac model is renewed by a Space Vehicle upload from the Control Segment only, which may be daily for Block II satellites, but in any case the almanac has an accuracy of 20,000m after five weeks from initial transmission (Van Dierondonck 1978).

Coordinate Systems.

The ECEF coordinates that are calculated from the equations in Table 3.2 are based on an ephemeris related to the World Geodetic System-1972 (WGS-72) datum. As at 0hrs 7th January 1987 the DoD determine and transmit the ephemeris based on the WGS-84 datum. Transformations therefore need to be considered when relating GPS results (WGS-72 or WGS-84) with local datums.

1) The transformations from geographic coordinates (Φ, λ, h) to geocentric cartesian coordinates (X, Y, Z) is straight forward and presented in Harvey (1986).

2) Since the GPS ephemerides are based on the geocentric World Geodetic System then most receivers simply output position results not in geocentric cartesian coordinates but on the specified WGS reference ellipsoid (Φ, λ, h) without any transformation. Most countries have elected to use a non-geocentric datum and an ellipsoid that best models their area of interest so a transformation is required to take positions from the geocentric coordinate system and present them on the local datum.

Up til now most datum transformations used in hydrographic surveying have been via a simple 3-parameter shift:

$$\begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix} = \begin{bmatrix} X_s \\ Y_s \\ Z_s \end{bmatrix} + \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix} \qquad 3.1$$

where X_1, Y_1, Z_1 are cartesian coordinates on the local datum.

X_s, Y_s, Z_s are geocentric cartesian coordinates on the GPS datum.

ΔX, ΔY, ΔZ are datum shifts from one datum to another determined locally.

In the simple case of a small area then a three parameter transform can be used to transform X and Y which will equate to E and N with the third parameter being the rotation between the two datums. For example this is used when transforming a relatively calibrated acoustic array

($4km^2$) onto the Doppler Transit determined positions for absolute orientation. Note that a further three-parameter transform is then executed on the acoustic array to move it from the Transit (Broadcast Ephemeris) datum to the local datum.

In determining the transform parameters in Equation 3.1 errors can be introduced by not considering any scale and rotation that exists between the accepted ground control coordinates and the GPS determined coordinates of the same points. Scale and orientation differences depend on the quality of the underlying control and if it is imperative that the GPS position determinations fit the existing control as well as possible then a seven-parameter transform may be considered. The difference could be due to the local control being established by poorly determined azimuths or a scale error in the surveyed control. Often in remote hydrographic surveys the control is determined as a local survey without connection to the national control network. Harvey (1986) presents the equations suitable for a 7-parameter transform.

As many localised coordinate datums used in hydrographic operations have been established with the Transit system the transformation between GPS (WGS-72) and Transit (Precise Ephemeris) is given by Meade (1982) as :

$$Xw = Xp - (0.827X + 1.26Y)10^{-6}$$

$$Yw = Yp - (0.827Y - 1.26X)10^{-6}$$

$$Zw = Zp - (0.827Z) \times 10^{-6}$$

where: Xp, Yp, Zp are coordinates in the Precise Ephemeris datum (can be approximated by the Broadcast Ephemeris).

X_w, Y_w, Z_w are coordinates in the GPS datum.

The transformation between WGS-72 and WGS-84 has yet to be officially released from the US Department of Defense. The seven parameters used presently (Feb 1987, origin unknown) to transform from WGS-72 to WGS-84 are:

$\Delta Z = +4.5m$

$RZ = -0.554$ second

$k = +0.2263$ ppm, all other terms are zero

Summary

The transition from Phase II to Phase III, the proposed SV constellation, is being re-scheduled to coincide with resumption of a U.S. satellite launch capability. It is envisaged Phase III GPS SV launches will commence in 1989.

Presently the navigation message is uploaded every 8-10 hours from the Ground Control Stations. This may be increased in Phase III. However in both cases the navigation messages sent from SV memory are refreshed hourly.

As at 0 hours GMT 7th June 1987 the Keplerian elements are calculated based on the WGS-84 datum. Position calculations from this ephemeris are also based on the WGS-84 and so transformations are required to relate raw GPS results with a local datum.

3.2 RECEIVER DESIGN AND PERFORMANCE

As the supply of receivers suitable for kinematic applications will expand from the present handful a general description of design features is outlined. The user must decide what features best suit the applications in mind. Results from different model GPS receivers vary due to differences in receiver hardware and the sophistication of the data processing.

The basic role of a GPS receiver used for real-time navigation is to track the SV signals to measure the pseudo-range and so determine position, and to measure the phase of the carrier signal to be able to decode the 50bps navigation message that is modulated onto the carrier. Standard and proprietary techniques are available for tasks such as SV selection, signal acquisition, tracking for measurement and data recovery. The various receivers have some common structures and components which are shown in Figure 3.12 and discussed below:

3.2.1 Antenna

Since the GPS signals are circularly polarised most antennas to date have a **vertical spiral** or **dipole** design to allow omni-directional reception. Lately the flat **microstrip** type is being used with a ground plane for static applications and without one for dynamic situations (eg. Motorola Eagle). The microstrip antenna appears the most rugged and simple in construction being suitable for single frequency and of low profile. In a dynamic situation, for example on a ship's mast, the antenna must be able to receive the signals from low elevation satellites even though the satellite is below the antennas normal horizon. To this end, the use of microstrip antennas with well defined reception horizons due to ground planes may not be suitable for dynamic operations. A pre-amplifier is located in the antenna housing. It provides for signal transmission through a coaxial cable with minimal loss of signal.

3.2.2 The Receiver

The main constituents of the receiver unit are:

- signal tracking and decoding circuitry
- oscillator
- navigation computer
- control and display unit

Signal tracking and decoding methods are dictated by performance demands weighed against production costs, with the three main configurations being:

1. Multiplex. Only a single hardware channel is used to scan the signals from different satellites, dwelling for one to five milliseconds, and returning to each satellite every 20 milliseconds so that the signals appear to be tracked continously to maintain four signal processing algorithims and so that the data message can be detected. No interchannel biases need be determined since all signals travel the same hardware paths. Pseudo-range measurement on some multiplex receivers ceases temporarily whenever a new satellite is initially acquired and tracked.

2. Sequential. It is a single channel hardware/software processing technique which receives one SV at a rate slower than, but asynchronous with the data message rate of 20ms, then switches over to another SV, for eg. two seconds. It is of lower cost but low performance as it needs to reacquire

the signal at each dwell point.

3. Parallel. For example, a five channel hardware configuration using the fifth channel to acquire, track and collect navigation messages. Initially interchannel biases must be calibrated but then, uninterrupted tracking of pseudo-range is possible.

The direct processing of the incoming high frequency signal would require expensive circuitry. To overcome this problem it is normal practice to heterodyne the incoming carrier frequency with a receiver generated carrier. This establishes a beat frequency. The resultant instantaneous signal is the carrier beat phase and when integrated with respect to time produces the **integrated carrier beat phase** which is a direct measurement of the change in range with time. Integrated carrier beat phase is derived by tracking the carrier phase using a phase locked loop (PLL) and computing the change in carrier beat phase over a specified interval of time. The prime reason for tracking the carrier phase in a navigation type receiver is to enable **demodulation** of the navigation message. Although all first generation GPS receivers demodulated the message, few made use of the inherently more accurate ranging information in the integrated carrier phase to filter the psuedo-ranges. Most navigation receivers now employ this technique.

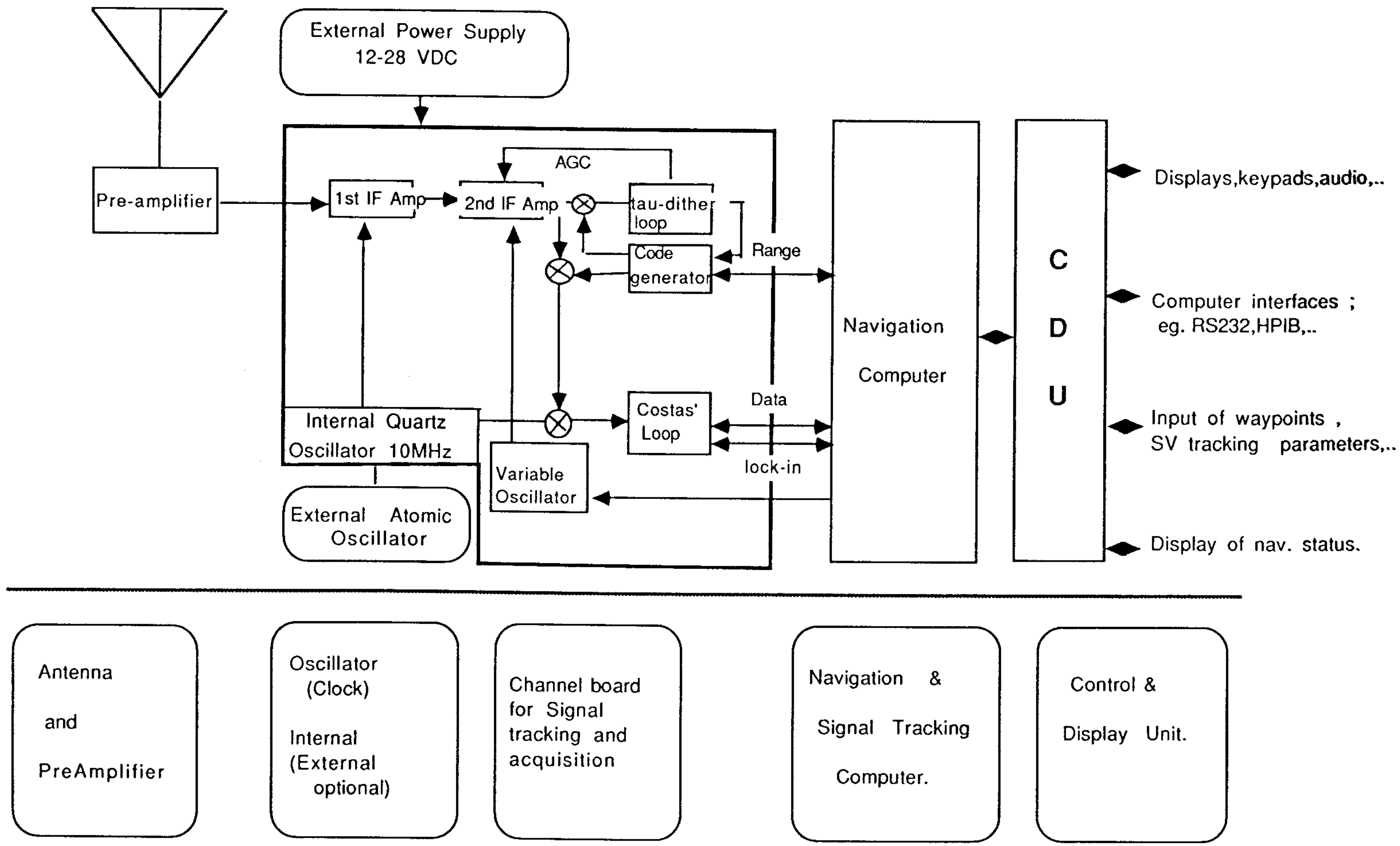
The Pseudo-Random Noise code (Chapter 3.1.2) of the GPS signals provides good multiple access properties amongst different satellites transmitting on the same frequency. Due to signal to noise considerations (the incoming signal has a 20 MHz bandwidth) it is not able to directly measure the arrival time of a particular PRN code so a replica code is generated in the receiver and is run in phase with the modulation of the incoming signal by a tracking loop. By measuring the time shift required to match the code, the receiver is able to determine the reception time. Knowing the transmit time, the flight time and **pseudo-range** can be calculated. The term 'pseudo' is used because the offset of the receiver clock against GPS time is not known precisely at reception time and thus gives rise to a range biased due to this as yet unknown time offset. The pseudo-ranges are corrected for modelled effects such as ionosphere, troposphere, etc. as discussed in Chapter 3.2.

These processes of pseudo-ranging, carrier phase measurement and data demodulation are carried out for all satellites used by the receiver has elected to use; the operation is termed Code Correlating. An alternative method leading to 'codeless' receivers, is termed squaring type channel operation but does not allow for data demodulation and pseudo-ranging.

Code Correlating Channel Operation.

Code correlating receivers can either dedicate an entire channel to acquire, track and process a satellite signal (parallel type) or carry out multiple processing on one or two channels (mutiplex or sequential type). In either case, be it a dedicated hardware channel or a software implemented channel, a channel's operation has the same inputs and outputs (see Figure 3.12). The input GPS signal is Doppler shifted in frequency by up to ±4.5KHz from the nominal frequency and contains bi-phase code (PRN) and data modulated onto the carrier signal (navigation message).

Figure 3.6 Block Diagram of Receiver Operation



The main functions of a channel are:

- carrier acquisition and tracking
- code acquisition and tracking
- navigation message data demodulation

Channel hardware and performance.

The technique most often used for PRN code measurement is firstly for the receiver to generate a replica code sequence and mix this with the receiver oscillator signal. Secondly this replica code is matched with the incoming signal and when the two signals are aligned then the bandwidth of the signal is considerably reduced in the frequency domain(Chapter 3.1.2). This alignment allows for PRN code de-spreading so the time of arrival of a code can be precisely determined. The technique is termed τ(tau) dithering (Allison and Daly 1985).

The phase of the locally generated PRN code is shifted incrementally, relative to the received PRN code, by the computer at a high rate until correlation is detected and the post correlation power exhibits a rise above that which might be attributed to noise. During the tracking of a satellite, the phase is periodically advanced and retarded by a small amount to generate an amplitude error signal for detection of the correlation peak (τ dither). Adjustments are made by the computer to keep the correlation at a peak.

The loop bandwidth of the τ dither loop is controlled by the software and different loop bandwidths are used in search and track modes. Acquisition may take up to 30 seconds if the computer has no prior knowledge of the expected code phase. During that time the locally generated code is shifted across the received code, until the correlation peak brings the loop into lock.

The Phase Lock Loop used in receivers is often termed the Costas loop, or carrier loop correlator, and initially searches to acquire the Doppler shifted carrier frequency caused by relative motion of satellite and receiver.

The selected tracking bandwidth is initially broad to allow for rapid acquisition given the frequency uncertainty of the carrier frequency as pre-adjusted by the controlling software. An estimate of Doppler shift can significantly reduce the search time. Narrowing the tracking bandwidth reduces error in phase due to noise, but too narrow a bandwidth causes serious degradation in the dynamic tracking performance of the loop. The loop can be adaptive with feedback from the controlling software. Once acquisition is achieved, the bandwidth for tracking can be 'hardwired' and controlled by the user. This latter technique is implemented in the TI4100 receiver. It has four tracking settings which can be selected by the user: The lowest dynamic setting for a static receiver and the highest dynamic setting for a moving receiver experiencing high accelerations.

Costas mechanization reconstructs the carrier signal and so detects the 50bps navigation data by comparison on the received signal with its own.

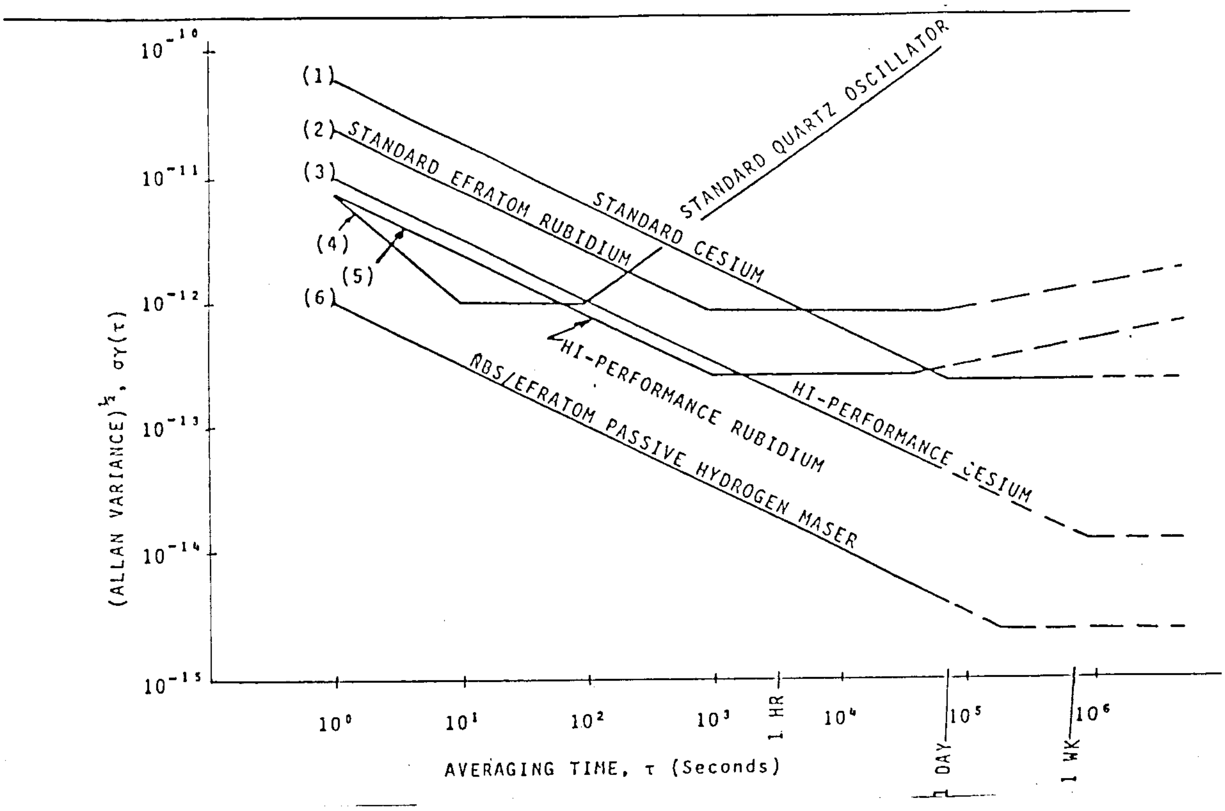
Squaring Channel Operation.

Although no navigation receivers presently employ squaring channels they are a useful way of accessing the P-code carrier signal and of monitoring the ionospheric refraction directly (Counselman and Ladd 1986). The incoming signal is mutliplied by itself resulting in a pure carrier with no code and data modulations. Even though squaring measurements are more precise than the code-correlating method the range ambiguity of squaring phase measurements is a multiple of 10cm and must be resolved.

3.2.3 Oscillators.

In a commercially available receiver the clock is driven by an oscillator, typically a quartz crystal oscillator. The navigation solution solves for the clock offset with respect to GPS system time at each epoch. In cases where a less than optimum satellite configuration leads to three or less visible satellites, and to an inability to solve the clock offset, the quartz crystal oscillator does not possess the long term stability. A systematic error would be evident in measured positions.

Figure 3.7 Comparison of Oscillator Frequency Stability
(EFRATROM, 1983)



Commercial rubidium vapour cell oscillators are available for situations where navigation coverage is to be extended in less than optimum configurations.

Figure 3.13 shows the standard quartz oscillator to be superior in performance to about 500 seconds. Above this time span the standard Rubidium's performance improves while that of the quartz degrades. Unfortunately the commercially available cesium beam tube and hydrogen maser oscillators are expensive and not suited for rugged, dynamic applications as excessive movement degrades performance considerably.

3.2.4 <u>Navigation Computer.</u>

Initially the computer must determine the set of satellites which will provide the most accurate position fix and then control the search pattern.

Once the sychronization of the PRN code and tracking of the carrier phase is achieved data format features like word, subframe starts and Z counts are recognised to determine unambiguous code transmission times. The navigation software decodes the satellite ephemerides, corrects the observables for those effects which can be modelled and then solves for position and the receiver clock offset. As the carrier phase has been tracked by a Costas loop, a precise integrated carrier phase value, biased by an integer ambiguity, is available for integration into the navigation solution. In doing so short term noise present on the raw psuedo-ranges is reduced. The mathmatical techniques for navigation solutions are presented in Chapter 5.

The outputs from the 'front end' tracking system in most receivers are:

: unambiguous pseudo-range

: decoded navigation message

: instantaneous carrier phase (fraction of a single carrier frequency cycle)

: integrated carrier phase; with integer cycle ambiguity.

: doppler frequency.

3.2.5 Control and Display Unit.

The CDU consists of any number of input and outputdevices that allow communication between receiver and user, such as keypads, LCD displays, and RS232 interfaces. The most basic display would supply antenna position and velocity, satellite status and tracking parameters. Some receivers allow input of waypoints, for example the SONY GTT2000, and displays the data to navigate to those points while other receivers, for example the Collins Navcore I, has no input or output device other than a RS232/422 port for the user to configure. As many users will be employing a real-time differential technique, the CDU should feature a facility for incorporation of data from another monitor receiver. Many of the present GPS receivers do not have this capability. However, conversion is easily achieved by replacing the EPROMS as already practised in ARGO and Trimble 4000 series.

3.3 RAW MEASUREMENTS AND SYSTEM CORRECTIONS.

3.3.1 Introduction

If GPS is to be understood and utilised in hydrographic surveying then familiarity with GPS measurements is a precursor to basic research. In this section the raw measurements are introduced along with various models that have been investigated during the initial phases of the GPS implementation. The phenomena that affect GPS signals are the atmosphere, relativity, group delay correction and SV clock correction. What is the magnitude and nature of the correction models that are applied to the GPS measurements? What does the contribution of the uncertainty in determining the **modelled** corrections have on expected range error? **Unmodelled** effects also contribute to error in position for a single receiver. The unmodelled effects include SV ephemeris, oscillator, multipath and receiver noise.

The aim of this section is therefore to define the errors and to determine the magnitude of them.

Code and Carrier Beat Phase Observables.

Pseudo-range: These measurements are made using the C/A or P code signal with the observed range from SV to receiver prefixed 'pseudo' since it has the effect of SV and receiver clock offsets present in the range that are later solved for and removed.

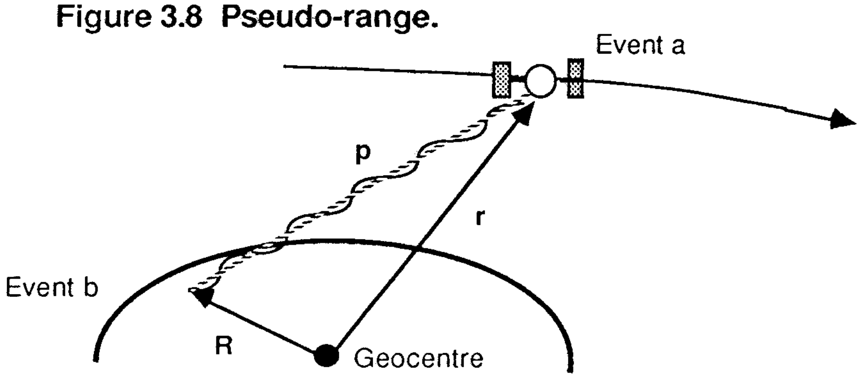
Geometric range vector: $\mathbf{p} = \mathbf{r} - \mathbf{R}$ (3.1)

where : $\mathbf{R}$ = position vector of receiver.

$\mathbf{r}$ = position vector of satellite.

If a SV transmits a single pulse at a known time **a** and it is received at time **b** then the flight time of that pulse, scaled by the speed of light, will give the exact range between the two. As the clocks in both the SV and receiver are offset from a common reference time and so the range determined is a pseudo-range.

Figure 3.8 Pseudo-range.



Pseudo-range:

$$P = c[(T) - (t)] + d_e + d_i + d_t + d_{noise} \qquad (3.2)$$

Correct Range:

$$p = c[(T-\Delta T)-(t-\Delta t)]-(d_e + d_i + d_t + d_{noise}) \qquad (3.3)$$

where: t = transmission time at SV.

Δt = SV clock offset with respect to reference time

T = raw reception time at receiver.

ΔT = receiver clock offset with respect to ref. time

c = speed of light

d_e = ephemeris error

d_i = ionospheric error

d_t = tropospheric error

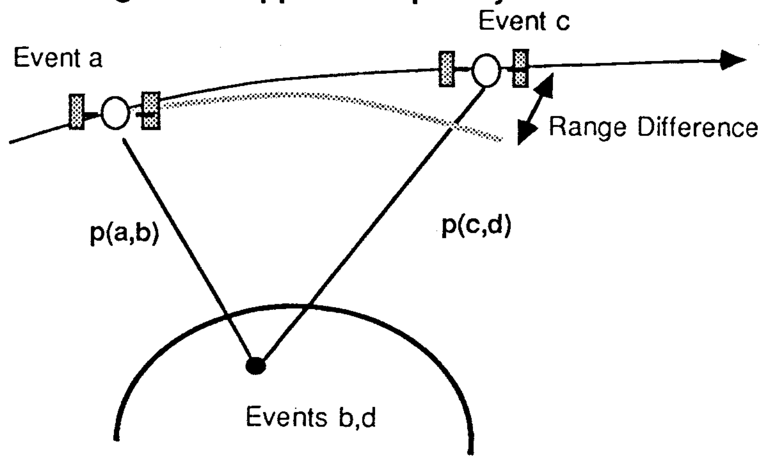
d_{noise} = receiver and background noise

Then the correct range is equal to the pseudo-range less all the error contributions :

$$p = P - c(\Delta t - \Delta T) - d_e - d_i - d_t - d_{noise} \qquad (3.4)$$

Integrated Doppler:

Figure 3.9 Integrated Doppler Frequency.



The received frequency of the carrier an any instant differs from that transmitted due mainly to the relative velocities between the SV and the receiver causing a Doppler effect of up to +4.5kHz. as the SV rises and -4.5kHz. when it is setting. This is commonly termed the instantaneous Doppler frequency.

The Integrated Doppler count is the sum of the received frequency measured against a constant receiver frequency within a time interval (Scherrer 1985) :

$$N = \int_{T(b)}^{T(d)} (F_{reference} - F_{received}) \, . \, dT \qquad (3.5)$$

$$= (F_{reference} - f).[T(b)] - f/c[p(a,b) - p(c,d)] \qquad (3.6)$$

where f = transmitted carrier frequency.

From (3.6) the Integrated Doppler, expressed in cycles or metres, is seen as a function of the pseudo-range difference as calculated across the integration period. Integrated Doppler is more precise than the pseudo-range, which is measured independently at time **a** and **c**, since it is sampled at a faster rate and is not affected by tropospheric effects or code measurement timing errors but does depend on SV oscillator stability.

Instantaneous Carrier Beat Phase.

The instantaneous phase of the carrier signal is the fractional part of a cycle which is formed when the phase of an oscillator signal of nominally constant frequency generated in the receiver (1575.42MHz for L1) is 'beat' with the incoming signal (King et al, 1985) :

$$\Phi = p + c(\Delta t - \Delta T) + d_e - d_i + d_t + d_{noise} \quad (3.7)$$

It can be expressed as part of a cycle or in metres (19cm. for L1 frequency) though many authors attach an ambiguity to the R.H.S. of (3.7) being the remaining integer number of cycles from receiver to SV (λN). The carrier phase changes according to the continuously integrated (accumulated) Doppler frequency shift of the incoming signal. It is like a very precise pseudo-range but with an integer number of carrier cycles missing. It is further discussed with receiver hardware in Chapter 3.2.

3.3.2 Modelled Corrections.

In this section the problems that the troposphere and the ionosphere introduce into pseudo-range and integrated carrier phase are discussed. A few of the more common models are presented. As it is presently not possible to easily monitor the troposphere and ionosphere these models still produce residual range errors. It is noted that research is being conducted in these areas and more refined models are being studied and developed. The nature of the relativistic, group delay and SV clock corrections are better known and so can be more precisely determined. Raw data collected in June 1986 from two Trimble 4000S receivers was processed with the models discussed. The processing also allowed the sensitivity of the models to be studied.

Tropospheric Correction

Ionospheric and tropospheric refraction have always exercised a limiting influence on correct range determination and so, positional accuracy. The troposphere is that part of the atmosphere which is located between the earths surface and a height of about 50km. The effective path length of waves passing through the troposphere is altered by both the ray bending and refractivity. The delay resultant from signal transmission through it, is not a function of the signal frequency as for the ionospheric correction, but is a function of the refractivity, ie. temperature, pressure and relative humidity. Since meteorological measurements are not available along the signal path, surface measurements are used to predict the current state of tropospheric refraction using mathematical models.

