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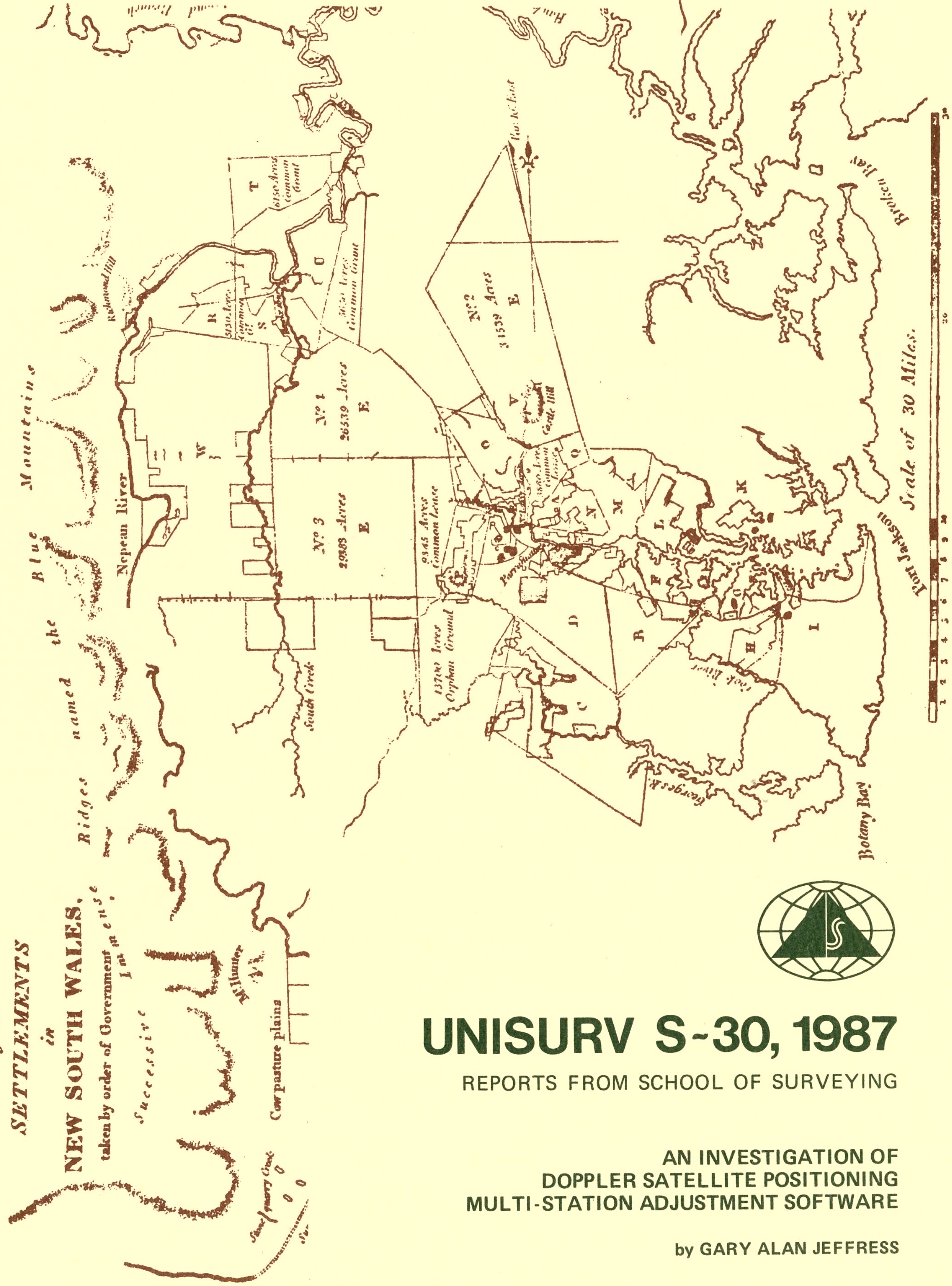

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REPORTS FROM SCHOOL OF SURVEYING

AN INVESTIGATION OF DOPPLER SATELLITE POSITIONING MULTI-STATION ADJUSTMENT SOFTWARE

by GARY ALAN JEFFRESS

UNISURV REPORTS S30, 1987

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To Margaret and Del Jeffress,

My Mum and Dad.

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ABSTRACT

The use of satellite positioning techniques is about to undergo accelerated growth with the introduction of the Global Positioning System (GPS). The forerunner to this new system is the TRANSIT system which uses doppler satellite positioning techniques. The body of knowledge pertaining to the TRANSIT system and the techniques that are used to derive accurate positions from the system have only been under investigation for the past 15 years or so.

The number of computer software packages that are available to reduce doppler satellite data in its most accurate mode, Multi-Station Adjustment, are very few. Very little comparison of these packages has been undertaken and very little investigation of the use of doppler satellite techniques has been made on networks involving large distances.

During the southern winter of 1982, a network of ten stations covering chord distances of over 2500 kilometers was observed in central Australia. This data set provided the ideal vehicle to investigate and compare the reduction of doppler satellite observations using the GEODOP and MAGNET software packages.

As yet the GPS system has not provided sufficient data to undertake a similar investigation. No comparison of GPS multi-station and TRANSIT mulit-station has been possible as the GPS satellite constellation is not yet fully operational. However, results of initial experimentation on GPS data has indicated that this system will greatly improve the accuracy that can be obtained by a satellite positioning system. It should be noted, however, that the sequential least squares adjustment techniques incorporated in the Doppler satellite adjustment software will also be used in the GPS adjustment software. Therefore

fully understanding the modeling and error sources in the TRANSIT multi-station software will greatly assist in the future development of multi-station software for the GPS system.

The computations for this project were carried out at the University of New South Wales.

CHAPTER 1

INTRODUCTION

Since the TRANSIT system of navigation satellites was made available to civilian users in 1967, surveyors and geodesists have been using Doppler Satellite Positioning to solve a variety of position fixing problems [Stone and Weiffenbach, 1961]. The accuracies of these derived positions vary from tens of metres, down to tens of centimetres depending on the observation methods used and the post processing techniques employed [A.C. Jones, 1984].

The basic principle of the DOPPLER EFFECT was first noted by Christian Johann Doppler in 1842. A TRANSIT satellite receiver measures the Doppler shift of two stable frequencies of 400 MHz and 150 MHz transmitted during each pass of the available TRANSIT satellites. The observed Doppler shifts together with the satellite's broadcast ephemeris, timing information and site information is recorded for later interrogation and post processing. Earlier receivers used punched paper tape as the recording medium. Later models use harsh environment magnetic tapes to store the observed data [T.A. Stansell, 1978].

The computation of the position of the receiver relies on knowing the position of the satellite at the time of observation relative to a fixed earth centered coordinate system. An ephemeris, or table of astronomic positions, describes the position of the satellite. Two ephemerides are available for the TRANSIT system; a predicted or broadcast ephemeris and an observed or precise ephemeris. Both the broadcast and precise ephemerides can be used for calculating position. Computations using the precise ephemeris give the best results.

There are two basic methods of determining latitude, longitude and spheroidal height. The first, known as point positioning, relies on the integrity of the ephemeris. This absolute position contains all ephemeris induced errors. The second operation technique, known as multi-station positioning, requires two or more receivers tracking the same satellite passes. As all receivers are subject to the same ephemeris biases, then relative positions will eliminate or reduce these biases.

To obtain the highest degree of accuracy using Doppler Satellite Positioning, three or more receivers observe a network of ground sites simultaneously. The relative positions between observing sites is determined using simultaneous least squares adjustment techniques. These techniques use redundant information to solve for the position of each site and the elements of the satellite orbits. The first computer software to carry out these adjustments was developed in the 1970's after the realisation that the TRANSIT system could be used accurately and economically for geodetic positioning.

Day to day users of the TRANSIT system do not rely on post processing of multi-station networks to determine geodetic positions. Surveyors generally use translocation methods which are convenient and can supply results in the field, if necessary. Most modern receivers such as the Magnavox MX1502, Motorola Mini-Ranger or JMR 2000 have onboard software to perform translocation computations using the broadcast ephemeris. This method of positioning has been investigated with results of relative position being accurate to one metre (1σ), over distances in excess of 200 Km [A.C. Jones, 1984]. Jones' investigations also compared translocation results to those obtained using multi-station adjustment techniques, using both broadcast and precise satellite ephemerides. A.C. Jones [1984] states:-

> "The repeatability achievable from the MX1502 on-board software is competitive with that achievable from GEODOP using precise ephemeris, even during periods of high solar radiation pressure. The repeatability of solutions derived from GEODOP using the broadcast ephemeris is severely degraded during such periods. All three modes of reduction give similar repeatability during less extreme conditions. However each is subject to different biases relative to ground truth value. The most consistent repeatability may be obtained using the precise ephemeris."

The end of the TRANSIT systems' life is predicted to occur during the mid 1990's and its subsequent replacement with the Global Positioning System (GPS) [King et al, 1985] is well under way. All indications show that the use of multi-station adjustment techniques for determining satellite derived positions will increase enormously. The purpose of this report is to investigate two independent software packages using TRANSIT data and to compare results to the best known ground truth. This report does not pretend to be exhaustive nor entirely conclusive but does set out to add to the understanding of multi-station reduction techniques from satellite derived observations.

The report comments briefly on the background of the TRANSIT system and the basic theory of the mathematical model used in the calculation of Doppler position. Reference is made to publications which supply more detail of these aspects. Errors in the model are also discussed with the major emphasis on atmospheric effects and timing problems.

As the TRANSIT system is an earth centred control system, the problems of the transformation from this earth centred coordinate system to a local coordinate system is discussed in Chapter 3. In particular the mechanisms for transforming Doppler satellite results onto the Australian National Spheroid (ANS) are reviewed.

Chapter 4 introduces the MAGNET and GEODOP software packages for the adjustment of Doppler satellite observations. In particular, GEODOP is discussed in terms of the mathematical modelling which is described in Chapter 2.

In Chapter 5 the results of the various adjustments and point position calculations are presented. The presentation compares the computed position coordinates with ground truth coordinates. These ground truth values are the result of a recently completed geodetic adjustment of the Australian primary geodetic network, and represent the most rigorous adjustment of a primary network to be carried out over an entire continent. This provides the best available control for comparison. The ground truth has proven to be extremely advantageous for the investigation which involves simultaneous observations of ten stations over such large distances.

As yet the GPS system has not provided sufficient data to undertake a similar investigation. No comparison of GPS multi-station and TRANSIT mulit-station has been possible as the GPS satellite constellation is not yet fully operational. However, results of initial experimentation on GPS data has indicated that this system will greatly improve the accuracy that can be obtained by a satellite positioning system. It should be noted, however, that the sequential least squares adjustment techniques incorporated in the Doppler satellite adjustment software will also be used in the GPS adjustment software. Therefore fully understanding the modeling and error sources in the TRANSIT multi-station software will greatly assist in the future development of multi-station software for the GPS system.

CHAPTER 2

ADJUSTMENT OF TRANSIT SATELLITE OBSERVATIONS

2.0 BACKGROUND.

The documentation of the TRANSIT system and the various techniques used for determining position are numerous. It shall suffice to briefly review the background of Doppler Positioning here with reference to more detailed explanation in previous publications.

The TRANSIT system is divided into three components :-

1. The space segment.

2. The control segment.

3. The user segment. [A.C. Jones, 1984]

A satellite receiver (user segment) observes the Doppler shift of the two stable frequencies, 400 MHz (nominally 399.968 MHz) and 150 MHz (precisely 3/8ths of the higher frequency) transmitted by any of up to six operating TRANSIT satellites (space segment). Together with these measurements the receiver records the satellite's broadcast ephemeris (predicted by the control segment) which is phase modulated onto each of the coherent signals at the time of transmission from the satellite

[Smith et al, 1976]. The message contains 6103 binary bits and is broadcast after every even two minute epoch of Universal Time.

The receivers used for the collection of data for this project were Magnavox MX1502's. These receivers use their own internal clock to acquire the relative time integration gates for Doppler count accumulation. This type of receiver is defined as operating in receiver time frame.

2.1 THE FUNDAMENTAL PRINCIPLES.

2.1.1 THE DOPPLER CURVE.

The Doppler shift of a frequency source is perceived by an observer when there exists relative motion between the observer and the frequency source. This effect is easily observed using sound waves. For example, if a car travelling towards a stationary observer sounds its horn, the sound of the horn has a high pitch as the car approaches, the actual (true) pitch as the car draws level with the observer and a lower pitch as the car draws away from the observer.

The Doppler Curve in Figure 2.1 results from observing the frequency of the transmitted signal of a passing satellite relative to time.

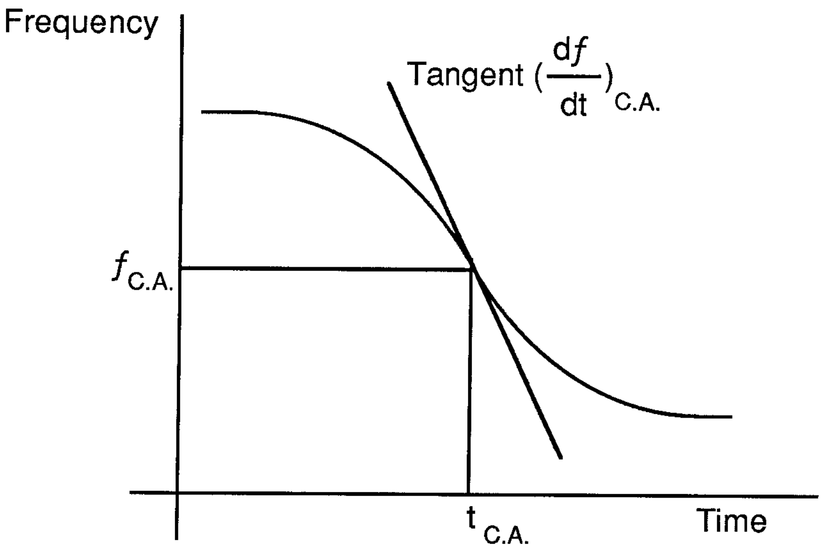


Figure 2.1 THE DOPPLER CURVE.

The curve contains three parameters that most fully represent the information contained in a set of satellite observations from a single pass. These are :-

1) The time of closest approach (C.A.) where the slope of the Doppler curve is a maximum.

2) The receiver to satellite range at closest approach which is represented by the magnitude of the maximum slope $(df/dt)_{C.A.}$ at time of closest approach.

3) The frequency offset between satellite and receiver frequency sources.

Both 1) and 2) above represent the geometric parameters that relate the position of the receiver to the position of the satellite at time $t_{C.A.}$. Number 3) above represents a nuisance parameter. This parameter is used to keep track of the stability of the frequency source in the receiver.

2.1.2 THE RANGE RATE EQUATION.

Fundamental to the formulation of Doppler positioning is the range rate equation. This describes the rate of change of the range of the receiver to the satellite during a pass. The actual measurements made are counts (N) of the Doppler cycles over the standard time interval of 28 or 32 seconds. Given a reference frequency f_i and the velocity of light in vacuo c, the Doppler frequency Δf_i can be related to the range rate r by :-

$$\Delta f_i = \frac{f_i}{c} r + \frac{\alpha}{f_i}$$

(2.1) [Kaula 1966]

The term α / f_i represents the ionospheric refraction effect. It is inversely proportional to f_i because the effect of an ionized medium on the velocity of microwaves is inversely proportional to f_i^2 .Since the ion density of the upper atmosphere at any instant is unknown, the parameter α must be measured. Hence the two frequencies 400MHz and 150MHz are used for this purpose. This will be further discussed in section 2.4.2.

2.2 DOPPLER OBSERVATION EQUATIONS.

This derivation of the observation equations is reproduced from G.J.Hoar [1981]. It is one of many published derivations included in the references.

Measurements recorded at the receiver and in the receiver time frame τ_i are related to the satellite position (which is known) at satellite time t_i . The relationship between τ_i and t_i are brought about by the following two assumptions.

Assumption 1.

Measurements are made (in receiver time scale τ_i) at the instants at which the time marks arrive at the receiver.

Assumption 2.

The satellite positions (in satellite time scale t_i) are given for instants at which the time marks are transmitted.

For the definition let the satellite transmit time marks at t_1 and t_2, and at these times let the satellite to receiver distances be s_1 and s_2 respectively.

This gives :-

$$\tau_1 = t_1 + \frac{s_1}{c}$$

$$\tau_2 = t_2 + \frac{s_2}{c}$$

Let f_s be the frequency transmitted by the satellite. Then the frequency received at the receiver f_r is given by (2.1) as :

$$f_r = f_s \left(1 - \frac{1}{c} \cdot \frac{ds}{dt} \right)$$

The observed quantity is the Doppler count N given by:-

$$N = \int_{\tau_1}^{\tau_2} (f_g - f_r) \, d\tau$$

(2.2)

where f_g is the frequency generated by the receiver. Expanding (2.2):-

$$N = \int_{\tau_1}^{\tau_2} f_g \, d\tau - \int_{\tau_1}^{\tau_2} f_r \, d\tau$$

(2.3)

It is assumed that f_g and f_s are constant for the duration of the pass. Considering separately the integrals in equation (2.3), this leads to :-

$$\begin{aligned} \int_{\tau_1}^{\tau_2} f_g \, d\tau &= f_g \, (\tau_2 - \tau_1) \\ &= f_g \, (t_2 + \frac{s_2}{c} - t_1 - \frac{s_1}{c}) \end{aligned}$$

$$\begin{aligned} \int_{\tau_1}^{\tau_2} f_r \, d\tau &= \int_{\tau_1}^{\tau_2} f_s \, d\tau \\ &= f_s \, (t_2 - t_1) \end{aligned}$$

Substituting in (2.3):-

$$N = (f_g - f_s)(t_2 - t_1) + \frac{f_g}{c}(s_2 - s_1)$$

(2.4)

which is the observation equation in the satellite time frame.

Using the receiver time frame :-

$$N = \int_{\tau_1}^{\tau_2} (f_g - f_r)\, d\tau$$

$$N = \int_{\tau_1}^{\tau_2} f_g\, d\tau - \int_{\tau_1}^{\tau_2} f_s\left(1 - \frac{1}{c}\right)\frac{ds}{dt}\, d\tau$$

or

$$N = (f_g - f_s)(\tau_2 - \tau_1) + \frac{f_s}{c}\int_{\tau_1}^{\tau_2} \frac{ds}{dt}\, d\tau$$

Now assume dt = dτ, that is the two rates are equal then :-

$$N = (f_g - f_s)(\tau_2 - \tau_1) + \frac{f_s}{c}\,(s(\tau_2) - s(\tau_1))$$

(2.5)

which is the observation equation in the receiver time frame. Equations 2.4 and 2.5 are known as range rate equations.

2.2.1 DETERMINATION OF TIME INTERVALS.

As stated in assumption 2 in the previous section, the satellite positions are given at times t_i (even two minute epochs of U.T.). To solve the observation equations we need them at times τ_i' so as to determine :-

$$\Delta t_i = \tau_i' - t_i \tag{2.6}$$

According to Anderle [1976] Δt_i can be determined to the order of 50 μsec. With the velocity of the satellites being 7500 m/sec then 50 μsec represents an error of 0.5 metres in the along track position of the satellite. Therefore the correction between adjacent positions at τ_1' and τ_2' is such that :-

$$s(\tau_2') - s(\tau_1') << 0.5\text{m}$$

To determine Δt_i

let $t = t_0$ and $\tau' = \tau_0'$ at lockon time where :-

t_i time scale is derived from f_s the satellite transmitted frequency

τ' time scale is derived from f_g the receiver generated frequency

Assume that $1/f_s$ is perfectly known having accounted for offset and drift corrections

Assume that f_g can be modelled by

$$f_g(t) = f_g(t_0) + f\,(t - t_0)$$

where $f_g(t)$ and f are constants and

$$\frac{d\tau'}{dt} = 1 + \frac{f_g - f_0}{f_0}$$

where f_0 is the nominal frequency (say 399.968 MHz)

The term

$$\frac{f_g - f_o}{f_o}$$

is termed the frequency offset.

It follows that :-

$$\int_{\tau'_0}^{\tau'_i} d\tau' = \int_{\tau_0}^{\tau_i} \left[1 + \frac{f_g(t_0)-f_o}{f_o} + \frac{f}{f_o}(t_1-t_0) \right] dt$$

giving

$$\tau'_i - \tau'_0 = t_i - t_0 + \left(\frac{f_g(t_0)-f_o}{f_o}\right)(t_1-t_0) + \frac{f}{2f_o}(t_1-t_0)^2$$

$$\Delta t_i = \tau'_i - t_i$$

$$= \underset{\overset{\uparrow}{\boxed{1}}}{\Delta t_0} + \underset{\overset{\uparrow}{\boxed{2}}}{\left(\frac{f_g(t_0)-f_o}{f_o}\right)}(t_1-t_0) + \underset{\overset{\uparrow}{\boxed{3}}}{\frac{f}{2f_o}}(t_1-t_0)^2$$

These terms can be expressed as :-

[1] - the receiver time delay. This value is determined for each instrument by the manufacturer [Brunell. 1979]. The receiver time delay consists of a systematic component and a random component. The Magnavox MX1502 has been designed to have a negligible systematic component. The random component has a magnitude of up to 100 μsec and is known as time jitter. For the computations in this project the time delay was set at 100 μsec.

[2] - the frequency offset. This varies from 100 to 1000 parts in 10^{10}.

[3] - the drift rate. This varies between ± 10 parts in 10^{10} per day.

The above coefficients can be estimated by measuring Δt for each pass.

$$\overline{\Delta t} = \frac{1}{n}\sum_{i=1}^{n}(\tau_i' - t_i - \frac{s}{c} - d)$$

where s/c is the propagation delay

and d is the receiver delay.

2.3 MATHEMATICAL MODEL FOR A SINGLE PASS.

2.3.1 DATA FILTERING.

With each satellite pass a receiver collects, processes and stores a large volume of digital data. The amount of manipulation of the data and subsequent storage depends on the number of advanced features the receiver has. Older receivers such as the JMR 1 or Magnavox Geoceiver merely observed and recorded the digital information onto cassette tape or paper tape. The majority voting of ephemeral data and position calculation was then post processed using a computer.

2.3.2 THE GUIER PLANE.

Modern Doppler receivers such as the Magnavox MX1502 have microprocessing capability. The majority voting and computation of position is determined for each pass as the data is received. The majority voted ephemeris, Doppler counts and computed position is then stored onto cassette tape. In order to minimise the complexity of the calculations used to determine position and to simplify data filtering the initial single pass computations are sometimes carried out in the Guier Plane. The Guier Plane is described in Figure 2.2.

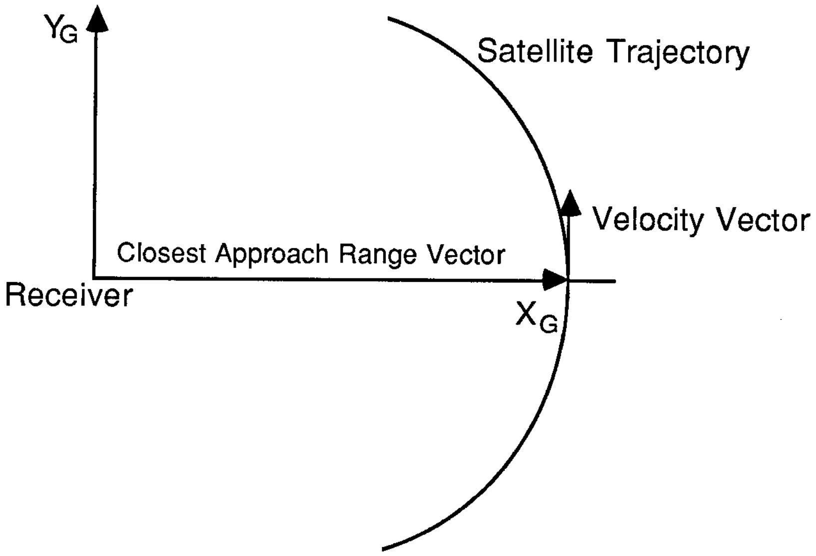


Figure 2.2 THE GUIER PLANE.

Where a) Receiver is the origin.

b) X-axis is aligned with the a Priori estimate of the range vector at closest approach.

c) Y-axis is aligned with the a Priori estimate of the velocity vector of the satellite at closest approach.

A three dimensional coordinate system is then derived from this plane with the Z-axis perpendicular in a normal right handed system.

The three parameters which represent the information contained in a single pass as discussed in section 2.1.1 can now be solved for and expressed as :-

$$\Delta X_G, \Delta Y_G, \Delta f_G$$

The precise derivation of these solutions can be found in Wells [1974], Ashkenazi and Gough [1975] and Hoar [1981]. It shall suffice to represent the solution in the generalised form where the parametric equations are :-

$$B X + T = V$$

where B is the design matrix,

X is the vector of unknown parameters,

T is the vector of absolute terms,

V is the vector of observational residuals.

The normal equation is expressed as :-

$$B^T G^{-1} B X + B^T G^{-1} T = 0$$

where G is the weight coefficient matrix.

Solving for :-

$$X = -(B^T G^{-1} B)^{-1} B^T G^{-1} T$$

$$= \begin{bmatrix} \Delta X_G \\ \Delta Y_G \\ \Delta f_G \end{bmatrix}$$

Here ΔX_G and ΔY_G indicate errors in slant range and along track in the broadcast ephemeris plus the error in receiver coordinates. V should be a good indication of the noise in the Doppler data.

The Guier plane is used for data filtering in program PREDOP (see Chapter 4). The results are then transformed back into the earth centered coordinate system (see Chapter 3). This is necessary as most advanced programs solve for satellite as well as receiver position.

2.3.3 THE PLANE OF LEAST MOVEMENT.

Software developed by Magnavox (see MAGNET Chapter 4) and that contained onboard the MX1502 do not use the Guier plane for data filtering [Hatch, 1976]. The normal equations are formed for the longitude and ellipsoidal height. The Gaussian elimination technique is then used to eliminate offset frequency and latitude corrections from the longitude and ellipsoidal height equations. These two equations then become almost identical. An exaggerated plot of these equations is given in Figure 2.3.

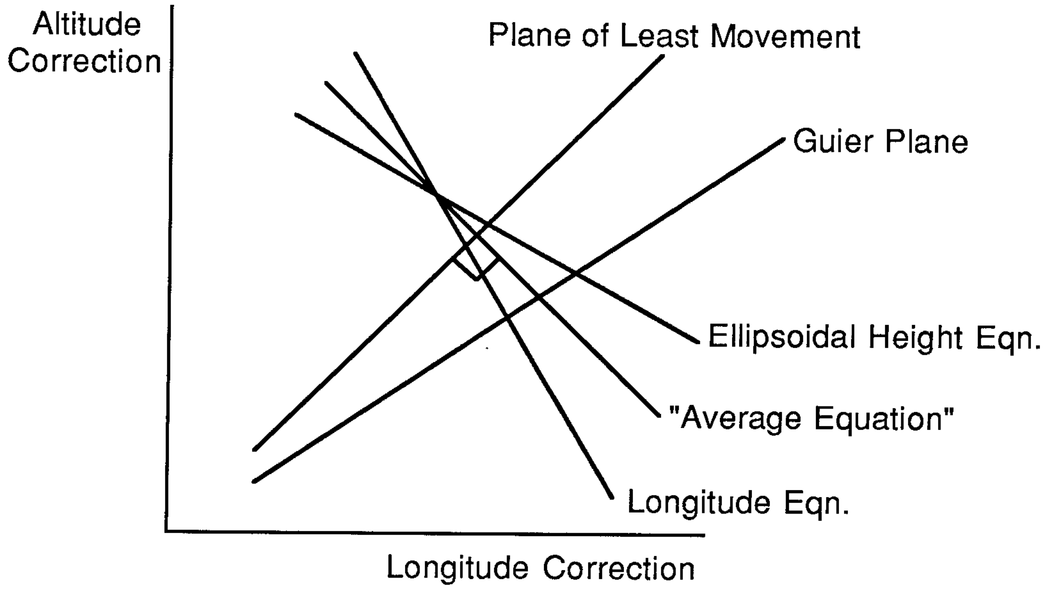


Figure 2.3 THE PLANE OF LEAST MOVEMENT

The use of this technique allows the data to tell which plane is least sensitive to orbit errors or receiver position errors. The plane of least movement is then defined as having its origin at the receiver and passing along a line perpendicular to the average equation which is derived by minimising the corrections to the longitude equation and the ellipsoidal height equation.