A tropospheric range correction model developed by Black (1978) considers the correction as the sum of the dry (gas component) and wet (water vapour content) parts:

$$\Delta\rho_T = \Delta\rho_{Td} + \Delta\rho_{Tw}$$

The dry part is given by :

$$\Delta\rho_d = 2.343 \,.\, P.\ ((T - 4.12)/T).\, I(h=h_d, \alpha)$$

The wet part by :

$$\Delta\rho_w = K_w \,.\, I(h=h_w, \alpha)$$

with: $I(h,\alpha) = \{1 - [(\cos\alpha)/(1 + (1 - l_c)h/r)]^2\}^{-\frac{1}{2}}$

where:

h_d 148.98(T-4.12) m above the station

h_w 13000 m.

l_c 0.85

K_w 0.12 for winter in maritime latitudes
0.28 for summer
0.36 for spring

r distance from center of earth to the station

P surface pressure in standard atmospheres

T surface temperature in °K

In Figure 3.10 the dry and wet part of the correction are shown as a function of the elevation angle. Note that the wet part is only a small quantity in comparison to the dry part and in the existing models the wet component (water vapour) is not precisely known. According to Remondi (1984) the tropospheric correction can be modelled within 2-5% of the dry part which is about 80% of the correction.

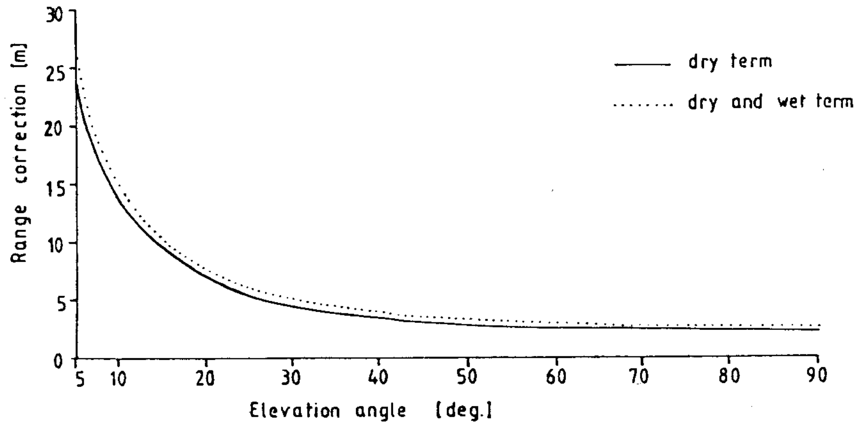


Figure 3.10 Tropospheric Range Correction Computed from the Black Model
(Landau H. & Eissfeller B.)

Saastamoinen (1973) presents formulas for the tropospheric delay in seconds for elevation angles greater than 20^0 as a function of the basic meteorological measurements (temp., pressure, relative humidity) plus elevation angle :

$$\tau_{atm} = 7.595\text{x}10^{-10} \sec z[P + (\frac{1255}{T} + 0.05)e - \tan^2 z]$$

where: τ_{atm} is tropospheric delay (seconds)

z is the zenith angle to satellite

P is the pressure in millibars

T is temperature in ^{o}K

e is the partial pressure of water vapour in millibar:

The partial pressure of water vapour may be computed from the relative humidity, RH (as a fraction of 1), by:

$$e = 6.108\ RH \exp \left[\frac{17.15T - 4684}{T - 38.45} \right]$$

Ashkenazi et al(1982) have analysed some models for tropospheric correction to Doppler Transit data and their results are presented in Figure 3.11. The standard base calculation is taken as Yionoulis which is the Hopfield model with series expansions for highest precision (Black 1978). The three models shown give horizontal position within 0.5m of the reference calculation. Applying a model appears to give horizontal position results twice as good as not applying any at all.

Figure 3.11 The Difference in Station Position Between the full Hopfield Model (Yionoulis) & other Common Models.(from Doppler Transit-Ashkenazi)

Tropospheric Model	Latitude	Longitude	Height
Hopfield simplified.	-0.07	-0.03	+0.01
Black	0.00	-0.04	-0.81
Saastamoinen	-0.30	-0.29	-1.45
No Model	+0.08	+0.99	-28.04

A simple mapping function, SAMSO (1974), produces the delay in metres, as simply a function of the angle of elevation to the SV and the height of the user above sea level:

$$dR = \left[\frac{2.4224}{(.026 + \sin E)} \right] EXP(-0.13346 \times H)$$

where H = altitude above sea level (km)

E = surface refractivity (elevation angle)

An abbreviated SAMSO mapping function is employed in the Trimble 4000S for real-time calculation, being

$$dR = 2.4224/(0.026 + \sin E)$$

Residual bias error expected from these models has been quoted as 1-2m by Martin (1978). A decoupling error can occur when two receivers located well apart experience differing tropospheric conditions and so the baseline vector is affected. Note that any error in tropospheric modelling directly affects the accuracy of the position determined from pseudo-ranges.

Since carrier phase (or Doppler frequency) can be integrated in time then the integrated carrier phase (or Doppler) is also affected by the tropospheric correction. The rate of change of the tropospheric correction is a function of the rate of change in elevation to a SV and of any change in the local meteorological conditions. When considering a single receiver then the rate of change of the correction (eg. SAMSO model) is greatest when the SV is on the horizon then decreases towards the zenith. Conversely the rate of change of the elevation angle is greatest at the zenith. Using the maximum rate of change in elevation (0.5^{o}/minute at the zenith for 35^{o}S) then the magnitude of the rate of change of the correction at 7.5^{o} elevation is 0.8m/minute while at 20^{o} it is 0.1m/minute. In other words if the correction is not applied then the error in the integrated carrier phase (or Doppler) will build up at the above rates. This error is virtually removed by the differential technique.

Ionospheric Correction

Ultraviolet radiation from the sun causes gas atoms in the atmosphere to ionize into electrons and positive ions. There exists a region of the atmosphere, from 80 to 1000 kms above the earths surface, in which the recombination time of the ionized particles takes longer so that there is always a residual ionization density present. During periods of shadowing from the suns rays, example night, the ionization density drops in the lower part of the ionosphere but recombination of the zone is never totally completed throughout the period. Whenever electromagnetic waves propagate through this zone a certain amount of refraction and attentuation is experienced being proportional to the inverse of the square of the transmitted frequency and directly proportional to the Total Electron Content (TEC) along the signal path. The dispersive group time delay in the ionosphere is given by (Royden, Miller & Buennagel, 1984):

$$t = AI/cf^2 \qquad 3.2$$

where A = 40.308 in SI units

I = total electron content (total number of electrons along path in electrons per square meter)

c = speed of light in m/s.

f = carrier frequency in Hertz.

The effect on carrier phase delay is equal to, but opposite in sign, to the effect on group (code) delay which is to say that the value of **t** is subtracted from raw pseudo-range values and added to integrated carrier beat phase values.

The most important factors that contribute to the electron content and geometric obliquity are :

Diurnal Variation (time of day)

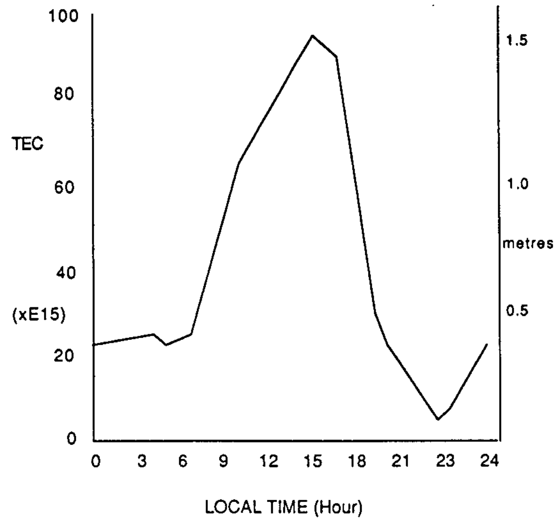
Latitude Dependency (geographic latitude)

Seasonal Variation (time of year)

Solar Cycle Variation (phase of sun spot cycle)

Figure 3.12

Total Electron Content , Canberra , June 5,7 1986



From the graph on Figure 3.12 it can be seen that maximum electron density was reached at 1400hrs local time and at this point the TEC is still only $95x10^{-15}$ which agrees with the present predicted low values in the sun spot activity cycle. The sunspot cycle has a mean period of 11.1 years, with a minimum period of about 8 years and a maximum period of around 14 years. The rise to the peak is shorter than the fall to the minimum with the height of the peaks following a longer period. The low TEC's observed in 1986 is one reason why the results from receiver point positioning are so stable as any error in the ionospheric model is only affecting a small correction of less than 1.6m as shown in Figure 3.12.

The model developed by Klobuchar is presently used by the GPS system and to date, even with near real-time parametric data, the model appears to reduce ionospheric correction by only 50 to 75% (Landau, et al 1985). Nevertheless the use of this information seems to be superior to neglecting ionospheric effects altogether. It is envisaged that later phases of GPS operation may improve the modelling technique. The polynomial coefficients of the model (three for amplitude of the correction, three for period of the delay) are part of the navigation message of GPS satellites. The diurnal behaviour of the time delay, τ_{ion}, is approximated by a simple cosine function:

$$\tau_{ion} = DC + A \cos \left[\frac{(t-\Phi) 2\pi}{P} \right]$$

where:

- t is the local time at receiver in seconds.
- Φ is the local time of maximum ionospheric correction (taken as 50400s = 2pm).
- DC is the base ionospheric time delay (taken as 5×10^{-9}s).
- A is the amplitude of the ionospheric delay function in seconds.
- P is the period of the ionospheric delay function in seconds.

A and P are computed by the user from the navigation message data α_i and β_i by the following relations:

$$A = \sum_{i=0}^{3} \alpha_{i-1} \; \Phi_m^{i-1}$$

$$P = \sum_{i=0}^{3} \beta\alpha_{i-1} \; \Phi_m^{i-1}$$

where Φ_m is the geomagnetic latitude of the ionospheric subpoint in semi-circles. If $|(t - \Phi)2\pi/P|$ exceeds $\frac{\pi}{2}$ the time delay is represented by the DC term only.

The elevation angle is considered by scaling τ_{ion} by an obliquity factor SF (Landau et al 1985) defined by :

$$SF = \sec[\sin^{-1}(\frac{r}{r+h} \cos E)]$$

where: E is the elevation angle

r is the mean earth radius

h is the mean ionospheric height of 350kms.

The Interface Control Document(ICD-GPS-200) suggests a different method to calculate the obliquity factor SF :

$$SF = 1 + 16 [0.53 - E]^3$$

where: E is the elevation angle in semi-circles (degrees/180)

The obliquity factor is also considered by Spilker (Spilker 1978) who calculates its value to range from 1 (vertical) to about 3 (low elevations) which is similar to the other methods.

The data recorded from the Trimble 4000S was all observed in the night time between 0000hrs and 0730hrs (June 1986), which is an ionospherically minimum and stable time period. The recording weekend was also characterised by low TEC as monitored by the local ionosphere service in Sydney for the Canberra area on the graph of Figure 3.12.

The full Klobuchar model (as per ICD-GPS-200) was coded into the author's correction model program to check the Trimble 4000S data. It was found that for all data analysed

the Trimble 4000S ionospheric correction applied in real time is simply a function of the elevation angle:

$$\tau_{ion} = 1 + 16 \times (0.53 - EL)^3 \times 5.10^{-09}$$

where: EL is elevation of SV in semicircles (degrees/180)

τ_{ion} is correction in seconds

The magnitude of the ionospheric correction can be determined by readings from a dual-frequency receiver as the delay is a function of the inverse of the square of the frequency (Equation 3.2). Single frequency receivers must use the mathematical model to estimate the effect. The effect of errors in the ionospheric modelling are most significant over longer lines if using a differential technique as the two paths through the ionosphere will also be somewhat different.

The actual difference between the Klobuchar model correction and the 'truth' as monitored by a dual frequency receiver, depends on the total magnitude of the ionospheric correction and may be up to 10-20m. when using a single frequency receiver alone.

Note that, like tropospheric modelling, any error in ionospheric modelling directly affects the accuracy of the pseudo-range position solution. Similarly the rate of change of the ionospheric correction applies to integrated carrier phase (or Doppler frequency) as the error is cumulative. To check the sensitivity of this error a 230km static baseline that was observed for 45 minutes was processed at UNSW using the raw integrated carrier phase. The baseline vector showed no change in length when ionospheric modelling was applied to the raw integrated carrier phase.

Relativity Correction

The two relativistic effects acting on the GPS timing system are the General effect caused by the difference in gravitational potential between the satellite and the user (the gravitational red-shift) and the Special effect as caused by the difference in velocities of the SV and user (time dilation). The Special effect can be further broken down to a secular and a periodic component since the SV orbit is eccentric, ie. has a nominal radius and a flattening. The general and secular effects are known and virtually constant for a given orbit with the general relativity correction being a function of the orbit radius and the secular relativity being a function of the average SV velocity squared.

The significant nett effect is that a ground receiver observes an increase in frequency of 447.9×10^{-12} sec/sec (µ38.7 microsec/day). To account for this the satellite clock frequency is purposely set low by 4.45×10^{-10} relative to the nominal 10.23 MHz .

The special periodic correction, Trel, is a function of the SV orbit radius, the eccentricity, and the eccentric anomaly and is the correction to the assumption that the special secular effect made when assuming a constant SV velocity and radius orbit (Spilker 1978). It compensates for the residual effect due to altitude variations when the SV orbits.

$$Trel = F.e.A^2.\sin Ek$$

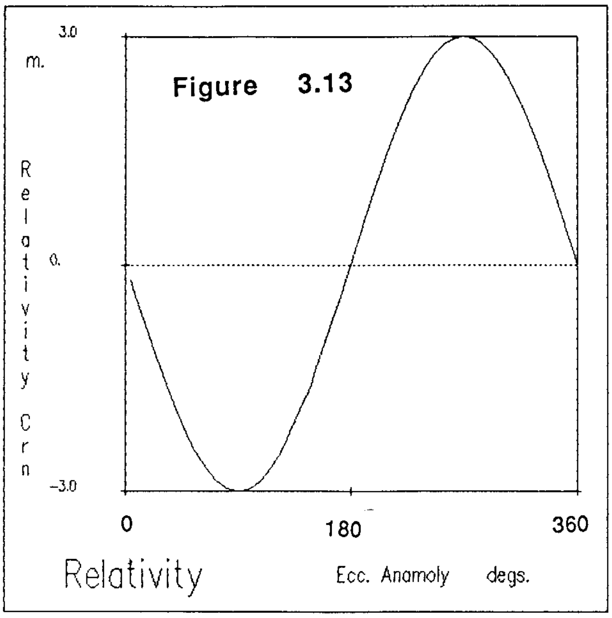
where: $F = -4.4 \times 10^{-10}$ sec/metres^2

e = eccentricity (dimensionless)

A = semi-major axis in metres

Ek = eccentric anomaly (angular measure from the perigee)

Figure 3.13 shows one 12 hour (sidereal) orbit in which the correction varies ±3m with maximums observed when Ek is ±90 degrees.



Group Delay Correction

The group delay correction, Tgd, is broadcast on the navigation message and is provided to the single frequency user as a correction term to account for the SV group delay differential between L1 and L2. It is calculated by the Control Segment from measurements taken by the SV contractor and could have a maximum value of 23 nanoseconds. The Tgd is the difference in the propagation times of the two signal paths upon radiation from the SV antennae. Dual frequency users do not apply it as their ionospheric delay corrections are identical to that of the CS, thus any differential is absorbed in the SV clock correction term, a_o.

Navigation data collected from Trimble 4000A receivers in March 1986 and in June 1986 show the Tgd of the seven SV's has remained constant, for eg.:

SV #	**Tgd**
6	0.0
11	$-0.23.10^{-08}$ secs. (-0.7m)

Space Vehicle Clock Correction

The user's equipment must correct for the SV clock being offset to GPS time with the following equation:

$$T = t_{sv} - \Delta t_{sv}$$

where: T = SV transmit time in GPS time.

t_{sv} = transmit time of PRN code determined by user's equipment.

Δt_{sv} = SV PRN code time offset from GPS time.

$= a._{fo} + a._{f1}(t-t_{oc}) + a._{f2}(t-t_{oc})^2$

with $a._{fo}$, $a._{f1}$, $a._{f2}$ being polynomial coefficients given in Subframe 1 of the navigation message.

t_{oc} = clock data reference time

The coefficients will normally be refreshed (from SV memory) and transmitted every hour during the first 24 hours since an upload, then for subsequent days after an upload they will be refreshed and transmitted every four hours (ref. ICD-GPS-200) The CS maintains all SV clocks to within one millisecond of GPS time so that all SV's transmit the same subframe and Z count without 1ms ambiguity. (Van Dierendonck 1978). As at 6th June, 1986, typically values of t_{sv} were:

SV #	t_{sv}
6	$-0.768x10^{-04}$ secs.
11	$-0.192x10^{-03}$ secs.

3.3.3 Unmodelled Effects.

Unlike the modelled systematic errors in which plausible models minimise biases, the effects that degrade positioning accuracy and over which the user cannot model are divided into two types:

- those common to the system such as ephemeris errors and satellite oscillator noise,
- those common to a single receiver with no correlation between other receivers like receiver oscillator noise and multipath. Unmodelled receiver effects also include interchannel bias (if of the parallel channel type) and limitations in analogue to digital conversion.

Ephemeris Errors

The prime source of the satellite ephemeris and clock errors is the inability of the Control Segment to precisely predict the satellite orbit and clock behaviour.

The transmitted GPS ephemerides, though Keplerian in appearance, are a set of succesive one hour predictions of the orbit for a period of time, typically less than 12 hours ahead. The ephemeris uploads that are transmitted from the upload stations are occurring approximately every 8-12 hours (January 1987), so that the AODE value does not exceed that value also. Since the ephemerides are a truncated set their validity is nominally one to two hours with new transmissions from internal satellite memory occurring every one hour and exhibiting smooth degradation, rather than 'jumps' in position. Extrapolation of the broadcast ephemeris beyond the one to two hours exhibits an exponential error. The errors, or 'jumps', that do appear whenever a new constellation is chosen or immediately after the decoding of new upload data by the user receiver give an indication of the accuracy of the ephemerides and of the resultant user error. To assess this effect data was collected from a static Trimble 4000A in March 1986 and the summary, Table 3.3, shows the position 'jumps' whenever a new upload of empherides to a SV occurs. Similarly Stolz & Gubbay (1986) found an immediate change in point position of ±10m whenever a different constellation was selected.

Table 3.3 Change in Position Due to Upload.

(Data from Static Trimble 4000A , West Australia , 21-25 March 1986)

ΔN , ΔE , ΔH are changes in position following an Upload from Ground Control

SV# circled has new Ephemeris Upload ; typically the AODE went from 10-12hrs. to 2hrs.

Constellation	PDOP	ΔN	ΔE	ΔH
(13) 6 9 12	4	8.1	8.5	8
6 11 (8) 9	7	0.4	4.5	17
13 (6) 9 12	4	0.4	0.2	0
(3) 6 (9) 12	4	4.3	3.6	7
13 11 8 (9)	4	3.2	7.6	6
(13) 6 9 12	4	2.7	2.2	2
13 6 (9) 12	5	5.7	5.6	3
13 6 (9) 12	4	14.0	9.5	8
(13) 6 9 12	4	5.8	5.8	6
(13) 6 9 12	4	1.6	1.5	1

Error in the pseudo-range due to the orbit deviating from the modelled ephemeris is due to perturbing accelerations that act on the satellite. Although these can be considered as linear over a short period of time they dictate that the GPS ephemerides are only valid for a few hours. The major perturbing force is the second order zonal harmonic due to the ellipsoidial nature of the earth's gravity field. The errors that are associated with ephemerides are radial, in-track and a cross-track, but appear in nature to the user as an error in range to the satellite similar to satellite clock error.

To determine the magnitude of the expected error in ephemerides is complicated but basically consists of 'unmodelled effects' plus an error which is a function of the time since last upload. Wells et al(1986) state that the characteristic ephemeris errors are expected to be of 1.0m radial, 6.5m along track and 3.0m in the across track directions. Bowen (1985) was able to distinguish between the satellite clock and ephemeris errors with data collected over 47 consecutive days in 1985 and concluded that ephemeris errors typically contributed 2.0m while satellite clock errors averaged 5.4m with the total User Range Error at 5.8m. These results applied before the Operational Control Segment was commissioned so uploads were every 24 hours. When the proposed 8 hour uploads are in operation these two errors should be reduced by a factor of three (Bowen 1985).

For single receiver point positioning the effect of ephemeris errors can be directly converted into an equivalent range error affecting position. In differential mode, in which two receivers are used to measure relative positions, the ephemeris errors tend to cancel out leaving a proportional error that cannot be eliminated. This error in satellite ephemeris can produce the same error in the relative positions of two recievers scaled by the ratio of the GPS receiver separation to the satellite altitude (King et al 1985). For example a 20m orbit error introduces a 1ppm error in the baseline though if more than four satellites are observed then the effect should be reduced.

Unmodelled Oscillator Behaviour

The nature of the drift of the SV clocks with respect to

GPS time is continually modelled and can be determined by applying the three clock coefficients transmitted in the navigation message. Most GPS receivers have a standard Quartz crystal oscillator with the option for connecting to an external atomic oscillator.

The magnitude of the residual error due to oscillator limitations can be determined and stability performance of oscillators compared by determing the Allan Variance which is obtained from direct frequency readings of the oscillator over a sampling period τ.

$$\sigma^2 y(\tau) = \left\langle \frac{(y_{k+1} - y_k)^2}{2} \right\rangle$$

where : y_{k+1} , y_k = frequency readings in Hz. sampled over τ seconds.

τ = ($y_k - y_{k+1}$) seconds.

< > = denotes an infinite time average.

Figure 3.7 is a plot of the more common value, $\sigma y(\tau)$, as a function of elapsed time since last clock update. For elapsed times less than one minute the quartz crystal has slightly better performance, but for longer elapsed time the standard Rubidium performance improves while the quartz degrades.

The phase error due to clock limitations (Clynch and Coco, 1986):

$$e = t * \sigma y(\tau) * f_{L1}$$

where: t = sampling time before reset.

$\sigma y(\tau)$ = square root of Allan Variance.

for eg.	Quartz crystal	1 x 10 -11
	Rubidium	5 x 10 -12
	Cesium	1 x 10 -13

f_{L1} = carrier frequency of L1 signal.

Bowen (1985) states that satellite clock predictability, which was found to be 90% of the User Range Error, may limit GPS user range accuracy to 3m (1σ) after 10 hours of clock prediction. Martin (1978) states that the satellite group and clock error produces 1.0m range error.

Multipath Effect

The multipath effect occurs where a signal arrives at a receiver via two or more possible routes so that at best they introduce range errors and at the worst the interfering signals are not decodable by the receiver. The effect is external to the receiver and can be caused by reflection from the sea surface or the ship's super-structure (Tranquilla, 1986).

The PRN code modulation of the GPS signal provides an inherent rejection to multipath interference signals which occur within one code width of the direct signal. In a dynamic case the nature of the reflecting surface would be random giving rise to a noise-like measurement error that could be 10 to 30m for C/A code pseudo-ranges (Martin 1978).

Receiver Noise

Receiver noise due to residual interchannel bias, analogue to digital conversion and mechanization is not correlated between different receivers. For parallel channel receivers the interchannel bias is calibrated by simultaneously passing the signal from one satellite through all hardware channels and noting the differences.

The code tracking method in receivers is typically by the tau (τ) dither technique. Tau dither operation is such that when the maximum correlation between incoming and internal C/A code occurs then lock is accepted and the correction is applied to complete the loop. The selection of noise bandwidth (as discussed in Chapter 3.2) is ideally as low as possible but has to be optimised with the demands of dynamic motions of the receiver. Martin (1978) calculated the standard error of measurement noise in a C/A code unit with a low noise bandwidth (1Hz) to be 1.0m (1σ RMS).

Analogue to Digital Conversion:

PRN Range measurements may be resolved to 1/50 of a code chip which gives a resolution of 6m (see Table 3.3). Wells (1986) quotes that PRN range resolution of 1/100 λ (3m) is typical. With the carrier phase wavelength being 19cm the resolution in the Costas tracking loop of 1/60 of a cycle leads to a resolution error of 3mm (1σ).

Mechanization:

Due to computer bit resolution, mathmatical approximations and algorithim uncertainties, errors are introduced in processing the data in the receivers of the magnitude 1m for pseudo-range and 0.1m for carrier phase bias.

3.3.4 Discussion

The purpose of this study into correction models and errors serves two purposes. Firstly it introduces the character and magnitude of the corrections that need be applied to raw GPS measurements. Secondly in doing so it highlights the shortcomings in the precision of the models and the errors in unmodelled phenomena.

Tropospheric corrections to pseudo-ranges vary from approximately 2.5m at the zenith to 20m at 7.5° elevation. The ionospheric correction is modelled by using the Klobuchar equations with coefficients supplied in the transmitted navigation message. The Klobuchar equations appear to model the ionospheric correction with an accuracy of only 50 to 75% (Landau et al 1985). By using dual frequency receivers then the ionospheric correction to each SV can be measured precisely at each receiver. The method some receiver manufacturers utilise the L2 frequency is by squaring its coded signal without decoding it (see Section 3.2). Research is still being carried out on refining both ionospheric and tropospheric models so they may be more reliable in the future. The spatial variability of the these corrections is of interest in precise positioning as use of the differential technique is based on systematic errors being equal at both monitor and mobile receivers. The SV clock correction is modelled by a second order polynomial with the three coefficients transmitted in the navigation message. Due to satellite oscillator noise unmodelled SV clock errors up to 10m in magnitude can occur. Unfortunately SV clock errors are difficult to isolate from ephemeris errors with only one or two receivers in real-time. Other system corrections that are well defined are the relativistic correction and the calibrated group delay.

The main division in Table 3.4 is between systematic and receiver dependent (non-systematic) error sources. In the case of real-time positioning the systematic errors are virtually removed by the differential technique. Receiver dependent errors such as multipath, analogue to digital conversion and mechanization are shown in Table 3.4 as in a 'worst case' situation. These random effects can be filtered (Chapter 5.2) from the pseudo-ranges by meshing with the integrated carrier phase, so increasing the precision of the pseudo-ranges.

From tests carried out by Stolz & Gubbay(1986) and Wells et al(1986) it appears that the results from C/A code are equivalent to P code for the Block I type satellites and experimental staging. These excellent C/A results could also be aided due to the current low sunspot activity and thus small ionospheric delays.

Unfortunately the DoD intends to degrade the C/A code accuracy to the civilian market for the upcoming Block II satellites, though still allowing the military and 'selected' users the precision of the P code. The values used to derive a UERE (Table 3.4) are thus indicative of the situation in 1986 and are very general as for example the ionospheric effect is presently low and stable.

Table 3.4 User Expected Range Error (UERE)
(1 sigma Standard Deviations L1 , C/A Code)

	Absolute			Differential	
	Bias	Random	Total	Random	Total
Space Segment					
Satellite Clock & Nav System Stability	3	0	3	0	0
Satellite Ephemeris Prediction	2.5	0	2.5	0	0
Propogation Link					
Ionospheric Delay	10	0	10	0	0
Tropospheric Delay	2	0	2	0	0
User Segment					
Receiver Noise					
-Mechanization	0	1	1	1	1
-Quantization	0	3	3	3	3
Multipath	0	3	3	3	3
UERE (RSS 1 sigma)	10.9	4.4	11.8	4.4	4.4
Accuracy Denial (SPS)	80	0	30	0	0
UERE (RSS 1 sigma - Accuracy Denial)			32.2		4.4

4. GPS SATELLITE COVERAGE AND RELIABILITY CONSIDERATIONS IN THE AUSTRALIAN REGION.

4.1 INTRODUCTION.

Continuously **available** 24 hour 2-dimensional operation is desired for GPS to be utilised as a prime navigation sensor in hydrographic surveying. The potential of GPS to replace many radio-positioning systems presently in use will be realised only if GPS coverage matches or exceeds that of existing systems (Doucet 1986). Basic to any navigation system is that it must exhibit a level of **integrity,** which is the ability for a system to detect and immediately notify the user of that system, that there is a system malfunction. The quality of the positioning service which GPS provides depends, amongst other factors, on its integrity and reliability. This chapter presents the nature of the GPS SV constellation geometry so that the problem of availability can be studied as well as its bearing on the integrity of the system. Integrity can be monitored from an overdetermined position fix with redundant ranges providing a statistical check on the system itself. This chapter also studies the accuracy that can be expected with GPS across the Australian region.

The GPS scheduling was such that the Block II satellite vehicles (SV's) were to be placed in orbit by the Shuttle between 1985 and 1987 with enough SV's in orbit by the end of 1986 to provide global 2-D positioning. The constellation build-up is being re-assessed due to the Shuttle disaster. An understanding of the nature of the constellation and its performance during the prototype stage, the eventual buildup and the operational configuration is useful.