The derivatives and solution corrections obtained from this approach are ideal for multi pass point positioning and translocation solutions. Hatch [1976] states that

" This special single pass solution provides the natural tool for residual editing (data filtering) of both individual Doppler measurements and entire passes."

2.4 ERRORS IN OBSERVED DOPPLER COUNTS.

2.4.1 CORRELATION.

The Magnavox MX1502, like most modern receivers, observe continuously integrated Doppler counts using a basic integration interval of 4.6 seconds. These short counts are then accumulated into longer counts. These longer counts are usually accumulated over a two minute period. To obtain the desired integration periods the two minute accumulations are subtracted. These differences contain a correlation which must be taken into account during the reduction process.

Magnavox have overcome this correlation by a process called 'pseudorange processing'. Instead of adding sequential Doppler counts together the average of the range equations is subtracted from each individual range equation. This effectively minimises the residuals in the ranges along with the resulting individual pseudo measurements being substantially uncorrelated.

2.4.2 IONOSPHERIC CORRECTION.

The ionosphere is that part of the earth's atmosphere between the altitude of about 50km to 400km above the surface of the earth. It consists mainly of electrons and ions at very low density. Ionisation is caused by ultra-violet radiation from the sun.

For microwaves this creates a dispersive medium based on the refractive index of the medium. The refractive index (n) for frequency f is given by :-

$$n = 1 + \frac{c_1}{f^2} + \frac{c_2}{f^4} + \ldots\ldots$$

where c_1 , c_2 , . . . are constants independent of frequency.

Ionospheric correction to path length s is :-

$$\Delta s = \int (n-1)\, ds$$

$$= \frac{b_1}{f^2} + \frac{b_2}{f^4} + \ldots\ldots$$

where b_1 , b_2 , . . . are constants independent of frequency.

The effect on Doppler count N is given by :-

$$\Delta N = N_{OBS} - N_{VAC}$$

$$= \frac{f}{c} (\Delta s_2 - \Delta s_1)$$

$$= \frac{a_1}{f} + \frac{a_2}{f^3} + \ldots\ldots$$

where a_1 , a_2 , . . . are constants independent of frequency.

The dispersion effect is used for determining the ionospheric correction. For TRANSIT frequencies 400Mhz and 150Mhz :-

$$N_{400} = N_{VAC} + \frac{a_1}{f_{400}} + \ldots.$$

$$N_{150} = \frac{150}{400} N_{VAC} + \frac{a_1}{f_{150}} + \ldots.$$

$$= \frac{3}{8} N_{VAC} + \frac{8}{3} . \frac{a_1}{f_{400}}$$

Hence :- $$\Delta N = N_{400} - N_{150}$$

$$= \frac{24}{55} (N_{150} - \frac{3}{8} N_{400})$$

The Magnavox MX1502 records not N_{150} but N_L :-

where $$N_L = \frac{8}{3} N_{150}$$

So $$\Delta N = \frac{9}{55} (N_L - N_{400})$$

For a vertical path Δs is of the order of 100 metres. This increases with more oblique paths. These techniques use only first order terms. The second and third order terms are small and vary with time and elevation.

2.4.3 TROPOSPHERIC CORRECTION.

The troposphere is that part of the earth's atmosphere extending from the surface of the earth to an altitude of about 30km. It consists of air made up of nitrogen 78%, oxygen 21%, argon 1% and other gases including carbon dioxide 0.03% and water vapor which varies.

The modeling of the tropospheric correction is complicated because of the fluid state of the atmosphere with time and altitude. The model which is most accepted and used for this project is that proposed by Hopfield [1971, 1976].

The Doppler correction between two data points 1 and 2 is given by :-

$$\Delta_{12} = \frac{f}{c}(\Delta s_{i2} - \Delta s_{i1}) \quad \text{where } i = \text{wet , dry}$$

This is then reduced into wet(w) and dry(d) components :-

$$\Delta_{12} = \frac{f}{c}(\Delta s_{d2} - \Delta s_{w2} - \Delta s_{d1} - \Delta s_{w1})$$

for the Hopfield model :-

$$\Delta_{12} = \pm 5\text{cm} \quad \text{at high elevation angles}$$
$$\Delta_{12} = \pm 45\text{cm} \quad \text{at low elevation angles } (< 20 \text{ degrees})$$

It should be noted that changes in surface values of wet and dry temperatures and pressure result in very small changes in the tropospheric correction. Most reduction programs including GEODOP and MAGNET use standard values which are corrected for site elevation.

2.4.4 TIME JITTER

This effect was discussed in section 2.2.1 and results from time delay in the receiver equipment as well as a random component. It is a correction that must be understood and accounted for. The Magnavox MX1502 has been designed to keep these errors to less than 100μsec which gives errors in final position of the order of ± 10 cm.

2.4.5 EFFECT OF RELATIVITY.

The effect of relativity is negligible on the final coordinate values, but is mentioned here merely to point out that it does exist. It is not taken into account in any of the software used to determine position from TRANSIT observations. The effect on the 400Mhz frequency in terms of ΔN is about $2 * 10^{-10}$. The correction takes the form :-

$$\Delta N = f * \Delta T * \frac{1}{c^2} \left[GM \left(\frac{1}{r_S} - \frac{1}{r_G} \right) - \frac{1}{2} \left(v_S^2 - v_G^2 \right) \right]$$

where :-

ΔN	correction to Doppler count
f	frequency
ΔT	integration time interval
c	speed of light
GM	gravitational constant
r_S, r_G	scalar values of the "centre of mass of satellite" and "centre of mass of receiver"
v_S, v_G	absolute velocities of satellite and receiver

CHAPTER 3.

DATUMS AND TRANSFORMATIONS.

3.1 INTRODUCTION.

As with all geodetic coordinate systems, the position of any point in space must be related to an origin. The ideal geodetic datum has its origin as the centre of mass of the earth. From this origin a mathematical model representing the closest proximation of the surface of the earth and an orientation is chosen. Pythagoras first postulated that this model was spherical. It was suggested that an ellipsoid (either prolate or oblate) would give a better representation. In 1735, the French Academy of Sciences sent geodetic expeditions to Peru and Lapland. These geodesists measured the length of one degree of arc along the meridian at each site. The comparison of lengths (one near the pole and one near the equator) showed the polar radius of the earth's surface to be shorter than the equatorial radius. They concluded that the earth's surface was better defined by an oblate spheriod. The mathematical model can now be expressed as an oblate spheroid or an ellipsoid having the following five parameters :- 1) a - semi-major axis

2) b - semi-minor axis

or f - flattening where $f = \dfrac{a - b}{a}$

or e^2 - eccentricity where $e^2 = \dfrac{a^2 - b^2}{a^2}$

3) X_0 rectangular coordinates of the centre

4) Y_0 - of the ellipsoid or centre of the earth's

5) Z_0 mass (also known as the geocentre)

This definition of rectangular coordinates has its orientation with the Z-axis coinciding with the mean rotation axis of the earth (the North Pole), the X-axis passing through the zero meridian (the Greenwich meridian), and the Y-axis perpendicular to the X-Z plane in a right handed sense. See figure 3.1.

The geographic coordinates ϕ (geodetic latitude), λ (geodetic longitude) and h (height above the reference ellipsoid) are related to the rectangular coordinates X,Y,Z by the following equations (Harvey, 1986)

$$X = (\nu + h) \cos \phi \cos \lambda$$

$$Y = (\nu + h) \cos \phi \sin \lambda$$

$$Z = [\, \nu (1 - e^2) + h \,] \sin \phi$$

where $$\nu = \frac{a}{\sqrt{\ (1 - e^2 \sin^2\phi)}}$$

The coordinates to be transformed are the result of a least squares adjustment and consequently have variance covariance matrices (VCV) which represent precision estimates. To transform the VCV into the cartesian frame the following is used.

$$VCV_{XYZ} = J.\ VCV_{\phi\lambda h}.J^T$$

where J is the Jacobian matrix and for single point J_n :-

$$J_n = \begin{bmatrix} \dfrac{ve^2\sin\phi\cos^2\phi\cos\lambda}{(1 - e^2\sin^2\phi)} - (v+h)\cos\lambda\sin\phi & -(v+h)\cos\phi\sin\lambda & \cos\phi\cos\lambda \\ \dfrac{ve^2\sin\phi\cos^2\phi\sin\lambda}{(1 - e^2\sin^2\phi)} - (v+h)\sin\lambda\sin\phi & -(v+h)\cos\phi\cos\lambda & \cos\phi\sin\lambda \\ \dfrac{\{ve^2\sin^2\phi\cos\phi + v\cos\phi\}\,(1-e^2)}{(1 - e^2\sin^2\phi)} + h\cos\phi & 0 & \sin\phi \end{bmatrix}$$

The Jacobian matrix above is used to transform the variance covariance of a single point. The conversion of more than one point the full Jacobian matrix is :-

$$J = \begin{bmatrix} J_1 & 0 & 0 & 0 & . & . & . \\ 0 & J_2 & 0 & 0 & . & . & . \\ 0 & 0 & J_3 & 0 & . & . & . \\ . & . & . & . & . & . & . \\ 0 & 0 & . & . & . & J_n & \end{bmatrix}$$

Similarly the transformation from cartesian coordinates back into ellipsoidal coordinates can be achieved using the following :-

$$\phi = \arctan \{ (Z + e^2 \nu \sin\phi) / R \} \text{ iterate}$$

$$\lambda = \arctan (Y / X)$$

$$h = R / \cos\phi - \nu$$

where $R = \sqrt{(X^2 + Y^2)}$

Also the variance covariance of these ellipsoidal coordinates can be derived from :-

$$VCV_{\phi\lambda h} = J . VCV_{XYZ} . J^T$$

where the Jacobian matrix is :-

$$J = \begin{bmatrix} A & YA/X & B \\ -Y/R2 & X/R2 & 0 \\ (X / Rcosf) + AC & (Y / Rcosf) + YAC / X & BC \end{bmatrix}$$

where :-

$$A \cong X\tan\phi / R^2(e^2 - \sec^2\phi) \qquad B \cong 1 / (R\sec^2\phi - e^2\nu\cos\phi)$$

$$C = R\sin\phi / \cos 2\phi - ve^2\sin\phi\cos\phi / (1 - e^2\sin^2\phi)$$

The Jacobian matrix for the conversion of more than one point is similar to that shown above.

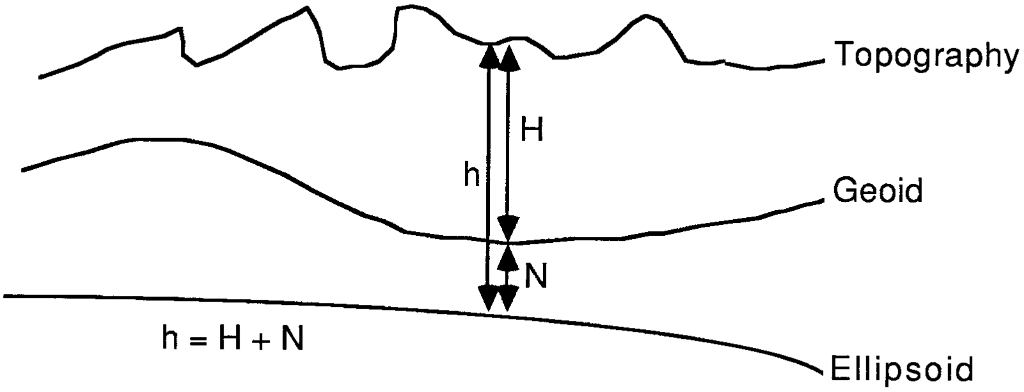
3.2 THE GRAVITY FIELD AND GEOIDS.

The above mathematical model represents an ellipsoid which closely follows the shape of the earth and assumes the earth has uniform density. This is not the case.

The best way to observe the effect of mass anomalies on the model is to study the deflection of the vertical over the surface of the earth. By doing this an understanding of "level" surfaces or equipotential surfaces is gained. The most obvious surface to choose for this investigation of an equipotential surface is that which corresponds to mean sea level, as this has some physical reality. It is for this reason that this special case of an equipotential surface is given the name GEOID.

The effect of the changes of gravity brought about by variations in the earth's density cause undulations in the geoid. The geoid will dip where mass deficiencies exist and conversely, the geoid will rise where a mass surplus exists. By comparing the surface of the geoid to the corresponding oblate ellipsoid described in 3.1.1 we find that the two surfaces deviate by up to about ± 100 metres. This deviation is known as the geoid height. The relationship between geoid height (N), elevation (H) (known also as orthometric height) and ellipsoidal height (h) is shown in Figure 3.1.

Figure 3.1 HEIGHT RELATIONSHIPS.



3.3 THE AUSTRALIAN GEODETIC DATUM.

The best mathematical oblate ellipsoid to choose when carrying out geodetic computations is that which best approximates the real conditions within the location of the computations. It is for this reason that the Australian National Spheroid (ANS) was chosen as it best approximates the geoid within the proximity of the Australian continent. The definition of the ANS is gazetted in the Australian Commonwealth Gazette of 6th October 1966 and gives the ellipsoidal parameters as :-

$$a = 6378160.0 \text{ m}$$

$$f = 1 / 298.25$$

It also defines the Australian Geodetic Datum by giving the coordinates of the Johnston Geodetic Station :-

Latitude	S 25° 56' 54."5515
Longitude	E 133° 12' 30."0771

Ellipsoidal Height as 571.2 metres.

3.4 TRANSIT SATELLITE EPHEMERIS COORDINATE SYSTEMS.

The history of the precise ephemeris and broadcast ephemeris coordinate systems is well documented in A.C. Jones (1984). The major changes being the result of introducing more up to date gravity models since the 1960's and by increasing the number of terms in the spherical harmonic modeling of the gravity field.

The gravity model currently being used for the broadcast ephemeris is WGS-72 (Hoar, 1982), and that for the precise ephemeris is NSWC 10E-1 (Kouba, 1983). The differences between the two models are of the order of one metre (Jenkins and Leroy, 1979). The ellipsoid for the NSWC 10E-1 geopotential model and precise tracking station network (TRANET) which is known as the NSWC 9Z-2 system has the following parameters.

$$a = 6378145 \text{ m}$$

$$f = 1 / 298.25$$

3.5 TRANSFORMATION OF COORDINATES.

In order to use TRANSIT Doppler observations on the Australian Geodetic Datum (AGD), it is necessary to transform the coordinates obtained on the NSWC 9Z-2 system onto the Australian National Spheroid. To do this, all seven possible degrees of freedom between the two spatial systems must be solved for. The seven parameters consist of three translations $\Delta X, \Delta Y, \Delta Z$; three rotations of the respective axes R_X, R_Y, R_Z and a scale factor B_S.

The seven transformation parameters for the conversion of precise ephemeris coordinates onto the ANS were computed using program

PARM which was developed in the School of Surveying. PARM uses the Bursa-Wolf model which is of the form :-

$$\begin{bmatrix} x_2 \\ y_2 \\ z_2 \end{bmatrix} = \begin{bmatrix} DX \\ DY \\ DZ \end{bmatrix} + (1 + B_S) \begin{bmatrix} 1 & -R_Z & R_Y \\ R_Z & 1 & -R_X \\ -R_Y & R_X & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix}$$

where		
	x_2, y_2, z_2	are ANS datum coordinates
	x_1, y_1, z_1	are NSWC 9Z-2 datum coordinates
	DX,DY,DZ	are the translations
	R_X, R_Y, R_Z	are the rotations
	B_S	is the scale factor

The same program was used to find the transformation parameters to convert the broadcast ephemeris to ANS and also broadcast ephemeris to precise ephemeris. The final values for these transformations are listed in table 3.1.

Table 3.1TRANSFORMATION PARAMETERS.

Parameter	NSWC 9Z-2 to ANS		Broadcast to NSWC 9Z-2		Broadcast to ANS	
	Value	Std. Dev.	Value	Std.Dev.	Value	Std. Dev.
Dx	116.00m	1.2m	-6.5m	±1.2m	108.65m	3.5m
Dy	50.47	1.2	-1.3	1.2	49.43	3.2
Dz	-137.19	1.5	-1.5	1.4	-137.49	3.9
Rx	0.23sec	0.04sec	-0.4sec	0.03sec	0.24sec	0.11sec
Ry	0.39	0.04	0.12	0.04	0.54	0.12
Rz	-0.47	0.04	0.15	0.04	-0.31	0.12
Bs	-0.699ppm	0.07ppm	-0.4ppm	0.1ppm	-1.22ppm	0.3ppm

[Allman and Veenstra,1984]

It should be noted that the sign convention adopted for these parameters is the standard geodetic convention, ie. that when looking along the positive axis towards the origin, anti-clockwise rotations are positive.

The seven parameters for each set of transformations were determined using coordinate values covering the whole of the Australian continent. These were then used in program DOPTRAN (also developed in the School of Surveying) to convert the final AGD84 coordinates [Allman and Veenstra, 1984] into both precise and broadcast ephemeris datums. These transformed coordinates were then used as the benchmark for the comparison of the Doppler reduction software solutions of the same data set.

CHAPTER 4

TRANSIT DOPPLER REDUCTION SOFTWARE

4.1 INTRODUCTION.

This chapter describes the various software used for the computation of a ten station network observing six TRANSIT satellites using Magnavox MX1502 satellite receivers. All the software described is available in the School of Surveying. Although developed overseas, the software, apart from the Magnavox MX1502 onboard software, has been modified to suit the computer facilities at the University of New South Wales.

In general there are five steps in the the reduction of TRANSIT Doppler observations. These are :-

4.1.1 MAJORITY VOTING.

The receiver collects satellite ephemeris data continuously. This ephemeris is described in terms of Keplerian elements. Due to the two minute logging of position, there is a repetition of Keplerian elements which describe the fundamental position of the satellite's orbit during the pass. The recording of each of these elements over the duration of the pass allows for checking against corrupt information. This process of checking the redundant information and subsequent condensing of the recorded data is known as majority voting.

Modern receivers such as the Magnavox MX1502 use onboard majority voting routines to process received pass information before storing satellite ephemeris and Doppler data onto magnetic tape.

4.1.2 PREPROCESSING.

Due to the enormous amounts of information gathered during one satellite pass, it is economic in terms of computer resources, to filter unwanted data before rigorous computation of receiver position. Preprocessing software is based on statistical testing of data within each pass.It is based on a comparison of observed Doppler counts with estimated values computed using first order estimates of receiver position. In this preprocessing stage the errors in the observed Doppler counts described in section 2.4 are compensated for.

This processing, in turn, produces a better first order estimate of position. A check of the stability of the frequency source of the receiver can also be obtained. It is common for a plot or table of X,Y,Z receiver coordinates and frequency offset to be produced by this type of software. This enables visual inspection of the quality of the observations as well as relying on the statistical estimates that are calculated.

4.1.3 SINGLE STATION POSITION CALCULATION.

Single station position can be determined using observed broadcast ephemeris using sequential least squares techniques. Using the general non linear mathematical model (Figure 4.1), which expresses the single satellite distance difference $s(\tau_2)$ - $s(\tau_1)$ to the geocentric coordinates of the receiver ground station r and the two consecutive positions of the satellite 1 and 2.

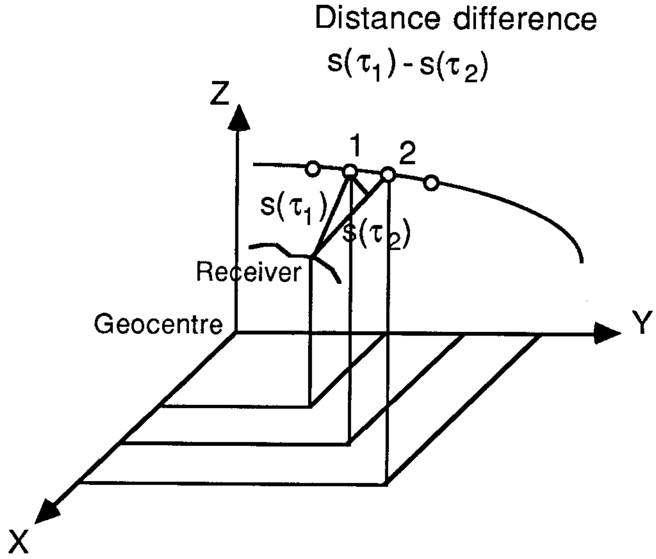


Figure 4.1THE GENERAL NON LINEAR MATHEMATICAL MODEL.

Hence :-

$$s(\tau_2) - s(\tau_1) = \sqrt{\{(x_1-x_r)^2+(y_1-y_r)^2+(z_1-z_r)^2\}} - \sqrt{\{(x_2-x_r)^2+(y_2-y_r)^2+(z_2-z_r)^2\}}$$

now expanding equation 2.6 gives :-

$$N = (fg - fs)(\tau_2 - \tau_1)$$

$$+ \frac{fs}{c}\left[\sqrt{\{(x_1-x_r)^2 + (y_1-y_r)^2 + (z_1-z_r)^2\}} - \sqrt{\{(x_2-x_r)^2 + (y_2-y_r)^2 + (z_2-z_r)^2\}}\right] \tag{4.1}$$

There is one equation of the form of (4.1) for each observed Doppler count. For a single pass at a receiver ground station there will be up to nine such equations. Generally the ground and satellite coordinates may be considered as unknowns along with the frequency offset. As long as there are a substantial number of degrees of freedom, ie. that the total number of observation equations substantially outnumbers the total number of unknowns, then all unknowns may be solved by least squares.

A set of Doppler observation equations such as (4.1) form a set of non-linear equations. Such a system of non-linear equations can be converted into a system of linear equations by choosing initial values for the unknown quantities and approximating the non-linear equations by a Taylor's expansion about the point defined by these approximations and the observed Doppler counts.

The next step is the simultaneous solution of an apparently expanding number of linear equations brought about by successive observation of satellite passes. This is most efficiently solved by dividing the large system into smaller segments and then combining these smaller segments into the final solution one at a time. This is done by using the process of matrix partitioning to obtain expressions for the current least squares estimates in terms of the prior estimates plus correction terms that are resolved by the current segment. This concept of sequential least squares is one of several algorithms which differ in detail. Some similar algorithms are phased adjustment [Tienstra, 1956], sequential adjustment [Krakiwsky, 1968] and Kalman filtering [Kalman, 1960].

4.1.4 MULTI-STATION AND PRECISE EPHEMERIS COMBINATION.

In order to compute multi-station adjustments or to substitute the broadcast ephemeris with the precise ephemeris, there needs to be a combining and sorting of observed passes with ephemeris. These routines are mainly concerned with the combination of files from the preprocessing software described in section 4.1.2.

For software designed to use precise ephemeris it is usual for these same algorithms to substitute files of precise ephemeris for the observed broadcast ephemeris. This software is the least cumbersome of the of the computational procedures as only a minimum of mathematical functions are carried out on the data.

4.1.5 MULTI-STATION POSITION CALCULATION.

The calculation of receiver positions which form multi-station networks is carried out using the same sequential least squares techniques described in section 4.1.3. The introduction of many ground station receivers greatly increases the number of observation equations of the form (4.1). The corresponding increase in the unknowns also adds to the complexity of the systems of equations.

The major benefit of the multi-station solution is that there is no increase in the number of unknowns in the satellite orbit. This then increases the degrees of freedom in the combined system of observation equations resulting in much better estimates of final receiver positions. The combination of multi-station networks with the precise ephemeris, which tightens the estimates of satellite positions, should theoretically produce the best solution of the final receiver positions.

4.2 THE MAGNAVOX MX1502 ONBOARD SOFTWARE.

The Magnavox MX1502 Satellite Surveyor is a robust field instrument which is capable of producing point position and translocation solutions in the field. The software is hard wired onto micro chips which reside on circuit boards within the receiver. This software is not accessible to the user and is activated by a series of command codes. The positions calculated use the broadcast ephemeris which is assumed to be error free for the calculation of point position. Errors in the broadcast ephemeris can be minimised by using translocation techniques (see Jones [1984]).

The translocation techniques are slow as due to memory limitations only 17 passes can be computed at any one time. Although translocation can give quite adequate results, it was not included in this project for comparison. See Jones [1984] and Wood [1984] for detailed solutions.

The point positions observed and calculated by the MX1502 were included in this project so as to compare rigorous post processing solutions to field determined positions.

4.3 PROGRAM MAGNET .

The Magnavox Advanced Products and Systems Company (incorporated in the U.S.A.) has proprietary rights to all software developed by the company. MAGNET is the Magnavox multi-station network adjustment software. Details of the algorithms are not available.

Most of the theory behind the MAGNET algorithms has been presented in papers by Magnavox staff. The main sources being Hatch, [1976]; Stansell, [1978]: Ross, [1982]; and Hoar,[1982].

The program uses data from Magnavox MX1502 receivers only and can process a maximum of 10 stations simultaneously. According to Ross [1982]:-

"It (MAGNET) performs a weighted least squares analysis on all the available satellite and Doppler data to produce an adjusted network which is the best fit to the acquired data."

Essentially MAGNET solves for 10 parameters in a single point solution. These are :-

* site latitude, longitude and ellipsoidal height.

* satellite positional errors, being along track error, across track error and out of plane error.

* receiver offset frequency

* rate of change of receiver offset frequency

* receiver time delay

* tropospheric correction

MAGNET computes site coordinates in satellite broadcast ephemeris datum, subsequently the initial site values entered must also be in the broadcast datum. This site initialisation comprises the first phase of the operation of the program.

The second phase of the program reads in the observed data from the MX1502. This phase is the preprocessing step described in section 4.1.2, where Doppler counts are modified to compensate for the errors due to the effects described in section 2.4. It is also the part of the processing that rejects unusable Doppler counts and unusable passes. The result of this phase yields a 2-dimentional position fix. At this stage the ellipsoidal height is a constrained parameter. This reduces the computation time and allows for faster filtering of unwanted or unusable Doppler counts.These results are then stored onto a direct access device (usually a disk). This now represents all edited data for a single site, the majority of which will be used in the adjustment phase.

After all sites have been processed in the second phase described above, then the adjustment phase can be activated. It is at this stage that the MAGNET software has its advantage over other multi-station adjustment programs. Here the user may instruct the program to compute the solutions in a variety of ways. There is the choice of using hyperbolic computation of the satellite ranges or by using the pseudorange method described in section 2.4.1, which is designed to reduce correlation. There is also the choice of selecting the minimum number of sites which observe each satellite pass. For example, setting this value to two will eliminate all passes that were observed by only one site. Similarly it is possible to ask that only passes which were observed by all ten sites be accepted into the computation. This, however, severely restricts the number of passes used in the adjustment and is not desirable for rigorous solutions. The effect of restricting satellite passes gives the user the ability to increase the degrees of freedom in the adjustment. This is done at the expense of disregarding usable passes. As the software incorporates rigorous least squares techniques then it would be advantageous to incorporate all usable data.

4.4 PROGRAM PREDOP.

Program PREDOP is the first of three major programs that make up the PREDOP-GEODOP software package for the rigorous least squares adjustment of Doppler satellite observations. PREDOP performs the preprocessing tasks described in section 4.1.2. It is capable of using data recorded on a variety of satellite receivers including Magnavox, JMR and Marconi. According to Lawnikanis, 1976 PREDOP has the following synopsis :-

" PREDOP does a first order ionospheric refraction correction on the Doppler counts and decodes the variable and fixed parameter words. A curve fit to each of the three variable parameters (see section 4.4.1). Then these smoothed functions and fixed parameters are used to compute the satellite orbit, which is transformed into a terrestrial coordinate system and an eight order Chebyshev polynomial is fitted to represent these XYZ's. Finally the Doppler counts are compared to theoretical values and edited appropriately before writing out the pass with interpolated meteorological data."

The program performs three major tasks, these being initial testing, data editing and data output.

4.4.1 INITIAL TESTING.

Before calculation of position the validity of the data is checked. Failing any of the following will result in pass rejection.

* Validation of satellite identification number by comparing to all known TRANSIT satellites.

* High or low Doppler count value within range.

* High or low Doppler difference within range.

* Variable parameter quantity within range. These being :-

ΔA_k - out of plane or semi-major axis component. Transmitted every two minutes.

ΔE_k - along track or eccentric anomaly component. Transmitted every two minutes.

$\Delta\eta_k$ - across track or crosstrack bias component. Transmitted every four minutes.

* At least 10 Doppler count pairs.

* All fixed parameters majority voted correctly.

* Pass header and variable lockon time agree.

* Pass header and fixed parameter satellite numbers agree.

* All variable parameters majority voted correctly.

* At least six variable parameters.

* At least four (four minute) points to fit. i.e. at least three $\Delta\eta_k$ intervals.

* Sum of residuals squared is less than Chi-squared 99% test statistic.

4.4.2 DATA EDITING.

Having passed the above tests, the satellite orbit is calculated. The Doppler counts are then compared to theoretical values in order to satisfy the following criteria :-

* Reject Doppler counts occurring below the cut off elevation of 15 degrees.

* Check for minimum number of Doppler counts and reject pass if to few.

* Maximum elevation below 15 degrees then reject pass.

* Check maximum elevation occurring before lockon time, if so reject pass.

* Establish point of closest approach and balance Doppler counts around this point.

* Check miscloses on each Doppler count, reject if too large. Reject pass if too few Doppler counts remain.

4.4.3 DATA OUTPUT.

For the data that passes all the above criteria, meteorological data is interpolated from default values. These being 15° C dry temperature, 10° C wet temperature and 1014 mb air pressure at sea level. These are then combined with updated Keplerian orbital parameters, lockon time, satellite XYZ coordinates and span along with Doppler counts. These values are then written to an output device as one file.

4.5 PROGRAM MERGE.

Program MERGE performs two tasks, firstly, that of combining satellite observations from all sites that make up the multi-station network. Secondly, it has the function of combining precise ephemeris with single site observations or multi-station observations.

These two tasks or modes of operation are described by Lawnikanis, 1976 as having the following synopsis :-

"Mode 0: The first file is read and copied to a scratch device. Then each additional input file is read and merged pass-by-pass with the previous "master" file on the previous scratch device. A record of each new station merged, the number of passes, the current scratch "master", and total number of passes are printed after the current merge phase.

The final "master" file is written on reading and merging the final input file, followed by a station and pass count summary.

Mode 1: The input file is rewound and merged for each specified number of fitted precise ephemeris file and written, provided the pass falls between the selected start and stop chronological time limits. A page header is printed, then a pass-by-pass summary of the pass number, lockon time, and the number and names of the active stations is output."

Program MERGE represents the only stage of the PREDOP-GEODOP processing when the user can influence the data being used in the final adjustment. This can only be achieved by limiting the chronological time span for acceptable passes or by eliminating passes from specified satellites. This is done by setting the required option card which is read at the beginning of the program.

4.6 PROGRAM GEODOP.

Geodop was developed in Canada in the early 1970's by Kouba and Boal, [Kouba and Boal,1975] and results from a combination of resources from the University of New Brunswick, Shell Canada Ltd. and the Geodetic Survey of Canada. In its original form GEODOP was designed to yield the most reliable relative positions for groups of up to 15 stations occupied simultaneously and to give reliable variance covariance estimates. The phase adjustment approach described in section 4.1.3 was employed which adds each pass to a comulative solution of all previous passes after satisfying built in statistical tests.

GEODOP reads in binary data files produced by programs PREDOP or MERGE. From these two programs the initial data has already undergone some statistical testing and Doppler counts have been corrected for the first order ionospheric refraction effect using the two frequencies (150 and 400MHz). The following is a brief summary of the modelling of the GEODOP adjustment and is reproduced from Kouba and Boal [1975].

4.6.1 TROPOSPHERIC REFRACTION CORRECTION.

GEODOP gives the choice of the simplified Saastamoinen correction model (Saastamoinen, 1973) or the Hopfield model (Hopfield,1972). For this project the Hopfield model was used for the adjustment. For range measurements the Hopfield model takes the following form :-

$$\Delta s = \frac{K_d}{\sin\sqrt{(E^2 + 6.25)}} + \frac{K_w}{\sin\sqrt{(E^2 + 2.25)}}$$

where Δs is the range correction in metres.

E is the elevation in degrees

$$K_d = 77.6 \frac{P}{T} [40136 + 148.72 (T - 273.16)] * 2 * 10^{-7}$$

$$Kw = 77.6 \frac{4810 e}{T^2} (11000) * 2 * 10^{-7}$$

where e is the partial vapour pressure in millibars

P is the atmospheric pressure in millibars

T is the temperature in degrees Kelvin

This gives the following corrected Doppler count N_{12}

$$N_{12} = N_{12} + (\Delta s \, . \, E_1 - \Delta s \, . \, E_2)/\lambda$$

where N_{12} is the uncorrected Doppler count

Δs is the range correction from the Hopfield model

E_1 is the satellite elevation at the beginning of the Doppler count

E_2 is the satellite elevation at the end of the Doppler count

λ is the wavelength of the carrier frequency.

4.6.2 SATELLITE ORBIT.

By the time GEODOP receives the satellite pass information the ephemeris of the satellite is represented as Chebyshev coefficients obtained by a least squares fit to satellite coordinates X,Y,Z (performed in PREDOP). For the precise ephemeris the derivatives X,Y,Z are also computed (performed by the Naval Weapons Laboratory United States, and read in using program MERGE). For broadcast ephemeris X,Y,Z coefficients are available at two minute intervals whereas the precise ephemeris X,Y,Z and X,Y,Z are available at one minute intervals.

For any time within the Chebychev fit, Δt, satellite coordinates and velocity vectors can be found using the following Chebychev polynomial expressions.

$$X(t) = \sum_{i=0}^{i=7} c_x^i \, T_i(t)$$

$$X(t) = \sum_{i=1}^{i=7} c_x^i \, T_i'(\tau)$$

where t is the required epoch

τ is the argument scaled to be within the required interval

c_x^i are the coefficients from the least squares fit to the X coordinate and the derivative with respect to t

T_i (t) and T_i' (τ) are Chebyshev polynomials and their derivatives with respect to τ.

The neglected eighth order coefficient for each coordinate are typically less than 0.5 metres as opposed to 2.0 metres for the lower order terms.

Similarly Y, Z, Y, and Z are obtained from coefficients c_y^i and c_z^i respectively.

In summary the input data for GEODOP consists of :-

- coefficients c_x^i, c_y^i, c_z^i
- measured Doppler counts and time intervals
- metrological data (temperature, pressure and partial vapour pressure)

4.6.3 THE MATHEMATICAL MODEL.

From the theoretical range rate equations 2.4 and 2.5, two error terms are added. These are :-

$$N + \varepsilon = (f_g - f_s)(t_2 - t_1) + U + \frac{f_g}{C}(s_2 - s_1) \tag{4.1}$$

$$N + \varepsilon = (f_g - f_s)(\tau_2 - \tau_1) + U + \frac{f_s}{C}(s_2 - s_1) \tag{4.2}$$

where ε represents random observation errors

and U represents undetermined systematic errors.

In GEODOP the undetermined systematic error is represented by :-

$$U_{12} = -\frac{\Delta N_{TR}}{100} dk + \frac{\delta}{dt}(s_2 - s_1)\,dt + \frac{\delta}{dr}(s_2 - s_1)\,dr \qquad (4.3)$$

where dk is the nominal tropospheric refraction correction expressed as a percentage.

dt is the nominal receiver delay plus the synchronisation error correction

dr is the vector of orbital biases (along track, across track and out of plane)

The range rate equations 4.1 and 4.2 are linearised in GEODOP using Taylor's expansion. The observation equation is then expressed in the following form

$$AX + CY + W - V = 0$$

where X is the vector of unknown site coordinates

Y is the vector of systematic errors contained in (4.3)

A & C are coefficient matrices

W is the vector containing miscloses or (C-0) terms

V is the vector of observation residuals.

The matrices A and C are formed by differentiating equations 4.1 and 4.2 with respect to the unknowns. Thus for the A matrix, the elements of the nth row pertaining to the ith station in the network has the following form :-

$$a_{n,3i-2} = ([X_s (t_2) - x_i] / s_2 - [X_s (t_1) - x_i] / s_1) / \lambda$$

$$a_{n,3i-1} = ([Y_s (t_2) - y_i] / s_2 - [S_s (t_1) - y_i] / s_1) / \lambda$$

$$a_{n,3i} = ([Z_s (t_2) - z_i] / s_2 - [Z_s (t_1) - z_i] / s_1) / \lambda$$

where the Doppler counts have been accumulated between epochs t_1 and t_2.

For matrix C the nth row corresponding to the same Doppler count accumulation, the elements are :-

$$[c_{n1}, c_{n2}, c_{n3}] = ([\frac{\delta s_2}{\delta X_s} . \frac{\delta X_s}{\delta U} . \frac{\delta U}{\delta r}]_{t=t_2} - [\frac{\delta s_1}{\delta X_s} . \frac{\delta X_s}{\delta U} . \frac{\delta U}{\delta r}]_{t=t_1}) / \lambda$$

where $\frac{\delta s}{\delta X}$ being the geometric partials

$\frac{\delta X}{\delta U}$ being the rotation to inertial partials

and $\frac{\delta U}{\delta r}$ being the variational partials

The remaining nth row terms for the C matrix are :-

$c_{n4} = t_2 - t_1$ being related to frequency offset

$c_{n5} = -(t_2 - t_1) \frac{\Delta N_{TR}}{100}$ being related to tropospheric refraction bias

$c_{n6} = ([\{ X_s (t_2) - X_i\} / s_2] . X_s(t_2) - [\{ X_s(t_1) - X_i\} / s_1] . X_s(t_1)) / \lambda$

being related to receiver timing bias.

For a network with m passes and n number of unknown sites, the number of unknown parameters is 3n + m(3 + 3n). As an example, the 10 station network for this project has of the order of 200 passes. This gives 6630 unknown parameters to solve for, far too many for a single adjustment. To solve this, sequential techniques are applied. This technique introduces a coordinate correction vector X and a corresponding variance-covariance matrix G . By processing pass by pass the Y vector parameters for each pass are eliminated. The resulting parameter set for the solution gets no larger than 6n + 3 unknowns. That is for the above example only 63 parameters compared to 6630.

The solution vectors are given by :-

$X = -G^{-1} [A^T.P.W - A^T.P.C (P_y + C^T.P.C)^{-1} C^T.P.W]$

$Y = - (P_y + C^T.P.C)^{-1} . (C^T.P.W + C^T.P.A.X)$

where

$G = [(P_x.A^T.P.A) - A^T.P.C (P_y + C^T.P.C)^{-1}. C^T.P.A]$

P is the inverted a priori weight coefficient matrix of the Doppler counts.

P_x and P_y are inverted a priori weight coefficient matrices corresponding to X and Y respectively.

For the coordinate corrections the variance-covariance matrix is given by

$$\Sigma_x = \bar{\sigma}^2 N^{-1}$$

where $\bar{\sigma}^2$ is the variance factor.

This is an a posteriori value and should be replaced by an a priori value based on experience.

4.6.4 GEODOP PROGRAM CONSTANTS.

The program GEODOP has adopted the following constants.

The speed of light c = 299792.50 Km/sec.

Earth rotation rate $w = 4.3752691 * 10^{-3}$ rad/min.

A priori variance factor $\sigma^2_o = 1.0$

A priori tropospheric refraction scaling factor $\sigma_{\Delta trop} = \pm 0.1$ (ie. 10%)

4.7 GEODOP VERSIONS - GEODOP3 AND GEODOP5.

For this project two versions of GEODOP were used for the reduction of the data set for a ten station network. The original version of GEODOP known as GEODOP3 has been used successfully within the School of Surveying since 1981. An updated version of GEODOP known as GEODOP5 was developed during the early 1980's by Geodetic Survey of Canada. GEODOP5 was installed in the School of Surveying in 1984.

The major changes to GEODOP3 to create the new GEODOP5 version are [Kouba 1984] :-

- up to six Keplerian orbital biases (previously only three; along track, across track and out of plane).
- up to four station biases (previously three) with the inclusion of frequency drift.
- improved tropospheric refraction.
- higher order ionospheric refraction.
- improved correlation of Doppler data between different simultaneously observed stations.
- improved correlation between stations.
- improved statistical testing on position corrections and station biases.

All the above have greatest effect on multi-station adjustments. The resulting difference in results are discussed in chapter five. One of the most apparent effects of the improvements is a massive increase in computer CPU time in execution. A sample data set of 170 passes observed on a ten station network took 3302.41 seconds to execute using GEODOP5, whereas the same data set took 1356.73 seconds to execute using GEODOP3. For a single point position using 88 passes the execution time increased from 45.22 seconds using GEODOP3 to 55.89 using GEODOP5.

The GEODOP5 program also introduces an efficient short-arc orbit computation technique [Kouba 1983]. This technique calculates satellite coordinates using first derivative velocities as well as second derivative accelerations evaluated from the GEM9 gravitational model. This technique is used for point and relative positions when using broadcast ephemeris.

An exact observational data set comparison of the two versions of GEODOP will not result in exactly agreeing solutions as the increase in the biases and related variances will produce different criteria for the modelling and rejection of Doppler data. However, results using default constraints have the solutions agreeing to within the expected standard deviations of the observations and computations. An example of a direct comparison is shown in Table 4.1.

	GEODOP3	GEODOP5
PREDOP PASSES	88	89
PASSES ACCEPTED	86	87
SAME PASSES REJECTED	2	2
SQ. SUM OF RESIDUALS	236.68	625.50
DEGREES OF FREEDOM	1823	1827
LATITUDE	S20 20 35.050	S20 20 35.061
LONGITUDE	E139 12 21.567	E139 12 21.695
ELLIPS. HT.	552.84	548.98
X	-4529711.24	-4529710.84
Y	3909115.43	3909110.18
Z	-2203541.84	-2203540.81
COORDS FROM PASS 1		
X	-4529713.1	-4529713.1
Y	3909124.9	3909119.8
Z	-2203536.9	-2203537.0

COMPARISON OF POINT POSITION USING BROADCAST EPHEMERIS

Table 4.1

CHAPTER 5

INVESTIGATION OF MULTI-STATION REDUCTION SOFTWARE

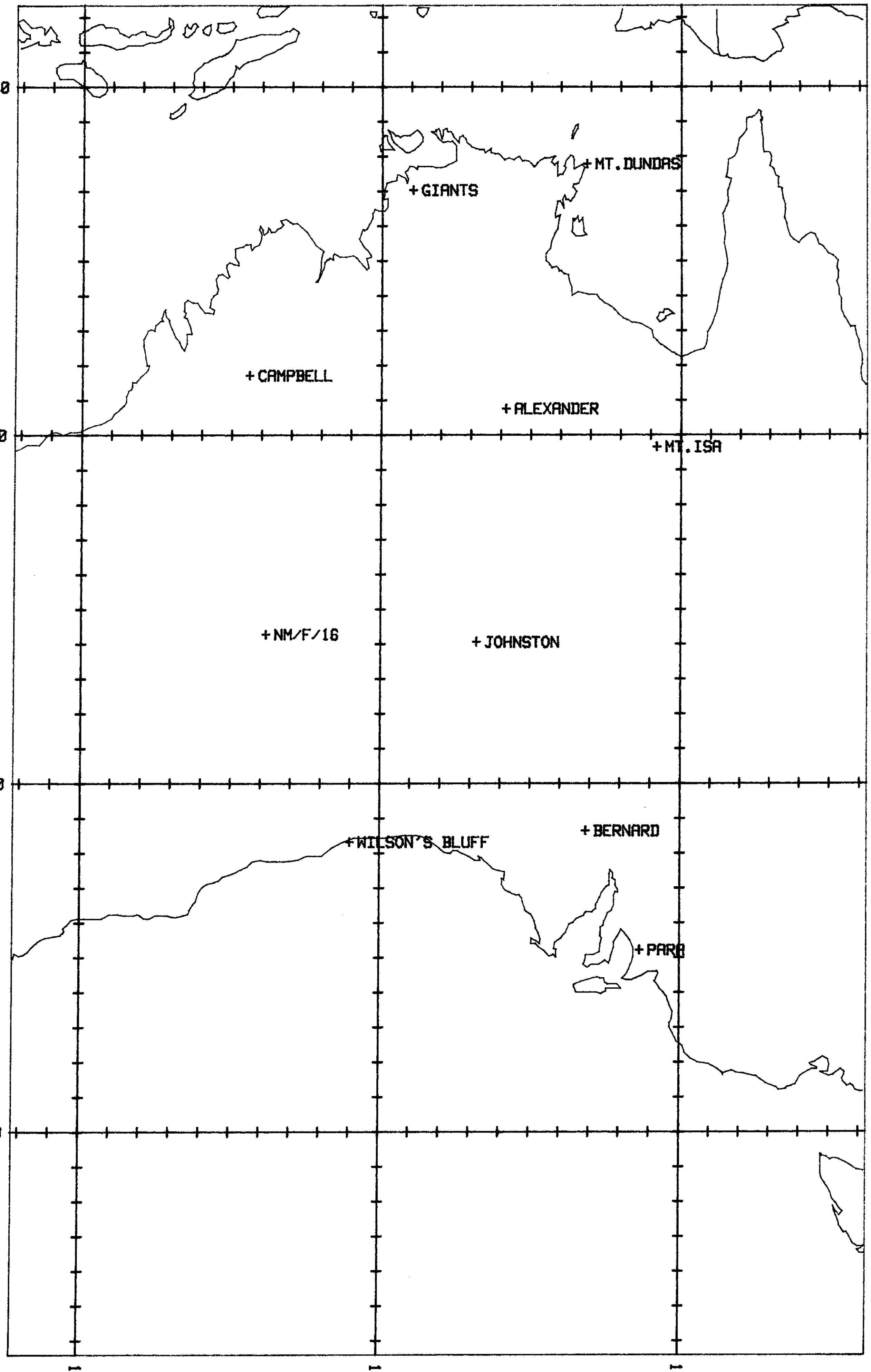
5.1 INTRODUCTION AND BACKGROUND.

It is well known that multi-station reduction techniques for Doppler positioning are capable of producing higher accuracies than point position or translocation techniques. Much of the experimentation in the use of multi-station techniques has been restricted to networks with inter station distances of less than one hundred kilometers. This has been mainly due to the high cost of acquiring data over larger distances and also the non homogeneity of ground truth for the larger networks.

During the southern winter of 1982 the National Mapping Council of Australia supported the continuation of the observation of multi-station Doppler networks from the Eastern States of Australia to the West. The Eastern networks had previously been observed with support of the Queensland Department of Surveying and Mapping. The first of these new networks covered the centre of the Australian Continent from the north coast of the Northern Territory to the southern coast of South Australia. A total of ten stations were observed simultaneously (see Figure 5.1) with the largest separation between stations having a chord distance over 2500 kilometers. The above network was chosen for this project because of its size and the number of stations being the maximum allowable sites for the MAGNET reduction software.

The observations for the ten station network were carried out for a period of five days with the three western stations continuing to observe for another ten days which represented the overlapping stations for the

Figure 5.1 MULTI-STATION NETWORK.



SCALE 90 minutes per cm

adjoining western network which contained a total of thirteen stations. All of the stations in both these networks were observed using Magnavox MX1502 receivers. It should be noted that all thirteen receivers gave reliable data throughout the entire observation period.

The result of these observations was a very large data set of multi-station Doppler which was suitable for investigation over a homogeneous network that forms part of the Australian Primary Control Network including the Johnston Origin. An adjustment of the entire Primary Network was carried out by Associate Professor John Allman at the University of New South Wales and was completed and adopted in 1984. This adjustment incorporated all known terrestrial observations, the multi-station Doppler networks using precise ephemeris, point position Doppler observations using precise ephemeris and some VLBI (Very Long Baseline Interferometry) baselines along with some SLR (Satellite Laser Ranging) baselines.The results of this adjustment form the ground truth to which the results of this project have been compared.

It should be pointed out that the observations under investigation form part of the data set on which the ground truth was determined. It could be argued that some bias will enter the results. For the purposes of this project it is considered that this bias will be minimal in view of the amount of terrestrial data , the independent precise point position Doppler and the baselines observed using different space techniques.

The observations for the network were carried out using the following TRANSIT satellites :-

30130	Oscar satellite launched May 1967
30140	Oscar satellite launched September 1967
30190	Oscar satellite launched August 1970
30200	Oscar satellite launched October 1973
30480	Nova satellite launched May 1981

During the period of observation (3rd June 1982 to 18th June 1982) the precise ephemeris was available on all five satellites. This then enabled a comparison of results computed using both precise and broadcast ephemerides.

5.2 DATUMS.

During the reduction of all the multi-station networks for the readjustment of the primary control network, three sets of transformation parameters were determined to convert the Doppler derived positions onto the Australian National Spheroid (see section 3.4 and Table 3.1). These transformations were needed for the precise ephemeris, the broadcast ephemeris and an independent set enabling transformation from broadcast to precise ephemeris datums.

In order to maintain integrity of the positions used in this project and to reduce computations, the final values of the positions of the observed stations as derived from the AGD84 results were transformed into both precise ephemeris and broadcast ephemeris datums. This then enabled direct comparisons of the results from the project to ground truth values.

The computation of the multi-station network results was carried out without any fixed station coordinate values to constrain the network. This free adjustment of the observations allows for maximum utilisation of the least squares techniques.

5.3 DATA HANDLING.

The original data recorded on cassette tapes in the ten MX1502 receivers are held at the School of Surveying, University of New South Wales. The data from these DC 30 HL cassette tapes were transfered to 9-track computer tape using a software development system incorporating a MFE Corp. 250 BH tape transport writing to a Digital PDP 11/35 with a 9-track tape drive (J. Brinsden, 1983). These 9-track tapes were then read on a Cyber 171 mainframe which forms part of the University computing facilities. The GEODOP package software was installed on the Cyber 171 and was capable of reading the data files from the 9-track tape. The MAGNET software was installed on a VAX 750 which then required the transfer of the data files from the Cyber 171 to the VAX 750. This process was performed directly. Both sets of software were capable of reading the MX1502 formatted data directly.

Table 5.1 shows the relationship of the site numbers used in the computations with the station name and published AGD84 coordinates. Table 5.2 indicates the number of usable satellite passes observed at each site along with the number of usable Doppler counts as determined by the MAGNET software.

Site	Name	Latitude	Longitude	Ht.
1	PARA	S34 47 11.4797	E138 41 28.7372	215.07
2	MT.ISA	S20 20 40.3812	E139 12 18.0603	510.60
3	BERNARD	S31 21 50.5868	E136 52 50.4689	202.06
4	MT.DUNDAS	S12 13 09.1011	E136 51 46.0627	71.80
5	JOHNSTON	S25 56 54.5515	E133 12 30.0771	566.30
6	ALEXANDER	S19 14 59.8131	E134 10 14.7924	375.29
7	GIANTS	S12 58 13.4715	E131 02 27.6302	145.40
8	WILSON BL.	S31 41 12.1786	E129 00 40.4026	86.52
9	NM/F/16	S25 43 36.1562	E126 10 22.2812	527.70
10	CAMPBELL	S18 17 29.8805	E125 35 14.4034	150.70

Table 5.1 STATION COORDINATES - AGD84

	Doppler	Geometry								Common Passes					
SITE	Count	NW	NE	SW	SE	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
1	1032	17	16	15	20	68	58	57	50	53	52	47	45	44	42
2	1189	22	20	18	19	58	79	64	54	50	52	47	52	40	43
3	1131	18	18	21	20	57	64	77	45	50	48	47	51	43	44
4	805	15	14	16	12	50	54	45	57	48	47	45	40	40	42
5	912	14	16	17	15	53	50	50	48	62	52	51	47	48	46
6	879	16	16	14	12	52	52	48	47	52	58	49	41	43	44
7	860	16	13	14	16	47	47	47	45	51	49	59	44	46	49
8	2492	44	36	50	41	45	52	51	40	47	41	44	171	144	138
9	2436	42	40	43	44	44	40	43	40	48	43	46	144	169	151
10	2308	44	42	39	41	42	43	44	42	46	44	49	138	151	166

Table 5.2 USABLE PASSES AND DOPPLER COUNTS (MAGNET).