So vital is a knowledge of the constellation at any forthcoming time that some receivers, like the Trimble 4000, has an in-built facility to predict and display SV configuration so that the user can plan to optimise the use of the receivers. A pre-analysis of the expected accuracies available is a pre-requisite to planning a suitable approach to the integration of GPS into hydrographic surveying.

4.1.1 Pre-Analysis.

An integral part of any GPS solution is an analysis of the correlation of parameters with the observations and geometry of the solution. The 'strength of figure' concept that is used in assessing radio-positioning fixes can be similarly used when analysing GPS for point-positioning. The concept of Geometric Dilution of Position (GDOP) is introduced which is an amplification factor that is applied to the pseudo-range error variances to give the combined position and clock error variance (Sturza 1984). The ideal DOP value would be unity though values of less than 7 are acceptable. The Position Dilution of Position (PDOP) gives a similar factor that applies to the 3-D position only. The 3-D position error can be approximated by the User Expected Range Error (UERE) multiplied by PDOP. For example a PDOP of 3 and UERE of 5m (1σ) would result in a user error of about 15m. The HTDOP value is used when considering the 2-D horizontal solution and the clock error which are the parameters of most interest in hydrographic surveying. Also of interest to hydrographic surveying is the DOP value for the 2-D horizontal solution only, HDOP. As 'position' in

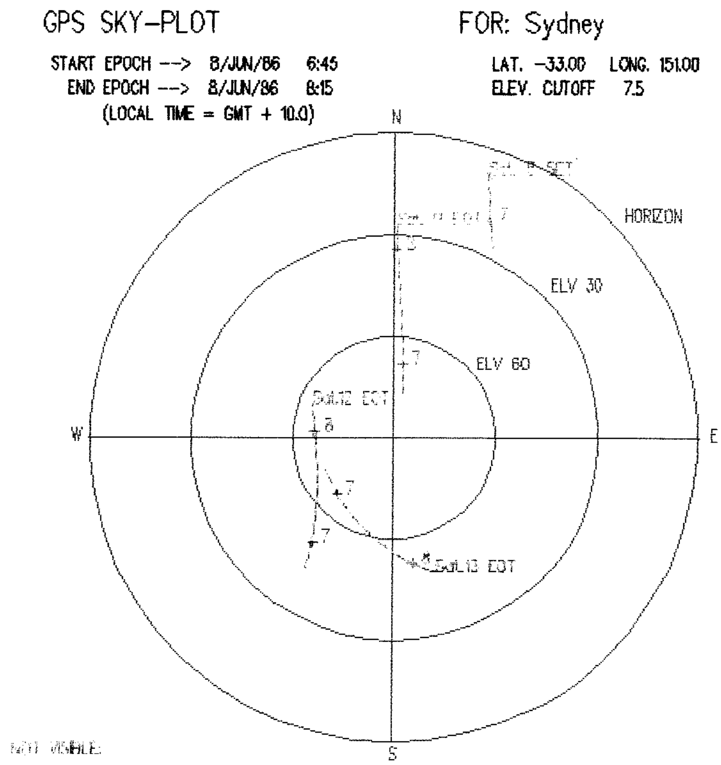


Figure 4.1 Skyplot

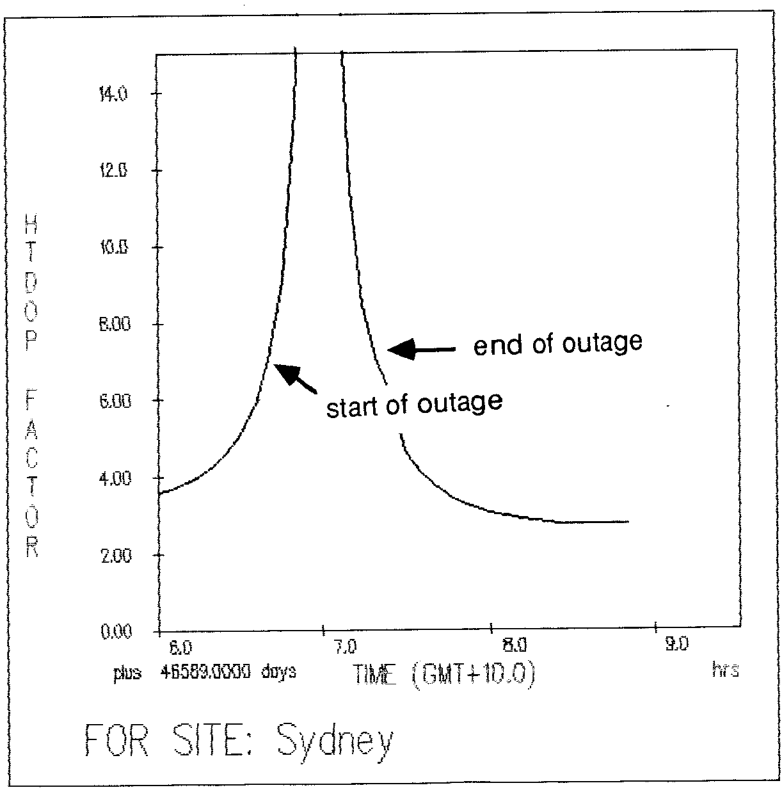


Figure 4.2 HTDOP during outage.

the hydrographic sense implies 2-dimensional horizontal coordinates then the product of HDOP with the UERE results in a multivariate expected error (1σ) in which there is a 39% chance that the position will be within that value.

A suite of software has been developed at the UNSW to both predict the satellite coverage for certain locations at certain times (spatially and temporaly) and to present this in graphical form such as skyplots and contour maps. The program requires an almanac file of SV's with the user inputting specific geographic locations, times of interest and a minimum elevation mask angle to SV's. It computes the satellite position at the time of interest by extrapolating the Keplerian almanac elements forward by the Brouwer theory (Cappellari, Velez and Fuchi 1976) then transforming the Keplerian elements to Earth Centred Earth Fixed (ECEF) coordinates. The line of sight vector is converted to an azimuth and vertical angle before determining if the SV is above the minimum elevation mask angle. The program determines which SV's are visible to the user at the location and searches through to find which set of three or four SV's yields the minimum DOP (Dilution of Position) values. The plots presented in this Chapter have been produced by summing results from a spatial domain (Australia) by cycling through time intervals then across the geographical grid to build up an array of data. As such the hours of coverage in one day show the sum total and give no indication of how the periods of unsuitable positioning (outages) are distributed through the day.

4.1.2 Outages.

The present and the proposed constellation envisaged for GPS yields occasional geometric configurations that result in periods of poor navigation solutions termed **outages.** This is an important term that is used whenever assessing the performance of a constellation and is defined as a period when GPS navigation is not possible due to a less than favourable number of visible satellites or when the DOP exceeds a specified value such as a HDOP greater than seven for example. Figures 4.1 and 4.2 are produced for the 8th June 1986 and show a coplanarity of four SV's at 7pm with the HTDOP plot reflecting the poor configuration which in this case lasts for 25 minutes. Obviously the present constellation does not allow 24 hour 2-D positioning.

4.1.3 Two Dimensional Solutions.

In hydrographic surveying the height determination of a vessel above an ellipsoid or geoid is rarely required. Its determination can be sacrificed for the sake of over-determining the three parameters of latitude, longitude and clock bias, or using a limited three SV coverage. Similarly if an atomic clock is used in conjunction with a receiver then the epoch solution need not solve for a clock bias as the clock bias remains practically constant.

The receiver should elect to constrain the height or clock parameters and make use of three suitable SV's if increasing GDOP values from four visible SV's give evidence of an outage.

When constraining height in the general case an altimeter (eg. barometric) will supply independent heights at each epoch. The approximation that the antenna will be a constant

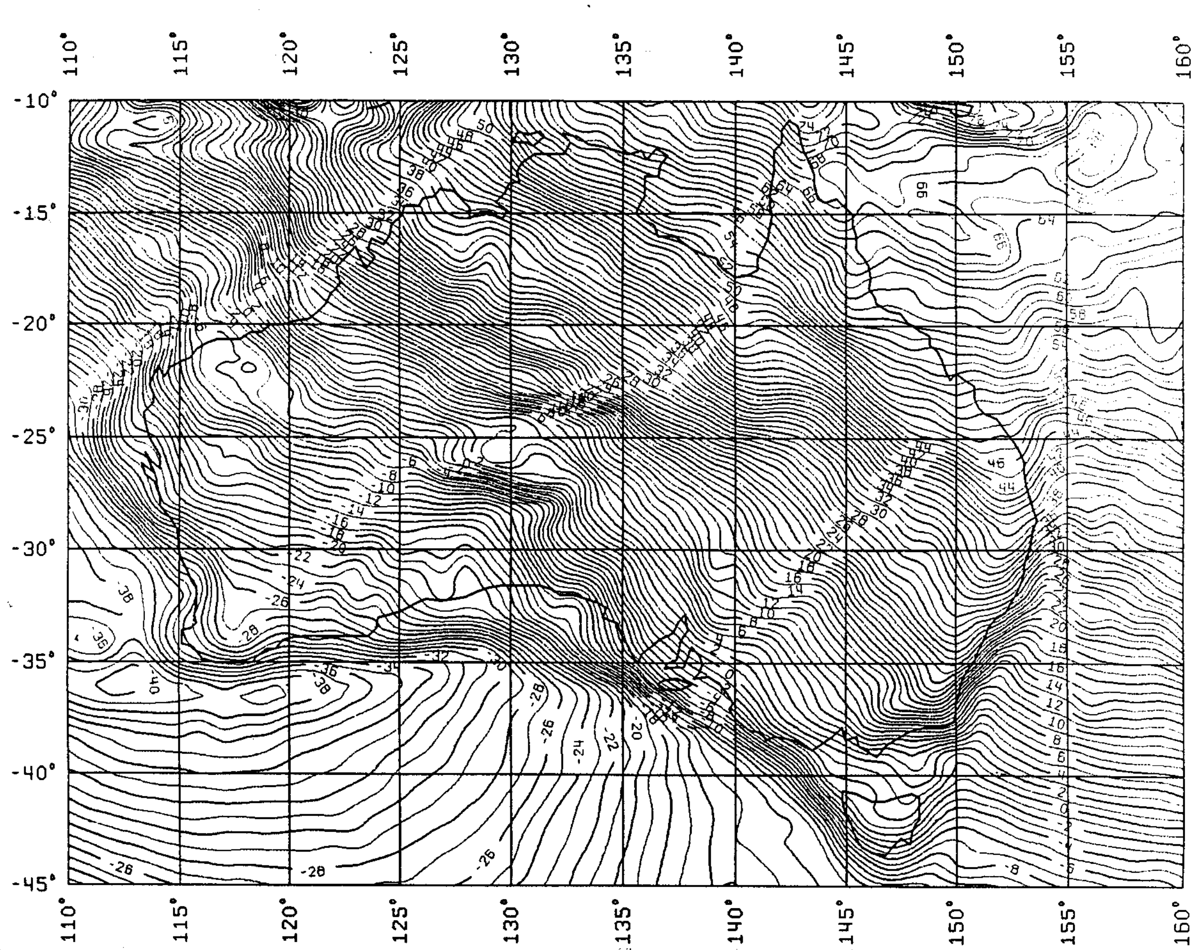
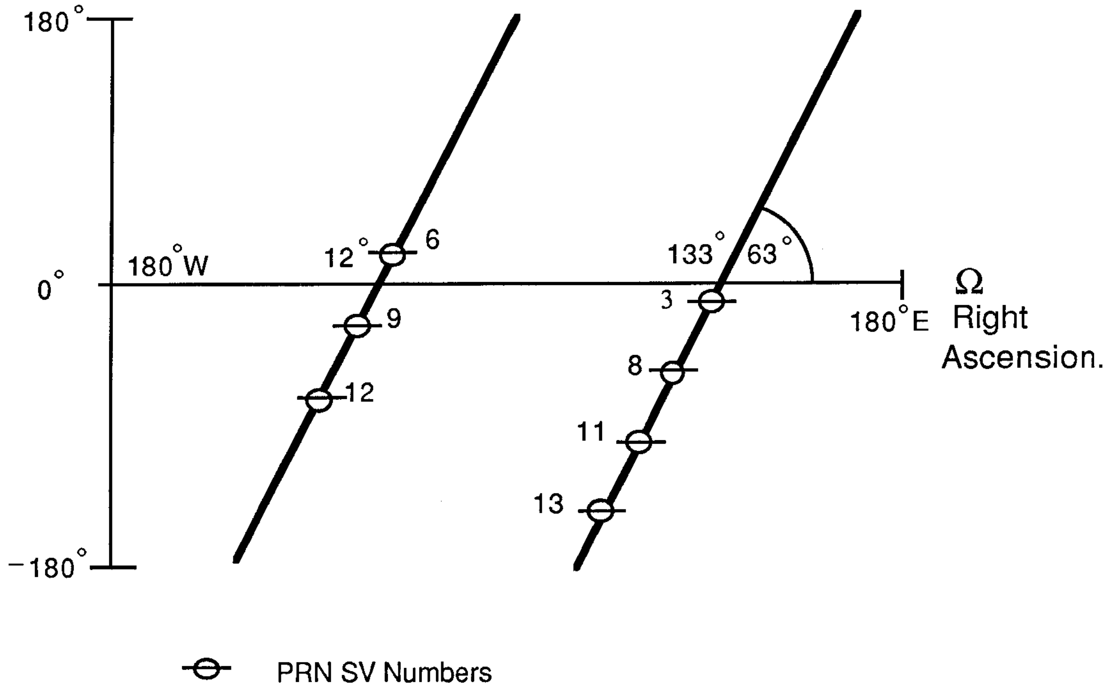


Figure 4.3 Geoidal Separation : Geoid and GRS-80 (WGS-84). From: R.Rapp.

Figure 4.4 SV Configuration - 1986



height above an ellipsoid is assumed in the case of a vessel on the ocean. The usual practice is to put an a-priori height value into the receiver. This a-priori value is the sum of the separation between the geoid and ellipsoid (geoidal separation) at the centre of survey operations and the height of the antenna above sea level. Four factors have to be considered to ensure that the assumptions do not introduce errors. These factors are:

1. The geoidal separation is not constant over an area. These values are published as tables, contour maps, or can be determined from coefficients of the earth's gravity field model. Geoidal separation slopes offshore Australia are noted to have a maximum variation of 10m in 250kms (Figure 4.1). The error in determining the geoidal separation could introduce a height error of 1 to 2m.

2. The departure of mean sea level from the geoid is commonly known as sea surface topography which is due to ocean currents, air pressure, wind stress, salinity variations, seabed topography, etc. Sea surface topography can introduce a height error of up to 2m. When operating in some areas the sea surface topography may vary by much more than this such as near deep ocean trenches.

3. The maximum tidal range in Australia is up to 9m at Broome, WA. The sea level at any one time could therefore be ±4.5m different from the mean sea level.

4. The motion of a vessel can cause the antenna to move up to ± 1.5m vertically. Any motion greater than this would surely limit survey operations as the quality of auxiliary data collection may well be too noisy.

The sum of all the four possible error sources in determining ellipsoidal height can be around 5m. To assess how a variation in this height affects the GPS determined position the a-priori ellipsoidal height in a Trimble 4000A (March, 1986) was varied from 0 to 35m when observing three SV's. As position varied by only ±0.2m it was not possible to distinguish between noise and an actual bias.

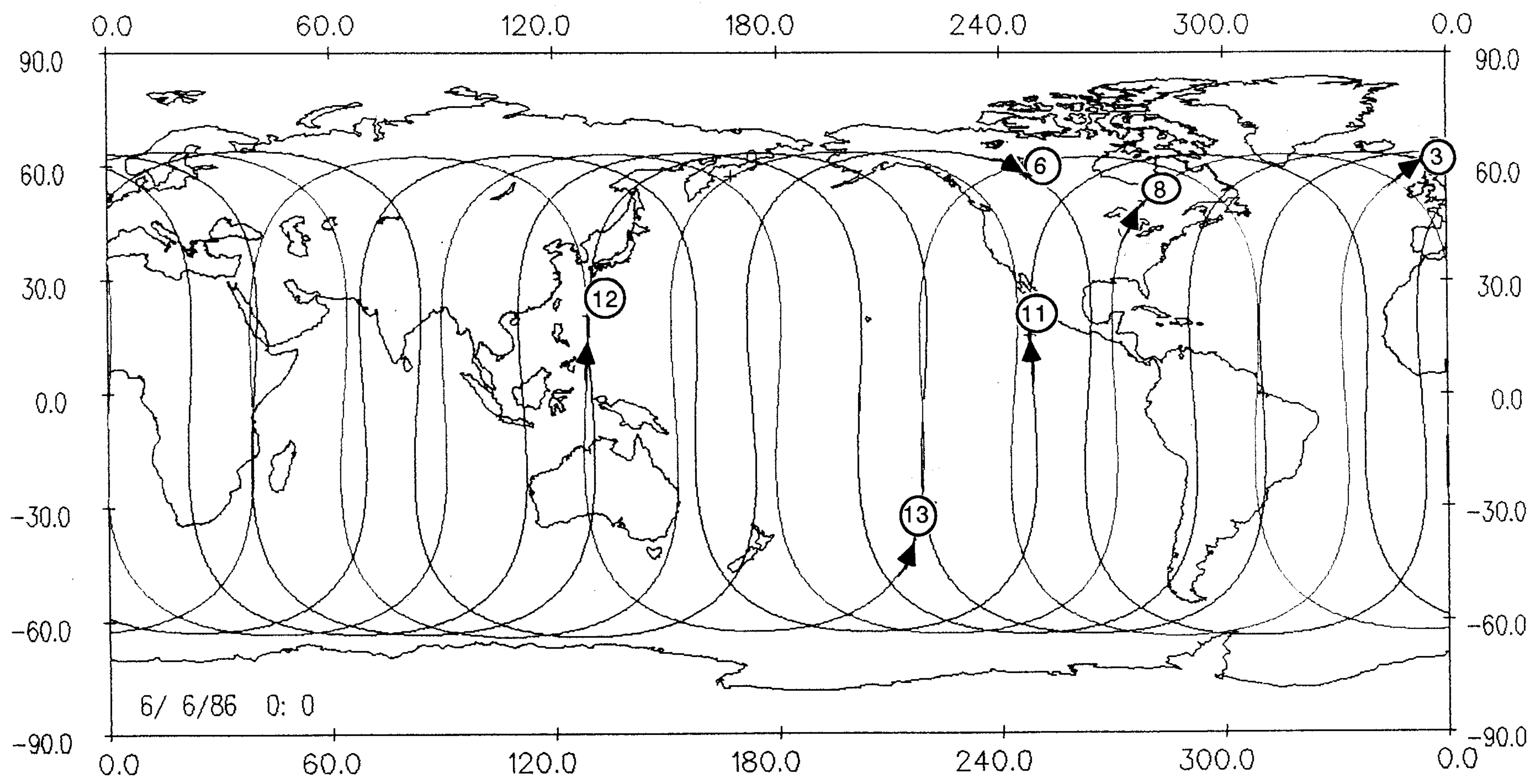
4.2 PRESENT CONSTELLATION - 1986

In the present Block I phase there are seven SV's in two orbital planes as shown by Figure 4.4. To relate Figure 4.4 to the earth-based observer and to visualise the track of those SV's over the earth all seven SV's have been plotted onto a world map for one 24 hour period (Figure 4.5). The motion of a SV is from west to east spanning a range of $\pm 63^{0}$ in latitude which is equal to the SV's inclination angle. The SV completes two orbits in 24 hours while the earth has completed one revolution underneath so producing the 'two cycle' ground track.

4.2.1 Results.

Visible Satellites: To obtain an initial indication of how long certain groups of satellites are visible above the elevation mask angle Figures 4.6, 4.7 and 4.8 were produced. These figures show the hours of visibility in a day in which the number of SV's stated, or more, are visible simultaneously. It can be seen that there are nearly twice as many hours in which three or more SV's are visible when compared with four or more SV's. Similarly the total hours when two or more SV's are visible compared with four or more SV's is three times greater. GPS receivers that can process less than four SV's simultaneously to determine position are

Figure 4.5 24 Hr. Ground Tracks , Block I , 7SV



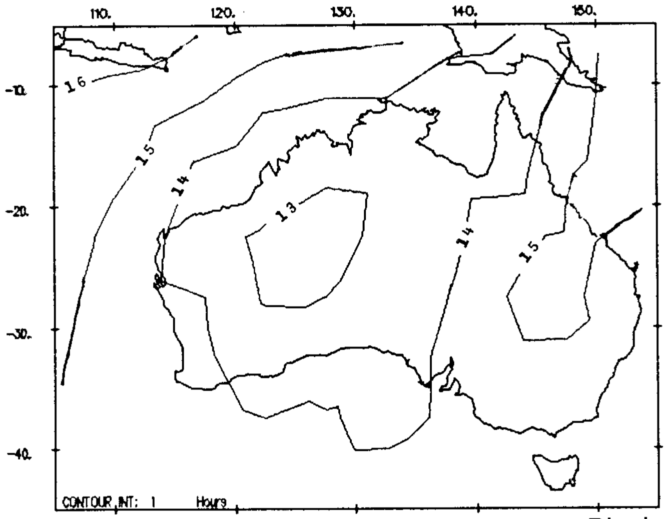


Figure 4.6 Hours Visibilty/Day for 2 or more Block I SV's

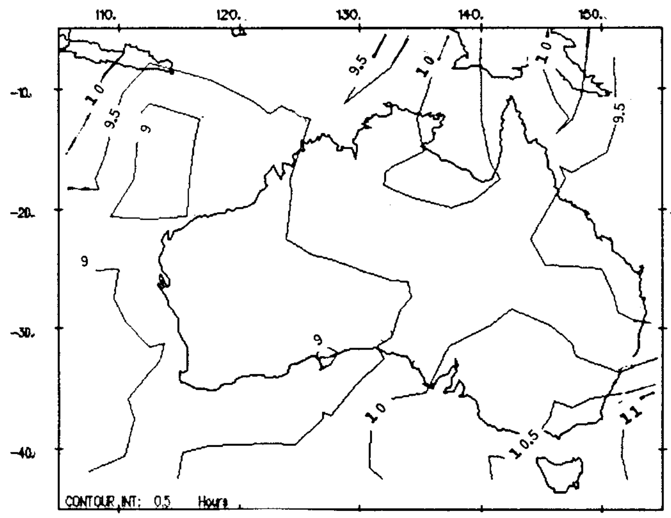


Figure 4.7 Hours Visibilty/Day for 3 or more Block I SV's

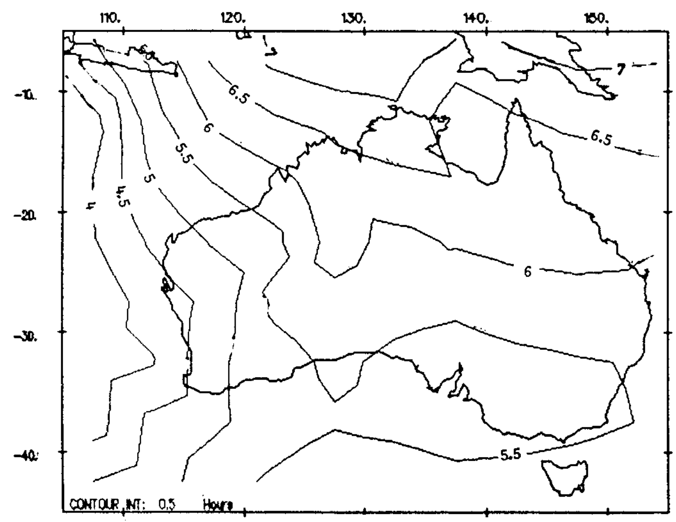


Figure 4.8 Hours Visibilty/Day for 4 or more Block I SV's

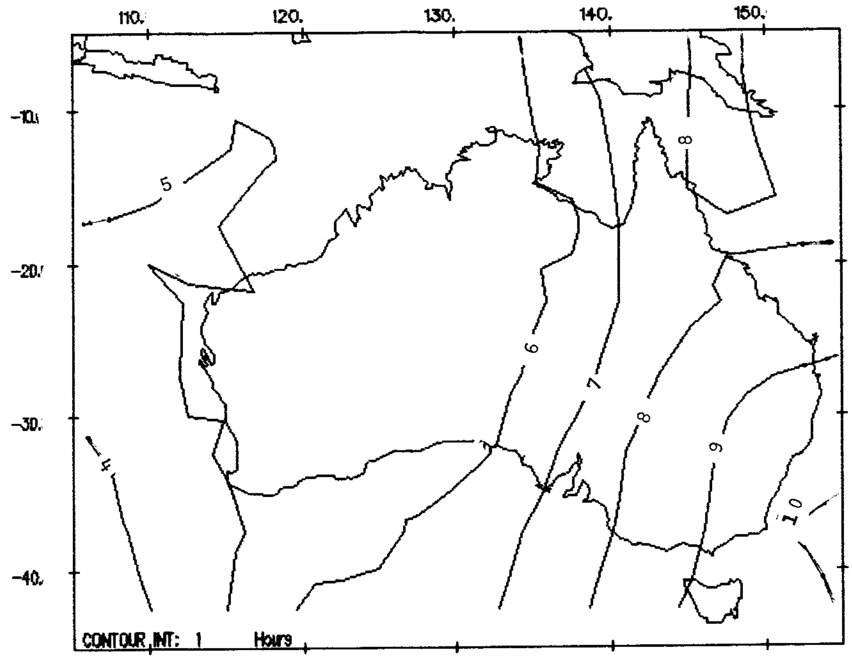


Figure 4.9 Hours HTDOP <7 ; Block I SV's

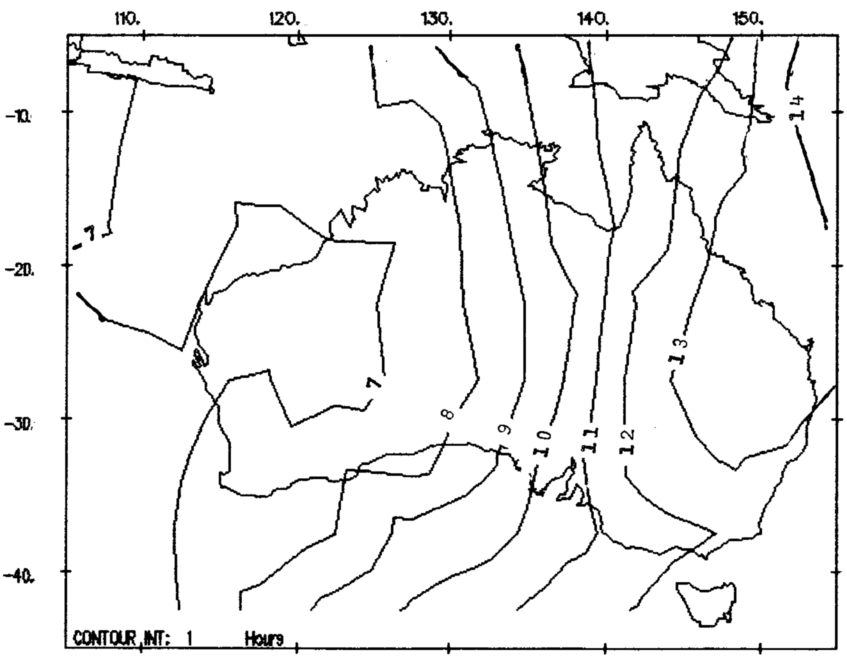


Figure 4.10 Hours HDOP <7 ; Block I SV's

obviously necessary to ensure greater hours of usage and procedures for such solutions are presented in Chapter 5.1

Hours of Acceptable Configuration: The number of hours that the SV's are visible does not give any clear indication as to their suitability for navigation so analysis by Dilution of Position or similar 'strength of figure' computations is necessary. The same input criteria (date and elevation mask) as used to determine the visible SV's was used to process both HTDOP and HDOP. The upper DOP limit was set to seven and where it was necessary to constrain parameters the standard error in height was set to 5m and that of the clock, to 1m. The clock in this case is assumed to be a Rubidium oscillator with no error buildup which means it can be used immediately two SV's are visible without requiring an offset determination. HTDOP is a useful indicator to assess the hours in which horizontal position and clock bias can be determined with a suitably high accuracy. Figure 4.9 is the plot of hours in which the HTDOP is less than or equal to seven showing that the most favourable conditions are in SE Australia and the least in the SW of Australia. The hours in which HDOP is suitable range from 13 in the east to 17 along the west of Australia (Figure 4.10). As long as the height and clock are constrained then the hours of suitable HDOP show when a minimum of two SV's are suitably located. The hours of suitable HDOP are probably optimistic as a free running Rubidium oscillator requires its offset determined every few hours to minimise error buildup which is not possible until three or more SV's are visible. The minimum HDOP over the area mapped is 1.2 with the maximum being very large due to outages.