5.4 RESULTS USING PRECISE EPHEMERIS.

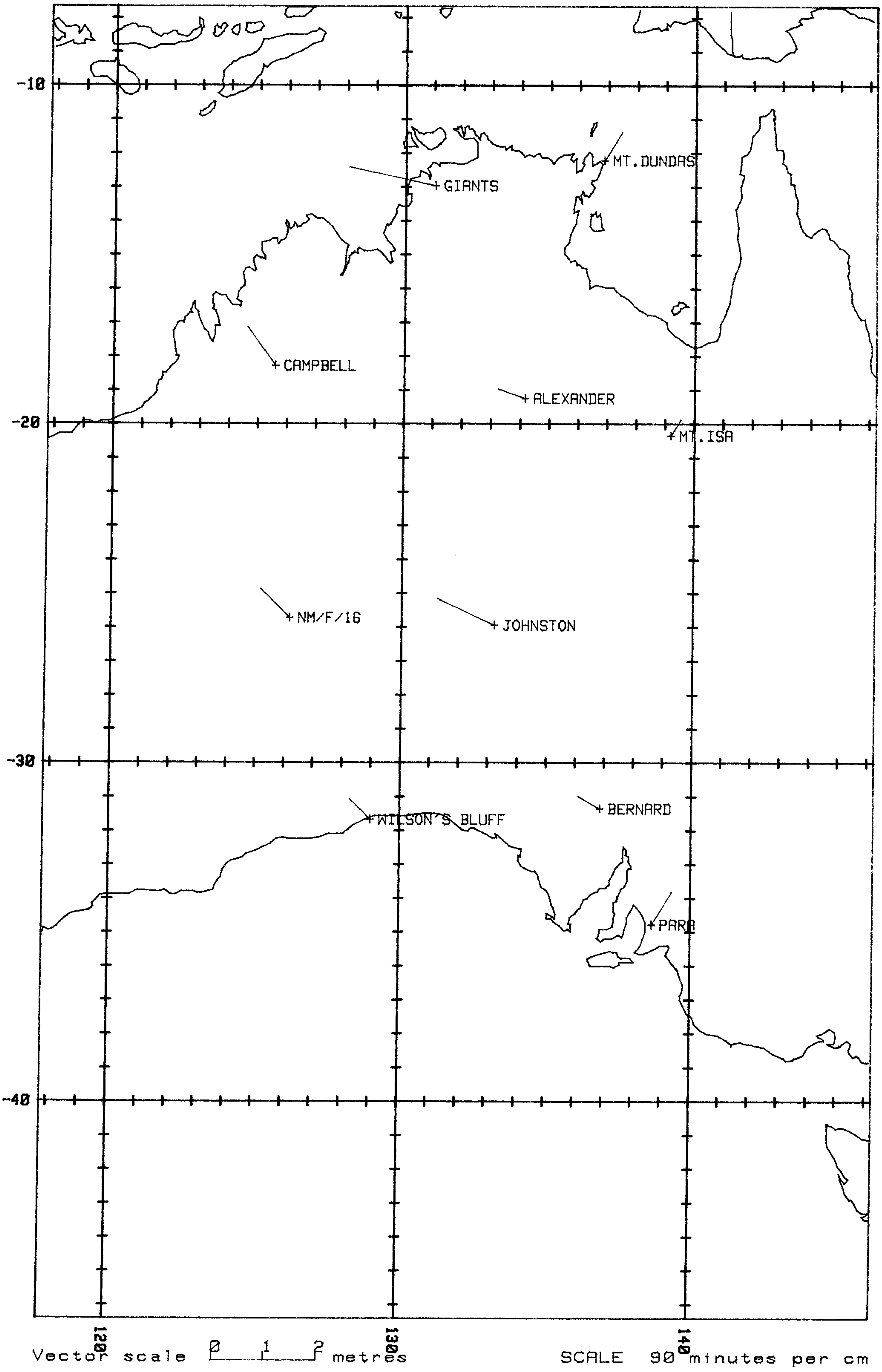
As neither the MX1502 software nor MAGNET software has the capacity to use the precise ephemeris the results discussed here refer to the two versions of the GEODOP software.

The results for all precise ephemeris computations appear in Appendix A. The data from each site has been computed using GEODOP3 and GEODOP5.

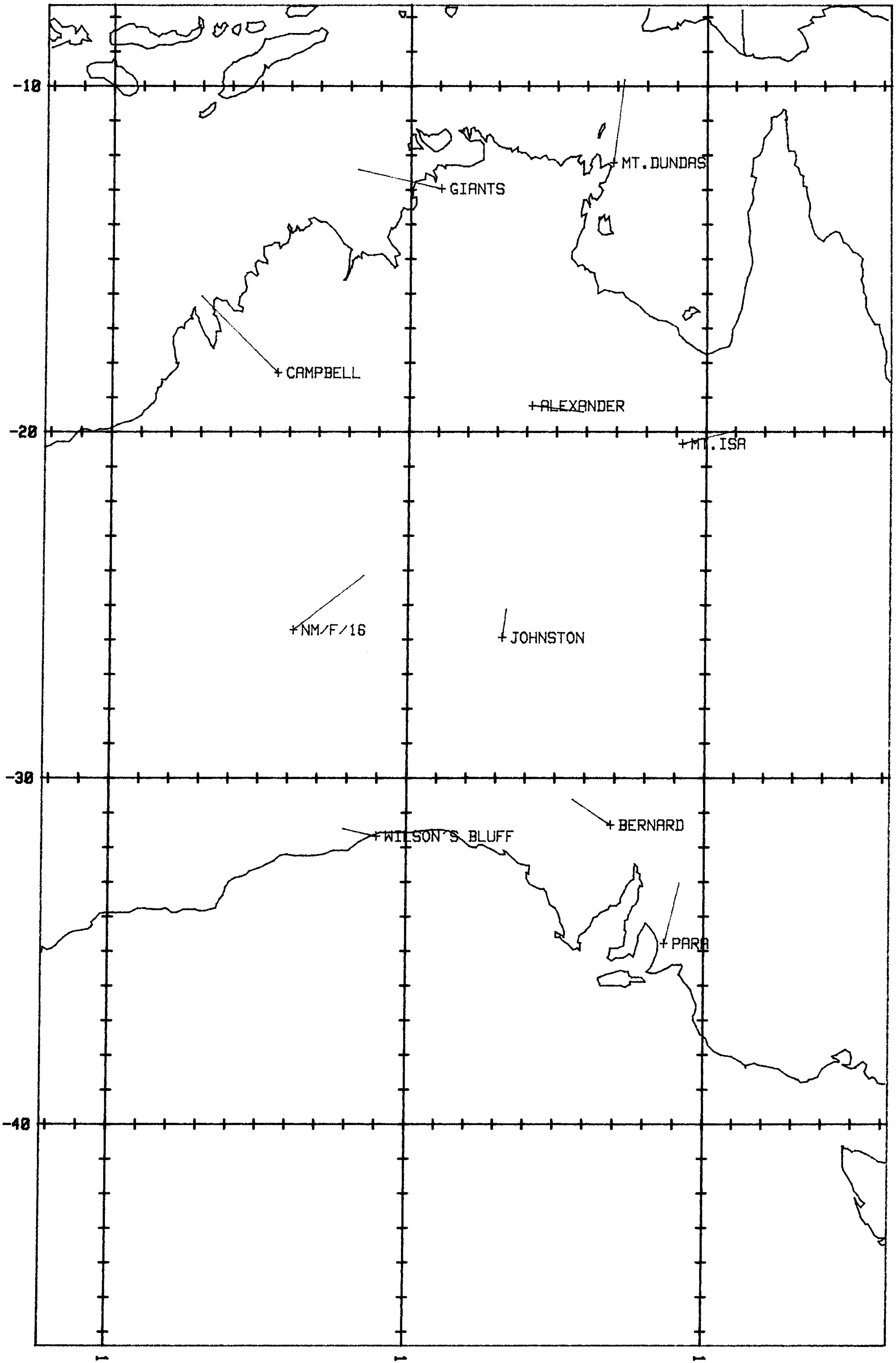
5.4.1 POINT POSITION.

An initial comparison of computing point positions using the precise ephemeris gave similar results from GEODOP3 and GEODOP5 in terms of the accuracy of the computed positions. These can be seen in Plot 1 and Plot 2. From the table in Appendix A (page 95) it appears that GEODOP3 has produced better results. For GEODOP3 the differences in latitude range from 0.184 metres to 0.269 metres where as GEODOP5 the differences in latitude range from -0.123 metres to 1.598 metres.

Plot 1. GEODOP3 - PRECISE POINT POSITIONS.



Plot 2. GEODOP5 - PRECISE POINT POSITIONS.



Vector scale 0 1 2 metres

SCALE 90 minutes per cm

The longitude differences for GEODOP3 range from -0.458 metres to 1.989 metres compared to GEODOP5 ranging from -1.561 metres to 1.869 metres. Note should also be made of the different number of passes used from the same data set. This reflects the changes to the statistical testing incorporated in GEODOP5. It appears that the changes have slightly degraded the results for large numbers of satellite passes.

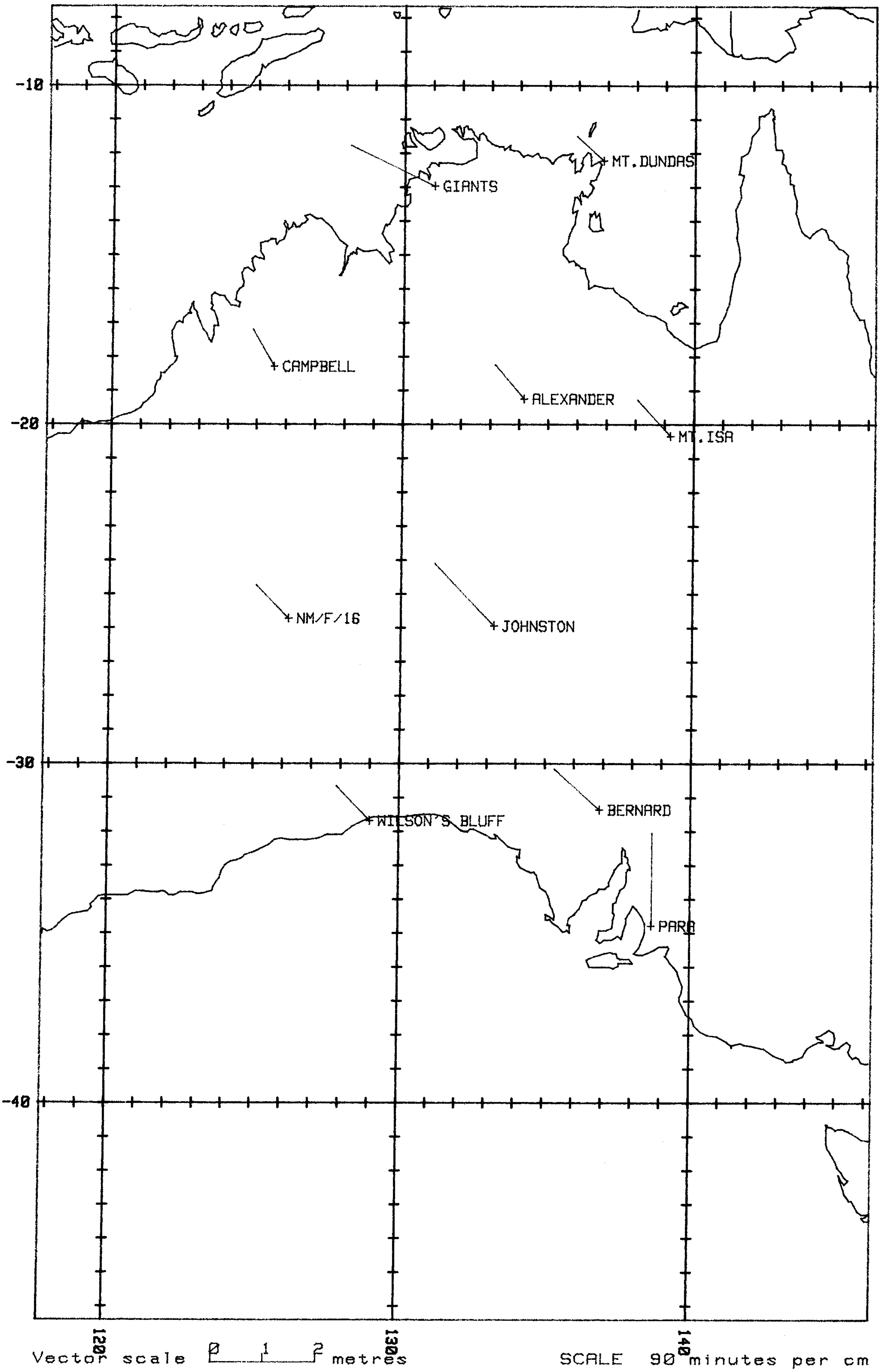
5.4.2 MULTI-STATION PRECISE EPHEMERIS.

The computation of the multi-station network was carried out twice in order to ascertain the effect of orbit constraints on the results. This experiment was included to confirm the results obtained by Jones 1984. Firstly both GEODOP3 and GEODOP5 were computed using the following orbital constraints :-

Along track 10 metres
Across track 10 metres
Out of plane 10 metres

As the adjustment has no fixed station coordinates the resulting solution is thus a free unconstrained adjustment. The results from GEODOP3 appear in Plot 3 and the results from GEODOP5 appear in Plot 5. These plots show the vector difference from the respective solutions to that of the ground truth values. The two plots appear very similar except for a small shift in the longitude to the west produced by GEODOP5. These two plots display the absolute positions whereas the relative positions of the adjustment will give a better indication of the precision of the final solutions. By meaning the differences in latitude and longitude and using this systematic error to block shift the results, a more

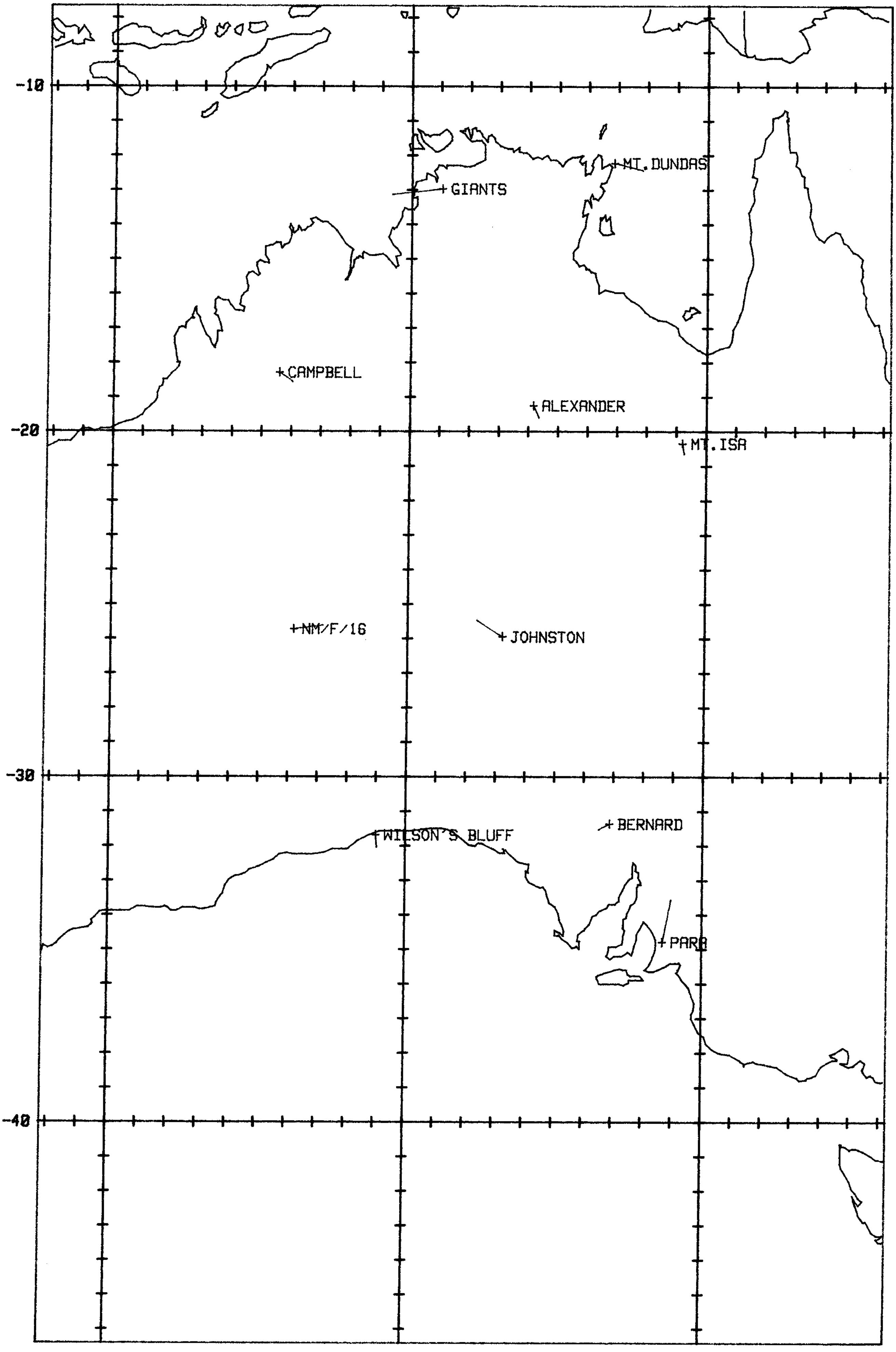
Plot 3. GEODOP3 MULTI-STATION ADJUSTMENT (10m orbit).



Vector scale metres

SCALE 90 minutes per cm

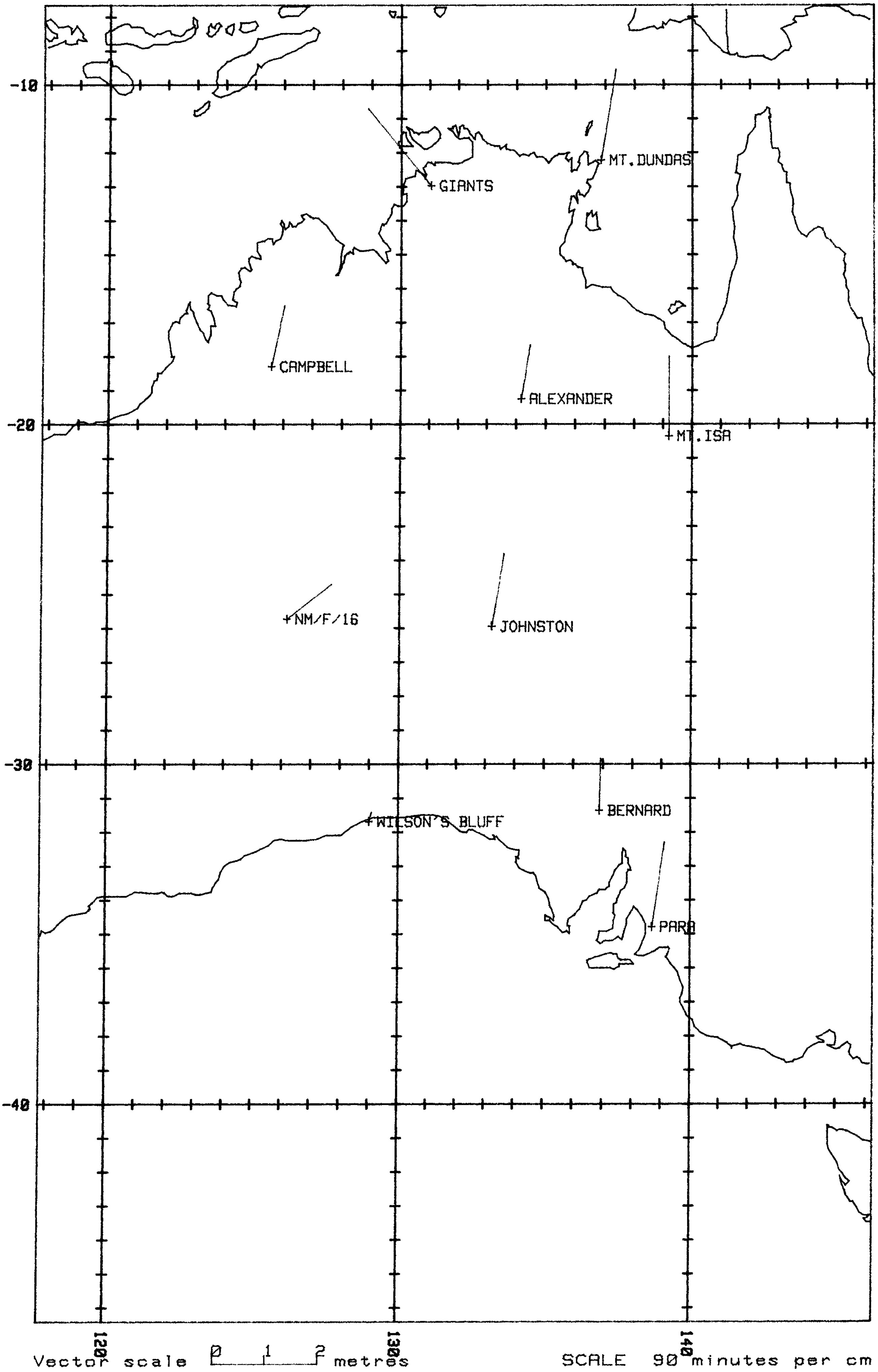
Plot 4. GEODOP3 - Plot 3 with block shift.



Vector scale 0 1 2 metres

SCALE 90 minutes per cm

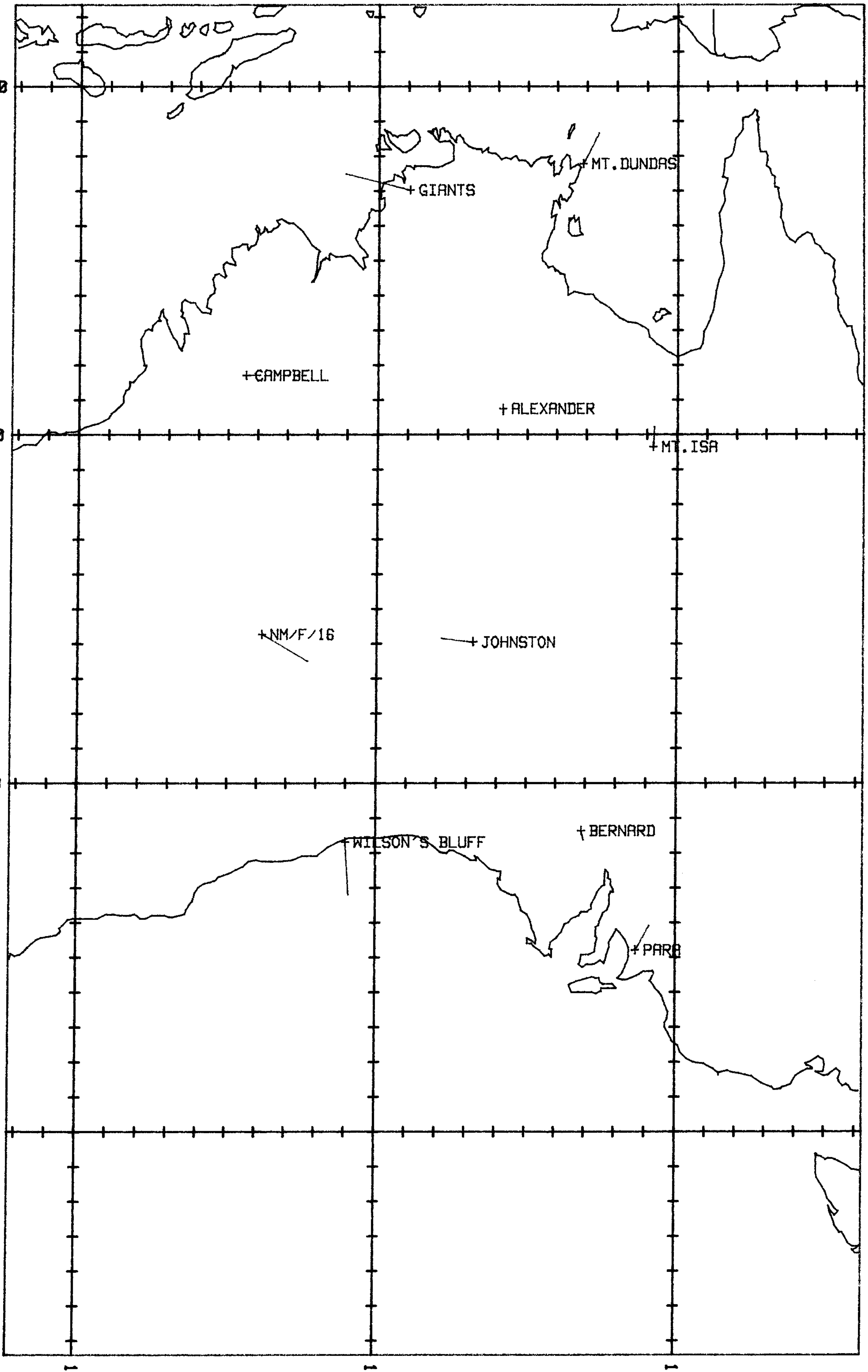
Plot 5. GEODOP5 MULTI-STATION ADJUSTMENT (10m orbit).



Vector scale 0 1 2 metres

SCALE 90 minutes per cm

Plot 6. GEODOP5 - Plot 5 with block shift.



SCALE 90 minutes per cm

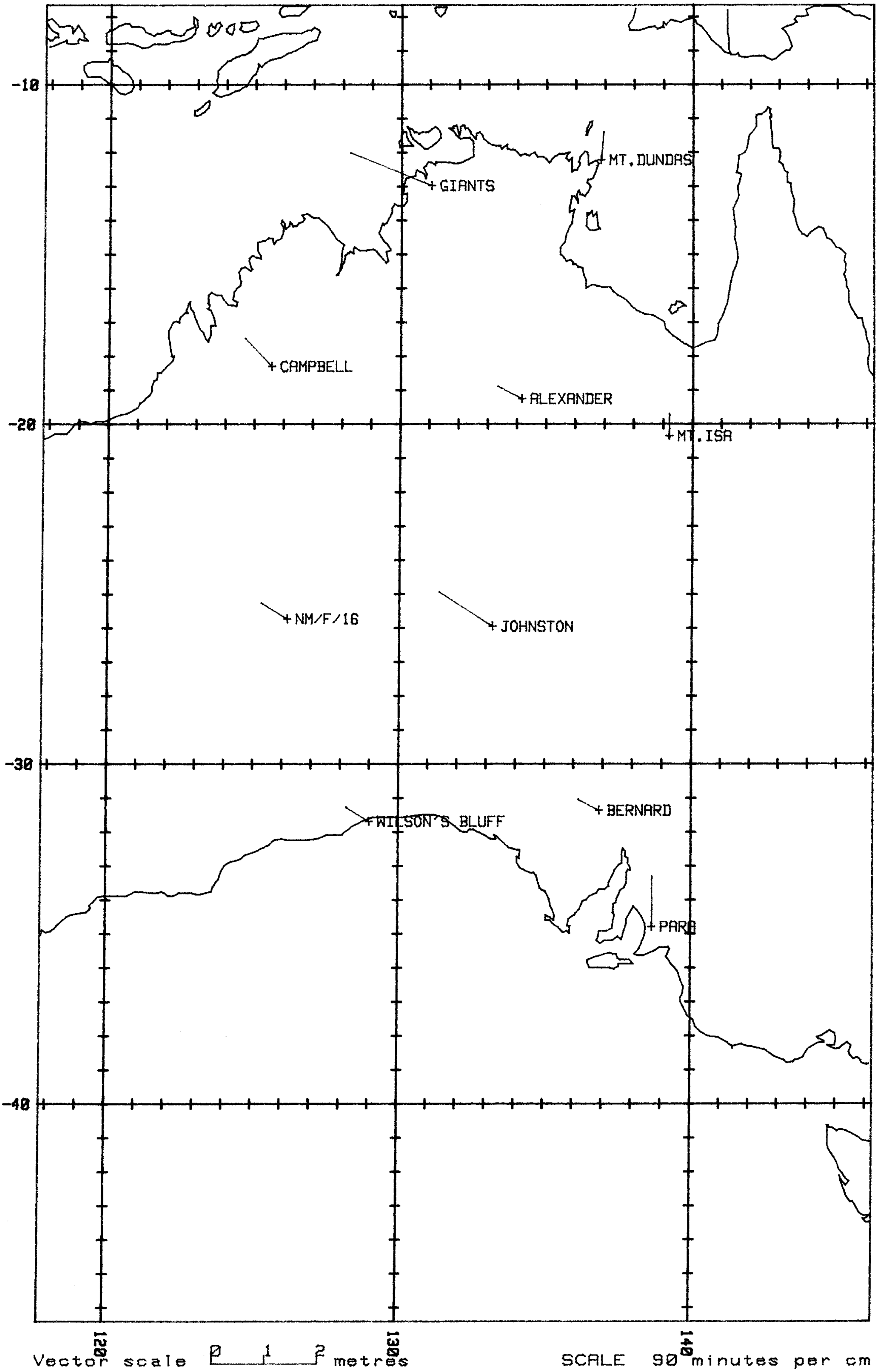
indicative set of results can be obtained. For GEODOP3 these are displayed in Plot 4 and for GEODOP5 the block adjusted results are displayed in Plot 6. From these plots it appears that the majority of the results of the final positions are well within one metre. Considering the station separations have chord distances between 2520 kilometers and 415 kilometers with 28 out of 45 separations having chord distances greater than 1000 kilometers the relative position accuracies are well below one part per million. Again a comparison of Plot 4 and Plot 6 shows that GEODOP5 has no advantage over GEODOP3.