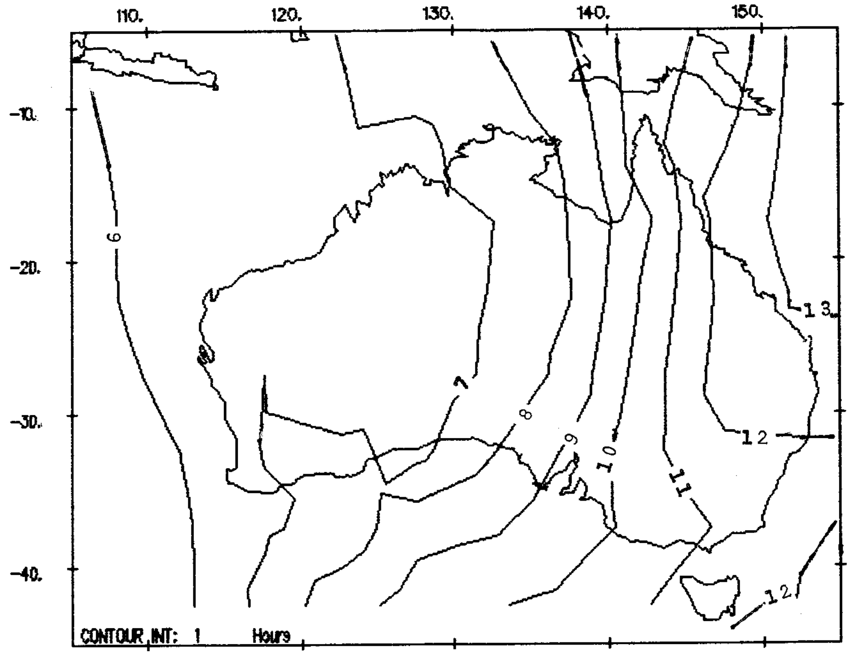


Figure 4.11 Hours/Day that Position Accuracy less than 25m.
Block I SV's; UERE=4.4m

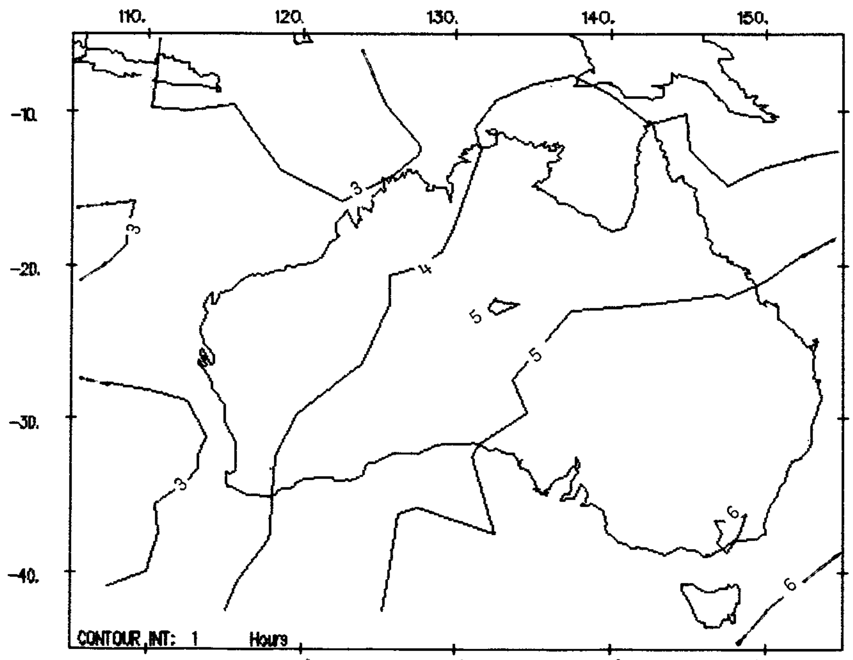


Figure 4.12 Hours/Day that Position Accuracy less than 25m.
Block I SV's ; UERE=11.8m.

Navigational Accuracy: Values for UERE have been developed in Chapter 3.3 for single receiver point positioning both with and without Selective Availability and for the multi-receiver differential technique. These three options have been analysed to give the hours of navigation in which the position error doesn't exceed the specified limit by determining when the product of UERE with the semi-major axis of the error ellipse (1σ) falls below that limit. Note that this error ellipse relating to horizontal position is multi-variate so the plots represent the 1σ level in which there is a 39.4% probability that the actual position is inside that limit (Cross 1983).

Figure 4.11 represents the number of hours coverage that would be possible with a differential GPS system that could make use of as few as two SV's. When single receiver operation is considered then Figure 4.12 gives an indication of the hours of usage envisaged.

4.2.2 Recent Developments.

SV's 6 and 8 were launched in 1978 and are operating well past their designed life-span of 6-7 years. In October 1986 the Rubidium oscillator on SV8 became too unstable to predict so the SV clock was switched over to run from the crystal quartz oscillator. The DoD flagged this SV as unhealthy while it attempted to model the crystal clock performance. Real-time navigation users were advised not to use SV8 as unpredictable errors in position could result. The use of SV8, still transmitting its unhealthy status message, in a point positioning solution on the 12th February 1987 gave a position 300m from the known coordinates. Positions in error by several kilometers are not uncommon when the user elects to use SV8.

As the atomic clock on SV6 is nearing the end of its lifetime the DoD decided in October 1986 to advance SV3 by 180° in its present orbit. SV3 will be in its new position by April 1987. This reconfigured 6 SV constellation results in lesser hours of 2-D positioning compared with the 7 SV constellation used in these simulations. If SV6 does become inoperable for real-time positioning then the reconfigured SV3 will ensure that an optimum five SV constellation is available for 2-D positioning. As at February 1987 SV3 was very near SV11 making it of limited use to point positioning.

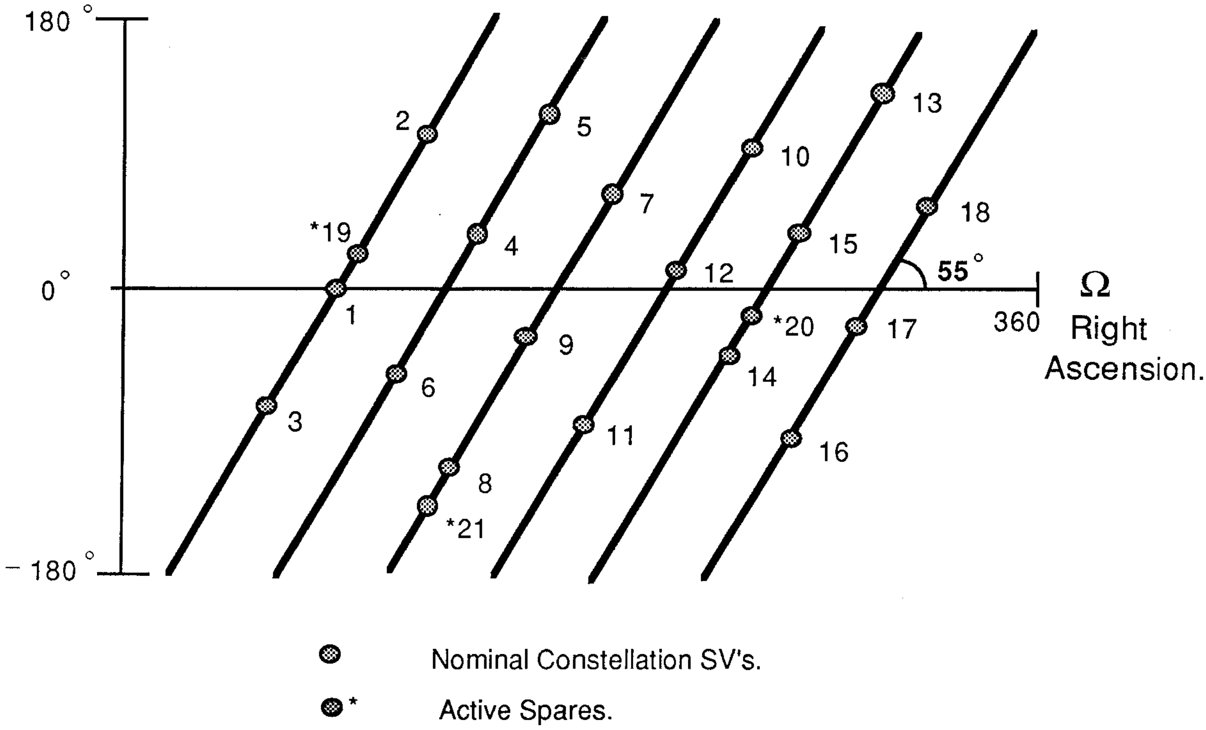
4.3 BLOCK II CONSTELLATION.

It is planned that the Block II constellation will consist of 18 satellites plus three spares switched on and operating since SV longevity is not decreased significantly by having them transmitting. SV orbit configurations are concisely defined by the **Walker constellation index**. The salient points of the Block II constellation are:

- there are a total of 18 SV's in orbit.
- there are to be 6 orbital planes equally placed in longitude around the equator; ie. every 60°.
- the relative phasing of the satellites will be 40°; this value is the angular increment in true anomaly that SV's in successive orbits have compared to those SV's in the previous orbit. For example, SV4 is 40^{0} ahead of SV1 as seen in Figure 4.13. The Walker constellation index for this 18SV constellation is written as 18/6/2. The first value states the total number of SV's, the second value is the number of orbital planes and the last value is termed the phasing

index. The phasing index is calculated by dividing the relative phasing of the SV's by 360/18.

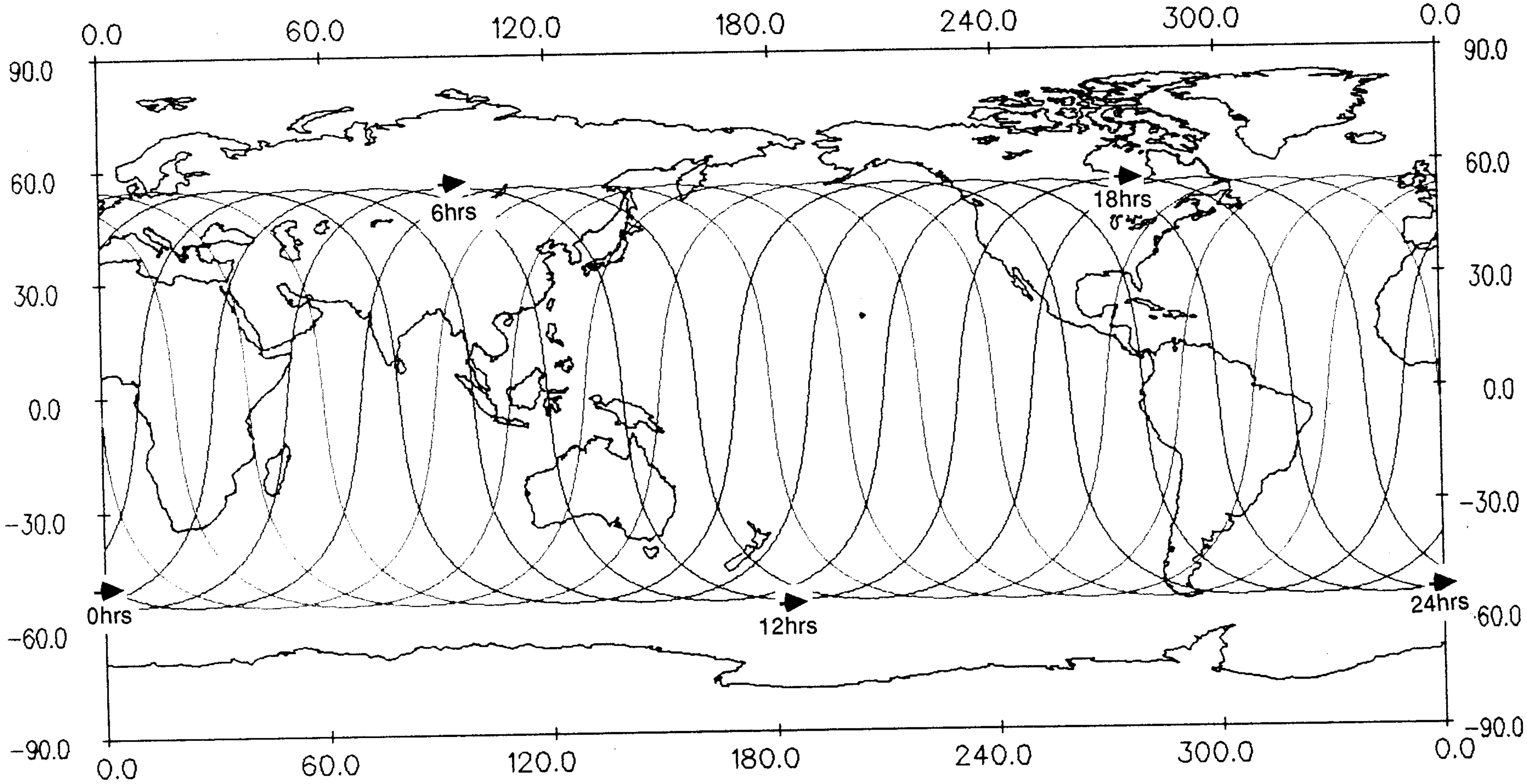
Figure 4.13 SV Configuration - Proposed Operational



Added to that configuration there will be three spare SV's placed in orbit for immediate back-up to give a final Walker configuration index of 18/6/2+3 (See Figure 4.13). This 21SV constellation will allow nearly 24 hour 2-D navigation since at least four SV's will be visible above the specified elevation mask of 5^{0}. It is superior to an 18/3 configuration as with only three orbital planes the occurrence of undesirable features that limit navigation are greater.

To illustrate and compare differences of the Block I with the Block II constellation the ground track is plotted on Figure 4.14 which shows nine separate tracks for the 18SV constellation (the three spare SV are not plotted). Only nine tracks are visible since half the SV's having Right

Figure 4.14 24 Hr. Ground Tracks , Block II ; 18SV



Ascensions that differ by 180° from the others and lag behind one other SV by 12 hours. The lesser inclination angle of 55° gives a more compressed ground track also.

The analysis of the full 21SV constellation requires a slightly different approach compared with the Block I SV's as now four SV's are continuously visible. With this constellation the maximum number of SV's visible at any one location varies from nine to ten while the minimum is four for a 7.5° elevation mask.

4.3.1 Results.

Nature of Outages: Even though there are always four SV's visible, outages still occur so by plotting the hours in a day in which HTDOP and HDOP are less than seven then the hours of outage for a location can be deduced. The data for Figures 4.15 to 4.17 were calculated using a one minute interval so any HTDOP/HDOP that spans less than a minute will not be added to the totals. An elevation mask of 7.5° regarded as valid in a clear offshore horizon, results in the majority of continental Australia experiencing little or no outages. Figure 4.15 shows the southern third of the Australian continent experiencing 6 to 24 minutes of outage with up to 36 minutes of outage across the southern offshore seas. When a 10° mask angle is selected, as used by the US FAA (Federal Aviation Administration), further outage zones appear (Figure 4.17) along a band centred at 12°S and in the Bass Strait/southern seas totaling 54 minutes. These longer outages (Figure 4.17) are made up of either two or four distinct outages in the day. Doucet (1986) found from analysis of outages in Canada that they typically last 5-30 minutes depending upon your position in them, move east to west and re-appear at the same time, earlier by four minutes, daily. In this 21SV simulation the outages in the Bass Strait area (39°S, 148°E) occur in two unique time periods; 16 and 14 minutes in duration respectively (for HTDOP, 7.5° mask) that occur 12 hours apart but with differing SV's. The pattern for HDOP outages are concurrent but last only four and three minutes respectively (Figure 4.16).

During outages the DOP values become very large giving rise to a meaningless 24 hour average DOP value so it is best to evaluate them by percentiles. Like all the plots produced in this Chapter, Figure 4.18 is from data analysed between the geographical bounds of 5°S to 45°S and 105°E to 155°E. Figure 4.18 shows the percentage of time (100% is 24 hours) in which HDOP/HTDOP are less than a given value (the Y axis) for a 7.5° mask angle. If we define a DOP value above seven as an outage it is seen that they occur over the study area for 0.30% of a day, for HDOP, and 0.80% for HTDOP. For 99.00% of the time the HDOP will be less than 2.8 while for 97.99% of the time the HTDOP will be less than 3.3. By increasing the elevation mask to 10° then outages are seen to occur for 0.40% of the day for HDOP and 1.00% for HTDOP. By knowing the nature of these outages then possible solutions can be planned to ensure the integrity of positioning. The technique of constraining height and clock to improve the hours of coverage are discussed in Chapter 5.1.

Navigational Accuracy: Figure 4.19 shows for a single receiver, with Selective Availability in which the UERE is

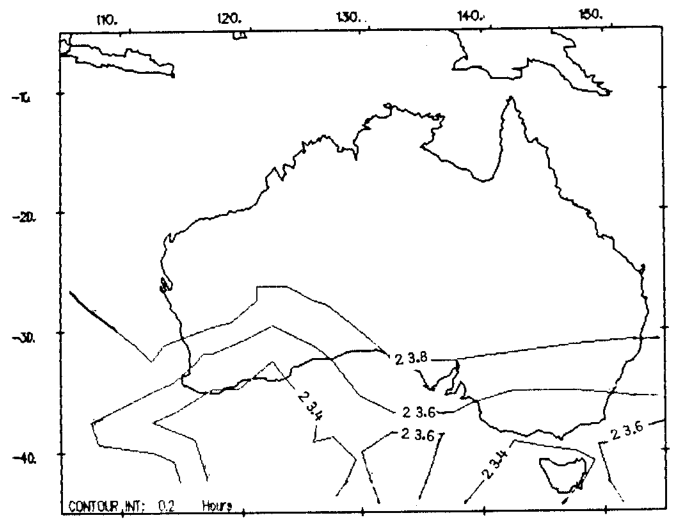


Figure 4.15 Hours HTDOP <7 ; Block II SV's

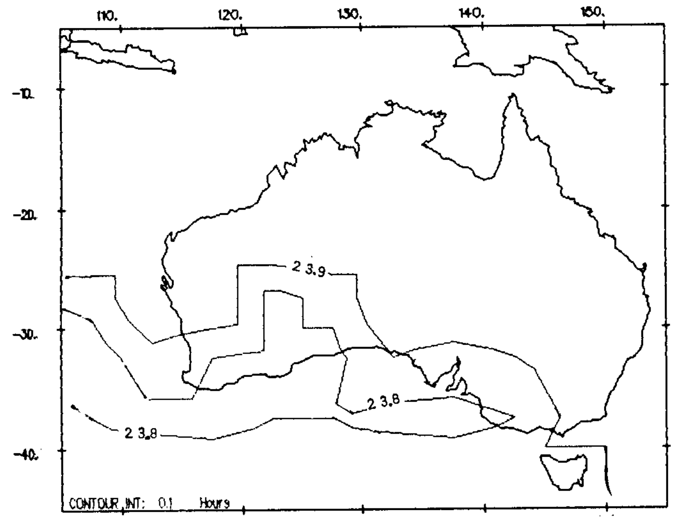


Figure 4.16 Hours HDOP <7 ; Block II SV's

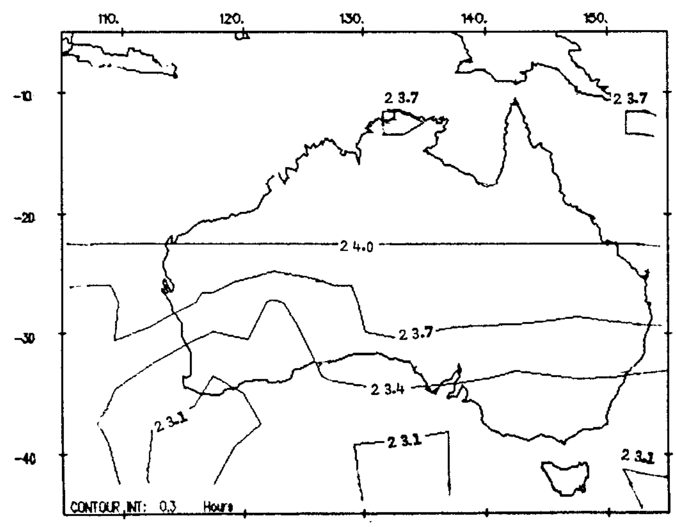
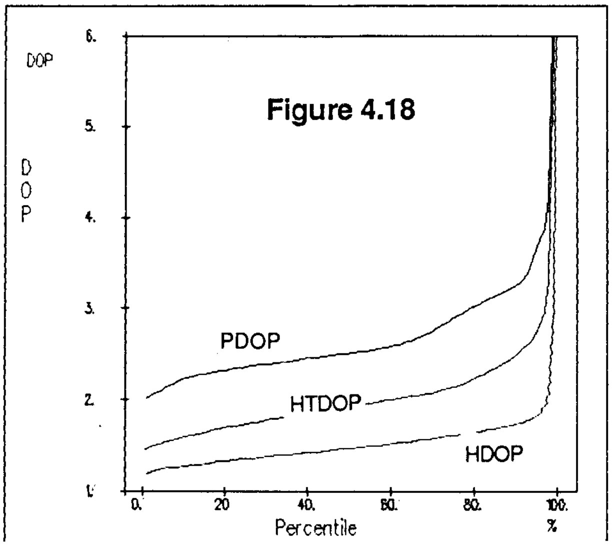


Figure 4.17 Hours HTDOP <7 ; Block II SV's ;10° Mask



Percentage of Time DOP is Less than Given Value; Block II SV's

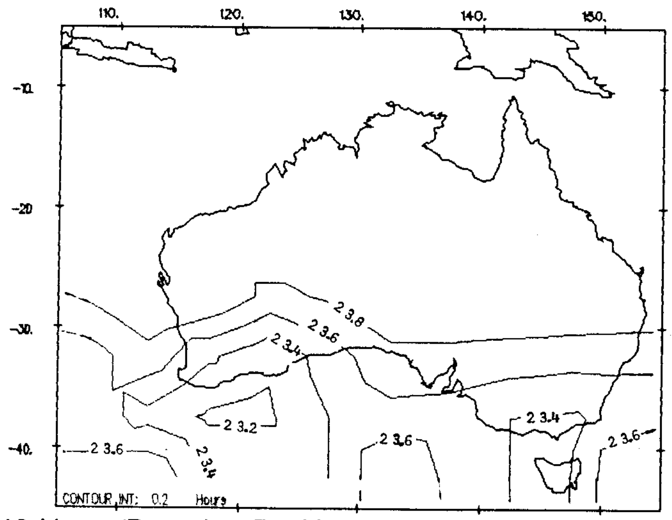


Figure 4.19 Hours/Day that Position Accuracy <100m. Block II SV's ; UERE=32m.

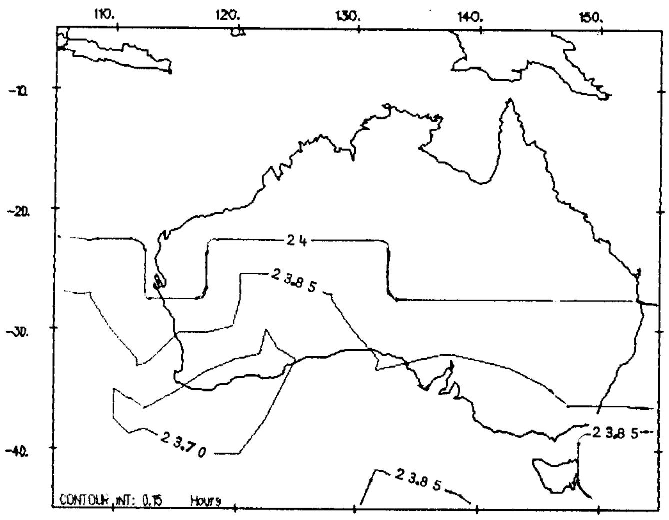


Figure 4.20 Hours/Day that Position Accuracy <25m. Block II SV's ; UERE=4.4m.

32m, the hours in which horizontal positioning accuracy is better than 100m(1σ). If differential GPS is considered where UERE is 4.4m then Figure 4.20 shows the hours in which horizontal positioning accuracy is better than 25m(1σ).

4.4 EFFECT OF SELECTIVE AVAILABILTY.

From tests carried out by Masters & Stolz (see Stolz & Gubbay 1986) and Wells et al (1986) it appears that positioning results from C/A code are almost equivalent to P code for the Block I type satellites and experimental staging. These excellent C/A results could in part be attributed to the current low sunspot activity and thus small ionospheric delays.

Unfortunately the DoD intends to degrade the C/A code accuracy to the civilian market for the upcoming Block II satellites, though still allowing the military and 'selected' users the precision of the P code. The policy of limiting C/A code accuracy and restricting P code availability is termed Selective Availabilty (SA). The service thus offered to civilians will be known as the Standard Positioning Service (SPS). The P code access will be known as the Precise Positioning Service. The three methods by which the degradation could be implemented are :

1. Degrading the Broadcast Ephemeris on the L1 carrier by transmitting truncated data.
2. Dithering the SV oscillator.
3. A mixture of truncated ephemeris and dithering of the oscillator.

The actual method to be utilised has not been specified by the DoD but if the first is implemented then a bias error in the ephemerides is envisaged, with the real-time point position accuracy becoming typically 100m 2drms. Note that 2drms is the square root of the sum of the squares of the two sigma error components along the major and minor axes of a probability ellipse, and is basically equivalent to 2xHDOPxUERE. The second option could see a slow or rapid dither, though if rapid dithering of the SV oscillator is used then ALL positioning services, C/A and P code, to all users would be degraded. A slow dither as the Radio Technical Commission for Maritime Services (RTCM, Kalafus 1985) state could be in the order of ±30m(1σ) giving the point position accuracy as 100m 2drms also.

Summary.

The methods to assess accuracy, reliability and coverage of a GPS constellation were introduced in this Chapter. Outages due to SV geometry can be predicted. Unfortunately outages due to SV failure are unpredictable as evidenced by the weakening Block I constellation.

The most useful indicator of accurate GPS coverage is from Dilution of Position plots. The HTDOP plots for the seven SV constellation show that positioning up to ten hours a day is possible when height only is constrained. If the receiver clock is also constrained then positioning for up to 14 hours a day is possible as seen on the HDOP plots.

From the data presented in this Chapter it can be concluded that the proposed 21SV constellation will not yield single receiver accuracies sufficient for the majority of hydrographic surveys in the Australian region. The intentionally degraded system accuracy is a result of DoD

Selective Availability policy. As such the Standard Positioning Service available to civilian users is expected to give single receiver accuracies of 100m (2drms). The 21SV constellation also produces two distinct periods of outages when using three or more SV's. These outages are considerably reduced if only two SV's can be used. In any case when less than four SV's are to be used in the receiver solution height or clock (or both) parameters will need to be constrained (see Chapter 5.1).

5. GPS PROCESSING TECHNIQUES

The results presented in Chapter 3 and 4 have shown that the accuracy of a GPS position fix can be affected by factors beyond the control of the civilian user. The systematic errors in GPS contribute to a significant proportion of the user expected range error (UERE). Since Dilution of Position (DOP) is taken to be a reliable indicator of point position accuracy it is expanded further in this chapter. Single receiver positioning accuracy with GPS is presently giving results within 10-20m of known control. Are there any processing methods to obtain the higher accuracy demanded for hydrographic surveying? This chapter aims to study what different processing techniques are available and how they affect positioning accuracy and precision. Single receiver point positioning techniques are introduced to solve for the general problem of 3-D positioning plus receiver clock bias from four or more SV's. What techniques are available to determine position when less than four SV's are available? To improve the accuracy of kinematic GPS the differential GPS technique shows promising results. If GPS is to be integrated into hydrographic survey operations then what are the issues to consider when implementing a differential GPS system? One of the basic assumptions in GPS is that systematic errors are highly correlated between two receivers thus any difference in simultaneous positions should be random in nature. An experiment detailed in Section 5.3.3 aims to study these correlations. Data is analysed from two Trimble 4000S receivers with separations ranging from 12m to 228km. Can such an experiment be used to evaluate the expected precision in relative positioning by differential GPS?

5.1 GPS POINT POSITION SOLUTION METHODS.

The methods for determining the user position on a specified ellipsoid will vary depending on the number and type of observations incorporated into the solution, whether any of the parameters are constrained and whether the receiver is being used in a static or kinematic mode.

5.1.1 Introductory Formulation

For most real-time navigation receivers the number of measurements (pseudo-ranges) will equal the number of parameters to be solved for. In most cases a Least Squares approach is not strictly necessary as redundancy does not exist. A solution by simultaneous equations provides the unique solution. When redundancy does exist then a Least Squares solution can be used. In both cases though a general Least Squares algorithim can be utilised as it allows for numeric processing simplicity and readily gives Dilution of Position outputs.

A specific case of the general Least Squares model in which the observations are equal to a function of the parameters only is termed the observation equations and it is solved by the **Parametric method**:

$$L = F(x) \qquad (5.1)$$

where:

L = true values of the observations

$= l + v$ (observations + true values of residuals)

x = true values of the parameters.

By taking a provisional value of x equal to $(x_o + \Delta)$ then the model can be linearised about this a-priori point

x_0 by Taylor's theorem and considering first derivatives only:

$$L = F(x_0) + \partial F/\partial x . \Delta \qquad (5.2)$$

where: $F(x_0) = c$ = calculated values of observations at x_0

$\partial F/\partial x = A$ = partials of function F with respect to parameters.

Δ = corrections to parameters

now expanding $\partial F/\partial x$ into matrix form:

$$\partial F/\partial x = A = \begin{bmatrix} \partial F_1/\partial x_1 & \partial F_1/\partial x_2 & . & \partial F_1/\partial x_4 \\ \partial F_2/\partial x_1 & & & \\ & . & & \\ & & . & \\ \partial F_4/\partial x_1 & & & . \end{bmatrix}$$

Writing (5.2) in the expanded convention already introduced gives:

$$\mathbf{l + v = c + A.\Delta}$$

rearranging : $w + v = A.\Delta$

where : $w = l - c$ misclose vector often termed the (O-C) vector.

The Least Squares solution of the corrections to the parameters is solved by :

$$w = A.\hat{\Delta}$$

$$\hat{\Delta} = (A^T.P.A)^{-1}.A^T.P.w$$

where:

P = weight matrix of observations

and whenever A is square and its inverse exists the solution is simply:

$$\hat{\Delta} = A^{-1}.w$$

Summary of Parametric Method of Least Squares.

1) General Model : $L = F(x)$

2) Parameter estimate : $\hat{\Delta} = A^{-1}.w$

3) Solution for parameters : $\hat{x} = x_0 + \hat{\Delta}$

4) Cofactor matrix of parameters : $Q = (A^T.P.A)^{-1}$

or if P = identity matrix, I then $Q = [A^T . A]^{-1}$

5) The covariance matrix of parameters :

$$C_{\hat{x}} = \sigma_0^2 \ . \ Q$$

6) For covariance of residuals and observations see Cross (1983)

Least Squares Point Position Solution using Pseudo-Ranges.

The basic observables for a 'navigation' solution are the four observed pseudo-ranges $\mathbf{l} = [r_1, r_2, r_3, r_4]^T$ which are required to solve for the four-state user vector $\mathbf{x} = [u_1, u_2, u_3, b]^T$ where: u_1, u_2, u_3 = users position components in geocentric or geographic coordinates.

b = user clock bias in metres = speed of light. dt

The basic relationship between pseudo-range, user position, SV position and clock bias is given as :

$$l_i = F(x) = \surd[(s_{i1} - u_1)^2 + (s_{i2} - u_2)^2 + (s_{i3} - u_3)^2] + b \quad (5.4)$$

where: s_{ij} = the given satellite coordinates; j = 1, 2, 3

A Taylor's series expansion of l_i (5.4) with linearisation about x_0 followed by dropping of all derivatives but the first one gives:

$$l_i = F(x_0) + [(\partial r_i/\partial x_1)(\partial r_i/\partial x_2)(\partial r_i/\partial x_3)(\partial r_i/\partial b)]. d \quad (5.5)$$

where:

d = [du₁, du₂, du₃, db] corrections to parameters.

and letting w = l - c (observed range - calculated distance to SV)

then : $w + v = a_i . d$ (5.5)

where a_i is a row vector in (5.5) given by:

$$a_i = \left[\frac{s_{i1} - u_1}{r_i - b} \quad \frac{s_{i2} - u_2}{r_i - b} \quad \frac{s_{i3} - u_3}{r_i - b} \quad 1 \right] \quad (5.6)$$

The **A** matrix, $(a_1, a_2, \ldots)^T$, is the partials of **l** with respect to **x** evaluated at x_0.

The corrections to the a-priori position are obtained by solving :

for the three parameters directly when only three SV's are visible. In the three SV case the real-time solution can be formulated from several options:

1. The vertical component, h, can have a relatively large weight assigned to its a-priori value in the **P** weight matrix. This method ensures that the **A** matrix retains its four column dimension and outputs all 4 parameters thus allowing easy switching from three to four SV constellations.

2. A "pseudo-observation" or constraint equation can be substituted into the standard algorithims whenever three SV's are used. For example a German manufacturer, Standard Elektrik Lorenz AG, propose to introduce an 'artificial satellite' with a known vertical range in the zenith into their prototype receiver.

3. By holding the parameter fixed and solving for three parameters the design matrix **A** can be reduced in size to a 3x3. A subset of $\mathbf{A_g}$ can be used to solve for horizontal position and clock offset and in this case would be :

$$\mathbf{A_g} = \begin{bmatrix} \partial r_1/\partial\phi & \partial r_1/\partial\lambda & \partial r_1/\partial b \\ \partial r_2/\partial\phi & . & . \\ . & . & . \\ . & . & . \end{bmatrix}$$

All these approaches require that the height of the antenna above the ellipsoid be known which is the sum of the geoidal separation and the height of the antenna above the sea surface. Complications to these assumptions have been discussed in Chapter 4.

Two Dimensional Solution with Constrained Clock

The case can be encountered whenever the constellation for the three parameters directly when only three SV's are visible. In the three SV case the real-time solution can be formulated from several options:

1. The vertical component, h. can have a relatively large weight assigned to its a-priori value in the **P** weight matrix. This method ensures that the **A** matrix retains its four column dimension and outputs all 4 parameters thus allowing easy switching from three to four SV constellations.

2. A "pseudo-observation" or constraint equation can be substituted into the standard algorithims whenever three SV's are used. For example a German manufacturer, Standard Elektrik Lorenz AG. propose to introduce an 'artificial satellite' with a known vertical range in the zenith into their prototype receiver.

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$$\mathbf{A}_g = \begin{bmatrix} \partial r_1/\partial\phi & \partial r_1/\partial\lambda & \partial r_1/\partial b \\ \partial r_2/\partial\phi & . & . \\ . & . & . \\ . & . & . \end{bmatrix}$$

All these approaches require that the height of the antenna above the ellipsoid be known which is the sum of the geoidal separation and the height of the antenna above the sea surface. Complications to these assumptions have been discussed in Chapter 4.

Two Dimensional Solution with Constrained Clock

The case can be encountered whenever the constellation provides only two suitable SV's though the user still requires horizontal position to be determined. The height above the ellipsoid is again constrained and need not be solved for while the clock must be synchronised to GPS time either externally or by previous GPS solutions. In this case the **A** matrix can be reduced to simply:

$$\mathbf{A_g} = \begin{bmatrix} \partial r_1/\partial\phi & \partial r_1/\partial\lambda \\ \partial r_2/\partial\phi & . \\ . & . \\ . & . \end{bmatrix}$$

5.1.3 Analysis

Covariance Analysis

An integral part of any GPS solution is an analysis of the correlation of parameters with the observations and geometry of the solution. The 'strength of figure' concept that is used in assessing radio-positioning fixes can be similarly used when analysing GPS for point-positioning. Assuming that the weight matrix of the observed pseudo-ranges is the identity matrix then the covariance of the parameters can be determined as:

$$C_x = \sigma_p^2 . [A^T . A]^{-1}$$

where σ_p^2 = pseudo-range variance factor.

So the position and clock offset co-factors from the diagonal elements (trace) of the co-factor matrix Q = $[A^T . A]^{-1}$ act as the amplification factors to the pseudo-range error variances to give the combined position and clock error variance. This introduces the concept of the dimensionless values termed Dilution of Position (DOP) given by Sturza (1991) as:

$$\mathbf{GDOP} = \sqrt{(Trace([A^T . A]^{-1}))}$$

PDOP = $\surd(\sigma_{u1}^2 + \sigma_{u2}^2 + \sigma_{u3}^2)/\sigma_p$

TDOP = $\surd(\sigma_b^2)/\sigma_p$

where σ_{u1}^2, σ_{u2}^2, σ_{u3}^2 = variances of users position. Components are in geocentric or geographic coordinate system.

σ_b^2 = variance of users clock bias.

σ_p = standard error of pseudo-ranges.

Also of interest to hydrographic surveying is the DOP value for the 2-D horizontal solution which can be computed from :

HDOP = $\surd(\sigma_\phi^2 + \sigma_\lambda^2)/\sigma_p$

HTDOP = $\surd(\sigma_\phi^2 + \sigma_\lambda^2 + \sigma_b^2)/\sigma_p$

Note that if Q = $[A^T.A]^{-1}$ is in terms of the ECEF geocentric system then the transformation matrix of $\mathbf{R_{e,g}}$ can be applied to transform the ECEF values to a local tangent plane system, typically in geographic components.

DOP Calculation with Constrained Clock.

When only three coordinate parameters are being solved for in the case of a three SV constellation and a precise clock being utilised then the contribution of the clock bias error variance has to be considered. Sturza (1984) developed the DOP position error variances as a function of the trace of the cofactor matrix (Q_c) for a constrained clock:

$$[\ (A_3^T A_3)^{-1} + k^2 A_3^{-1}.S.S^T.A_3^{-T}\ ]$$

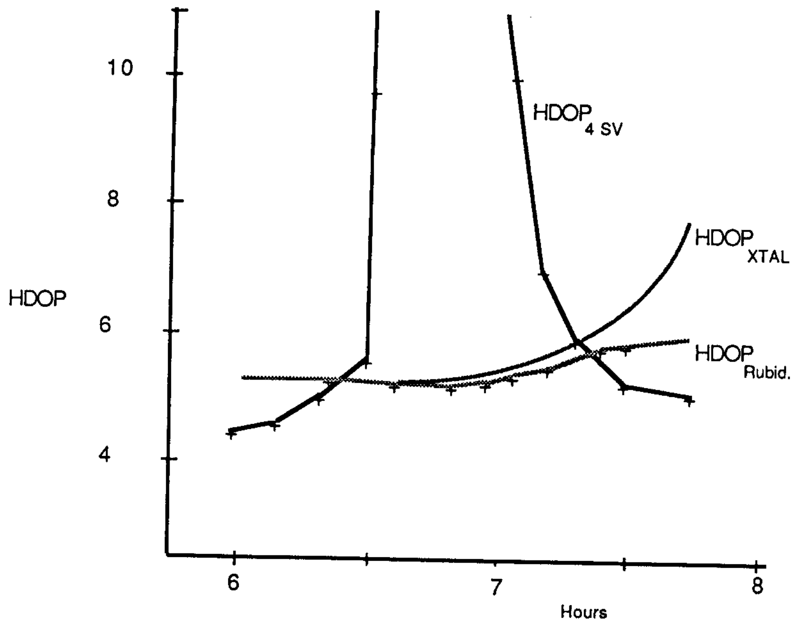
where: A_3 = Partial derivatives of measurements with respect to parameters (3 x 3 design matrix).

k^2 = σ_b^2/σ_p^2 = ratio of clock bias error variance to pseudo-range residual error variance.

$S = [\ 1\ 1\ 1\ ]^T$

A simulation was run using UNSW software to study the performance of both a crystal Quartz and a Rubidium oscillator during an outage, with the values for σ_b (with respect to time) taken from Sturza (1984). Figure 5.1 spans 0600-0800 hours on the 5th June 1986 which includes an outage that occurred when observing four SV's. The three most suitable SV's were then selected to minimise the DOP and the effect of oscillator behaviour applied in the HDOP calculation. During the 40 minute outage the Rubidium oscillator bias error variance did not exceed 1m and so the effect was negligible on HDOP. A similar value for the crystal Quartz oscillator bias error was over 40m and so contributed to its greater HDOP.

Figure 5.1 Contribution of Clock Error to HDOP



Site: 5th June 1986 , Sydney , (+10hrs. GMT)

DOP Calculation with Constrained Height.

For the other case in a three SV constellation where the height component is constrained, similar DOP calculations as for the constrained clock can be formed with:

$k^2 = \sigma_v^2/\sigma_p^2$ = ratio of height error variance to pseudo-range residual error variance.

The Nature of σ_p

It is of interest in pre- and post-analysis of the position solution to inspect the absolute accuracy for alternative options like:

- single receiver operation in point positioning
- differential implementation with two receivers
- effect of Selective Availability on single receiver

Position accuracy is a function of the product of two variables. The first is that associated with the variability of satellite geometry which is defined by the various DOP parameters. DOP values do not exhibit an evenly distributed range about a mean value, ie. they are non-Gaussian. The second variable is the variability of the errors inherent in the pseudo-range measurements, the standard error σ_p. This standard error is based on the assumption that there is no correlation between SV measurement errors.

As 'position' in the hydrographic sense implies 2-dimensional horizontal coordinates then HDOP is often considered as a value to indicate the potential accuracy of the horizontal position. Since HDOP is multivariate the product of it with UERE will result in an expected error (1σ) in which there is a 30% chance that the position will be within that value.

For example, with reference to Table 3.4:

Method	HDOP	x	UERE 1σ	=	Absolute Standard Error
Single Receiver	4.0	x	14.5m.	=	56.0m.
Differential	4.0	x	4.4m.	=	17.6m.
Selective Avl.	4.0	x	91.0m.	=	364.0m.

Pre-Analysis

There is no available analytical method for determining the statistical variability of the DOP values so the approach taken in the UNSW software is to perform large numbers of computations that cover all the spatial (area) and temporal (time) limits that are of interest. The DOP values are distributed across time in a non-Gaussian fashion. For example with the BLOCK II constellation four or more SV's are continuously visible globally with an elevation mask angle of 5°. However, large DOP values still occur for short periods. Due to outages when DOP values become very large the average DOP value becomes meaningless and it is better to evaluate accuracy in terms of percentiles as in Figure 4.18.

Intuitively the optimum four SV configuration that minimises the GDOP would be three SV's evenly distributed on the horizon with one SV in the zenith. A minimised GDOP though does not always lead to an optimised selection criteria. This is because SV's close to the horizon are often rising or setting and low elevation atmospheric modelling is more unstable. Some authors (eg. Stein 1985) propose that SV selection should be based on maximising the volume of tetrahedron formed between the receiver and the SV's.

5.2 FILTERING

The user expected range error summary (Table 3.4) shows that non-systematic errors contribute 4.4m in the case of differential GPS. Since Dilution of Position values can not be reduced then filtering techniques are introduced to minimise random receiver dependent errors and hence improve the precision of a GPS position fix. The techniques of filtering can be applied to GPS at two different stages of the computations although they are inter-related, that is, filtering of the observed pseudo-ranges before position computation or filtering of the state parameters such as position and velocity.

In the first case the individual pseudo-ranges are assumed to have a set of random errors present (with zero mean) due to multipath and high frequency propagation noise. The noise in these pseudo-ranges can be reduced by employing the integrated carrier beat phase measurements as proposed by Hatch(1982).

The filtering of the state parameters, typically position, clock bias, velocity and clock drift can be carried out with knowledge of the dynamics of the receiver and even though this is slightly more complex it does allow for optimal filtering.

5.2.1 Meshing of Pseudo-range and Carrier Phase Measurements.

Hatch(1982) introduced a simple method to smooth the raw pseudo-ranges with integrated carrier phase values across epochs to yield at least an order of magnitude improvement in random pseudo-range noise.

The pseudo-range, although unambiguous, does exhibit short term noise in the order of a few metres due to receiver mechanization and atmospheric propagation effects. Lachapelle et al (1986) found raw TI4100 pseudo-range noise to be 3-6m RMS, while data collected on Trimble 4000S (June 1986) showed the RMS of raw pseudo-ranges to be about 2-3m. The more common form of the carrier beat phase measurement is the integrated Doppler frequency (Section 3.2.1) which is obtained by integrating the observed Doppler frequency of the carrier across an epoch interval resulting in a more precise, but not more accurate, determination of the change in range to the satellite across that epoch. The Trimble receiver determines the integrated Doppler frequency, in cycles (See Figure 3.9 in Chapter 3.3), by integrating the instantaneous Doppler frequencies between epochs:

$$\text{Integrated Doppler} = \sum_{i=1}^{i} D_i . dt \qquad (5.1)$$

where: D = instantaneous Doppler frequency in Hz.

i = number of epochs

Typical results from processing Trimble data on the UNSW geodetic GPS baseline program show integrated Doppler RMS noise to be below the centimetre level.

If the initial integrated Doppler bias, $\overline{P}_0$, could be determined then incremented at every epoch by ΔP (the change in range by integrated Doppler frequency) a relatively noise free pseudo-range value would result. The following equation (Hatch 1982) determines the initial bias by mapping the pseudo-range and integrated Doppler frequency measurements back to an initial integrated Doppler frequency bias.

$$\overline{P}_0 = \sum_{i=0}^{N} (p_i - \sum_{j=1}^{i} M_j) / N \qquad (5.2)$$

where: $\overline{P}_0$ = best estimate of the initial bias after epoch i.

P_i = pseudo-range at epoch i.

$\sum_{j=1}^{i} M_j$ = sum of integrated Doppler freq. from the epoch i = 0 to i. Note j = epoch interval i, i+1.

N = number of epochs since start.

The most precise estimate of pseudo-range, at any epoch i, can only be calculated by post-processing when all the data is available, since $\overline{P}_0$ can then be determined from equation (5.2) as $\hat{P}_i$:

$$\hat{P}_i = \overline{P}_0 + \sum_{j=1}^{i} M_j \qquad (5.3)$$

In the real-time situation results from post-processing are not available so meshing, when only data up to the current measurements are available, is done with a recursive form of (5.2) and (5.3) resulting in:

$$P_{i+1} = W_1(P_i + M_{i+1}) + W_2(P_{i+1}) \qquad (5.4)$$

where: P_{i+1} = 'best' pseudo-range value at time i+1

N = Nth successive epoch without loss of lock

W_1 = N/N+1 initially = 0

W_2 = 1/N+1 initially = 1

This filter (5.4) takes the previously optimised range and maps it to the current expected range by adding the integrated Doppler frequency. This is then combined with the current raw range to a lesser and lesser degree. Lachapelle et al (1986) used this technique on TI4100 data noting that the counter N is reset to zero when the integrated Doppler frequency loses lock.

Equation (5.4) was written into the author's program and Trimble data processed with it to analyse the nature of its effectiveness. The Trimble 4000S produced a full set of raw and processed observations every 15 seconds. From this data set the raw pseudo-range was taken and the modelled tropospheric and ionospheric corrections along with relativity, group delay and SV clock corrections applied to get an unfiltered corrected pseudo-range. This value plus the **R**aw **I**ntegrated **D**oppler were meshed using equation (5.4) and then compared with the Trimble's own filtered pseudo-range. Figure 5.2 shows the difference between the two values for a static antenna after the Trimble had been running for 30 minutes. The result from this trial exhibits a classical result from a dampened oscillator which was similar on the other three channels.

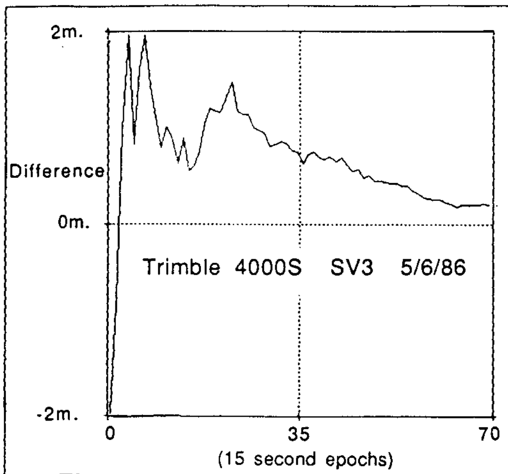


Figure 5.2 Filter Performance
Difference of Meshed Raw Range/Int. Doppler with Trimble Smoothed Raw Range

Lachapelle (1986) states that the advantage of using this simple filter are that due to its simplicity it can be incorporated in the real-time solution and its response to dynamics is rapid compared with a more complex Kalman filter in which responses can easily be muffled. Unfortunately when loss of lock occurs the filter reverts back to pure pseudo-range positioning for a period of time. The Sercel TR5S uses this technique and it is believed that the Trimble 4000 series incorporates a similar filter under the user option termed "Doppler Aiding".

5.2.2 Kalman Filtering.

When all the parameters that one is interested in (ie. the state) are varying in time due to dynamics of the platform then the sequential estimation technique of Kalman Filtering will give the optimal real-time estimate of those parameters. It is a recursive algorithim in which the previous state and its covariance matrix plus the observations from the current epoch are used.

This technique is regularly used for computing position of a ship at sea using shore-based radio navigation systems. The process of computing the ship's position at any instant in real-time (time t_j in Figure 5.3) is called **filtering.** The computation of the position at which the ship is expected to be at a subsequent time(based on last measurement t_m) is called **prediction** and estimation of where the ship was once all data is available, in a post operation sense, is called **smoothing.**

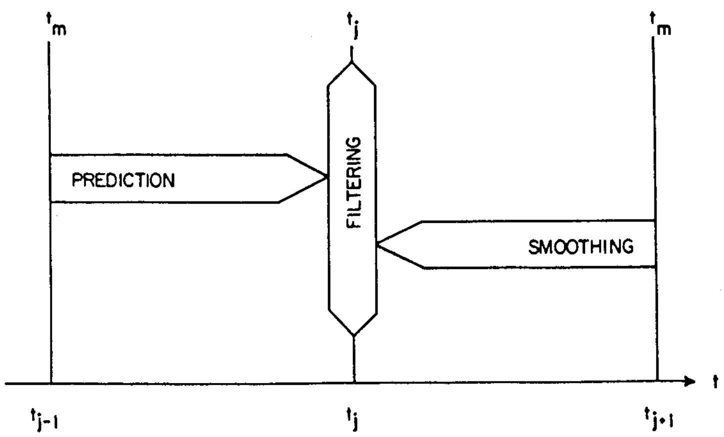


Figure 5.3 Relationship between Prediction, Filtering and Smoothing. (Schwarz 1983)

The advantages of Kalman Filtering over Least Squares are that the Kalman technique forces a data organization that minimises data retention and so is more computer efficient. Kalman filtering gives the same result as if **all data** were available for a Least Squares solution albeit with very large matrix operations and inversions.

Definitions

A typical **functional linear model** which relates observations to parameters at time **t** is given by:

$$l(t) = A(t).x(t) + e(t) \quad (5.5)$$

Using convention from Schwarz (1983) then:

$l(t)$ = vector of observations at time t

$x(t)$ = " " parameters " " "

$e(t)$ = measurement noise vector with covariance matrix $C^e(t)$

$A(t)$ = design matrix at time t.

An example of this model would be the four pseudo-range solution for position and clock offset in a GPS receiver at a single epoch. For a dynamic platform a model exists that relates parameters at time **t+1** to parameters at time **t**; in other words we have some information on how the parameters vary with time - referred to as a secondary model or **dynamic model**. A classic example of this is a survey ship sailing a straight line at constant velocity.

The linearised model is:

$$x_{k+1} = \Phi_{k+1,k} . x_k + u_{k+1,k} \quad (5.6)$$

where: x_k = state vector at time k

x_{k+1} = state vector at time k+1

$\Phi_{k+1,k}$ = transition matrix from state x_k to state x_{k+1}

$u_{k+1,k}$ = system noise with zero mean and covariance matrix $C^{u}_{k+1,k}$ (unknown errors in dynamic model)

Note that Equation (5.6) is a recursive relation in that a future estimate of x_{k+1} can be obtained from the previous estimate x_k by the **transition matrix** defined by the physical laws controlling the dynamic process - the simplest model is linear behaviour. The unmodelled effects of the dynamic process (variations from the model: $u_{k+1,k}$), independent of measurement noise, affect the prediction process accuracy and are called process noise.

For a GPS determined position onboard a seismic ship a typical 8-**state vector** would be :

$$x(t)^T = [X, Y, Z, b, \dot{X}, \dot{Y}, \dot{Z}, \dot{b}]^T \qquad (5.7)$$

where: X Y Z b = geocentric coordinates and clock offset.

$\dot{X}, \dot{Y}, \dot{Z}, \dot{b}$ = change in coordinates and clock offset with respect to time.

The dynamic model would relate these states through a transition matrix such as:

$$\Phi_{k+1,k} = \begin{bmatrix} 1 & 0 & 0 & 0 & \Delta t & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & \Delta t & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & \Delta t & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & \Delta t \\ & & & & 1 & 0 & 0 & 0 \\ & & & & & 1 & 0 & 0 \\ & & 0 & & & & 1 & 0 \\ & & & & & & & 1 \end{bmatrix}$$

where: $\Delta t = t_{k+1} - t_k$

In this example, of a GPS receiver onboard a seismic ship, the system noise would be due to any vessel accelerations that have not been accounted for in the dynamic model (transition matrix). The covariance matrix for the process noise C^u is given in Gelb(1974) and is developed in Appendix

B for this example resulting in :

$$C^u = \begin{bmatrix} \Delta t . Q_1 + 1/3(\Delta t)^3 . Q_2 & 1/2(\Delta t)^2 . Q_2 \\ 1/2(\Delta t)^2 . Q_2 & \Delta t . Q_2 \end{bmatrix}$$

where : Q_1 = Process noise for X, Y, Z, b

Q_2 = Process noise for $\dot{X}, \dot{Y}, \dot{Z}, \dot{b}$

Equations

The primary observation model and the dynamic model are combined to produce the Kalman Filter equations which involve a **prediction** of the state vector and its covariance, then an **update** of the state by meshing the raw observations in an optimal manner. Each element of the **Filter Gain** matrix as defined in Figure 5.3 is essentially the ratio between statistical measures of the uncertainty in the state estimate and the uncertainty in an observation. The predicted value of X_k is compared to the value derived from observations at t_k with the relative gain of each derived from the covariance matrix of prediction and observation.

The flow diagram (Figure 5.4) shows the filter's recursive nature, giving an optimal estimate of the state vector based on all observations to t_k without necessity to store all data. Information on the previous measurement is contained in the state vector and its covariance matrix.

Note that as the time interval between updates increases then the process noise covariance matrix C^u will grow rapidly and so the entire covariance of the predicted state will grow with greater gain being placed on the epoch observations. At no stage is the magnitude of the process noise ever required in the filter, instead the expected error contribution through the covariance has to be

Figure 5.4 **Kalman Filter Equations**

Prediction Equations

$$\hat{x}_k(-) = \Phi_{k,k-1} \cdot \hat{x}_{k-1}$$

$$C^x_k(-) = \Phi_{k,k-1}\, C^x_{k-1}\, \Phi^T_{k,k-1} + C^u_{k,k-1}$$

where :

$x_k(-)$ ... State vector estimate before update

$x_k(+)$ ... State vector estimate after update

Φ ... Transition matrix

C^x ... covariance matrix of parameters

C^u ... covariance matrix of system noise

Update Equations

$$\hat{x}(+) = \hat{x}(-) + K\{L - A.\hat{x}(-)\}$$

$$C^x(+) = \{I - K.A\}\, C^x(-)$$

$$K = C^x(-)\, A^T\{A.C^x(-)\, A^T + C^e\}^{-1}$$

where :

K ... Gain Matrix

C^e ... covariance of measurement noise

A ... design matrix (partials measurement w.r.t state)

I ... identity matrix

L ... measurements

Kalman Filter Procedure

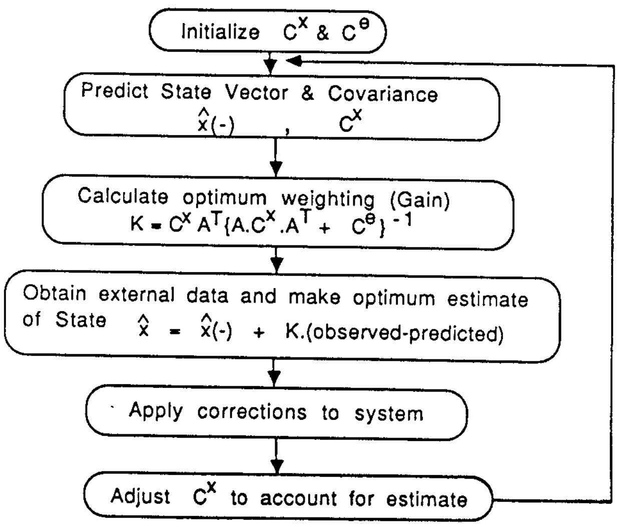


Figure 5.5

determined.