The second series of multi-station adjustments used orbital constraints of :-

Along track 2 metres
Across track 2 metres
Out of plane 2 metres

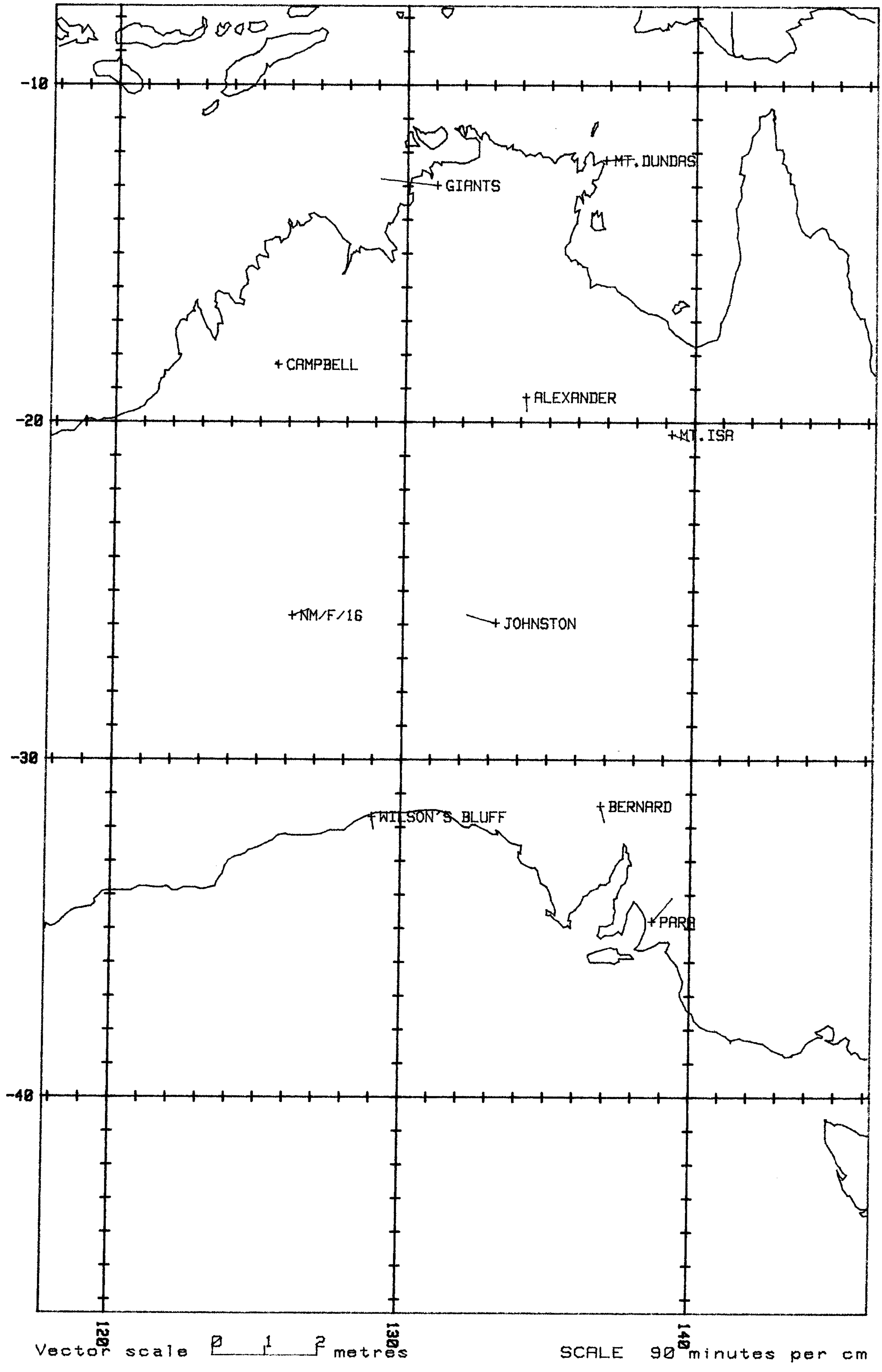
Although there is no major improvement of the relative positions after taking out the block shifts as seen in Plot 8 and Plot 10 there appears to be slight improvement in the absolute positions as the block shifts calculated on these results are smaller than those from the 10 metre orbital constraint adjustments. It is interesting to note that Jones, 1984 discovered a predominant east-west orientation of displacement vectors when compared to ground truth. Jones used GEODOP3 to compute his multi-station solutions. The same east-west orientation appears in Plot 1, Plot 3 and Plot 7, all GEODOP3 multi-station precise ephemeris solutions. This east-west orientation is not evident in the GEODOP5 results.

Plot 7. GEODOP3 MULTI-STATION ADJUSTMENT (2m orbit).

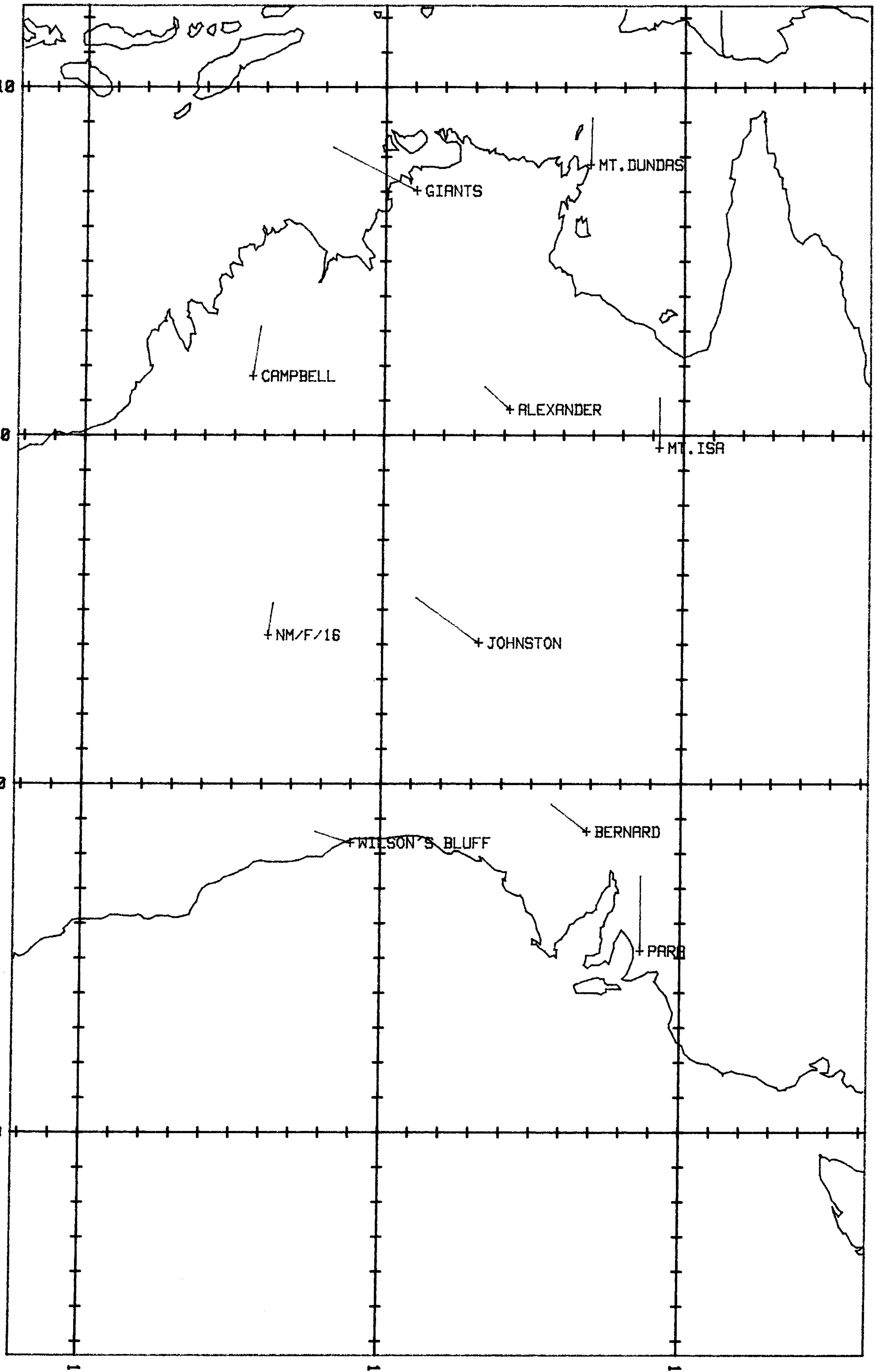


Vector scale 0 1 2 metres SCALE 90 minutes per cm

Plot 8. GEODOP3 - Plot 7 with block shift.



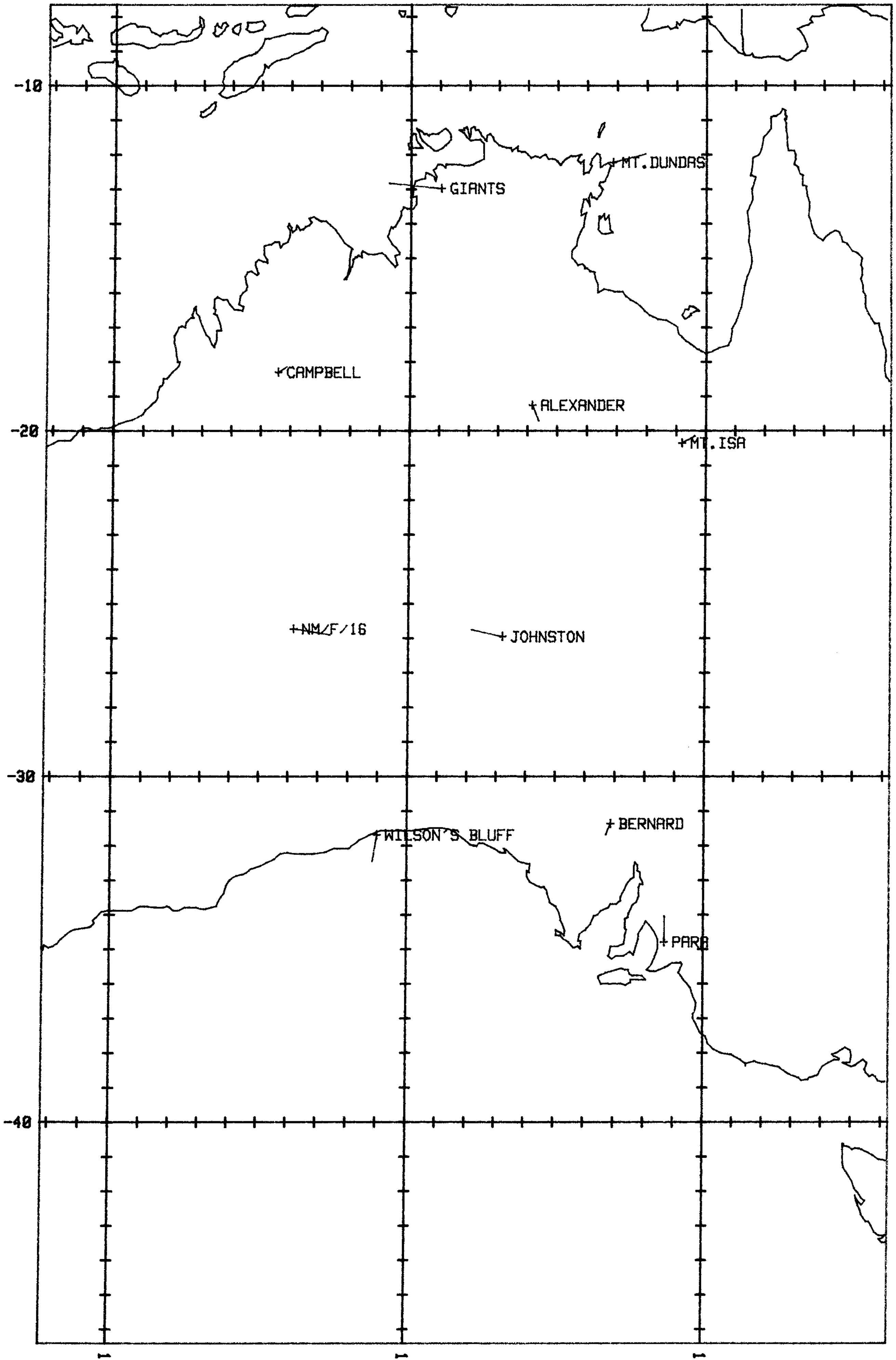
Plot 9. GEODOP5 MULTI-STATION ADJUSTMENT (2m orbit).



Vector scale 0 1 2 metres

SCALE 90 minutes per cm

Plot 10. GEODOP5 - Plot 9 with block shift.



Vector scale 0 1 2 metres SCALE 90 minutes per cm

5.5 RESULTS USING BROADCAST EPHEMERIS.

5.5.1 MULTI-STATION.

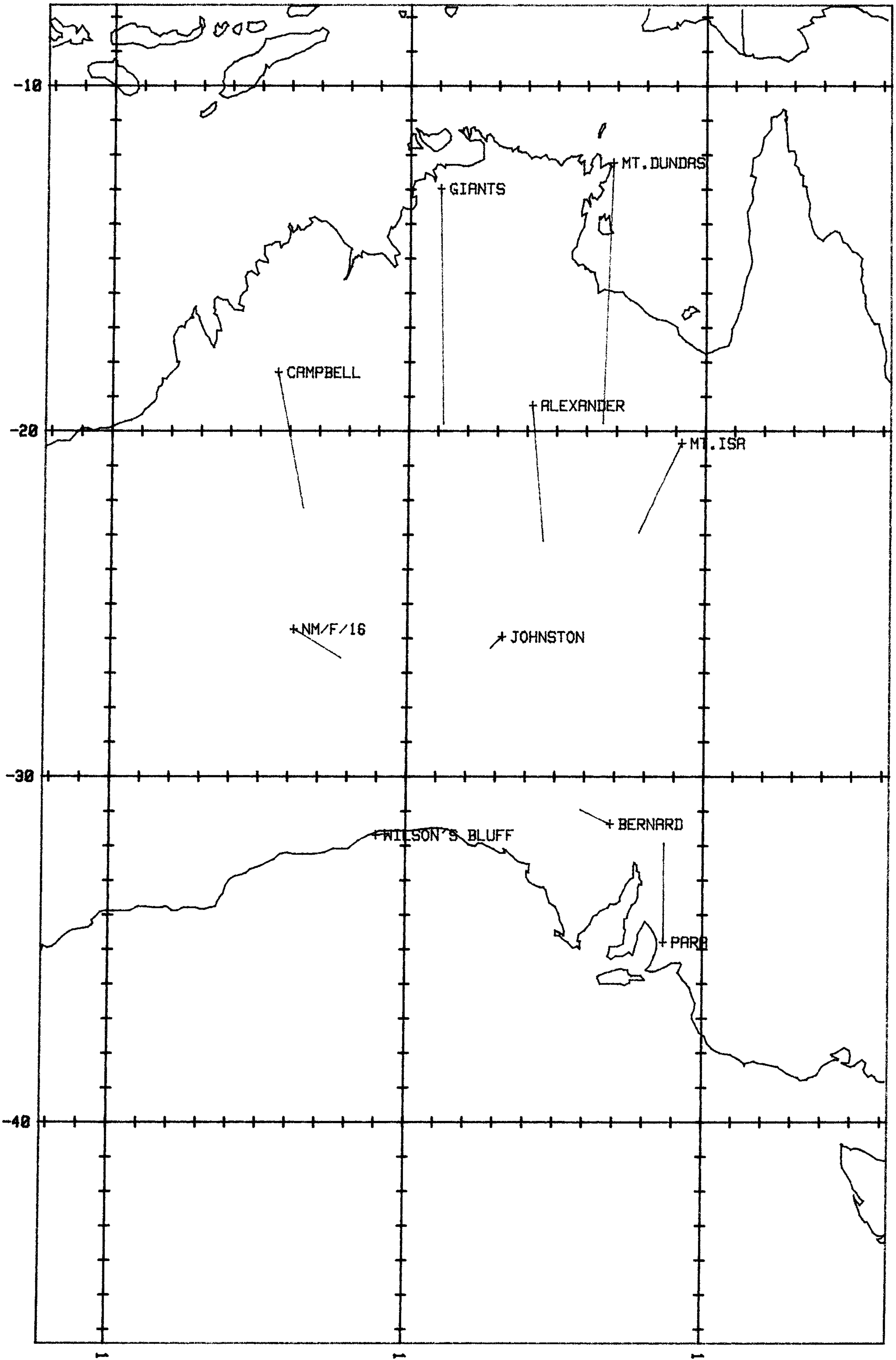
For the broadcast ephemeris solutions a comparison can now be made of the GEODOP software and the MAGNET software. Both GEODOP3 and GEODOP5 have been used as well as MAGNET being used in pseudorange mode and hyperbolic mode (see section 4.3).

A comparison of Plots 11,13,15 and 17 show a definite north-south bias in the orientation of the displacement vectors which appears in the results of all four software solutions. This could be explained by a systematic error in the broadcast ephemeris in the along track direction. This could be the result of poor atmospheric drag modeling or fluctuations in the solar drag intensity usually brought about by sunspot activity or solar flares on the surface of the sun.

An interesting phenomenon appears in Plot 11 derived from the GEODOP3 multi-station adjustment. This is the tendency for the vectors to pull towards the centre of the network. This was also noted by Jones, 1984 when using a dataset of 11 stations. Jones dismissed the theory that this was a program induced phenomenon as a smaller subset of five stations did not display the same tendency. It is interesting that this effect is not shown in Plots 13, 15 and 17 which represent the GEODOP5 and MAGNET solutions. It appears that the changes in the modeling of GEODOP5 have eliminated this effect.

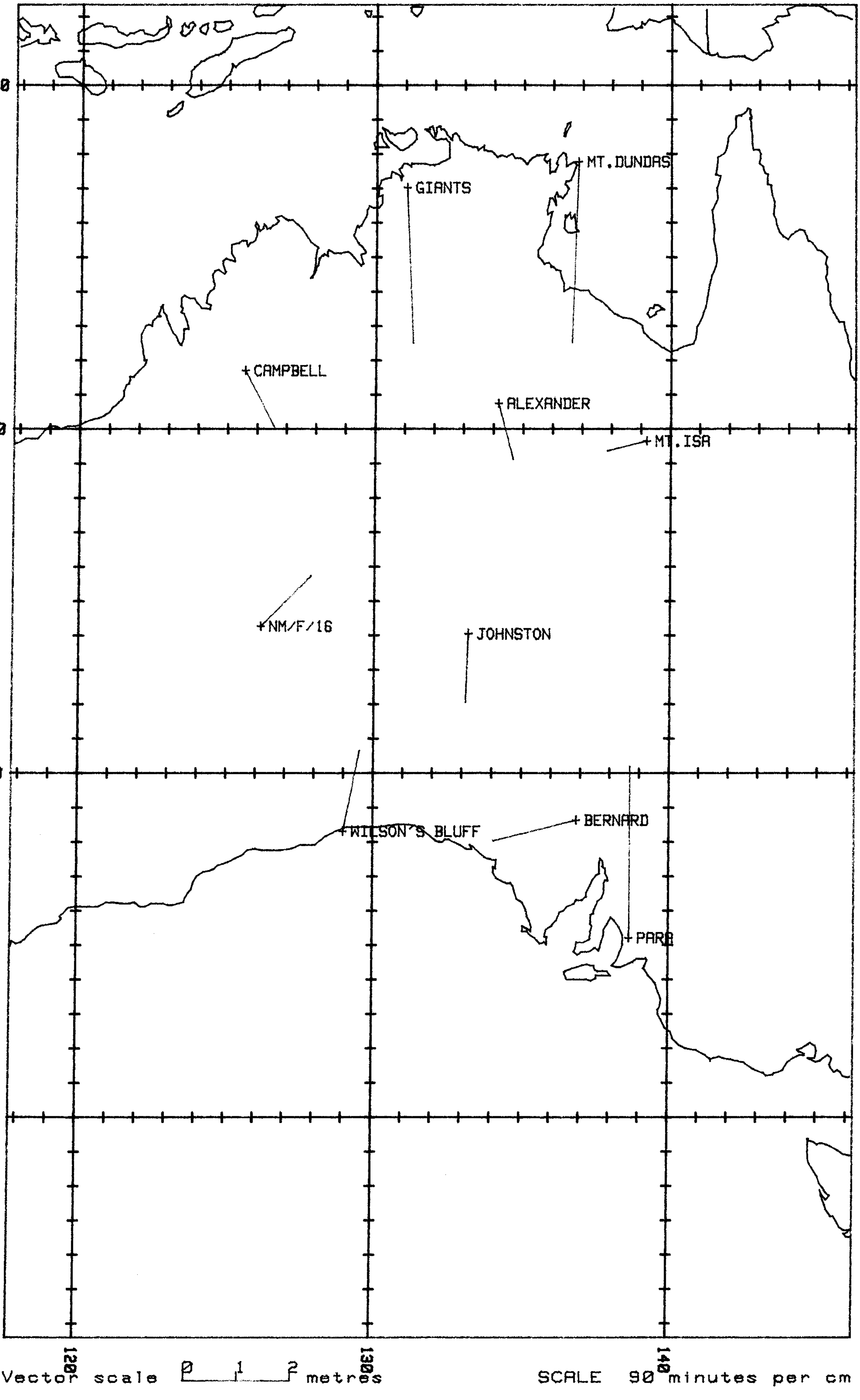
It can be seen from Plots 15 and 17 that the MAGNET program does not have the effect of pulling the vectors towards the centre of the network. Both plots do however show a strong correlation which indicates that MAGNET in pseudorange mode gives very similar results to those in hyperbolic mode. The hyperbolic mode appears to give

Plot 11. GEODOP3 MULTI-STATION ADJUSTMENT (Broadcast).

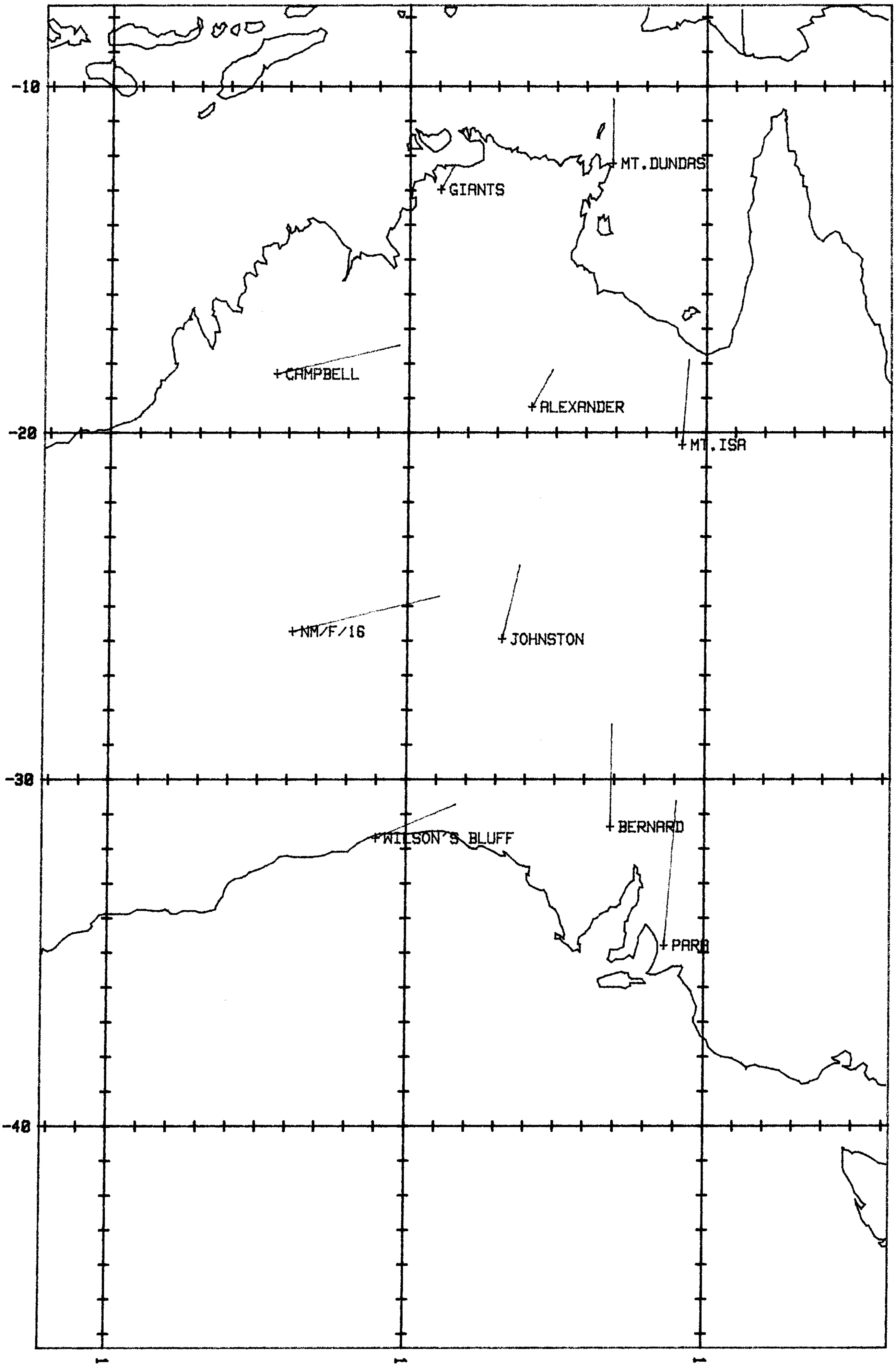


Vector scale 0 1 2 metres SCALE 90 minutes per cm

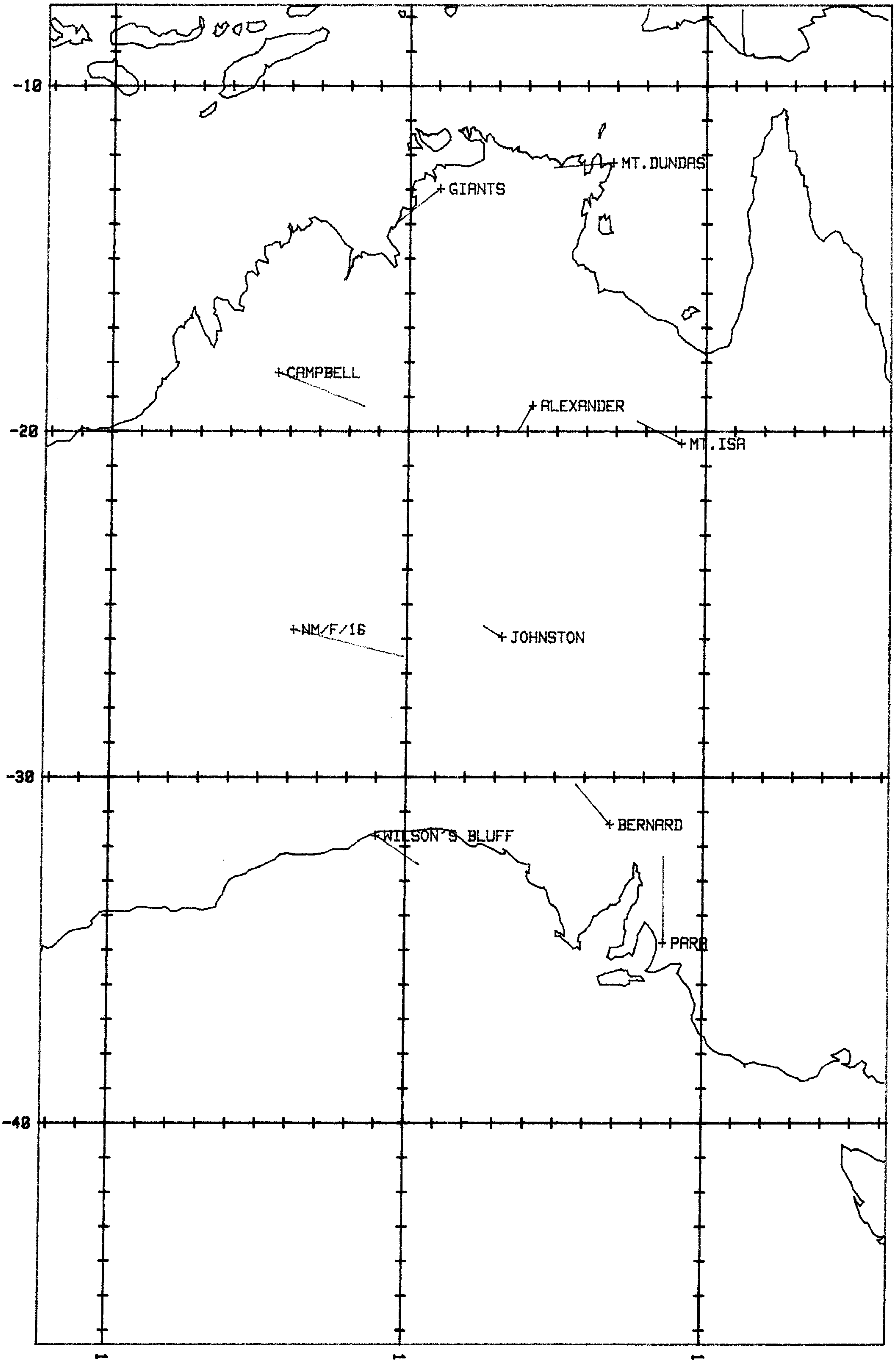
Plot 12. GEODOP3 - Plot 11 with block shift.



Plot 13. GEODOP5 MULTI-STATION ADJUSTMENT (Broadcast).



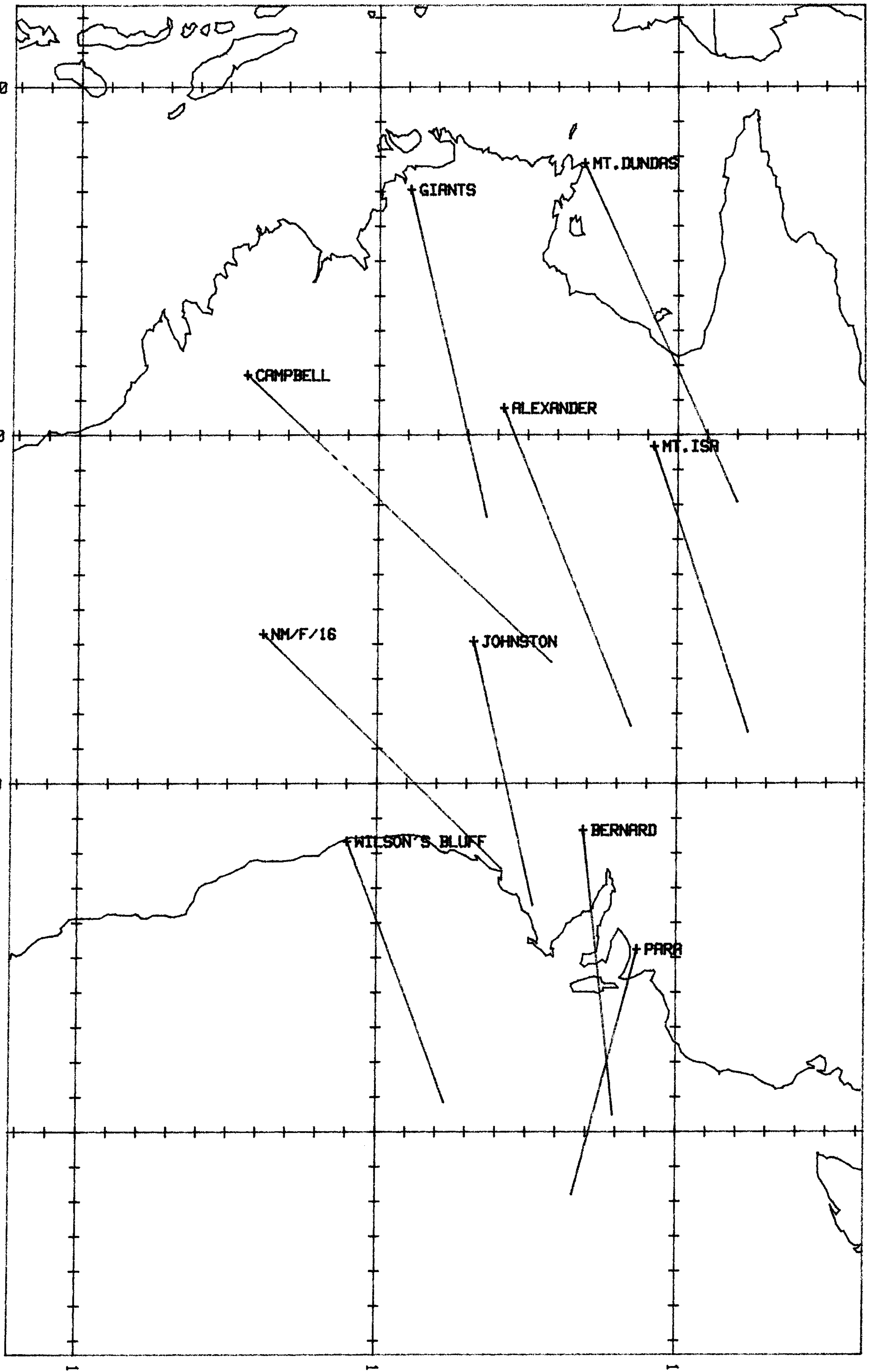
Plot 14. GEODOP5 - Plot 13 with block shift.



Vector scale metres

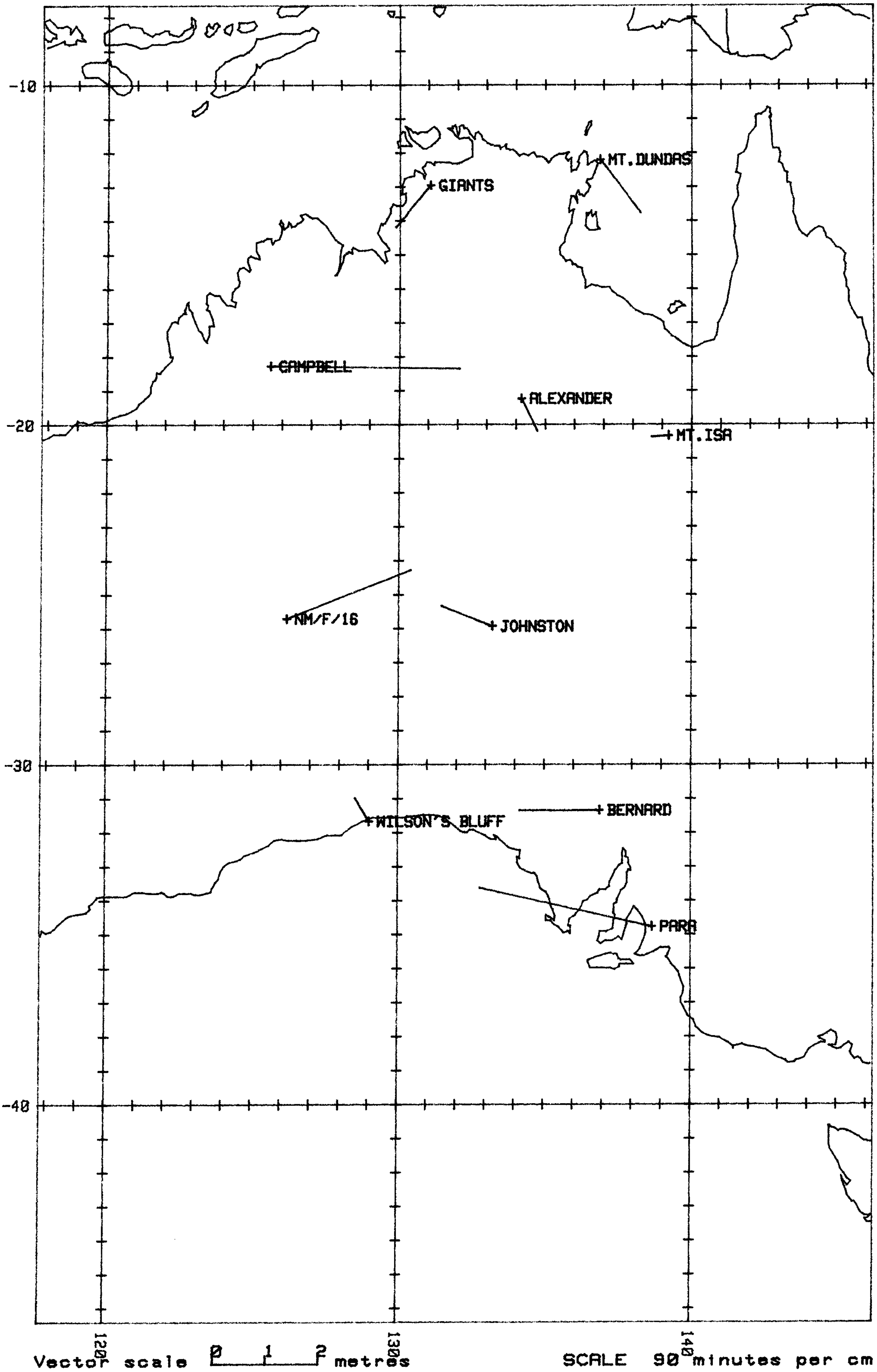
SCALE 90 minutes per cm

Plot 15. MAGNET MULTI-STATION ADJUSTMENT(Pseudoranging).



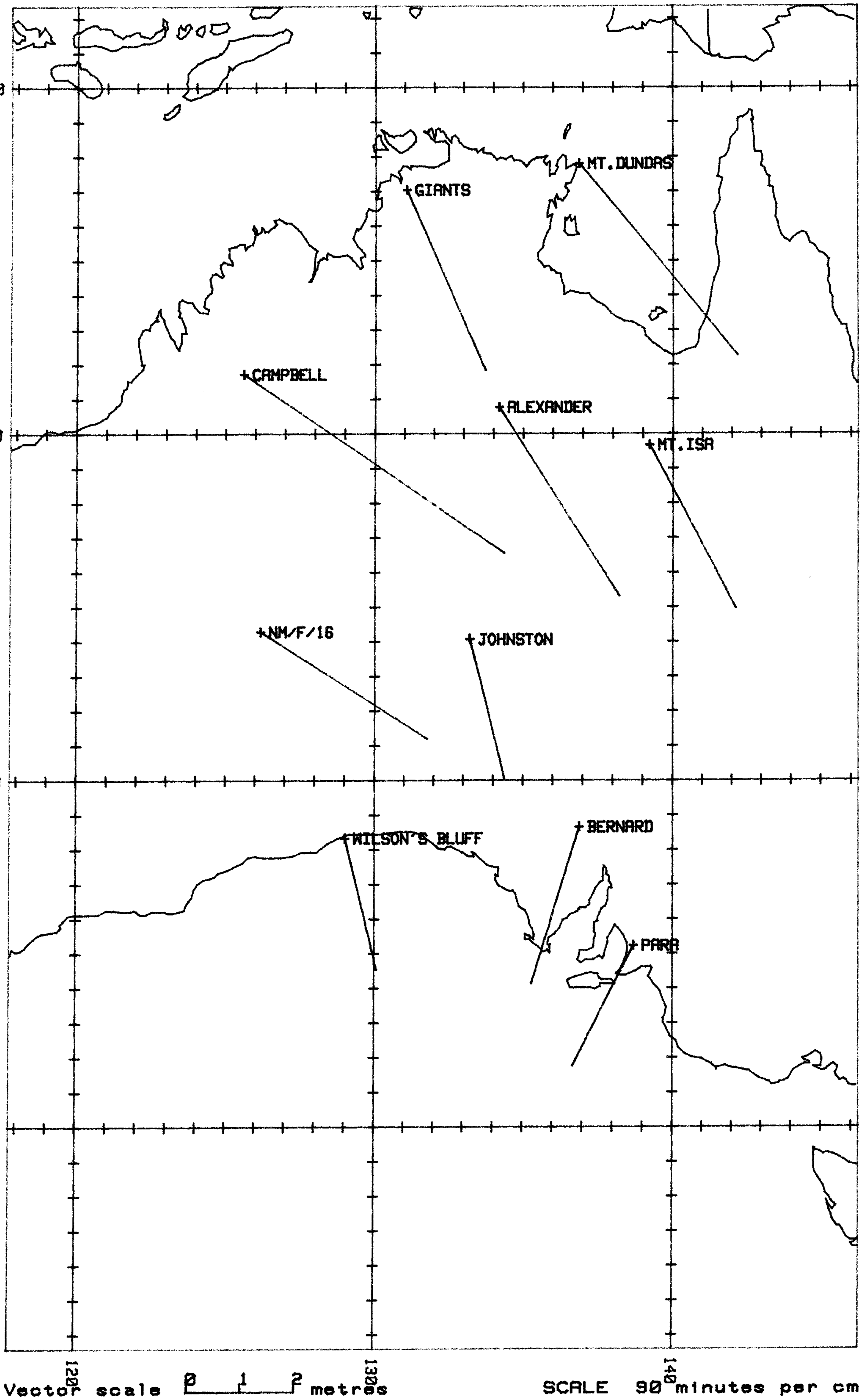
Vector scale 0 1 2 metres SCALE 90 minutes per cm

Plot 16. MAGNET - Plot 15 with block shift.



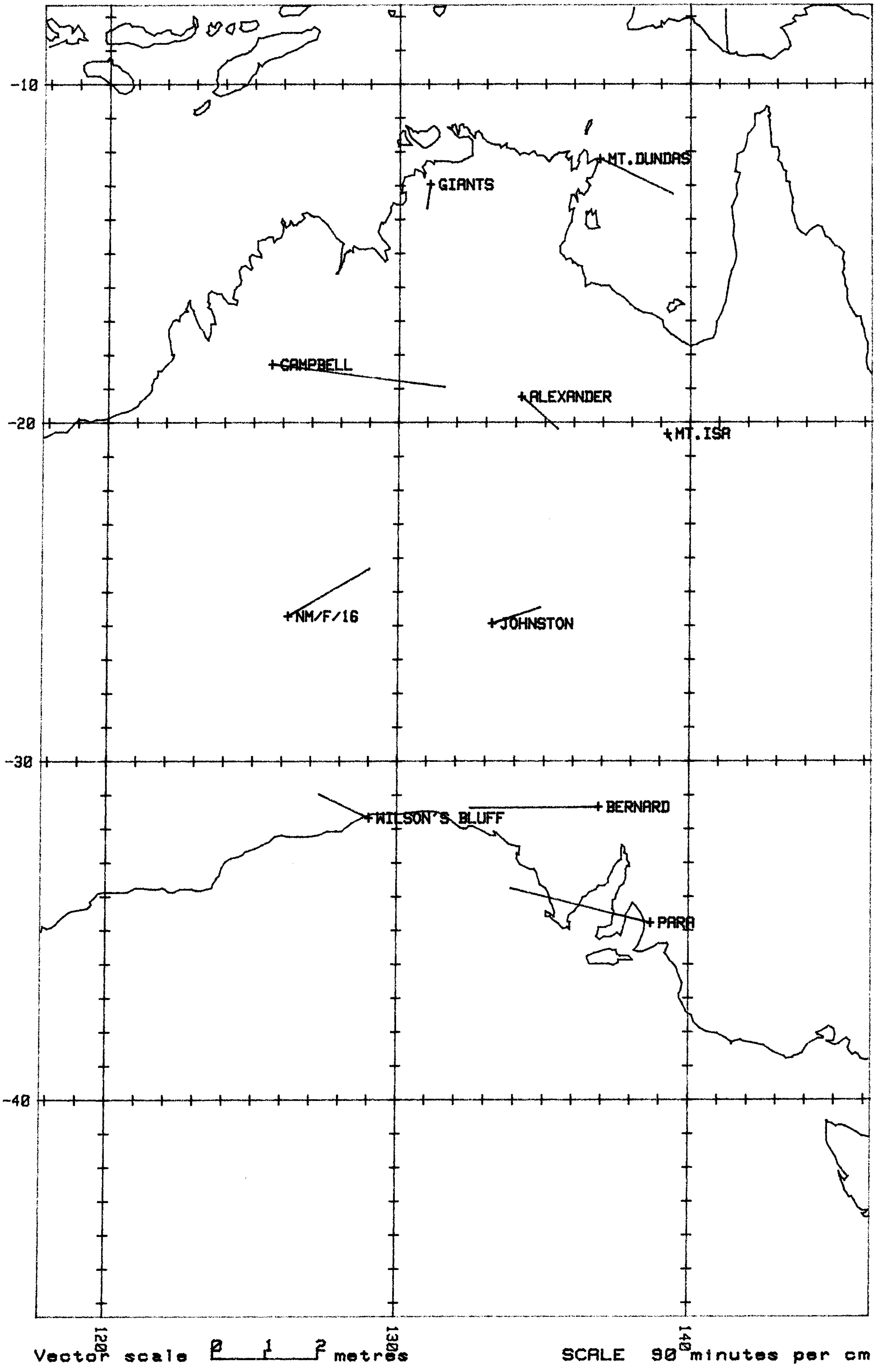
Vector scale 0 1 2 metres SCALE 90 minutes per cm

Plot 17. MAGNET MULTI-STATION ADJUSTMENT (Hyperbolic).



Vector scale 0 1 2 metres SCALE 90 minutes per cm

Plot 18. MAGNET - Plot 17 with block shift.



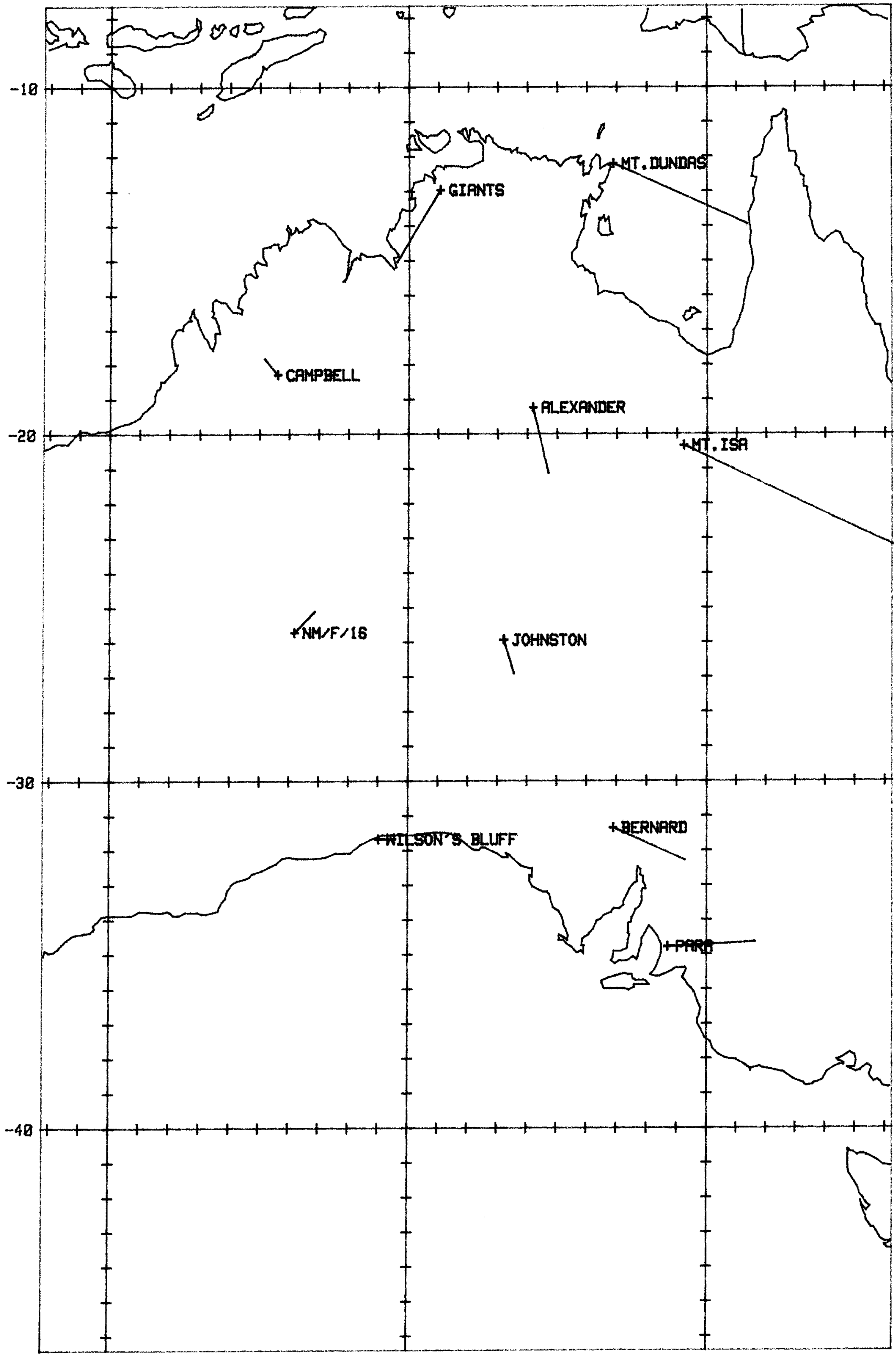
slightly better absolute values. Both MAGNET results appear to be inferior to the GEODOP results in absolute terms and marginally less accurate in relative positioning when comparing the block shifted results in Plots 12,14,16 and 18. The best results of the multi-station adjustments using the broadcast ephemeris is displayed by GEODOP5 with latitude differences varying from -0.678 metres to 1.573 metres and longitude differences varying from -2.468 metres to 1.338 metres.

5.5.2 POINT POSITION.

The point position computations using broadcast ephemeris were calculated with four independent Doppler programs. These were GEODOP3, GEODOP5, MX1502 and MAGNET which result in the absolute position vector displacements in Plots 19, 20, 21 and 22 respectively.The results vary with little to no correlation between the different solutions. It should be noted that the two versions of GEODOP show no correlation in the final results except that the total number of passes used from the data does not vary greatly. This indicates that the rejection criteria is similar for both versions of GEODOP. The two Magnavox programs show similar results but vary in the total number of passes used for the solutions. Although the height component of the solutions is not under investigation in this project, it is interesting to note the large differences in height computed by the MX1502 shown in the tables in Appendix B.

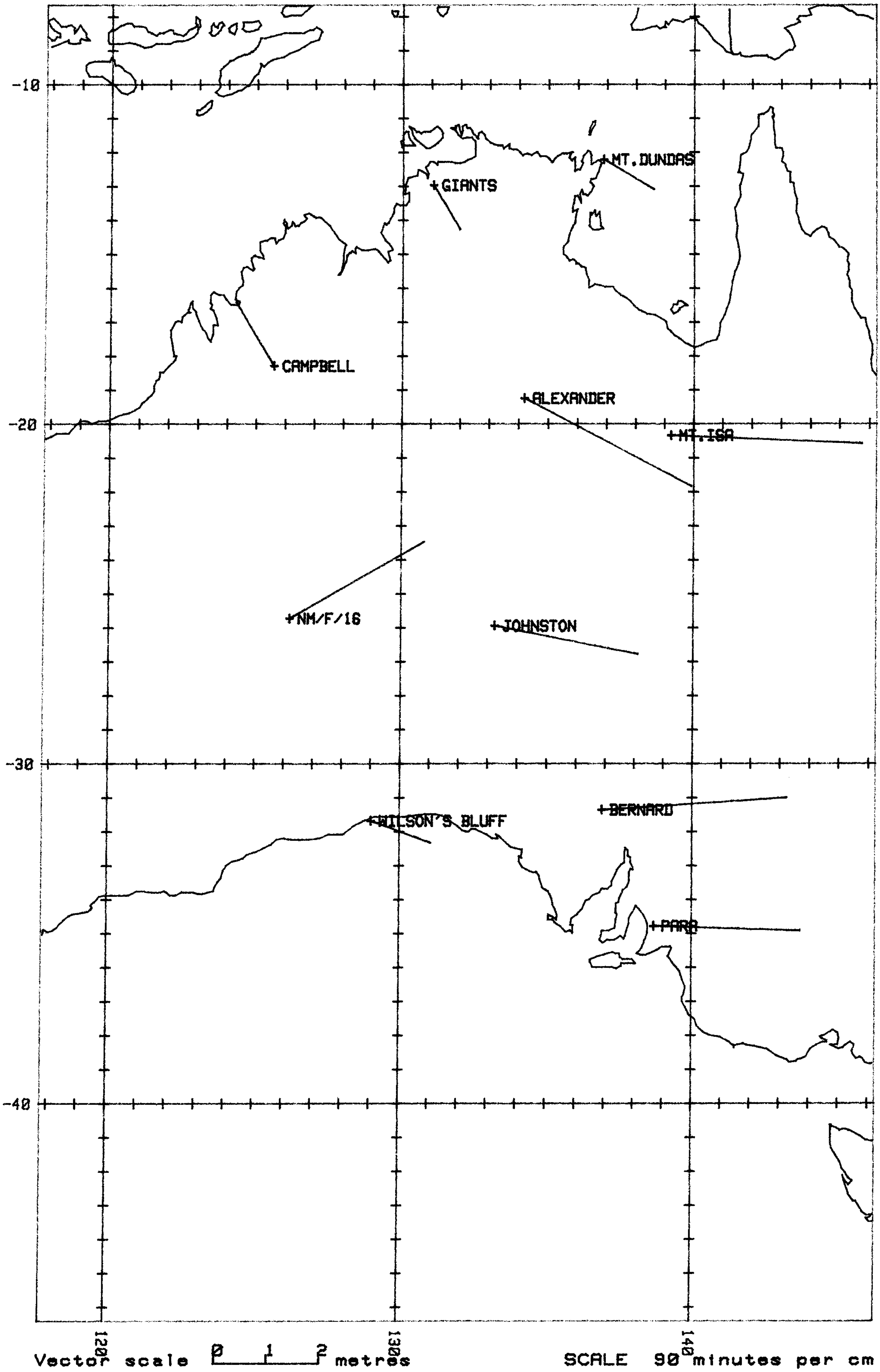
The magnitude of the vectors of both Magnavox program solutions are similar, however, there appears to be a systematic bias in the longitude computed by the MX1502 as all have negative differences between

Plot 19. GEODOP3 BROADCAST POINT POSITIONS.