The 8-state vector can be simplified for the cases in which:

- a precise clock is used,
- the elevation is constrained and need not be solved for,
- the receiver is static.

Relationship of Kalman Filtering to Sequential Least Squares.

It is possible to formulate the kinematic position solution algorithims with the more familiar sequential Least Squares approach. Sequential Least Squares can be regarded as a special case of the Kalman Filter. In other words Sequential Least Squares is the Kalman Filter applied to parameters that do not change with time and so Δt is zero in all the Kalman equations. This leads to a transition matrix with all elements zero, a state vector that is not time dependent, and a weight of zero applied to the dynamic model.

The basic Sequential Least Squares equations are presented in Appendix C. Cross (1983) presents examples of Sequential Least Squares where as new measurements are carried out (at more recent epochs) then the initial solution or estimate for that most recent epoch, t_k, is upgraded by the inclusion of these new measurements. This solution is then used as the starting point for the next epoch's state at t_{k+1} with simple approximations made on the behaviour (static or dynamic) between epochs t_k and t_{k+1}.

The formal equivalence of the Kalman Filter and Sequential Least Squares equations is demonstrated in Cross(1983) and Schwarz(1983).

In summary, by redefining the state vector before update as the initial Least Squares estimate we can directly relate the Kalman update equations to Sequential Least Squares.

5.2.3 Sequential Least Squares.

The sequential Least Squares approach to filtering kinematic GPS has been studied and documented by Cannon et al (1986), Kleusberg (1986) and Seeber et al(1986), all using data sets from TI4100 receivers. The Sequential Least Squares approach has been taken by these researchers for the meshed pseudo-range/carrier phase kinematic solution, rather than Kalman filtering. Seeber et al (1986) states that it was not possible to formulate a sufficiently precise dynamic model so the models employed have simple or no assumptions as to dynamics.

The nature of the GPS measurements are that the pseudo-ranges give good absolute positioning accuracy though the noise level is at the 2-5m level whereas carrier phase measurements have noise levels two orders of magnitude smaller and give very precise information on change in the platform's position between two epochs.

By definition sequential Least Squares is used to estimate parameters that are **not** changing with respect to time so for a kinematic application **Cannon** considers the solution of a fixed vector between two successive position updates (epochs). The previously optimally determined position and clock bias at epoch t_k is used as a-priori data and the three coordinate unknowns and clock bias at epoch t_{k+1} along with the three coordinate differences and relative clock drift across $(t_{k+1}-t_k)$ are to be solved for. The total number of unknowns is eight; six coordinate unknowns, a clock bias and drift. Since the GPS receiver tracks four SV's there are eight observations; four pseudo-ranges at

t_{k+1} plus four phase measurements accumulated over (t_{k+1} - t_k). The differential corrections from a static monitoring receiver can be applied to the measurements of the kinematic receiver at the start of this computation cycle.

The sequential algorithim is derived from the Kalman filter equations by assuming a constant velocity between epochs as determined across epochs t_{k-1} and t_k to predict initial parameters at t_{k+1}.

Two observation equations are formed; one for the single epoch pseudo-range solution and the other for the change in phase between epochs. Cannon also makes use of differential data from a monitor GPS receiver to reduce systematic errors and this method referred to as delta single differences, is discussed in Section 5.3.

Starting from the known position with a-priori statistics, the vector of unknown parameters at t_k is x_k^o with covariance matrix C_k^o. Using the velocity estimate the corresponding vector at t_{k+1} (x_{k+1}^o) and its covariance matrix (C_{k+1}^o) are;

$$x^o = \left| \begin{array}{c} x_k^o \\ \hline x_{k+1}^o \end{array} \right|$$

$$C^o = \left| \begin{array}{c|c} C_k^o & 0 \\ \hline 0 & C_{k+1}^o \end{array} \right|$$

The partitioning is such that the solution of x_{k+1}^o is really of main interest. The estimated parameter vector and covariance matrix after adjustment are :

$$\hat{x} = x^o + \hat{K}$$

$$\hat{C} = C^o + K.A.C^o$$

where: $\hat{\delta} = -K.w$

$$K = C^o.A^T[C_1 + A.C^o.A^T]^{-1}$$

and: $\hat{\delta}$ ...estimated corrections to vector of unknown parameters x^{o}.

K ...Gain matrix

A ...Design matrix

C_l ...Covariance matrix of observations

w ...misclosure vector (ref. Cannon(1986) Equations (13),(14))

The approach is similar to that taken by **Kleusberg** who uses triple differencing (delta single differences that are differenced over satellites) so eliminating any receiver clock errors. However, if receiver clocks are stable in time the relevant parameters can be modelled to aid cycle slip detection in phase measurement and blunder detection in psuedo-ranges.

Although not strictly sequential Least Squares the approach **Seeber** takes is similar to the Hatch method in that no a-priori knowledge of vehicle dynamics is assumed. The integrated carrier phase across two epochs is used to give the best estimate of the new position then meshing in of the psuedo-ranges based on a Gain matrix which is derived by assessing the relative magnitude of the pseudo-range and phase covariance matrices gives this method its sequential nature. The Gain matrix at t_k is derived from:

$C_k = \sigma_r^2 . Q$ (Q is the matrix of normals)

= Covariance of parameters from psuedo-ranges

$\Delta C_{k-1,k} = \sigma_{\Delta r}^2 . Q$ Covariance of parameters from integrated carrier phase across epochs t_{k-1} to t_k.

1. Provisional estimate of covariance matrix:

$$C_k^* = \hat{C}_{k-1} + \Delta C_{k-1,k}$$

2. Update with pseudo-range information:

$$C_k = C_k^* - G_k . C_k^*$$

3. where the Gain matrix is:

$$G_k = C_k^*(C_k^* + C_k)^{-1}$$

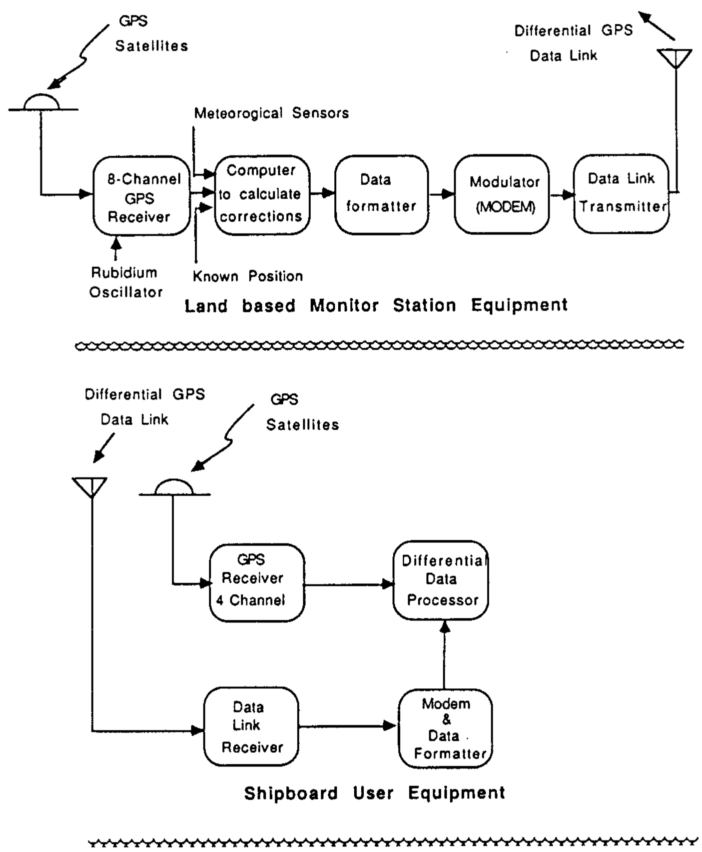
5.3 RELATIVE POSITIONING WITH DIFFERENTIAL GPS.

It has been shown in previous sections that it is not possible to detect and remove the effect of systematic errors by processing measurements from a single kinematic GPS receiver. Residual propagation effects, SV clock and ephemeris errors can not be determined with a kinematic receiver. Although real-time filtering increases the precision of the position by reducing the effect of random noise it does not improve the absolute accuracy of the position. Many authors including Lachapelle et al (1986) and Blanchard (1986) discuss processing techniques by linearly combining measurements (pseudo-ranges or both pseudo-ranges and integrated carrier phase) from two receivers - called differential GPS. To ensure accuracies better than 10-20m presently achievable with single GPS receivers then differential GPS must be considered for hydrographic surveying. Differential GPS is carried out by differencing simultaneous measurements from two receivers and so determining the relative position between receivers.

5.3.1 Differential Techniques

The basic form of differential GPS requires one monitor receiver to be located on an accurately defined ground mark so that the observed data can be compared with the calculated range and phase data then the differences are transmitted to a mobile receiver so that they can be applied with opposite sign (Figure 5.6). This section aims to outline the techniques needed to implement a differential system.

Figure 5.6 **Differential GPS Configuration**



Single Differencing.

There exists two methods of processing differential data with single differences :

1) Measurement type differential GPS. Differencing between two receivers at one epoch is accomplished by subtracting equations in the form of (3.2) and (3.7) from each other. It is the difference of measurements from two receivers observing the same SV that eliminates the effects of instabilities in the ephemeris, SV clocks and the majority of the propagation effects. Differencing by this method allows for ΔR (the baseline components ΔX, ΔY, ΔZ) and Δb (relative receiver clocks bias) to be determined at each epoch. Cannon (1986) states that for medium accuracy applications that require 5-10m (1σ) single differenced pseudo-ranges can be used whereas for higher accuracy

applications that demand 0.5-2m (1σ) relative pseudo-ranges and phase measurements can be used.

In the case of differencing carrier phase measurements :

$$\Delta\Phi = f(\Delta R, r, \Delta b, \Delta N)$$

where: $\Delta\Phi$ = differenced carrier phase

r = satellite position

ΔN = differenced ambiguity of integer cycles.

In the case of differencing pseudo-range measurements :

$$\Delta\rho = f(\Delta R, r, \Delta b)$$

where: $\Delta\rho$ = differenced pseudo-ranges

2) Position type differential GPS. The method of differencing positions is similar to 1) in that the reference receiver position is known but the correction data is computed from differences in the known survey coordinates and GPS measured coordinates. These coordinate errors ($\Delta\Phi$, $\Delta\lambda$, Δh) can be applied to the second receiver to correct its navigation solution.

Delta Single Differencing.

This is the difference between two stations and between successive epochs which has all the advantages of single differencing, mentioned previously, to virtually eliminate systematic effects as well as bringing the sequential nature of processing into the solution for handling kinematic applications.

In the case of differencing carrier phase measurements :

$$\delta\Delta\Phi = f(\Delta R, r, \Delta b)$$

Double Differencing.

This is the difference of two single differences (between station differences) related to two different satellites at the same epoch. The method solves for the baseline components, ΔR, and the ambiguity term, ΔN, while eliminating both SV and receiver clock biases.

In the case of differencing carrier phase measurements :

$$\Delta\Delta\Phi = f(\Delta R, r)$$

5.3.2 Differential GPS

The GPS point position solution is affected by systematic and random errors. These are subsequently magnified by SV geometry. All errors have been discussed in Chapters 3, 4, and 5. The basic concept of differential GPS is similar to that employed in differential Loran C which involves placing a monitor receiver on a coordinated point and comparing the known location with that calculated by GPS. The differences are then broadcast to nearby users who can improve their position solutions. The systematic errors are:

- **Ionosphere and troposphere delays**. When the mathematical correction model differs from the actual case, then errors occur. Signal paths vary from SV to mobile user and SV to monitor station though the magnitude of atmospheric inhomogenities on GPS is not presently well determined.

- **Ephemeris and satellite clock errors**. SV clock errors are compensated for by differential processing and the ephemeris error is also minimised. A small proportional error remains which is a function of the ephemeris accuracy and separation of the user and monitor station. This decorrelation is caused by the different line of sight component of the SV's 3-D orbital error on the two differing line of sights.

- **Selective Availability**. This error introduced by the U.S. DoD could be in the order of 30m (1σ) for a single pseudo-range and so is the main error source that can be minimised by the differential operation.

With removal of common errors the accuracy is then limited to those errors unique to a single receiver's operation : interchannel bias determination, analogue to digital signal conversion and mechanization during signal processing. The geometry of the system at any one time which is derived from the DOP values does not alter appreciably for typical separation distances as envisaged for hydrographic applications (Table 5.1):

Table 5.1: Effect of Baseline Length on DOP & Azimuth/Elevation to a SV. 1800hrs. 6/6/86 Sydney

	Baseline Length		
	0km.	100km.	500km.
GDOP	3.56	3.56	3.56
HTDOP	3.18	3.18	3.18
Azimuth to SV 6.	104.2^{0}	104.2^{0}	104.2^{0}
Elevation to SV 6.	66.6^{0}	67.76^{0}	71.3^{0}

5.3.2.1 Transmitted Message

The Radio Technical Commission for Maritime Services (RTCM 1985) and Blanchard (1986) consider that the measurements should be corrected, rather than measured positions, since users may be selecting different groups of satellites due to the earth's curvature and physical obstructions that block a low SV, or differing SV selection criteria. Since up to 10 SV's may be visible at any one time in the Block II constellation there are theoretically 210 combinations of four SV's and the monitor would be unable to transmit all those position corrections at an acceptable rate. Even if only 10 combinations gave sufficiently low Dilution of Position values, that would involve transmissions of 20 position corrections compared with 10 measurement corrections. In the case above it has been assumed that the monitor GPS receiver has the capability to receive 10 SV's simultaneously. Similarly it has been assumed that the mobile receiver is of cheaper design and capable of receiving only four SV's simultaneously. A simple two receiver operation in which SV selection is strictly controlled may find that corrections to positions are more easily processed and so more suitable than measurement type corrections. With the present system (1986) transmissions as simple as voice communication with $\Delta E, \Delta N$ position corrections for a given constellation every 1/2 hour was found suitable for calibrating an offshore acoustic array in NW Australia in March 1986 (Section 6.2.3). In this way the system was continually monitored for integrity by the static shore station giving a measure of confidence to the point positioning as well as providing the corrections.

The RTCM have proposed a format that consists of 16 message types that can be transmitted at differing rates as given in Table 5.2

The RTCM state that the differential data link to support the messages must allow reliable communication at a data rate of at least 50 baud. For hydrographic surveying priority must be given to ensure that message types 1, 2, and 4 are transmitted at the optimum rate so Blanchard(1986) proposes that the other message types be relegated to the background and repeated less often. The main components for a general GPS differential system are shown in Figure 5.6.

Table 5.2 Pseudo-lite Message Types (RTCM 1985).

Message Type No.	Message Type	Repeat Rate for Hydrographic Survey
1	Differential Corrections	Hi
2	Delta Differential Corrections	Hi
3	Station Parameters	Lo
4	Surveying(Int. Carrier Phase)	Hi/Lo
5	Constellation Health	Lo
6	Null Frame	N/A
7	Beacon Almanacs	Lo
8	Pseudolite Almanacs	Lo
9	High Rate Differential Correction	Lo
10	P-Code Differential Corrections	N/A
11	C/A Code L1,L2 Delta Corrections	Lo
12	Health Message	Lo
13-15	To Be Decided	N/A
16	Special Messages	Lo

Real-time Differential Data Links

The purpose of the data link is to relay correction messages from the monitor station to the field user with the update rate being determined by vessel dynamics and precision required. The link must be designed to allow real-time processing, have strict message content and timing, have high reliability and a long range capability.

In its simplest form the user really only need be in range of a transmitter of simple data signals on a voice grade channel. A wide variety of frequencies and techniques have been considered:

Meteor Burst - as meteorites enter the earth's atmosphere they produce a trail of matter that allows radio waves to be reflected off. Their occurrence is frequent enough to allow continuous communication though present antennas need to be steerable.

Ionospheric bounce - for long distances but not continuous.

Sky wave - The trend in the development of relative GPS communication equipment will be toward the use of narrow bandwidth, extremely frequency-stable, low power transmitting and receiving equipment with an emphasis on simplicity and reliability (Wells,1986). Current technology is adequate however new dedicated communication link receiver designs, for example single-board, single frequency, narrowband receivers, will reduce the unit cost and increase system reliability. Transmissions are suitable up to a few hundred kilomtres with frequencies around 2MHz.

Pseudo-lite - In this case the monitor station transmits differential corrections in place of the standard navigation message on a GPS L band signal therefore no separate data link receiver is required. The same antenna circuitry as what the SV signals are obtained on can be used by the receiver to read the pseudo-lite signal. This may lead to cheaper overall user equipment costs and since the pseudo-lite signal is tied to GPS time it can provide the user with an additional range and so permit acceptable navigation accuracy during outages. The system integrity is improved as the messages warn the user when an unacceptable SV signal error occurs.

Satellite relay - present civilian satellite communication is via Inmarsat which is expensive to use and requires directional (steerable) antennas. Equipment costs will drop with the introduction of Standard-C micro satellite communication terminals along with omnidirectional antennas (due mid 1988) so Inmarsat could become more suitable. The recent licensing in USA for Geostar satellites allows the L band to be used for civilian one way messaging making this a potential option.

Implementation Considerations

Four important questions regarding implementation of differential GPS must be addressed:

1. What rate will differential corrections be transmitted ?

2. What if the user has not decoded the most recently refreshed hourly ephemerides and is using different ones to the monitor?

3. Do different models of receivers give differing positions for the zero-baseline test?

4. Could mobile users be operating on differing filter settings to the monitor. (Monitor on none, while mobile using a Kalman filter.)

The RTCM (1985) and other groups have studied some of those problems in detail and the general consensus to the above problems are :

1. The differential correction transmission rate will be about 15 seconds based on their simulations of Selective Availability to keep error buildup below 5m.

2. The age of the SV ephemerides is transmitted from the monitor station and so the user can compare the two. In most cases the mobile user's data will be older and so the navigation message should be decoded immediately, otherwise the previous hours ephemerides should be buffered in the receiver and used until the monitor updates.

3. Different GPS units appear to exhibit different position update characteristics probably due to filter settings or channel measurement methods. There is no published material on whether the raw observations are the same for different receiver models which is a basic criteria for differential GPS. A zero-baseline test involves one antenna feeding two

receivers simultaneously. By this method systematic errors are removed and only inter-receiver differences are measured. Ideally two receivers suitable for differential GPS should show little or no difference with this test.

4. Differential pseudo-range corrections are normally applied to the users raw observations before entering the position filter. If differential position corrections are transmitted and applied to a user's filtered position then errors could occur since the corrections are from 'instantaneous' readings and are being applied to a filtered value so re-introducing unfiltered noise.

In conclusion, simple position type differential corrections are unlikely to be of wide application for a multi-user environment where the method to correct measured pseudo-ranges before calculating position is more suitable. The measurement type differential approach assumes that the monitor GPS can receive more than four SV's simultaneously whereas the mobile unit receives only four SV's. It is possible for the mobile user to convert the differential pseudo-range corrections to a differential position correction and this may be a simpler alternative as it involves less computation than calculating the position from corrected pseudo-ranges.

The ideal receiver will have a facility to directly accept the input of the measurement or position corrections so that its internal processor can process them rapidly. The rate of applying the differential corrections will depend on the nature of the Selective Availability.

Measurement Type vs. Position Type Differential GPS

Intuitively it is expected that both differential processing approaches give the same final mobile receiver position. Even from simulations of receiver separations of up to 500kms the geometric configuration of the SV's barely alters (Table 5.1). Because of this similar geometry the design matrices for both receiver's solutions are similar and so the effect of systematic errors is virtually the same. To further evaluate the two approaches to differential GPS, test data was processed and the results are shown in Section 5.3.3.

5.3.3 Trimble 4000S Differential Experiment

A series of tests were carried out that aimed to study the performance of two GPS receivers operating simultaneously. Both static and kinematic tests were attempted to give an insight into receiver characteristics and processing techniques.

Aims of the Tests:

1) If two receivers can be connected to receive the signal from a single antenna then the only differences that will be seen in the measurements are due to differing receiver calibrations, internal oscillator and receiver signal processing differences. Systematic errors such as propagation effects, SV clock, SV ephemeris along with multipath are effectively nulled by use of a single antenna. Such a test is called the **zero-baseline test**. For real-time differential GPS the results of such a test should show the magnitude of any interchannel bias calibration errors and the effect that differing filter settings have on receivers.

2) In all the tests it was aimed to study how **accurate** the

GPS determined position was when compared with the survey control. What effect does updated ephemeris have on the position determination?

3) By setting up two receivers on a short static baseline with the antenna spacing about 12m then the combined effect of systematic and random errors can be studied. The advantage of such a short separation is that the **relative position** can be measured precisely. Also the change in DOP values at both stations is negligible so systematic errors will be identical for both receivers.

4) It was aimed to study the effect of systematic errors on longer lines of over 200kms. Results may show a degradation of relative position due to errors that are dependent on baseline length such as SV ephemerides or ionospheric effects.

5) The data collected from the static tests can provide an ideal chance to compare processing using both the **measurement type and position type differential techniques**. With a static test the errors of the relative positions of the antennas is at the centimetre level. If one antenna was continuously mobile then the errors in determining its position by independent means could easily be at the metre level and may hide any differences from processing.

6) To overcome the problem of measuring the position of a **kinematic antenna** a test was devised in which one antenna remained static and the kinematic antenna was moved between precisely surveyed pillars. The kinematic antenna remained on each pillar for a few minutes before moving. The aim of the kinematic experiment was to note what problems occurred

when moving the antenna (loss of lock) and to see if the relative positions were degraded by movement.

The basic assumption to the success and accuracy of differential GPS is that **two receivers should exhibit the same errors in position, within limits, at simultaneous epochs**. The relative position difference between the receivers should therefore be more reliable and precise than single receiver position.

Experimental Method:

Two Trimble 4000S receivers were used to collect data on an accurately surveyed network at the UNSW between 5-7th June 1986 and in Queensland on the 27th May 1986. In all cases the two receivers observed the same set of four SV's for periods ranging from 15 minutes to 50 minutes before switching to a new set of SV's (ie. a new experiment) to minimise DOP values. Even though the Trimble 4000S measures the integrated carrier phase as well as the integrated Doppler frequency and pseudo-ranges, making it more ideal for static survey applications, the later two measurements are usually available on cheaper GPS navigation units and were used to process this data.

Unfortunately the zero-baseline test was not carried out as information on the antenna pre-amplifier was unavailable and so an antenna signal splitter could not be designed.

Baseline tests varying in length from 12m to 8900m were carried out in NSW with data being logged simultaneously every 15 seconds. The Trimble 4000S receiver allows synchronized logging based on GPS time. In all UNSW tests one antenna was located on GAS2 pillar which is a first order survey control station on the UNSW Geography and

Surveying building rooftop. The other stations used in the UNSW grounds were related by precise survey to GAS2. All survey stations used outside the UNSW grounds are part of a first order control network. The long line measured in Queensland was also between two first order survey stations. A total of 15 tests were attempted with seven static and one kinematic test analysed.

Comparison with Survey Control:

The data logged from the Trimble 4000S includes the point position solution in both Earth Centred Earth Fixed (ECEF) coordinates and geographic coordinates expressed on the WGS-72 datum. Only survey station GAS2 was known on the Geodetic Model of Australia 1982 (GMA82) geodetic datum which can be transformed into the WGS-72 datum. Other survey stations used in these tests were based on the Australian Geodetic Datum 1966 (AGD66) in which case the transformation to WGS-72 is unknown. In order to compare the Trimble WGS-72 data with the ground control provided, the WGS-72 positions of all points had to be determined. This was carried out by firstly calculating the geodetic baseline solutions from GAS2 to the other stations using the Trimble software, TRIMVEC. The WGS-72 baseline vectors agreed to better than 0.1m when compared with the AGD66 vectors. The second step was to transform the GMA82 coordinates of GAS2 into WGS-72 datum. Finally the GPS determined baseline vectors were used to radiate from GAS2 and so determine the WGS-72 coordinates of the other stations. This method resulted in an accuracy sufficient to benchmark GPS point solutions against. The WGS-72 coordinates of the Queensland stations, TW17 and Tinana, were supplied by Division of Mapping and Surveying, Queensland.

Once WGS-72 coordinates were available for all survey stations the relative positions (baselines) were determined in both northerly and easterly components.

Data Analysis Techniques:

Two computer programs were used to investigate different approaches to processing of the GPS data to determine relative positions.

The first program processed data by the measurement type differential technique. The a-priori coordinates of the static monitor site were input and the pseudo-range 'observed minus calculated' values (O-C) derived by computing the range to the SV and comparing with the measured range. These O-C values are then applied to the pseudo-range measurements from the second receiver and the position solution determined is in terms of the a-priori monitor site.

The second program allows processing by the position type differential technique. In this case the GPS position from the static monitor is subtracted from that of the second receiver resulting in baseline components ie. $\Delta\Phi$, $\Delta\lambda$, ΔH. The absolute coordinates of the second receiver (mobile) can be determined by adding the a-priori coordinates of the monitor site.

Data logged from the Trimble 4000S includes both the raw pseudo-ranges as well as a set filtered by the integrated Doppler frequency (see Section 5.2.1). Data was processed with both the raw and the filtered pseudo-ranges for comparison.

Static Results:

As stated previously it was not possible to carry out the zero-baseline test. The seven baseline tests carried out and anaylsed are summarised in Table 5.3. Single receiver point positions varied in a random fashion from known survey control values by up to 14.5m (PDOP was always less than seven). These position differences were similar to those observed with a Trimble 4000A receiver in March 1986 (Table 3.3). As stated in the 4000S manual a position fix with a PDOP less than seven will give the most reliable solution. The positions determined (latitude, longitude, height) all drifted from the known positions with the rate of drift proportional to the PDOP. Greatest drift was noted in the height which could initially be 20m different from the known ellipsoidal value then drift another 20m in the 40 minutes of observation as PDOP increased to over 10. **In summary real-time horizontal positions were better than 15m when PDOP was less than seven.**

Single receiver point positions determined from raw pseudo-ranges exhibited greater random noise than those processed with the filtered pseudo-range (see Section 5.2.1). When differencing raw observations then the differenced value also appears with noise. When filtering data is processed by the differential technique the results are a less noisey solution but exhibit a drift in position. It has not been determined whether the filtering introduces the differing drifts or if some other error does. All data processed in Table 5.3 is from filtered data.

Table 5.3 - Static Differential Results

Test	Time (mins)	Length (m)		Mean Difference from Control	Range	
A	15	12	ΔE	+0.6	+1.0	+0.1
			ΔN	-1.8	-3.3	-1.1
			ΔH	+2.3	+4.8	+1.6
B	25	12		-0.3	-0.7	+0.3
				+0.1	+0.1	-0.1
				+1.5	+1.7	+1.2
C	23	400		+0.4	+0.9	-0.1
				-0.4	-1.0	+0.1
				-1.3	-2.5	-0.5
I	45	8900		+1.4	+2.7	+0.7
				+0.6	+1.6	-0.1
				-3.0	-3.5	-2.9
J	50	8900		-0.7	-1.1	-0.6
				+1.1	+1.6	-0.4
				+2.4	+2.9	+2.3
L	25	3000		-1.6	-2.3	-1.3
				+1.3	+3.0	+0.5
				-0.4	-0.9	-0.2
Q'land	30	228500		+0.9	+1.6	-0.8
				+1.4	+1.7	+1.3
				+0.9	+2.8	-1.9
MEAN & (Std Dev)			ΔE	0.1(1.0)	0.3(1.7)	-0.2(0.7)
			ΔN	0.4(1.2)	0.5(2.1)	0.0(0.7)
			ΔH	0.3(2.0)	0.8(3.1)	-0.1(1.9)

The column titled 'Mean Difference from Control' in Table 5.3 shows the difference between the mean differential baseline component and the known value from control. The length of time the values were meaned varied from 15 to 50 minutes. In real-time positioning it is not possible to determine mean values for a kinematic receiver. Instantaneous differential corrections have to be applied at each epoch. An instantaneous differential error is therefore considered in the column titled 'Range' in which the spread of errors is tabulated. The most extreme value is during

Test I in which the error in determining the instantaneous easterly component of the receiver separation was +2.7m in error. Although heights are not normally considered in hydrographic operations the results show relative height to be less precisely determined than horizontal position.