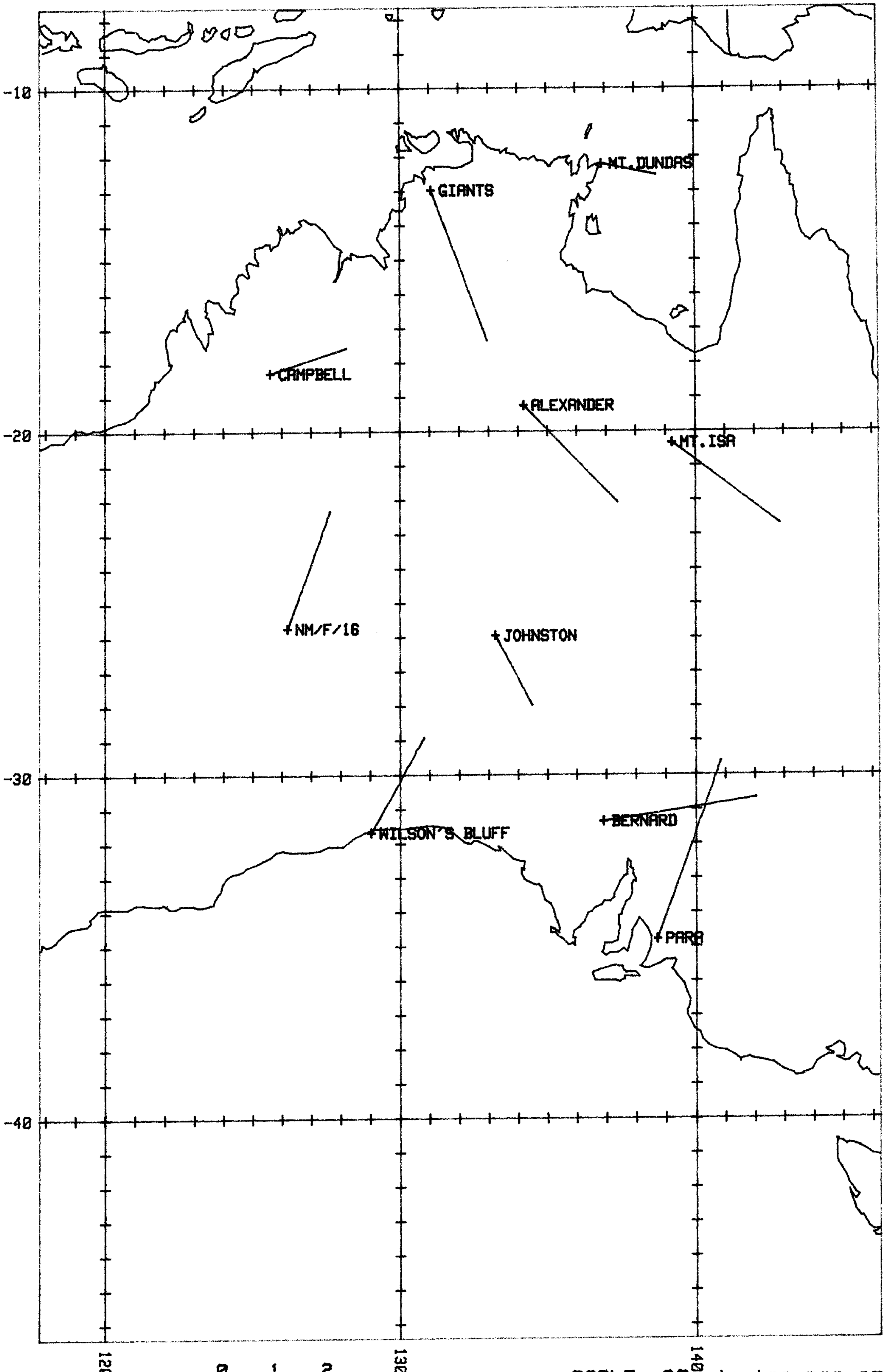
Vector scale 0 1 2 metres SCALE 90 minutes per cm

Plot 20. GEODOP5 BROADCAST POINT POSITIONS.

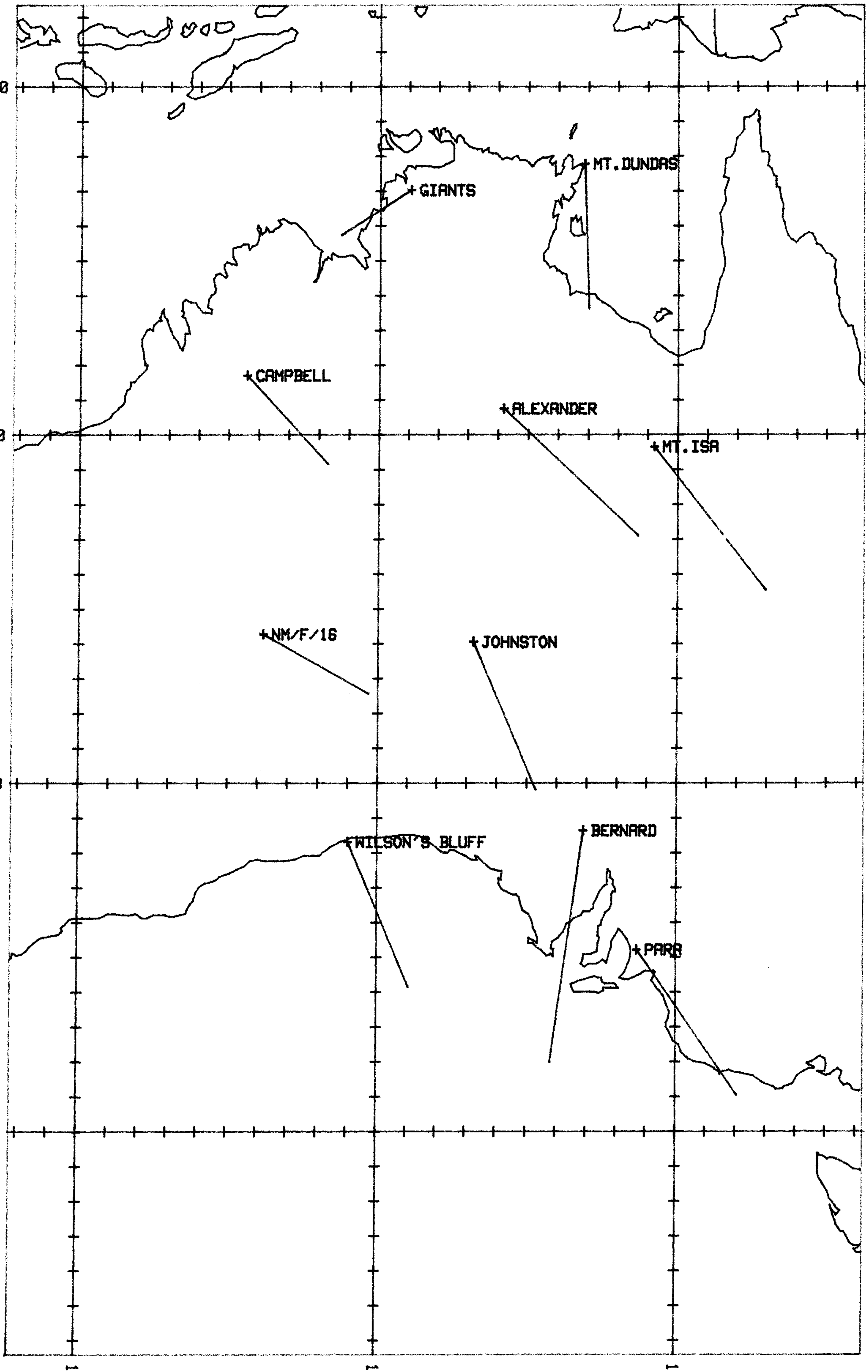


Vector scale 0 1 2 metres SCALE 90 minutes per cm

Plot 21. MX1502 POINT POSITIONS.



Plot 22. MAGNET POINT POSITIONS.



Vector scale 0 1 2 metres SCALE 90 minutes per cm

-0.835 metres and -3.463 metres. MAGNET, however, shows a similar systematic bias in the calculation of latitude ranging from -0.860 metres to -4.435 metres. These two programs, according to Magnavox, are similar in their modeling. One suggestion is that the onboard software of the MX1502 is not as rigorous as that of MAGNET. As the GEODOP programs do not show these same biases it appears that the Magnavox modeling has a minor systematic effect.

Overall the results of the point positioning using broadcast ephemeris are quite good as they generally lie within the five metre absolute precision quoted by most manufacturers of Doppler equipment. These results probably reflect the large number of satellite passes observed. It should also be noted that the three stations that observed two hundred passes show no increase in accuracy. This was expected.

CHAPTER 6

CONCLUSIONS

The aim of this project was to add to the understanding of multi-station reduction techniques of Doppler satellite observations and to examine two independent software packages on a data set which covers an enormously large area with ten stations simultaneously observing for a long period of time. The results in themselves are not conclusive, but do add to those results that have already been established. In drawing some conclusions it must be kept in mind that the size of the data set used for this project was very large (five days observations with three stations continuing to observe for a further ten days). The optimum observing period to obtain similar results was not considered.

After stating the above the following conclusions are drawn from the results.

1.When considering the use of satellite positioning for precise geodetic measurement a precise ephemeris should be incorporated in the computation.

2. Improvements to GEODOP5 over GEODOP3 have made no difference to the relative positioning results when using the precise ephemeris. Considering the increased expense in CPU time that GEODOP5 requires, then GEODOP3 should be used when undertaking precise geodetic satellite Doppler computations.

3. Some systematic biases have been removed from GEODOP with GEODOP5 when using broadcast ephemeris. GEODOP5 does give slightly superior multi-station relative positions over GEODOP3 when using broadcast ephemeris.

4. Relative positioning precisions using MAGNET multi-station adjustment are marginally better using the hyperbolic mode over the pseudoranging mode. Further testing is required to confirm this conclusion.

5. Relative positioning accuracies using multi-station adjustment with the broadcast ephemeris are similar for both GEODOP and MAGNET.

6. All software packages including the MX1502 produced similar precisions for point position using the broadcast ephemeris. Point position using the precise ephemeris gives much improved precision over the broadcast ephemeris.

7. The accuracy of multi-station adjustments are not affected by larger station separation distances. Subsequently the larger the network in terms of station separation distances the more accurate the solution becomes in terms of parts per million.

Finally it would be appropriate to comment on the future of satellite positioning techniques. The computation of multi-station networks observed using any satellite system will require some kind of sequential least squares adjustment. With the introduction of GPS there will be an ever increasing demand to determine the optimum amount of data to be observed. Refinements to the modeling of the adjustment techniques will need to continue. The continued growth of the use of satellite surveying and geodesy will need to be matched by continued research into the accuracies that can be achieved by satellite positioning.

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APPENDIX A
COORDINATE VALUES CALCULATED USING PRECISE EPHEMERIS

AGD84 - AGD84 TRANSFORMED TO PRECISE EPHEMERIS DATUM WITH ECCE.
PRE3PTS - PRECISE POINT POSITIONS COMPUTED USING GEODOP3
PREVPTS - PRECISE POINT POSITIONS COMPUTED USING GEODOP5
M10PRE3 - PRECISE MULTI-STATION 10 METRE ORBIT CONSTRAINTS USING GEODOP3
M10PREV - PRECISE MULTI-STATION 10 METRE ORBIT CONSTRAINTS USING GEODOP5
M02PRE3 - PRECISE MULTI-STATION 2 METRE ORBIT CONSTRAINTS USING GEODOP3
M02PREV - PRECISE MULTI-STATION 2 METRE ORBIT CONSTRAINTS USING GEODOP5

400 PARA		S34 47 6.3793	DIFF sec	DIFF m	E138 41 32.8285	DIFF sec	DIFF m.	213.68	DIFF m
PRE3PTS	71PASSES	6.359	0.021	0.647	32.847	-.018	-0.458	214.46	-0.78
PREVPTS	32PASSES	6.34	0.038	1.171	32.843	-.013	-0.331	215.83	-2.15
M10PRE3	73PASSES	6.323	0.05	1.726	32.804	0.024	0.610	215.30	-1.62
M10PREV	69PASSES	6.325	0.05	1.664	32.840	-.011	-0.280	213.08	0.60
M02PRE3	73PASSES	6.347	0.032	0.986	32.825	0.004	0.102	214.73	-1.05
M02PREV	68PASSES	6.339	0.040	1.233	32.800	0.029	0.737	214.27	-0.59

499 MT.ISA		S20 20 35.1296	DIFF sec	DIFF m	E139 12 21.5499	DIFF sec	DIFF m.	550.36	DIFF m
PRE3PTS	88PASSES	35.119	0.011	0.338	21.546	0.004	0.116	553.28	-2.92
PREVPTS	89PASSES	35.121	0.008	0.246	21.591	-.040	-1.160	552.10	-1.74
M10PRE3	87PASSES	35.106	0.023	0.707	21.524	0.026	0.754	553.64	-3.28
M10PREV	81PASSES	35.079	0.051	1.568	21.551	0.000	0.000	550.72	-0.36
M02PRE3	87PASSES	35.117	0.013	0.400	21.544	0.006	0.174	552.96	-2.60
M02PREV	82PASSES	35.102	0.028	0.861	21.536	0.014	0.406	551.93	-1.57

611 BERNARD		S31 21 45.4904	DIFF sec	DIFF m	E136 52 54.4526	DIFF sec	DIFF m.	203.52	DIFF m
PRE3PTS	86PASSES	45.483	0.008	0.246	54.433	0.019	0.502	204.66	-1.14
PREVPTS	85PASSES	45.474	0.016	0.493	54.421	0.032	0.846	206.30	-2.78
M10PRE3	86PASSES	45.464	0.026	0.801	54.414	0.039	1.031	205.22	-1.70
M10PREV	84PASSES	45.458	0.033	1.016	54.455	-.001	-0.026	202.92	0.60
M02PRE3	86PASSES	45.484	0.007	0.216	54.434	0.018	0.476	204.60	-1.08
M02PREV	84PASSES	45.474	0.017	0.524	54.422	0.030	0.793	204.16	-0.64

870 MT.DUNDAS		S12 13 3.9470	DIFF sec	DIFF m	E136 51 49.4563	DIFF sec	DIFF m.	131.52	DIFF m
PRE3PTS	50PASSES	3.929	0.018	0.553	49.470	-.013	-0.393	131.93	-0.41
PREVPTS	48PASSES	3.895	0.052	1.598	49.465	-.008	-0.242	130.30	1.22
M10PRE3	57PASSES	3.922	0.025	0.768	49.452	0.005	0.151	132.39	-0.87
M10PREV	63PASSES	3.889	0.058	1.782	49.469	-.011	-0.332	129.25	2.27
M02PRE3	57PASSES	3.929	0.018	0.553	49.459	-.002	-0.060	131.47	0.05
M02PREV	63PASSES	3.918	0.029	0.891	49.459	-.001	-0.030	130.49	1.03

10 JOHNSTON		S25 56 49.2731	DIFF sec	DIFF m	E133 12 33.9488	DIFF sec	DIFF m.	573.42	DIFF m
PRE3PTS	68PASSES	49.256	0.017	0.523	33.902	0.047	1.308	570.78	2.64
PREVPTS	70PASSES	49.255	0.018	0.554	33.946	0.002	0.056	570.53	2.89
M10PRE3	66PASSES	49.234	0.040	1.231	33.900	0.049	1.363	571.59	1.83
M10PREV	67PASSES	49.232	0.041	1.262	33.923	0.026	0.723	568.81	4.61
M02PRE3	66PASSES	49.251	0.022	0.677	33.904	0.044	1.224	570.72	2.70
M02PREV	66PASSES	49.245	0.028	0.862	33.899	0.050	1.391	570.04	3.38

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 686 ALEXANDER S19 14 54.2585 DIFF  DIFF  E134 10 18.4088 DIFF   DIFF  406.95  DIFF
                              sec    m                       sec    m.             m
PRE3PTS  64PASSES      54.253 0.006 0.184             18.388 0.021  0.613  408.16 -1.21
PREVPTS  59PASSES      54.263 -.004-0.123             18.448 -.039 -1.139  408.86 -1.91
M10PRE3  62PASSES      54.236 0.022 0.676             18.386 0.023  0.672  409.14 -2.19
M10PREV  63PASSES      54.224 0.035 1.076             18.408 0.001  0.029  406.11  0.84
M02PRE3  62PASSES      54.250 0.008 0.246             18.389 0.019  0.555  408.17 -1.22
M02PREV  63PASSES      54.244 0.014 0.430             18.389 0.019  0.555  407.30 -0.35

 838 GIANTS    S12 58  8.3418 DIFF  DIFF  E131  2 31.3114 DIFF   DIFF  193.36  DIFF
                              sec    m                       sec    m.             m
PRE3PTS  59PASSES       8.330 0.012 0.369             31.246 0.066  1.989  195.05 -1.69
PREVPTS  65PASSES       8.330 0.012 0.369             31.249 0.062  1.864  195.44 -2.08
M10PRE3  61PASSES       8.316 0.026 0.799             31.247 0.064  1.929  196.00 -2.64
M10PREV  62PASSES       8.293 0.049 1.506             31.264 0.048  1.447  192.10  1.26
M02PRE3  61PASSES       8.321 0.021 0.645             31.250 0.062  1.869  194.90 -1.54
M02PREV  62PASSES       8.315 0.027 0.830             31.249 0.062  1.869  193.34  0.02

1140 WILSON BL S31 41  7.3846 DIFF  DIFF  E129  0 44.6581 DIFF   DIFF   65.69  DIFF
                              sec    m                       sec    m.             m
PRE3PTS 230PASSES       7.372 0.013 0.400             44.640 0.018  0.474   67.86 -2.17
PREVPTS 237PASSES       7.363 0.021 0.647             44.643 0.015  0.395   67.22 -1.53
M10PRE3 233PASSES       7.362 0.022 0.678             44.629 0.029  0.764   68.47 -2.78
M10PREV 208PASSES       7.379 0.006 0.185             44.661 -.002 -0.053   65.54  0.15
M02PRE3 233PASSES       7.376 0.009 0.277             44.638 0.020  0.527   67.73 -2.04
M02PREV 210PASSES       7.377 0.007 0.216             44.628 0.030  0.790   66.98 -1.29

1005 NM/F/16   S25 43 31.1374 DIFF  DIFF  E126 10 26.5542 DIFF   DIFF  525.08  DIFF
                              sec    m                       sec    m.             m
PRE3PTS 203PASSES      31.111 0.027 0.831             26.544 0.010  0.279  525.9  -0.82
PREVPTS 206PASSES      31.104 0.034 1.046             26.611 -.056 -1.561  523.09  1.99
M10PRE3 203PASSES      31.105 0.032 0.985             26.549 0.005  0.139  526.26 -1.18
M10PREV 198PASSES      31.116 0.022 0.677             26.591 -.036 -1.003  522.59  2.49
M02PRE3 203PASSES      31.116 0.021 0.646             26.547 0.007  0.195  525.21 -0.13
M02PREV 197PASSES      31.117 0.020 0.615             26.559 -.004 -0.111  524.03  1.05

1698 CAMPBELL  S18 17 24.9563 DIFF  DIFF  E125 35 18.2055 DIFF   DIFF  171.40  DIFF
                              sec    m                       sec    m.             m
PRE3PTS 200PASSES      24.931 0.025 0.769             18.184 0.022  0.646  173.55 -2.15
PREVPTS 193PASSES      24.909 0.048 1.476             18.146 0.059  1.733  171.43 -0.03
M10PRE3 197PASSES      24.932 0.024 0.738             18.189 0.017  0.499  174.00 -2.60
M10PREV 189PASSES      24.917 0.039 1.199             18.217 -.010 -0.294  170.27  1.13
M02PRE3 197PASSES      24.939 0.018 0.553             18.185 0.021  0.617  172.83 -1.43
M02PREV 189PASSES      24.929 0.027 0.830             18.189 0.017  0.499  171.52 -0.12
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DIFFERENCES OF COMPUTED VALUES FROM AGD84 VALUES

POINT POSITIONS

PRECISE POINT POSITIONS COMPUTED USING GEODOP3

STATION	DLAT	METER	DLONG	METER	DHT	PASSES
400 PARA	0.021	0.647	-0.018	-0.458	-0.78	71
499 MT.ISA	0.011	0.338	0.004	0.116	-2.92	88
611 BERNARD	0.008	0.246	0.019	0.502	-1.14	86
870 MT.DUNDAS	0.018	0.553	-0.013	-0.393	-0.41	50
10 JOHNSTON	0.017	0.523	0.047	1.308	2.64	68
686 ALEXANDER	0.006	0.184	0.021	0.613	-1.21	64
838 GIANTS	0.012	0.369	0.066	1.989	-1.69	59
1140 WILSON BL	0.013	0.400	0.018	0.474	-2.17	230
1005 NM/F/16	0.027	0.831	0.010	0.279	-0.82	203
1698 CAMPBELL	0.025	0.769	0.022	0.646	-2.15	200

PRECISE POINT POSITIONS COMPUTED USING GEODOP5

STATION	DLAT	METER	DLONG	METER	DHT	PASSES
400 PARA	0.038	1.171	-0.013	-0.331	-2.15	72
499 MT.ISA	0.008	0.246	-0.040	-1.160	-1.74	89
611 BERNARD	0.016	0.493	0.032	0.846	-2.78	85
870 MT.DUNDAS	0.052	1.598	-0.008	-0.242	1.22	48
10 JOHNSTON	0.018	0.554	0.002	0.056	2.89	70
686 ALEXANDER	-0.004	-0.123	-0.039	-1.139	-1.91	59
838 GIANTS	0.012	0.369	0.062	1.869	-2.08	65
1140 WILSON BL	0.021	0.647	0.015	0.395	-1.53	237
1005 NM/F/16	0.034	1.046	-0.056	-1.561	1.99	206
1698 CAMPBELL	0.048	1.476	0.059	1.733	-0.03	193

DIFFERENCES OF COMPUTED VALUES FROM AGD84 VALUES

MULTI-STATION NETWORKS

PRECISE MULTI-STATION 10 METRE ORBIT CONSTRAINTS USING GEODOP3

STATION		DLAT	METER	DLONG	METER	DHT	PASSES
400	PARA	0.056	1.726	0.024	0.610	-1.62	73
499	MT.ISA	0.023	0.707	0.026	0.754	-3.28	87
611	BERNARD	0.026	0.801	0.039	1.031	-1.70	86
870	MT.DUNDAS	0.025	0.768	0.005	0.151	-0.87	57
10	JOHNSTON	0.040	1.231	0.049	1.363	1.83	66
686	ALEXANDER	0.022	0.676	0.023	0.672	-2.19	62
838	GIANTS	0.026	0.799	0.064	1.929	-2.64	61
1140	WILSON BL	0.022	0.678	0.029	0.764	-2.78	233
1005	NM/F/16	0.032	0.985	0.005	0.139	-1.18	203
1698	CAMPBELL	0.024	0.738	0.017	0.499	-2.60	197
	MEAN	0.030	0.911	0.028	0.791	-1.70	
	S.D.	0.031	0.964	0.033	0.944	2.19	

PRECISE MULTI-STATION 10 METRE ORBIT CONSTRAINTS USING GEODOP3 ADJUSTED BY BLOCK SHIFT.

STATION		DLAT	METER	DLONG	METER	DHT	PASSES
400	PARA	0.026	0.815	-0.004	-0.181	0.08	73
499	MT.ISA	-0.007	-0.204	-0.002	-0.037	-1.58	87
611	BERNARD	-0.004	-0.110	0.011	0.239	0.00	86
870	MT.DUNDAS	-0.005	-0.143	-0.023	-0.640	0.83	57
10	JOHNSTON	0.010	0.320	0.021	0.572	3.53	66
686	ALEXANDER	-0.008	-0.234	-0.005	-0.120	-0.49	62
838	GIANTS	-0.004	-0.112	0.036	1.138	-0.94	61
1140	WILSON BL	-0.008	-0.233	0.001	-0.027	-1.08	233
1005	NM/F/16	0.002	0.074	-0.023	-0.652	0.52	203
1698	CAMPBELL	-0.006	-0.173	-0.011	-0.292	-0.90	197

PRECISE MULTI-STATION 10 METRE ORBIT CONSTRAINTS USING GEODOP5

STATION	DLAT	METER	DLONG	METER	DHT	PASSES
400 PARA	0.054	1.664	-0.011	-0.280	0.60	69
499 MT.ISA	0.051	1.568	0.000	0.000	-0.36	81
611 BERNARD	0.033	1.016	-0.001	-0.026	0.60	84
870 MT.DUNDAS	0.058	1.782	-0.011	-0.332	2.27	63
10 JOHNSTON	0.041	1.262	0.026	0.723	4.61	67
686 ALEXANDER	0.035	1.076	0.001	0.029	0.84	63
838 GIANTS	0.049	1.506	0.048	1.447	1.26	62
1140 WILSON BL	0.006	0.185	-0.002	-0.053	0.15	208
1005 NM/F/16	0.022	0.677	-0.036	-1.003	2.49	198
1698 CAMPBELL	0.039	1.199	-0.010	-0.294	1.13	189
MEAN	0.039	1.194	0.000	0.021	1.36	
S.D.	0.042	1.280	0.040	0.625	1.92	

PRECISE MULTI-STATION 10 METRE ORBIT CONSTRAINTS USING GEODOP5 ADJUSTED BY BLOCK SHIFT.

STATION	DLAT	METER	DLONG	METER	DHT	PASSES
400 PARA	0.015	0.470	-0.011	-0.301	-0.76	69
499 MT.ISA	0.012	0.375	0.000	-0.021	-1.72	81
611 BERNARD	-0.006	-0.177	-0.001	-0.048	-0.76	84
870 MT.DUNDAS	0.019	0.589	-0.011	-0.354	0.91	63
10 JOHNSTON	0.002	0.068	0.026	0.702	3.25	67
686 ALEXANDER	-0.004	-0.117	0.001	0.008	-0.52	63
838 GIANTS	0.010	0.312	0.048	1.426	-0.10	62
1140 WILSON BL	-0.033	-1.009	-0.002	-0.074	-1.21	208
1005 NM/F/16	-0.017	-0.517	-0.036	-1.025	1.13	198
1698 CAMPBELL	0.000	0.006	-0.010	-0.315	-0.23	189

PRECISE MULTI-STATION 2 METRE ORBIT CONSTRAINTS USING GEODOP3

STATION	DLAT	METER	DLONG	METER	DHT	PASSES
400 PARA	0.032	0.986	0.004	0.102	-1.05	73
499 MT.ISA	0.013	0.400	0.006	0.174	-2.60	87
611 BERNARD	0.007	0.216	0.018	0.476	-1.08	86
870 MT.DUNDAS	0.018	0.553	-0.002	-0.060	0.05	57
10 JOHNSTON	0.022	0.677	0.044	1.224	2.70	66
686 ALEXANDER	0.008	0.246	0.019	0.555	-1.22	62
838 GIANTS	0.021	0.645	0.062	1.869	-1.54	61
1140 WILSON BL	0.009	0.277	0.020	0.527	-2.04	233
1005 NM/F/16	0.021	0.646	0.007	0.195	-0.13	203
1698 CAMPBELL	0.018	0.553	0.021	0.617	-1.43	197
MEAN	0.017	0.520	0.020	0.568	-0.83	
S.D.	0.018	0.568	0.048	0.791	1.62	

PRECISE MULTI-STATION 2 METRE ORBIT CONSTRAINTS USING GEODOP3 ADJUSTED BY BLOCK SHIFT.