Data was processed using the measurement type and position type differential corrections. No difference in the resultant position was noted so all data presented in Table 5.3 was processed with the position type differential GPS technique. It is noted that computation for the position type differential GPS correction is much simpler than the measurement type technique.

Experiment J is illustrated further with the plots of the Trimble position for both GAS2 and Watsons Bay stations shown in Fig. 5.7 through to Fig. 5.10. The maximum deviation from WGS-72 survey control values for any given epoch is 4.3m for longitude at Watsons Bay and even though that is not excessive in this case the differential solution reduces the maximum errors to below 1.6m for any given epoch. The drift in the differential baseline longitude component (Fig. 5.13) is 3.2m in 50 minutes. This is not an unusual trend and was seen in the other short (12m) and longer (228kms) baseline results. The duration of Experiment J is noted as 50 minutes which was the longest of all the experiments as DOP values for a given four SV constellation seldom remain under eight for a one hour period.

As shown in Figures 5.9 and 5.10 the rate of longitude drift is different at the two receivers. This differing rate gives rise to the drift in relative positions for static receivers as shown in Figure 5.12. These differing drift

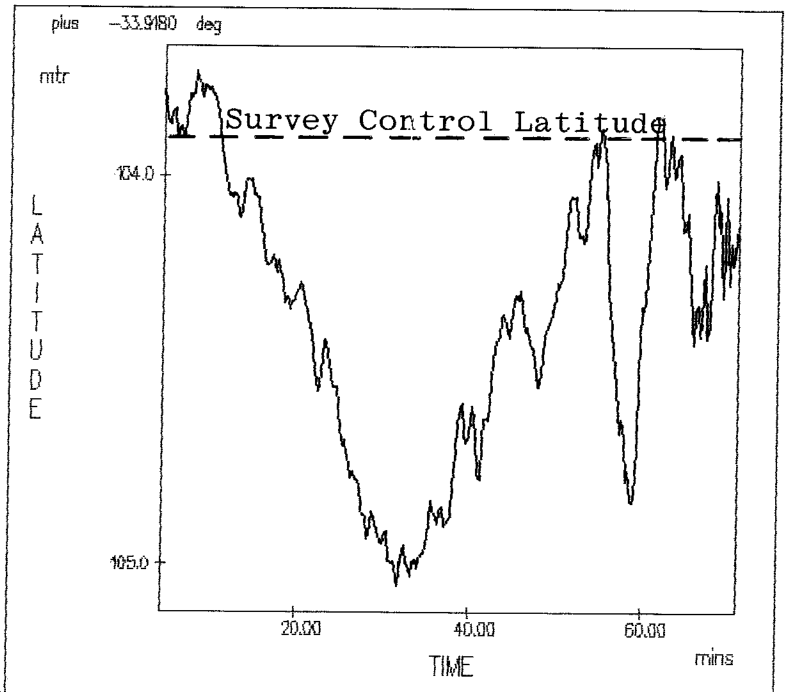


Fig. 5.7 Latitude: Trimble Point Solution: GAS2 : Test J.

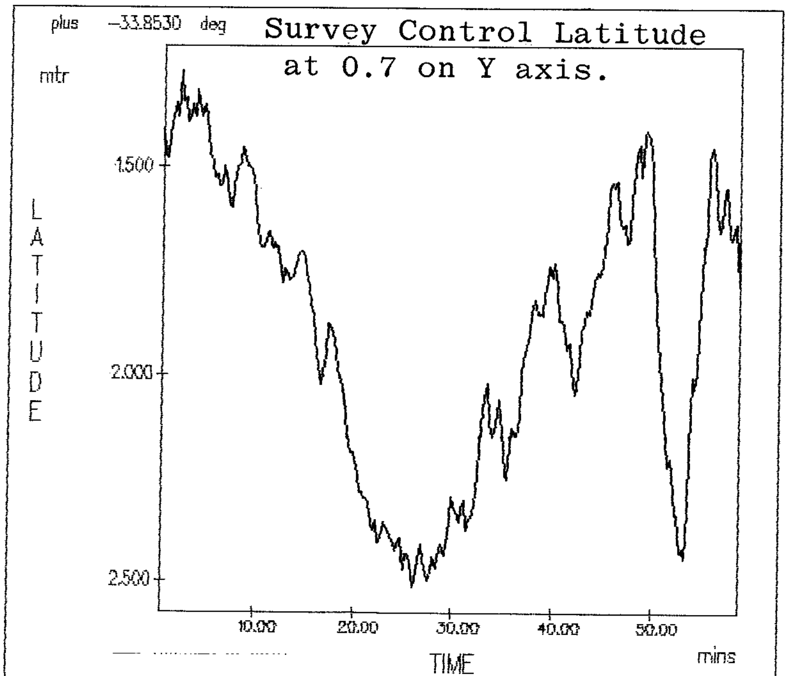


Fig.5.8 Latitude: Trimble Point Solution: Watsons Bay: Test J.

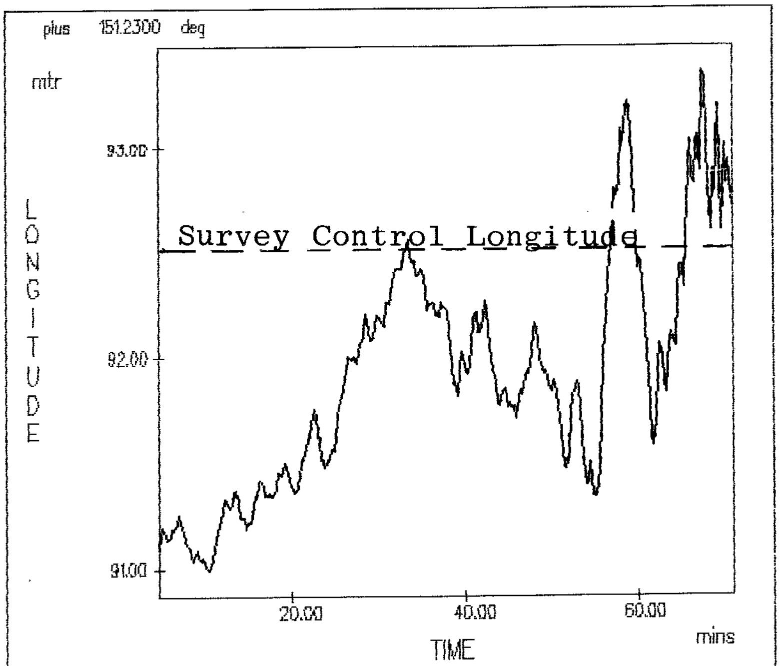


Fig. 5.9 Longitude: Trimble Point Solution: GAS2: Test J.

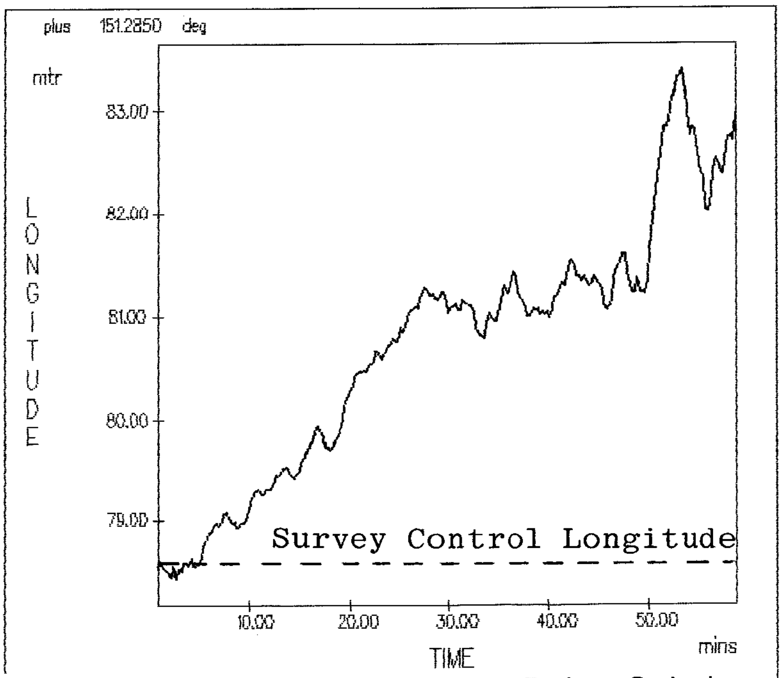


Fig 5.10 Longitude: Trimble Point Solution: Watsons Bay: Test J.

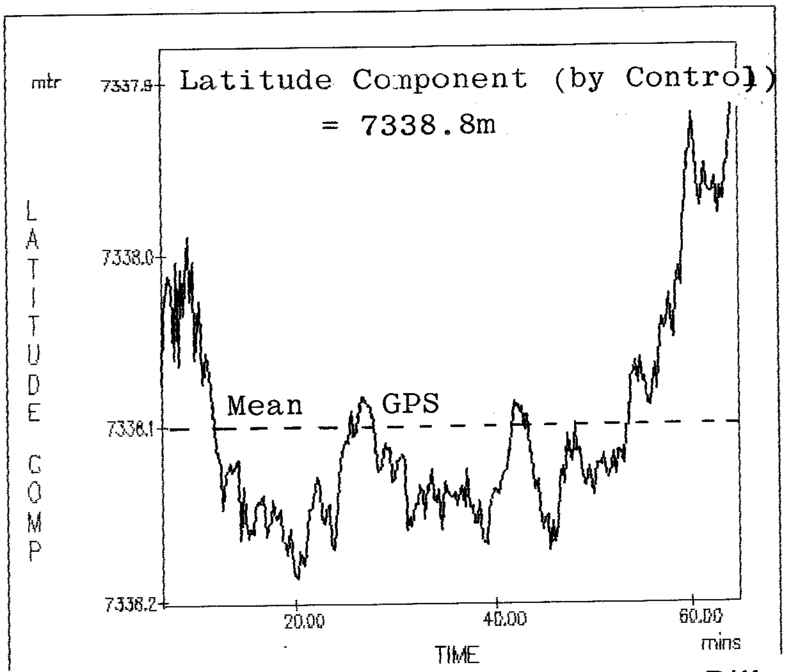


Fig 5.11 Latitude Baseline Component by Differential GPS: Test J.

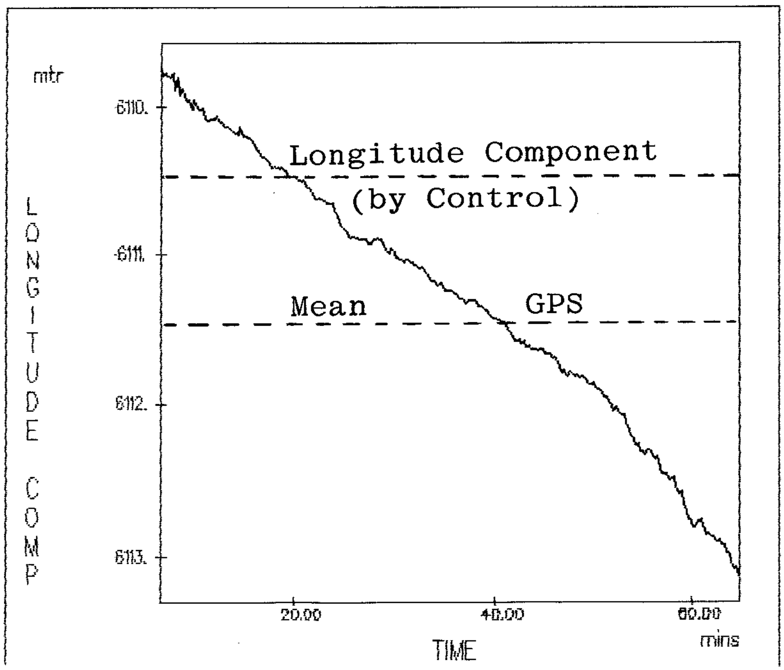


Fig 5.12 Longitude Baseline Component by Differential GPS: Test J.

rates were evident in all static data analysed but the reason was not determined. Even over the 12m line in which the geometry to the SV's is insignificantly different systematic GPS errors should be discounted. It was not known if multipath, receiver tracking noise or filtering caused these differing drift rates. A zero-baseline test would have proven if the drift was receiver dependent or not.

Kinematic Test

The kinematic test was carried out to study if problems occurred when moving the antenna, such as loss of lock or increased pseudo-range noise, and to see if relative positions were affected by movement.

Experiment G was carried out by placing one antenna on the first order station (pillar) on the UNSW Geography and Surveying building, GAS2. The roving antenna was initially placed on an adjacent pillar, no more than 12m away. This roving antenna was lifted and placed on other adjacent pillars long enough to gather a few updates, with the antenna eventually returning to the initial pillar after 11 minutes. The advantages of such an experiment are that it is tightly controlled since the relative coordinates of the survey pillars are known to better than 5mm and so a secondary real-time positioning system is not required to verify positions. Also the survey stations are so close that DOP values are no different between antennas so any differential error can be assumed due to non-system errors such as receiver characteristics or multipath.

Kinematic Results:

Data from two previous kinematic experiments was characterised by loss of lock due to a break in electrical

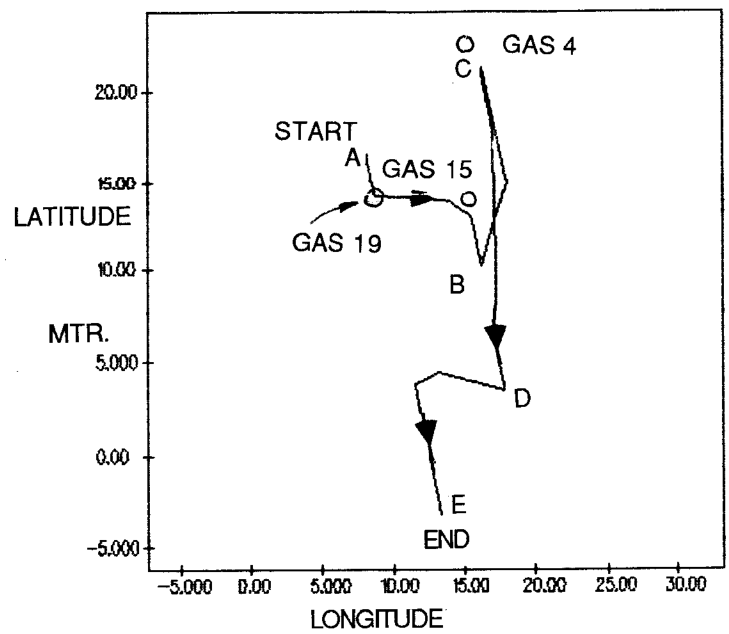


Fig 5.13 Movement of GPS Antenna: Single Receiver Solution.

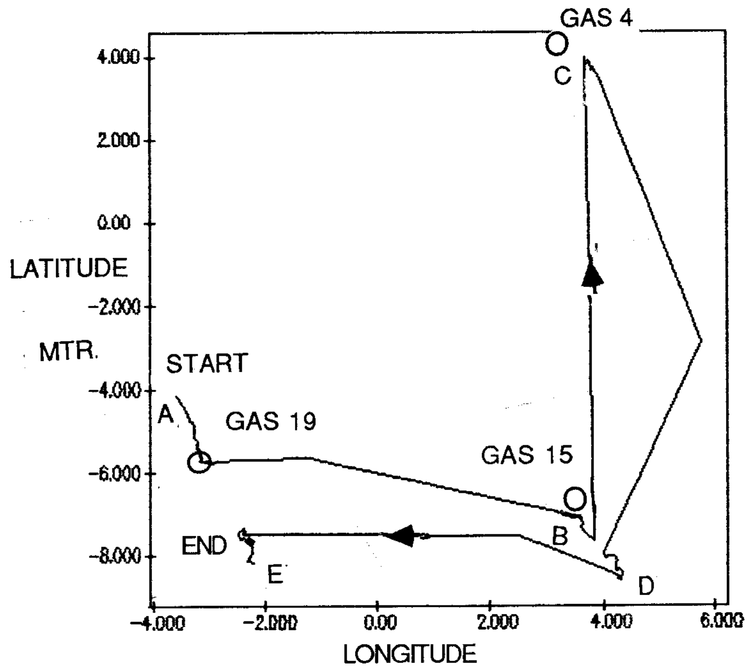


Fig 5.14 Movement of GPS Antenna: Differential Correction from Monitor.

contact between the antenna cable and the antenna whenever it was moved. This experiment did not suffer from loss of lock but is noted for the high PDOP values of 9.2 at the start, reaching 16.0 at the end. This may explain the very large position drift rates seen in Figure 5.13.

Figure 5.13 shows the mobile antenna starting at survey pillar GAS19 then tracking to pillars GAS15, GAS4, back to GAS15 and GAS19. Points labelled (A) to (E) correspond to the antenna being placed on GAS19, GAS15, GAS4, GAS15 then GAS19 respectively. Points (A) and (E) represent the same location, GAS19, but the single receiver solution shows a position difference of 20.6m after 11 minutes. Once the differential data from GAS2 (monitor) is applied to the mobile receiver then results are markedly improved (see Figure 5.14). Differential results still show a 2.0m difference at GAS15 and a 2.5m difference at GAS19. This poor repeatability at GAS19 would be due to the deteriorating PDOP as the results are just outside the limits found during the static experiments.

Summary and Discussion.

A zero-baseline test is a suitable test to assess the similarity of receiver performance prior to differential operation in real-time. Such a test isolates systematic and non-receiver errors from the internal receiver errors. It allows the magnitude of receiver errors to be assessed as well as filter performance. If an antenna splitter box is unavailable to feed two receivers then a very short baseline test in an environment free from multipath is an alternative. Ideally any survey stations used should have geodetic coordinates that can be precisely transformed to the current GPS datum. The tests carried out with two Trimble 4000S receivers over the 12m baseline points to the need for a zero baseline test to determine why differing receivers exhibit differing drifts in position. Future tests along this line should compare a number of different models of receivers capable of operating in a real-time point position mode. Results from such a multi-receiver test would show what accuracies are possible if it is ever desired to mix receivers in a differential operation. Mixing receivers would be advantageous for logistics but might be sacrificial in accuracy.

From the data analysed it appears that differential GPS, based on pseudo-ranges, can give instantaneous accuracies in horizontal position to better than 3m. The limiting factor is the differing drift rate in positions at both receivers which may well be solved by processing with integrated carrier phase (or integrated Doppler frequency) by implementing a sequential filter such as discussed in Section 5.2.3. GPS receivers that supply integrated carrier phase presently cost more than those that measure pseudo-ranges. Some receivers, such as the Trimble 4000A, measure pseudo-range and Doppler frequency. From analysis of the data it appears that the integrated Doppler frequency can be used in lieu of integrated carrier phase with no drop in accuracy for hydrographic surveys.

Results show that as DOP increases to values greater than seven then the accuracy of the point position deteriorates as well as the relative positions between receivers. Dynamic results show no obvious reduction in accuracy due to antenna movement.

Computations to process position type differential GPS present no computational burden to an external computer. When processing using the measurement type differential technique the O-C values determined at the monitor station must be added to the raw measurements at the mobile receiver. Processing then proceeds as dicussed in Section 5.1. This method requires more computational effort than position type differential GPS and so is best handled in the EPROM of a mobile receiver rather than an external computer.

6. GPS INTEGRATION INTO THE HYDROGRAPHIC ENVIRONMENT.

Integration of GPS with other navigation sensors is carried out with the aim to improve the overall accuracy of the positioning fix or increase the time that positioning is available by introducing system redundancy. The present constellation (1986), as outlined in Chapter 4, consists of only seven satellites so continuous real-time positioning must be achieved by integration of GPS with another positioning sensor. The software managing the integration can either be operating in an on-line computer or resident in EPROM in one of the navigation sensors. An example of a central computer system with a variable number of radio-navigation and marine sensors is shown in Figure 6.1 in which all sensor data is initially handled by an interface bus system that pre-processes the information and then passes it to the main computer in a compressed form upon request.

6.1 INTEGRATION TECHNIQUES.

6.1.1 Interfacing.

As is the case with radio-navigation systems it is the operators, the surveyors and navigators, who have already developed large libraries of specialized software that aid the execution of survey tasks efficiently and output steerage and navigation data to monitors, plotters and other devices. These users are often faced with producing 'one-off' special purpose navigation systems as well as having a standard survey package for tasks such as bathymetry. The variability in the nature of hydrographic survey tasks along with the number and combinations of positioning sensors is

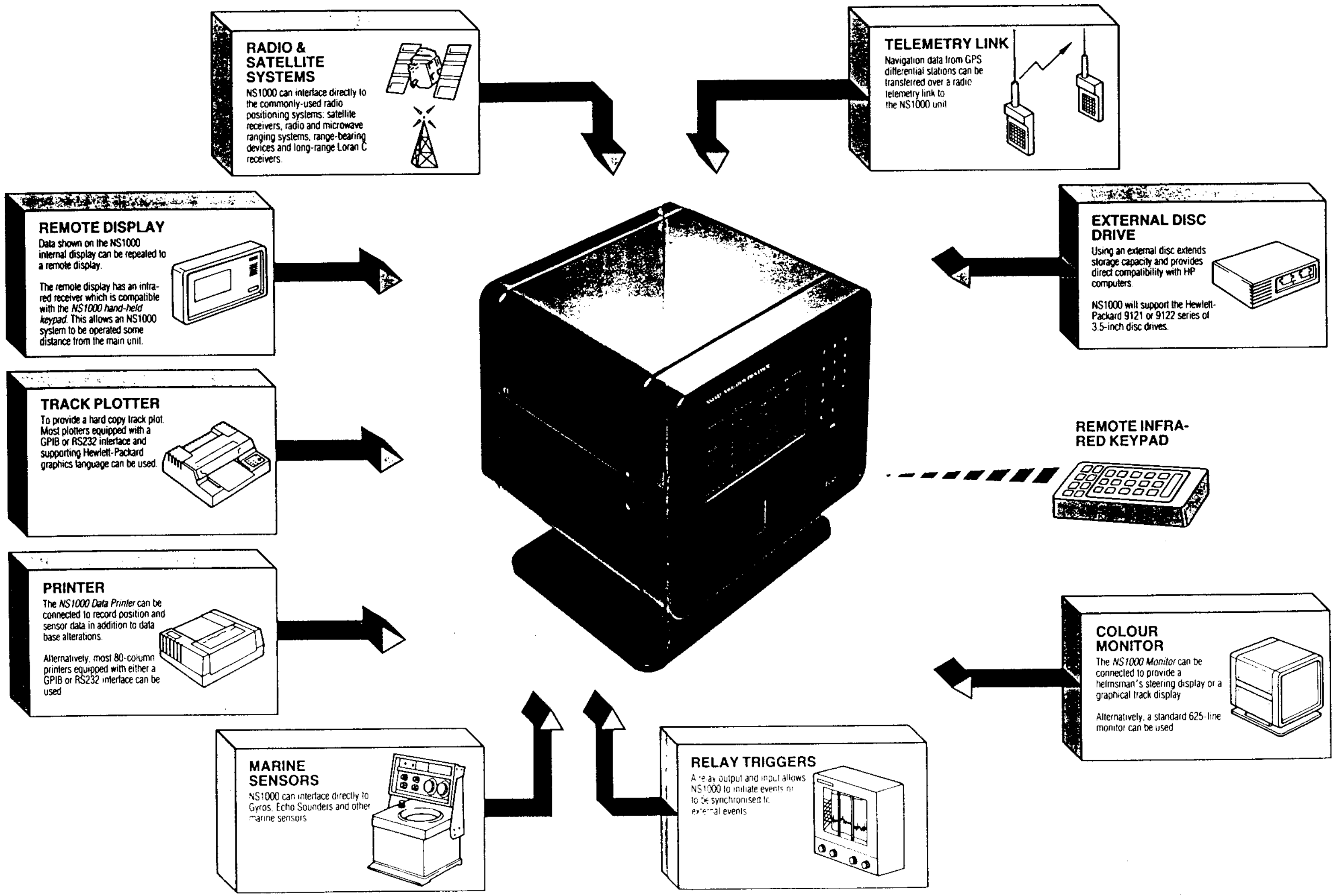


Figure 6.1 Example of an Integrated Navigation System.

further enhanced with the inclusion of a GPS sensor and so a technical knowledge of interfacing these sensors with computers is vital to the understanding of integration of systems.

From a survey of GPS navigation type receivers on the market as at 1986 the two main interfaces available are the serial type (eg. RS-232) and a more complex GPIB (IEEE 488 standard).

The **serial** interface simply sends the data along the line as a series of high or low voltage pulses, that is bits of information either 1 or 0 with seven or eight of these bits forming a byte representing an ASCII character. A serial connection only needs two lines (signal ground and data line) for a one way data transmission and three lines for a simple two way data transfer. Serial data communication is very suitable for radio transmission of the differential message through modem and radio communication means. So popular is this interface that almost all receivers have at least one serial port to access data and control the receiver operations.

This interface has limitations when interfacing as an on-line computer needs one serial interface 'card' for each RS-232 device it supports such as a GPS receiver and a printer. The rate of data transfer is also limited which can be restrictive in some kinematic applications.

The **General Purpose Interface Bus** (GPIB) requires that each device be assigned a unique code number (select code) so it can be addressed individually. There is usually just one cable linking all GPIB devices in a piggy back fashion. The connecting cable consists of enough wires to allow data to be transmitted in a rapid parallel fashion (one byte at a time) and send service requests from other devices at the same time. Any on-line computer would only require just one interface card to communicate with up to 15 separate devices and due to its popularity many GPS navigation receivers are supporting this interface.

6.1.2 Integration Methods.

There are two main methods of integrating sensors to form navigation systems:

1. The optimal method of integration is to mesh all data in real-time with the aim here to combine information in a rational manner from as few or as many sensors available. There is a need in this case to understand the behaviour of the sensor error characteristics so that data can be meshed optimally, most probably through a Kalman filter. Unfortunately the error characteristics from a single sensor with non-redundant measurements are very difficult to assess in real-time.

2. Another common technique is to let one sensor function as the prime navigation device with the others being used to quality control the primary device, for example ARGO radio navigation as prime with the lane count control by comparison with GPS. Other examples are such that one sensor could act as a calibration system to the other as in the case of absolute calibration of an acoustic array with GPS. Similarly the position solution with the lowest residuals could be the selection criteria for the prime device.

6.2 INTEGRATION OF GPS WITH OTHER NAVIGATION SYSTEMS.

6.2.1 GPS with Inertial Navigation Systems.

Initially there was interest in this form of integration due to the fact that first generation receivers were of the slow-sequencing type, dwelling on each individual satellite for a few seconds, and so the INS bridged the periods between new GPS updates. Now receivers being used for kinematic applications supply independent fixes at a rapid rate, typically once a second, and so INS is of more interest to maintain navigation during periods of outages.

Up till now INS have not been used onboard vessels for hydrographic surveys since they are extremely expensive to purchase and, although they give good relative position, they do not supply absolute positions without updates from an external source. The demands for positioning a vessel offshore are presently at the 3-10m level and are expected to become more demanding in the future, so differential GPS integrated with INS may eventually be used to monitor absolute vessel dynamics to this level.

Although INS is not capable of stand-alone operation, but needs to be regularly updated by an absolute positioning system, their performance lends to interaction with GPS and merging in an integrated system which can optimise the particular advantages from each system.

The Inertial Measuring Unit (IMU) provides from its accelerometers, three components (orthogonal) of accelerometer information in a reference coordinate frame (usually local-level) which is mechanically stabilized by its gyroscopes. The acceleration components, when integrated with respect to time, yield velocity in the three dimensions.

The 'strap-down' method where accelerometers and gyros are mounted on a non-stabilized orthogonal framework attached to the vehicle, is showing potential as being cheaper and as accurate as the stable platform type (Schwarz 1986). Data from the strap-down gyros are used for determining the orientation of the accelerometers as they vary with vehicle attitude.

With developments in new strap-down hardware such as ring-laser gyroscopes, strap-down IMU's and the software to process the data, the costs should be reduced substantially.

Comparative performances between GPS and INS equipment are presented in Table 6.1.

Table 6.1 GPS vs. INS.

GPS	INS
-gives absolute global position.	-gives relative position since observing starts.
-updates absolute position at 1Hz.	- updates relative position at 20Hz.
-can experience outages of 5-25 minutes.	-maintains functions independent of vehicle dynamics or signal interference .
-can use accurate 3-D velocity input for aiding the PLL to maintain lock and reduce cycle slips	- errors a function of time since updates.

The two main approaches for integrating INS and GPS are:

1) Using the precise relative dynamics information from INS as an input to the GPS receiver to adapt the tracking loop parameters to maintain lock or aid fast reacquisition of code and carrier when GPS experiences outages. It is also possible to navigate on INS alone during typical outage

periods of 5-25 minutes since the expected error growth of INS is minimal. Graham and Johnston (1986) simulated the error growth of INS with hourly GPS updates and show (Figure 6.2) INS error buildup as nominally zero up to 30 minutes then increasing exponentially before being reset to zero by means of a GPS update.

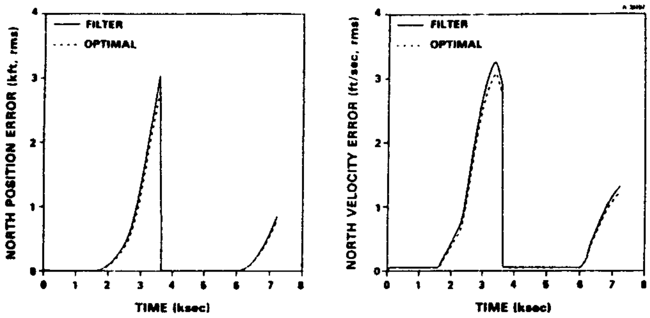


Figure 6.2 GPS aided/Strapdown INS Errors
1.8ksec = 30 minutes
(Graham & Johnston 1986)

INS not only provides navigation during periods of outages but can also considerably reduce the time required to re-acquire and lock onto the GPS signals once SV's become visible again. INS can also bridge gaps caused by cycle slips.

2) Using the GPS absolute position as an update to the INS Kalman filter and so make use of its faster output and ability to monitor vehicle dynamics more precisely. Because the errors of unaided INS grow slowly compared with vehicle dynamics these Kalman filter updates need only be incorporated every few minutes.

Discussion.

As well as the limitations discussed, the high capital cost and failure rate of present INS units have been factors in non-acceptance of it as a hydrographic sensor. There is hope that the future strapdown INS units will be cheaper and more reliable (Schwarz 1986) so more suitable for integration with GPS in hydrographic surveying systems.

The INS/GPS sensor will most probably be accepted more readily in airborne laser bathymetry where massive efficiencies in bathymetric data capture are possible.

6.2.2 GPS with LoranC.

For a position to be determined by LoranC a receiver needs to monitor two 'time delays' between transmitting stations which implies that at least three transmitting stations are operating with a configuration that gives a suitable 'strength of figure'. For an integrated GPS/LoranC system to operate then two GPS satellite signals plus a single LoranC time delay constitute three lines-of-position which is sufficient for solving the horizontal position and receiver clock offset. One such unit, the Trimble 10X, uses three or more GPS satellite signals when the HTDOP is suitable else it switches to the two GPS SV / one time delay approach when needed with mechanization via a Kalman filter. While GPS is acting as prime sensor the various systematic errors in LoranC such as land path and atmospheric variations can be determined. Then when the GPS SV's set, the LoranC updates are more precise as systematic errors have been detected.

The main advantage of this integration would be to extend the present GPS coverage of 12hrs/day for 2-dimensional positioning and so use the two satellite coverage and gain three to five hours extra GPS navigation and carry positioning over the short GPS outages. It allows for position fixing when neither GPS nor LoranC is capable of acting as a stand-alone system.

6.2.3 GPS and Acoustic Navigation.

For remote locations, where radio-navigation is not viable, a sub-sea long baseline acoustic array is usually deployed with the absolute calibration being carried out with a Doppler Transit (Transit) satellite receiver. Because of the irregular nature of Transit fix updates leading to dead reckoning errors during deployment and the long time delays in absolute calibration a typical four transponder array may take up to three days before it can be guaranteed to have an absolute accuracy of only ±20m.

Even with the limited usable window for GPS positioning the fact that GPS gives continuous real-time positions with single receiver accuracy of better than ±20m already makes it superior to Transit as the absolute global navigation sensor in an integrated acoustic system.

A case study in which the author was in charge of using integrated GPS and acoustics is discussed. This highlights the benefits in deployment, calibration, and in logistics and economics of GPS over Transit positioning.

CASE STUDY :

The following hydrographic survey was carried out for a private resource development company. Due to its location in the remote NW Shelf of Australia and the accuracy demanded, then an integrated satellite and acoustic navigation system was used. Figure 6.3 and 6.4 show the interfacing and equipment layout onboard the survey vessel used to deploy and calibrate the acoustic transponder array.

The discussion highlights important points to note for future operations. The drilling site was located 250kms offshore North West Australia (Western Australia). The

Figure 6.3 **Integrated Satellite and Acoustic System**

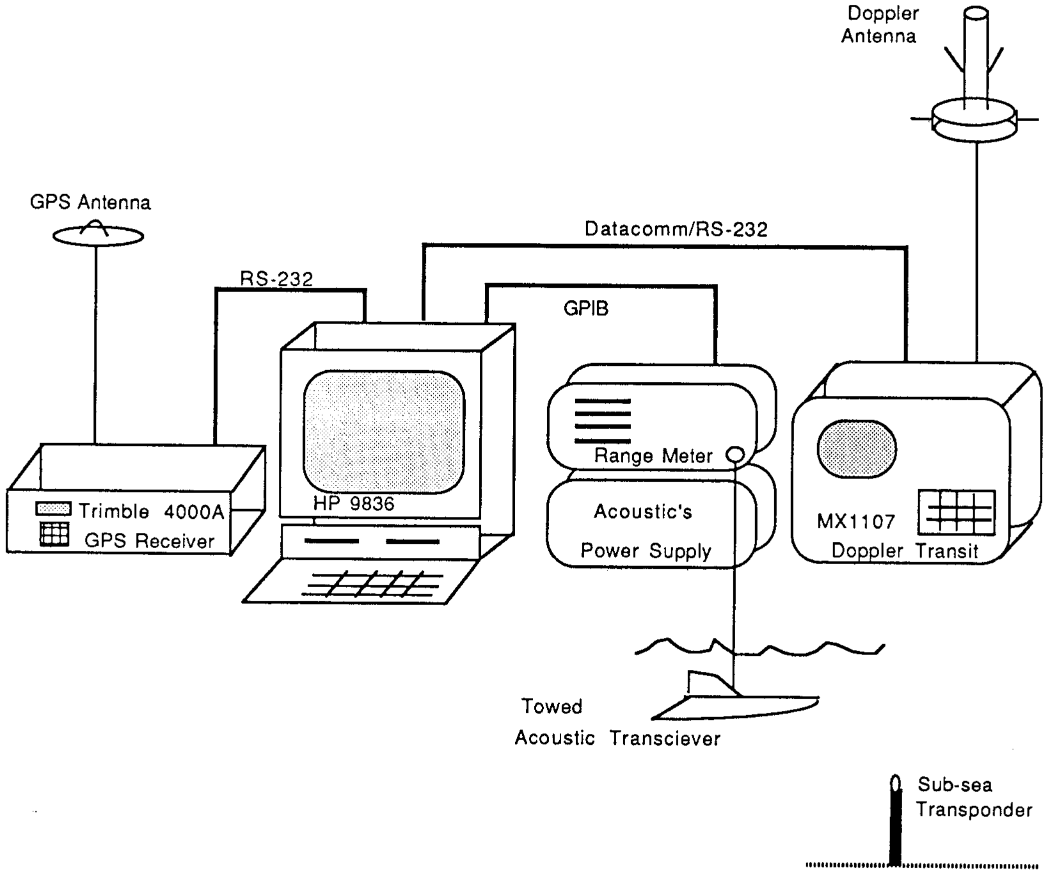
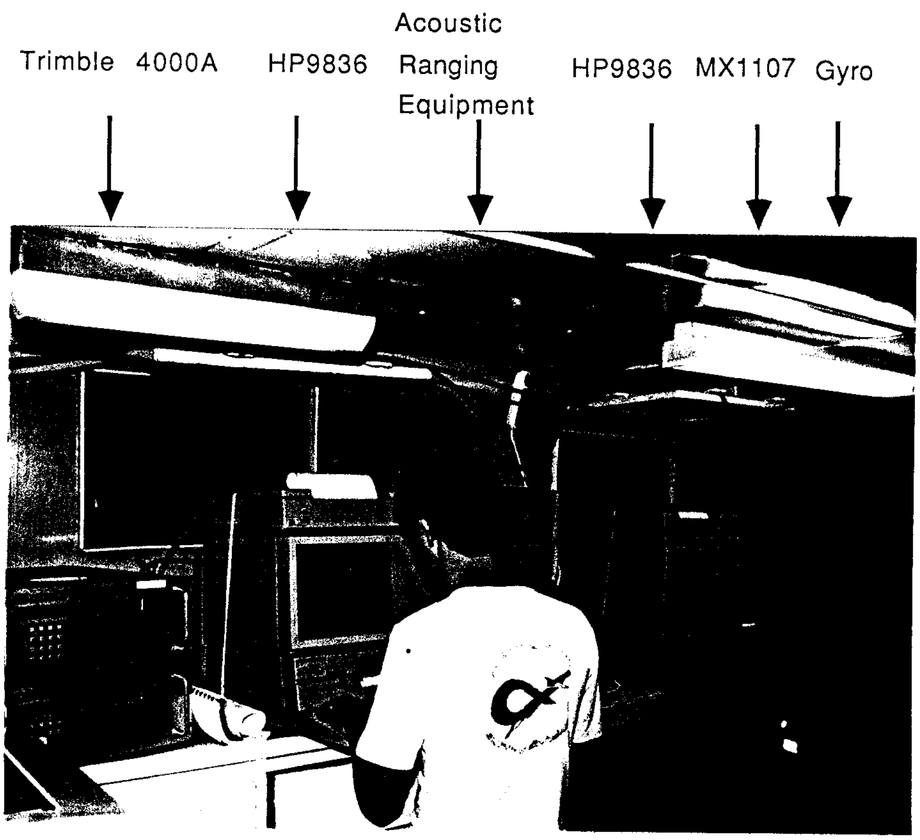


Figure 6.4 Integrated System Layout onboard Survey Vessel (March 1986)



operation was completed in March 1986 immediately after the typhoon season. The aim was to carry out a **site survey** over a 2x2km square grid involving bathymetry and side scan sonar then to deploy surface location bouys and **position an oil-rig** within 20m radius of the desired drilling location with an accuracy of ±5m.

The method used was to deploy four acoustic transponders (on the seabed) using the shipboard GPS so ensuring 24 hour real-time navigation. The speed of sound in the water column (90m deep) had to be measured and this was to be followed by a relative calibration of the array. To calibrate the array in an absolute sense the use of differential GPS corrections from a monitor GPS receiver located on Troughton Island approximately 100kms away was used.

The equipment onboard the survey vessel (Figure 6.4) included one Trimble 4000A GPS receiver, two HP9836 Computers(1Mb RAM), a Magnavox MX1107 Dual Frequency Transit Receiver, the Acoustic Navigation Equipment and one SSB Radio Transceiver. Onshore at Troughton Island the surveyor had one Trimble 4000A GPS receiver, and a SSB Radio Transceiver.

GPS Monitor Station

The monitor GPS receiver was established on the island with the antenna over an established survey mark that had been connected to the Australian Geodetic Datum (AGD) with Shoran in the 1960's. The survey mark was occupied again in 1985 with Transit receivers to derive a local three parameter datum shift. As such the "absolute" coordinates are not known precisely but must be accepted since the original seismic survey used this data and the sub-sea geology has been mapped with reference to the survey marks. GPS position remained within 15m of those ground coordinates during the seven day operation. That accuracy is usually only just achievable after three days observing with a kinematic Transit receiver offshore (Geomex Surveys 1984). The duty of the surveyor at this station was to keep in contact with the vessel, to track the same SV constellation and radio the mean coordinates (WGS-72) every 15 minutes. Voice communication from shore to survey vessel was used since a reliable and easily mobilised digital communication link for differential GPS message transmission was not available.

Deployment

The GPS window in which it was at least possible to perform 2-D positioning was between 0200-0400hrs and 0900-1530hrs and so the Transit receiver was used to navigate the vessel from the island to arrive at the location at 0100hrs. Acoustic equipment was prepared while waiting for the GPS SV's to rise. A program on the HP computer to take the GPS latitude and longitude, apply the three parameter datum shift from WGS-72 to AGD then calculate the bearing and distance from the vessel to the proposed transponder drop locations was checked. As soon as the GPS outputted positions with a PDOP less than 7 the deployment of all 4 transponders over the 2km grid took only 45 minutes. No differential correction was used for this deployment as calibration had to follow anyway. Immediate results from an uncalibrated array showed the range residuals on a four-way fix to be less than 5m which reflects the consistency in deployment by GPS. As a comparison, the accuracy of initial deployment of the first transponder with Transit is a function of the time since last update and can easily be 100m in error. Subsequent deployment of transponders by the Transit method would have involved dead-reckoning and ranging from two deployed transponders so errors in position and rotation of the array are increased. Initial range residuals for an acoustic fix when transponder deployment has been from Transit are typically 30m compared with 5m for GPS.

Relative Calibration

Relative calibration was performed between the GPS windows to give the best estimate of the relative positions of each transponder to the others.

The results from the Least Squares sequential adjustment of four sub-sea transponders from 24 well distributed 'stations' give the following errors:

	Xpder 1	Xpder 2	Xpder 3	Xpder 4
Xpder RMS	0.36m.	0.50m.	0.58m.	0.53m.

Absolute Calibration

A SV observing schedule was planned prior to 0900hrs and transmitted to the monitor station. Absolute calibration commenced by sailing to 18 well spread locations, stopping the vessel and recording simultaneous positions from GPS and the acoustic array along with the gyro reading so that antenna and shipboard acoustic transceiver could be related to a common point. Data collection was completed within 75 minutes and on completion the monitor station transmitted the GPS positions so that a differential correction consisting of a ΔE and ΔN could be formed by datum shifting the monitor station coordinates and subtracting them from the AGD coordinates of the ground mark. These simple differential corrections were applied to the mobile coordinates and used as an input, along with the acoustic positions, to a least squares transformation program which translates and rotates the acoustic array into the GPS determined coordinates without deformation.

The results from the Least Squares fit of 18 simultaneous acoustic and differential GPS fixes are given below. The column, Residual, is the distance between simultaneous GPS position and Acoustic position after it has been translated and rotated to minimise residuals.

Table 6.2 Results of Absolute Calibration of Acoustic Array with GPS.

Fix#	Time(hrs)	Residual(m)
1	0925	2.4
2	0930	6.3
3	0932	7.3
4	0937	10.7
5	0938	9.0
6		rejected as > 15m.
7	0950	2.1
8	0955	5.6
9	0956	9.2
10	1001	11.1
11	1010	8.4
12	1011	7.0
13	1015	5.4
14	1020	2.7
15		rejected as > 15m.
16	1032	6.1
17	1037	4.4
18	1040	2.0

Mean Residual : 6.87m.

Movement of Acoustic Array onto GPS positions:
Translation : 42.89m East
8.89m South
Rotation : -0.05°

The mean residual between the acoustic net and the GPS coordinates is 6.9m with the greatest individual residual being 11.1m. Typical results from Transit calibration would show the mean to be about 15-20m with some individual residuals over 25m. The fact that the East/West translation of 32m is greater than the stated GPS point positioning accuracy of 20m is probably due to the intermediate relative calibration which does not constrain absolute position. But the residuals do show the repeatability of GPS due to its independent epoch solution and although residuals were acceptable they are most probably caused by small time tagging errors when attempting to obtain simultaneous data.

Results.

The site survey and rig-positioning was carried out using the acoustics alone and once the rig was anchored and movement was confined to ±1m a confirmation survey by GPS commenced. This involved 1/2hrs simultaneous collection of fixes and the transmission of five minute averages from the island monitor station to the rig. The differential GPS position agreed to within 4.0m of the acoustic position and so confirmed that the absolute calibration from a dynamic platform by differential GPS is over an order of magnitude faster than Transit and gives superior absolute accuracy.

6.2.4 GPS to Accept Differential Message and Range.

Even though the RTCM (SC-104) drafted a differential message standard it may not be implemented **per se** since the end user's requirements are so varied and some will compromise exact implementation to use a more concise message for the sake of cheaper equipment. The differential system has already been discussed in Chapter 5 but one possible idea, the pseudo-lite concept mooted, was the possibility of ranging from the pseudo-lite. Pseudo-lite ranging (Section 5.3.2.2) could introduce a further line-of-position which could be utilized in an otherwise weak SV configuration to minimise outages.

If some of the communication links are to be operating at radio-positioning frequencies then range measurement will be a useful feature in them and provision should be made in the GPS receivers to include this range very simply as a pseudo static satellite with no clock bias. Communication links operating on the 2MHz frequency are one system that appear suitable for such a scheme.

6.3 LIMITS TO GPS INTEGRATION.

The main limitation will be **Selective Availability** in the Standard Positioning Service reducing the single receiver point solution to 100m 2drms. The effect of Selective Availability has been introduced in Chapter 4.4 where it was debated whether a bias error or a dither would be the technique used. Any form of Selective Availability will enforce a differential technique on hydrographic users. The rate at which the bias or dither occurs will have a bearing on the degree of complexity that has to be used to minimize it.

Mobile radio-navigation antennas need only be sited on a vessel to ensure that the beacons on the horizon are unobstructed. GPS antennas need to have a clear view of the sky above 5^{o} elevation to ensure continuous operation. **Physical obstructions** that block the SV signal such as port buildings or proximity to tall oil rigs will cause multi-path or even loss of lock. For example, GPS operations in certain parts of the Port of Sydney would be limited near wharfs due to tall buildings and while under bridges.

Since the GPS antenna is best mounted on the tallest mast to ensure an unobstructed view the **ships dynamics** result in high jerk rates at the antenna which can cause cycle slips or at worst loss of lock.

7. SUMMARY AND CONCLUSIONS.

Unlike other positioning systems GPS satellites transmit a variety of signals and codes that can be received and processed by an even greater number of techniques. The various processing techniques result in a range of position accuracies. Hydrographic surveying demands kinematic positioning with accuracies typically below five metres from a system that exhibits a high level of integrity (coverage and reliability). Even though GPS is presently experimental in nature a single receiver gives position accurate to better than 15m. With GPS usage to date and the reliabilty shown with the present constellation the hydrographic survey industry believes GPS will have a massive impact as a positioning sensor in the future. GPS can meet the range of applications found in hydrographic surveying since it is easy to mobilise, exhibits a suitably high level of integrity and accuracies obtainable with more sophisticated processing are acceptable. As GPS receivers become cheaper to manufacture then the cost effectiveness, compared to land-based radio-positioning systems, becomes even greater.

To summarise this study the following points are vital to note when considering the integration of GPS into hydrographic survey operations:

1) **Satellite coverage.** When considering the suitability of using GPS as a navigation sensor then the question of integrity, reliability and coverage must be defined and assessed. The suitability of GPS for real-time positioning is partly a function of the geometric configuration of the

visible SV's, called the Dilution of Position. Presently (1987) there are six healthy SV's and the periods of accurate horizontal positioning can be extended if the height parameter is constrained so that only three SV's need be used for a solution. Similarly if the receiver clock bias and drift is eliminated by the use of an atomic clock then positioning with only two SV's is possible. The proposed 21SV constellation may not be in place til the mid-1990's. Even then short outages ranging from 5-25 minutes will occur when using four SV's. Again, position determination from three or even two SV's is possible with height and clock constrained. If total failure of some SV's occur then GPS navigation will have to be aided with an independent positioning system.

2) The mathematical models used to eliminate **range errors** due to the effect of the troposphere and ionosphere on measurements in real-time are by no means exact. Research is still being carried out in these fields. Atmospheric models become unreliable below 7.5° elevation and the ionospheric model may only be 50% effective. With a single GPS receiver it is not possible to differentiate between the SV ephemeris and SV clock errors. The greatest limitation to accuracy that may be evident in the Block II constellation is that of Selective Availability which may introduce over 30m error in range. Random noise in pseudo-range measurement is introduced by limitations inherent with processing of signals in the receiver. As a result of these errors the User Expected Range Error for Block I SV's (C/A code) is 12m and for Block II SV's could be 32m.

3) To improve the precision of the determined position then real-time **filtering techniques** are recommended. One suitable method is to filter raw pseudo-ranges with either the integrated carrier phase or Doppler frequency. It is envisaged that the integrated Doppler frequency will be available on navigation type receivers since the Doppler frequency is usually monitored in the signal tracking loop. The Trimble 4000S data processed with the integrated Doppler frequency meshing filter showed that pseudo-range noise decreased from 2-3m to less than 1m after 35 updates. Another commonly used method is optimal filters such as Kalman filtering and sequential Least Squares. These have been implemented by various researchers (Section 5.2.3). The raw pseudo-ranges and integrated carrier phase are used in a filter that estimates the position, velocity, and clock bias and drift. Cannon et al (1986) found that processing TI4100 pseudo-range data with the differential GPS technique produced accuracies of better than six metres. When integrated carrier phase data was also used in a sequential approach the accuracy was better than two metres. For hydrographic surveying a GPS receiver should process data with, as a minimum, a pseudo-range filter and ideally an optimal filter. In either case the user must be able to monitor the degree of filtering applied at any epoch or he should be able to constrain the variances of a-priori parameters such as height and external clock.

4) To solve the problems of unmodelled systematic effects such as SV clock, SV ephemeris and propagation link effects

then **Differential GPS** is advocated. This technique virtually removes the effect of systematic errors including Selective Availability. As such it is recommended for increasing the accuracy obtainable from GPS positioning in hydrographic surveying. The distance between the static monitor receiver and the mobile user is expected to be within a few hundred kilometres. The implementation of differential GPS requires a suitable communication link over which position type or measurement type differential corrections are sent. The measurement type corrections will be more suitable for a multi-user situation. Differential GPS also improves the reliability and integrity of the positioning service as a static receiver is dedicated to monitoring the GPS measurements.

5) Until SV coverage is such that outages do not occur, even with two SV's, GPS will have to be **integrated with other positioning systems to ensure continuous operation for hydrographic survey operations.** Inertial Navigation Systems (INS) meet many of the demands placed on such a 'back-up' system in that they are accurate and totally self-contained. Unfortunately INS is very expensive but advances in 'strap-down' INS technology may reduce costs. Another possible option to span total outages is to use the communication link as a ranging device and so produce another 'line of position' that can be used in the GPS position solution. The other option is to use an independent positioning system such as acoustics or radio-positioning.

6) **Limitations to GPS.**

- The current schedule projects the next launch to be in

February of 1989 and 10 Block II satellites to be launched within a year. This will hopefully lead to 24 hour, 2-D worldwide coverage in 1990. During the interim period, there is the chance that an additional satellite will fail (as one SV will be 11 yrs old and another will be 9 yrs old), which could reduce 2-D world coverage.

- Since a GPS antenna will have to be mounted on a ship's mast to obtain an unobstructed view of the SV's then the ship's dynamics may cause loss of lock with the signals. To overcome this the tracking bandwidth has to be increased which also increases pseudo-range noise. The rolling of a ship may cause loss of lock to low elevation SV's. Tiltmeters should be used to monitor the roll of the ship and compensate for the fluctuating antenna position.

- In differential GPS the distance between monitor and mobile receivers can be such that ionospheric corrections at either receiver differ and so introduce an unacceptable error. To overcome this receivers capable of using the L2 frequency (P code) are required to determine the magnitude of the correction and apply it at each receiver.

8) To confirm GPS receivers are operating within limits a user must be able to rapidly test receivers for calibration and compatibilty with other models. **A zero-baseline test with two or more receivers is recommended as it allows the user to check simultaneous performance with respect to filtering and calibration.** Research on meshing data from different models of receivers needs to undertaken so that any possible problems are identified.

GPS is already having an impact on hydrographic survey operations. As receiver prices drop and more SV's go up there is no reason why GPS can not be used as the prime positioning sensor in the future.

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APPENDIX A

TRANSFORMATION MATRIX - Earth Centred Earth Fixed to Geographics.

The transformation matrix $R_{e,g}$ is constructed from the partials of ∂ECEF/∂Geographics (also clock bias) and is of the form :

$$R_{e,g} = \begin{bmatrix} \partial X/\partial\phi & \partial X/\partial\lambda & \partial X/\partial h & 0 \\ \partial Y/\partial\phi & \partial Y/\partial\lambda & \partial Y/\partial h & 0 \\ \partial Z/\partial\phi & \partial Z/\partial\lambda & \partial Z/\partial h & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

which has been expanded in Harvey(1986) to :

$$\begin{vmatrix} \dfrac{Ne^2\sin\phi\cos^2\phi\cos\lambda}{(1-e^2\sin^2\phi)} - (N+h)\cos\lambda\sin\phi & -(N+h)\cos\phi\sin\lambda & \cos\phi\cos\lambda & 0 \\ \dfrac{Ne^2\sin\phi\cos^2\phi\sin\lambda}{(1-e^2\sin^2\phi)} - (N+h)\sin\lambda\sin\phi & (N+h)\cos\phi\cos\lambda & \cos\phi\sin\lambda & 0 \\ \dfrac{\{Ne^2\sin^2\phi\cos\phi}{(1-e^2\sin^2\phi)} + N\cos\phi\}(1-e^2) + h\cos\phi & 0 & \sin\phi & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix}$$

APPENDIX B

DERIVATION OF PROCESS NOISE COVARIANCE MATRIX

The general formula of this matrix is given in Gelb(1974)pp.75 for the continuous case as:

$$\Gamma_k Q_k \Gamma_k^T = \int_{T_k}^{T_{k+1}} \Phi(t_{k+1},\tau).G(\tau).Q(\tau).G^T(\tau).\Phi^T(t_{k+1},\tau).d\tau \quad (3)$$

where : Q_k is the covariance matrix for the discrete case.

$Q(\tau)$ is the spectral density matrix for the continuous case.

Krishnamurti et al (1985) introduces the transformation matrix **G** to allow process noise **Q** to be specified in a local level system then transformed to the ECEF system. The nature of this **G** matrix is expanded in Harvey (1986) for the case of Geographics to the ECEF system. The **Q** matrix is divided into two 4x4 matrices with :

Q_1 = Process noise for X, Y, Z, b

Q_2 = Process noise for $\dot{X}, \dot{Y}, \dot{Z}, \dot{b}$

Equation (3) corresponds to :

$$Q(\tau) = \int_0^{\tau} \Phi(\tau).\begin{bmatrix} Q_1(\tau) & 0 \\ 0 & Q_2(\tau) \end{bmatrix}.\Phi^T(\tau).d\tau \quad (4)$$

where :

$$\Phi(\tau) = \begin{bmatrix} I & \tau \\ 0 & I \end{bmatrix}$$

(with I being a 4x4 identity matrix)

multiplying out (4) :

$$Q(\tau) = \int_0^{\tau} \begin{bmatrix} Q_1 + Q_2\tau^2 & Q_2\tau \\ Q_2\tau & Q_2 \end{bmatrix} \quad (5)$$

then integrating (5) and replacing τ with Δt for the discrete case:

$$Q(\Delta t) = C^u = \begin{bmatrix} \Delta t.Q_1 + 1/3(\Delta t)^3.Q_2 & 1/2(\Delta t)^2.Q_2 \\ 1/2(\Delta t)^2.Q_2 & \Delta t.Q_2 \end{bmatrix} \quad (6)$$

APPENDIX C

SUMMARY OF SEQUENTIAL LEAST SQUARES

For a set of measurements L_1 we can obtain a Least Squares estimate of the parameters $\hat{\mathbf{x}}_1$ and covariance of the parameters $\mathbf{C}_{\hat{x}1}$ using the procedure and convention as in Chapter 5.1.

If a new set of measurements L_2 become available we can obtain a new estimate of the same parameters $\mathbf{x}$ and their covariance $\mathbf{C}_x$ by:

$$\hat{x}_2 = \hat{x}_1 + \hat{\delta x}$$

$$C_{\hat{x}2} = C_{\hat{x}1} + C_{\hat{x}}$$

The general form of the sequential process, solving at epoch i, is given by Cross(1983) as :

$$\hat{x}_i = \hat{x}_{i-1} - N_{i-1}^{-1}.A_i^T(W_i^{-1} + A_i.N_{i-1}^{-1}.A_i^T)^{-1}(A_i.\hat{x}_{i-1} - w_i)$$

$$C_{\hat{x}i} = C_{\hat{x}i-1} - N_{i-1}^{-1}.A_i^T(W_i^{-1} + A_i.N_{i-1}^{-1}.A_i^T)^{-1}(A_i.N^{-1})$$

where : $N_{i-1} = A_{i-1}^T.W_{i-1}.A_{i-1}$

W = weight matrix

The formal equivalence of the Kalman Filter and Sequential Least Squares equations is carried out in Cross (1983) and Schwarz (1983).

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