STATION	DLAT	METER	DLONG	METER	DHT	PASSES
400 PARA	0.015	0.466	-0.016	-0.466	-0.22	73
499 MT.ISA	-0.004	-0.120	-0.014	-0.394	-1.77	87
611 BERNARD	-0.010	-0.304	-0.002	-0.092	-0.25	86
870 MT.DUNDAS	0.001	0.033	-0.022	-0.628	0.88	57
10 JOHNSTON	0.005	0.157	0.024	0.656	3.53	66
686 ALEXANDER	-0.009	-0.274	-0.001	-0.013	-0.39	62
838 GIANTS	0.004	0.125	0.042	1.301	-0.71	61
1140 WILSON BL	-0.008	-0.243	0.000	-0.041	-1.21	233
1005 NM/F/16	0.004	0.126	-0.013	-0.373	0.70	203
1698 CAMPBELL	0.001	0.033	0.001	0.049	-0.60	197

PRECISE MULTI-STATION 2 METRE ORBIT CONSTRAINTS USING GEODOP5

STATION	DLAT	METER	DLONG	METER	DHT	PASSES
400 PARA	0.040	1.233	0.029	0.737	-0.59	68
499 MT.ISA	0.028	0.861	0.014	0.406	-1.57	82
611 BERNARD	0.017	0.524	0.030	0.793	-0.64	84
870 MT.DUNDAS	0.029	0.891	-0.001	-0.030	1.03	63
10 JOHNSTON	0.028	0.862	0.050	1.391	3.38	66
686 ALEXANDER	0.014	0.430	0.019	0.555	-0.35	63
838 GIANTS	0.027	0.830	0.062	1.869	0.02	62
1140 WILSON BL	0.007	0.216	0.030	0.790	-1.29	210
1005 NM/F/16	0.020	0.615	-0.004	-0.111	1.05	197
1698 CAMPBELL	0.027	0.830	0.017	0.499	-0.12	189
MEAN	0.024	0.729	0.025	0.690	0.09	
S.D.	0.025	0.778	0.057	0.892	1.36	

PRECISE MULTI-STATION 2 METRE ORBIT CONSTRAINTS USING GEODOP5 ADJUSTED BY BLOCK SHIFT.

STATION	DLAT	METER	DLONG	METER	DHT	PASSES
400 PARA	0.016	0.503	0.004	0.047	-0.68	68
499 MT.ISA	0.004	0.132	-0.011	-0.284	-1.66	82
611 BERNARD	-0.007	-0.206	0.005	0.103	-0.73	84
870 MT.DUNDAS	0.005	0.162	-0.026	-0.720	0.94	63
10 JOHNSTON	0.004	0.133	0.025	0.701	3.29	66
686 ALEXANDER	-0.010	-0.299	-0.006	-0.135	-0.44	63
838 GIANTS	0.003	0.101	0.037	1.179	-0.07	62
1140 WILSON BL	-0.017	-0.514	0.005	0.100	-1.38	210
1005 NM/F/16	-0.004	-0.114	-0.029	-0.801	0.96	197
1698 CAMPBELL	0.003	0.101	-0.008	-0.191	-0.21	189

APPENDIX B
COORDINATE VALUES CALCULATED USING BROADCAST EPHEMERIS

AGD84 - AGD84 TRANSFORMED TO BROADCAST EPHEMERIS DATUM WITH ECCE.
MX1502 - BROADCAST POINT POSITIONS COMPUTED USING MX1502
MNETPTS - MAGNET POINT POSITIONS WITH HYPERBOLIC COMPUTATION
G3POINT - BROADCAST POINT POSITIONS COMPUTED USING GEODOP3
G5POINT - BROADCAST POINT POSITIONS COMPUTED USING GEODOP5
G3MULTI - BROADCAST MULTI-STATION USING GEODOP3
G5MULTI - BROADCAST MULTI-STATION USING GEODOP5
MNETHY0 - MAGNET MULTI-STATION WITH PSUDORANGE COMPUTATION
MNETHY1 - MAGNET MULTI-STATION WITH HYPERBOLIC COMPUTATION

400 PARA		S34 47 6.3409	DIFF sec	DIFF m	E138 41 32.8301	DIFF sec	DIFF m	212.84	DIFF m
MX1502	69PASSES	6.229	0.112	3.451	32.887	-.056	-1.424	222.33	-9.49
MNETPTS	73PASSES	6.432	-.090	-2.773	32.919	-.088	-2.237	209.41	3.43
G3POINT	75PASSES	6.338	0.003	0.092	32.908	-.077	-1.958	214.51	-1.67
G5POINT	75PASSES	6.345	-.003	-0.092	32.962	-.131	-3.331	210.30	2.54
G3MULTI	75PASSES	6.286	0.055	1.695	32.795	0.035	0.890	214.60	-1.76
G5MULTI	67PASSES	6.251	0.090	2.773	32.841	-.010	-0.254	209.05	3.79
MNETHY0	68PASSES	6.494	-.152	-4.684	32.774	0.056	1.424	213.15	-0.31
MNETHY1	68PASSES	6.417	-.075	-2.311	32.777	0.053	1.347	213.54	-0.70

499 MT.ISA		S20 20 35.0548	DIFF sec	DIFF m	E139 12 21.5505	DIFF sec	DIFF m	548.99	DIFF m
MX1502	88PASSES	35.107	-.051	-1.568	21.636	-.084	-2.436	561.54	-12.55
MNETPTS	84PASSES	35.145	-.089	-2.737	21.638	-.086	-2.494	549.99	-1.00
G3POINT	86PASSES	35.162	-.106	-3.260	21.829	-.277	-8.034	562.53	-13.54
G5POINT	87PASSES	35.061	-.005	-0.154	21.701	-.150	-4.351	549.00	-0.01
G3MULTI	88PASSES	35.112	-.056	-1.722	21.517	0.033	0.957	553.76	-4.77
G5MULTI	81PASSES	35.002	0.053	1.630	21.543	0.007	0.203	547.54	1.45
MNETHY0	77PASSES	35.234	-.178	-5.474	21.625	-.073	-2.117	548.51	0.48
MNETHY1	79PASSES	35.158	-.102	-3.137	21.619	-.067	-1.943	547.97	1.02

611 BERNARD		S31 21 45.4437	DIFF sec	DIFF m	E136 52 54.4514	DIFF sec	DIFF m	202.70	DIFF m
MX1502	60PASSES	45.429	0.015	0.462	54.582	-.130	-3.436	212.89	-10.19
MNETPTS	80PASSES	45.589	-.144	-4.435	54.424	0.027	0.714	199.75	2.95
G3POINT	86PASSES	45.464	-.020	-0.616	54.512	-.060	-1.586	205.08	-2.38
G5POINT	85PASSES	45.436	0.008	0.246	54.612	-.160	-4.228	202.79	-0.09
G3MULTI	86PASSES	45.435	0.009	0.277	54.427	0.025	0.661	205.34	-2.64
G5MULTI	84PASSES	45.380	0.064	1.971	54.453	-.001	-0.026	199.32	3.38
MNETHY0	66PASSES	45.622	-.177	-5.451	54.478	-.026	-0.687	201.19	1.51
MNETHY1	77PASSES	45.543	-.098	-3.018	54.411	0.040	1.057	202.35	0.35

870 MT.DUNDAS		S12 13 3.8523	DIFF sec	DIFF m	E136 51 49.4455	DIFF sec	DIFF m	130.22	DIFF m
MX1502	61PASSES	3.860	-.007	-0.215	49.487	-.041	-1.239	81.65	48.57
MNETPTS	62PASSES	3.943	-.090	-2.766	49.449	-.003	-0.091	126.61	3.61
G3POINT	60PASSES	3.943	-.090	-2.766	49.500	-.054	-1.632	130.58	-0.36
G5POINT	65PASSES	3.873	-.019	-0.584	49.485	-.038	-1.149	128.77	1.45
G3MULTI	60PASSES	4.017	-.164	-5.040	49.438	0.007	0.212	130.41	-0.19
G5MULTI	61PASSES	3.816	0.036	1.106	49.427	0.018	0.544	126.42	3.80
MNETHY0	56PASSES	4.064	-.211	-6.484	49.560	-.113	-3.416	124.89	5.33
MNETHY1	57PASSES	3.973	-.120	-3.687	49.563	-.117	-3.536	124.66	5.56

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  10 JOHNSTON   S25 56 49.2144 DIFF    DIFF   E133 12 33.9402  DIFF    DIFF   572.76  DIFF
                                sec      m                      sec      m                m
MX1502    64PASSES      49.259 -.044 -1.354             33.971  -.030 -0.835  578.90 -6.14
MNETPTS   65PASSES      49.307 -.092 -2.831             33.991  -.050 -1.391  567.42  5.34
G3POINT   68PASSES      49.237 -.021 -0.646             33.949  -.008 -0.223  571.01  1.75
G5POINT   70PASSES      49.233 -.018 -0.554             34.058  -.117 -3.255  566.32  6.44
G3MULTI   68PASSES      49.222 -.007 -0.215             33.931  0.009  0.250  571.89  0.87
G5MULTI   66PASSES      49.169 0.046  1.416             33.955  -.014 -0.390  566.23  6.53
MNETHY0   62PASSES      49.379 -.164 -5.047             33.989  -.048 -1.336  567.83  4.93
MNETHY1   62PASSES      49.302 -.087 -2.677             33.969  -.028 -0.779  567.82  4.94

 686 ALEXANDER S19 14 54.1836 DIFF    DIFF   E134 10 18.3984  DIFF    DIFF   406.03  DIFF
                                sec      m                      sec      m                m
MX1502    65PASSES      54.246 -.061 -1.876             18.472  -.073 -2.132  417.72-11.69
MNETPTS   58PASSES      54.264 -.079 -2.429             18.502  -.103 -3.008  405.74  0.29
G3POINT   64PASSES      54.226 -.041 -1.261             18.411  -.012 -0.350  408.10 -2.07
G5POINT   64PASSES      54.241 -.056 -1.722             18.530  -.131 -3.826  406.60 -0.57
G3MULTI   64PASSES      54.269 -.085 -2.614             18.409  -.009 -0.263  408.81 -2.78
G5MULTI   61PASSES      54.160 0.023  0.707             18.415  -.016 -0.467  403.56  2.47
MNETHY0   57PASSES      54.383 -.198 -6.088             18.497  -.098 -2.862  402.98  3.05
MNETHY1   58PASSES      54.303 -.118 -3.628             18.491  -.092 -2.687  402.94  3.09

 838 GIANTS     S12 58  8.2550 DIFF    DIFF   E131  2 31.2892  DIFF    DIFF   192.68  DIFF
                                sec      m                      sec      m                m
MX1502    64PASSES       8.351 -.095 -2.919             31.332  -.042 -1.266  203.41-10.73
MNETPTS   62PASSES       8.284 -.028 -0.860             31.237  0.052  1.567  188.74  3.94
G3POINT   63PASSES       8.301 -.045 -1.383             31.257  0.032  0.964  193.48 -0.80
G5POINT   64PASSES       8.284 -.028 -0.860             31.311  -.020 -0.603  192.98 -0.30
G3MULTI   63PASSES       8.404 -.148 -4.548             31.293  -.003 -0.090  193.13 -0.45
G5MULTI   60PASSES       8.239 0.017  0.522             31.282  0.007  0.211  189.45  3.23
MNETHY0   61PASSES       8.460 -.204 -6.269             31.347  -.057 -1.718  186.27  6.41
MNETHY1   59PASSES       8.369 -.113 -3.473             31.349  -.059 -1.778  187.15  5.53

1140 WILSON BL S31 41   7.3386 DIFF    DIFF   E129  0 44.6440  DIFF    DIFF    74.23  DIFF
                                sec      m                      sec      m                m
MX1502   228PASSES       7.279 0.060  1.848             44.690  -.045 -1.185   96.2 -22.04
MNETPTS  206PASSES       7.430 -.090 -2.772             44.697  -.052 -1.370   62.86 11.37
G3POINT  234PASSES       7.339 0.000  0.000             44.659  -.014 -0.369   68.14  6.09
G5POINT  233PASSES       7.354 -.014 -0.431             44.697  -.052 -1.370   61.78 12.45
G3MULTI  237PASSES       7.337 0.001  0.031             44.656  -.011 -0.290   68.93  5.30
G5MULTI  206PASSES       7.317 0.021  0.647             44.712  -.067 -1.765   63.10 11.13
MNETHY0  168PASSES       7.502 -.162 -4.990             44.728  -.083 -2.186   65.27  8.96
MNETHY1  171PASSES       7.422 -.082 -2.526             44.672  -.027 -0.711   65.91  8.32

1005 NM/F/16    S25 43 31.0807 DIFF    DIFF   E126 10 26.5345  DIFF    DIFF   525.11  DIFF
                                sec      m                      sec      m                m
MX1502   182PASSES      31.007 0.074  2.277             26.570  -.035 -0.976  535.22-10.11
MNETPTS  184PASSES      31.119 -.037 -1.139             26.619  -.084 -2.341  522.14  2.97
G3POINT  201PASSES      31.067 0.013  0.400             26.551  -.016 -0.446  526.06 -0.95
G5POINT  201PASSES      31.032 0.049  1.508             26.645  -.110 -3.066  518.66  6.45
G3MULTI  202PASSES      31.100 -.018 -0.554             26.574  -.038 -1.059  526.59 -1.48
G5MULTI  194PASSES      31.059 0.022  0.677             26.652  -.117 -3.261  520.14  4.97
MNETHY0  165PASSES      31.228 -.146 -4.493             26.727  -.191 -5.324  520.89  4.22
MNETHY1  169PASSES      31.149 -.067 -2.062             26.670  -.134 -3.735  521.98  3.13

1698 CAMPBELL   S18 17 24.8859 DIFF    DIFF   E125 35 18.1796  DIFF    DIFF   171.36  DIFF
                                sec      m                      sec      m                m
MX1502   190PASSES      24.870 0.016  0.492             18.240  -.059 -1.733  161.48  9.88
MNETPTS  184PASSES      24.942 -.055 -1.691             18.242  -.061 -1.792  166.32  5.04
G3POINT  198PASSES      24.876 0.010  0.307             18.169  0.010  0.294  172.94 -1.58
G5POINT  201PASSES      24.845 0.041  1.261             18.149  0.030  0.881  168.37  2.99
G3MULTI  199PASSES      24.972 -.085 -2.613             18.200  -.020 -0.587  173.01 -1.65
G5MULTI  189PASSES      24.868 0.018  0.553             18.274  -.093 -2.731  167.63  3.73
MNETHY0  159PASSES      25.066 -.179 -5.503             18.413  -.232 -6.814  164.85  6.51
MNETHY1  166PASSES      24.999 -.112 -3.443             18.380  -.199 -5.845  165.69  5.67
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DIFFERENCES OF COMPUTED VALUES FROM AGD84 VALUES

POINT POSITIONS

BROADCAST POINT POSITIONS COMPUTED USING MX1502

STATION	DLAT	METER	DLONG	METER	DHT	PASSES
400 PARA	0.112	3.451	-0.056	-1.424	-9.49	69
499 MT.ISA	-0.051	-1.568	-0.084	-2.436	12.55	88
611 BERNARD	0.015	0.462	-0.130	-3.436	10.19	60
870 MT.DUNDAS	-0.007	-0.215	-0.041	-1.239	48.57	61
10 JOHNSTON	-0.044	-1.354	-0.030	-0.835	-6.14	64
686 ALEXANDER	-0.061	-1.876	-0.073	-2.132	11.69	65
838 GIANTS	-0.095	-2.919	-0.042	-1.266	10.73	64
1140 WILSON BL	0.060	1.848	-0.045	-1.185	22.04	228
1005 NM/F/16	0.074	2.277	-0.035	-0.976	10.11	182
1698 CAMPBELL	0.016	0.492	-0.059	-1.733	9.88	190

MAGNET POINT POSITIONS WITH HYPERBOLIC COMPUTATION

STATION	DLAT	METER	DLONG	METER	DHT	PASSES
400 PARA	-0.090	-2.773	-0.088	-2.237	3.43	73
499 MT.ISA	-0.089	-2.737	-0.086	-2.494	-1.00	84
611 BERNARD	-0.144	-4.435	0.027	0.714	2.95	80
870 MT.DUNDAS	-0.090	-2.766	-0.003	-0.091	3.61	62
10 JOHNSTON	-0.092	-2.831	-0.050	-1.391	5.34	65
686 ALEXANDER	-0.079	-2.429	-0.103	-3.008	0.29	58
838 GIANTS	-0.028	-0.860	0.052	1.567	3.94	62
1140 WILSON BL	-0.090	-2.772	-0.052	-1.370	11.37	206
1005 NM/F/16	-0.037	-1.139	-0.084	-2.341	2.97	184
1698 CAMPBELL	-0.055	-1.691	-0.061	-1.792	5.04	184

BROADCAST POINT POSITIONS COMPUTED USING GEODOP3

STATION	DLAT	METER	DLONG	METER	DHT	PASSES
400 PARA	0.003	0.092	-0.077	-1.958	-1.67	75
499 MT.ISA	-0.106	-3.260	-0.277	-8.034	13.54	86
611 BERNARD	-0.020	-0.616	-0.060	-1.586	-2.38	86
870 MT.DUNDAS	-0.090	-2.766	-0.054	-1.632	-0.36	60
10 JOHNSTON	-0.021	-0.646	-0.008	-0.223	1.75	68
686 ALEXANDER	-0.041	-1.261	-0.012	-0.350	-2.07	64
838 GIANTS	-0.045	-1.383	0.032	0.964	-0.80	63
1140 WILSON BL	0.000	0.000	-0.014	-0.369	6.09	234
1005 NM/F/16	0.013	0.400	-0.016	-0.446	-0.95	201
1698 CAMPBELL	0.010	0.307	0.010	0.294	-1.58	198

BROADCAST POINT POSITIONS COMPUTED USING GEODOP5

STATION		DLAT	METER	DLONG	METER	DHT	PASSES
400	PARA	-0.003	-0.092	-0.131	-3.331	2.54	75
499	MT.ISA	-0.005	-0.154	-0.150	-4.351	-0.01	87
611	BERNARD	0.008	0.246	-0.160	-4.228	-0.09	85
870	MT.DUNDAS	-0.019	-0.584	-0.038	-1.149	1.45	65
10	JOHNSTON	-0.018	-0.554	-0.117	-3.255	6.44	70
686	ALEXANDER	-0.056	-1.722	-0.131	-3.826	-0.57	64
838	GIANTS	-0.028	-0.860	-0.020	-0.603	-0.30	64
1140	WILSON BL	-0.014	-0.431	-0.052	-1.370	12.45	233
1005	NM/F/16	0.049	1.508	-0.110	-3.066	6.45	201
1698	CAMPBELL	0.041	1.261	0.030	0.881	2.99	201

DIFFERENCES OF COMPUTED VALUES FROM AGD84 VALUES

MULTI-STATION NETWORKS

BROADCAST MULTI-STATION USING GEODOP3

STATION	DLAT	METER	DLONG	METER	DHT	PASSES
400 PARA	0.055	1.695	0.035	0.890	-1.76	75
499 MT.ISA	-0.056	-1.722	0.033	0.957	-4.77	88
611 BERNARD	0.009	0.277	0.025	0.661	-2.64	86
870 MT.DUNDAS	-0.164	-5.040	0.007	0.212	-0.19	60
10 JOHNSTON	-0.007	-0.215	0.009	0.250	0.87	68
686 ALEXANDER	-0.085	-2.614	-0.009	-0.263	-2.78	64
838 GIANTS	-0.148	-4.548	-0.003	-0.090	-0.45	63
1140 WILSON BL	0.001	0.031	-0.011	-0.290	5.30	237
1005 NM/F/16	-0.018	-0.554	-0.038	-1.059	-1.48	202
1698 CAMPBELL	-0.085	-2.613	-0.020	-0.587	-1.65	199
MEAN	-0.050	-1.530	0.003	0.068	-0.95	
S.D.	0.084	2.569	0.023	0.623	2.73	

BROADCAST MULTI-STATION USING GEODOP3
ADJUSTED BY BLOCK SHIFT.

STATION	DLAT	METER	DLONG	METER	DHT	PASSES
400 PARA	0.105	3.225	0.032	0.822	-0.81	75
499 MT.ISA	-0.006	-0.192	0.030	0.889	-3.82	88
611 BERNARD	0.059	1.808	0.022	0.593	-1.69	86
870 MT.DUNDAS	-0.114	-3.509	0.004	0.144	0.76	60
10 JOHNSTON	0.043	1.315	0.006	0.182	1.82	68
686 ALEXANDER	-0.035	-1.083	-0.012	-0.331	-1.83	64
838 GIANTS	-0.098	-3.018	-0.006	-0.158	0.50	63
1140 WILSON BL	0.051	1.561	-0.014	-0.358	6.26	237
1005 NM/F/16	0.032	0.976	-0.041	-1.127	-0.53	202
1698 CAMPBELL	-0.035	-1.083	-0.023	-0.655	-0.70	199

BROADCAST MULTI-STATION USING GEODOP5

STATION	DLAT	METER	DLONG	METER	DHT	PASSES
400 PARA	0.090	2.773	-0.010	-0.254	3.79	67
499 MT.ISA	0.053	1.630	0.007	0.203	1.45	81
611 BERNARD	0.064	1.971	-0.001	-0.026	3.38	84
870 MT.DUNDAS	0.036	1.106	0.018	0.544	3.80	61
10 JOHNSTON	0.046	1.416	-0.014	-0.390	6.53	66
686 ALEXANDER	0.023	0.707	-0.016	-0.467	2.47	61
838 GIANTS	0.017	0.522	0.007	0.211	3.23	60
1140 WILSON BL	0.021	0.647	-0.067	-1.765	11.13	206
1005 NM/F/16	0.022	0.677	-0.117	-3.261	4.97	194
1698 CAMPBELL	0.018	0.553	-0.093	-2.731	3.73	189
MEAN	0.039	1.200	-0.029	-0.794	4.45	
S.D.	0.045	1.393	0.057	1.484	5.14	

BROADCAST MULTI-STATION USING GEODOP5
ADJUSTED BY BLOCK SHIFT.

STATION	DLAT	METER	DLONG	METER	DHT	PASSES
400 PARA	0.051	1.573	0.019	0.539	-0.66	67
499 MT.ISA	0.014	0.430	0.036	0.997	-3.00	81
611 BERNARD	0.025	0.771	0.028	0.767	-1.07	84
870 MT.DUNDAS	-0.003	-0.094	0.047	1.338	-0.65	61
10 JOHNSTON	0.007	0.215	0.015	0.404	2.08	66
686 ALEXANDER	-0.016	-0.493	0.013	0.326	-1.98	61
838 GIANTS	-0.022	-0.678	0.036	1.005	-1.22	60
1140 WILSON BL	-0.018	-0.554	-0.038	-0.971	6.68	206
1005 NM/F/16	-0.017	-0.523	-0.088	-2.468	0.52	194
1698 CAMPBELL	-0.021	-0.647	-0.064	-1.938	-0.72	189

MAGNET MULTI-STATION WITH PSUDO RANGE COMPUTATION

STATION	DLAT	METER	DLONG	METER	DHT	PASSES
400 PARA	-0.152	-4.684	0.056	1.424	-0.31	68
499 MT.ISA	-0.178	-5.474	-0.073	-2.117	0.48	77
611 BERNARD	-0.177	-5.451	-0.026	-0.687	1.51	66
870 MT.DUNDAS	-0.211	-6.484	-0.113	-3.416	5.33	56
10 JOHNSTON	-0.164	-5.047	-0.048	-1.336	4.93	62
686 ALEXANDER	-0.198	-6.088	-0.098	-2.862	3.05	57
838 GIANTS	-0.204	-6.269	-0.057	-1.718	6.41	61
1140 WILSON BL	-0.162	-4.990	-0.083	-2.186	8.96	168
1005 NM/F/16	-0.146	-4.493	-0.191	-5.324	4.22	165
1698 CAMPBELL	-0.179	-5.503	-0.232	-6.814	6.51	159
MEAN	-0.177	-5.448	-0.087	-2.504	4.11	
S.D.	0.178	5.485	0.129	3.334	4.96	

MAGNET MULTI-STATION WITH PSUDO RANGE COMPUTATION
ADJUSTED BY BLOCK SHIFT.

STATION	DLAT	METER	DLONG	METER	DHT	PASSES
400 PARA	0.025	0.764	0.143	3.927	-4.42	68
499 MT.ISA	-0.001	-0.026	0.014	0.386	-3.63	77
611 BERNARD	0.000	-0.003	0.061	1.816	-2.60	66
870 MT.DUNDAS	-0.034	-1.035	-0.026	-0.912	1.22	56
10 JOHNSTON	0.013	0.401	0.039	1.168	0.82	62
686 ALEXANDER	-0.021	-0.640	-0.011	-0.358	-1.06	57
838 GIANTS	-0.027	-0.821	0.030	0.786	2.30	61
1140 WILSON BL	0.015	0.459	0.004	0.318	4.85	168
1005 NM/F/16	0.031	0.955	-0.104	-2.821	0.11	165
1698 CAMPBELL	-0.002	-0.055	-0.145	-4.310	2.40	159

```
        MAGNET MULTI-STATION WITH HYPERBOLIC COMPUTATION
          STATION          DLAT   METER  DLONG   METER   DHT PASSES

  400 PARA              -0.075 -2.311  0.053   1.347 -0.70     68
  499 MT.ISA            -0.102 -3.137 -0.067  -1.943  1.02     79
  611 BERNARD           -0.098 -3.018  0.040   1.057  0.35     77
  870 MT.DUNDAS         -0.120 -3.687 -0.117  -3.536  5.56     57
   10 JOHNSTON          -0.087 -2.677 -0.028  -0.779  4.94     62
  686 ALEXANDER         -0.118 -3.628 -0.092  -2.687  3.09     58
  838 GIANTS            -0.113 -3.473 -0.059  -1.778  5.53     59
 1140 WILSON BL         -0.082 -2.526 -0.027  -0.711  8.32    171
 1005 NM/F/16           -0.067 -2.062 -0.134  -3.735  3.13    169
 1698 CAMPBELL          -0.112 -3.443 -0.199  -5.845  5.67    166


          MEAN          -0.097 -2.996 -0.063  -1.861  3.69
          S.D.           0.099  3.046  0.161   2.807  4.56


        MAGNET MULTI-STATION WITH HYPERBOLIC COMPUTATION
                      ADJUSTED BY BLOCK SHIFT.
          STATION          DLAT   METER  DLONG   METER   DHT PASSES

  400 PARA               0.022  0.685  0.116   3.208 -4.39     68
  499 MT.ISA            -0.005 -0.140 -0.004  -0.082 -2.67     79
  611 BERNARD           -0.001 -0.022  0.103   2.918 -3.34     77
  870 MT.DUNDAS         -0.023 -0.691 -0.054  -1.675  1.87     57
   10 JOHNSTON           0.010  0.319  0.035   1.082  1.25     62
  686 ALEXANDER         -0.021 -0.632 -0.029  -0.826 -0.60     58
  838 GIANTS            -0.016 -0.476  0.004   0.083  1.84     59
 1140 WILSON BL          0.015  0.471  0.036   1.150  4.63    171
 1005 NM/F/16            0.030  0.934 -0.071  -1.874 -0.56    169
 1698 CAMPBELL          -0.015 -0.447 -0.136  -3.984  1.98    166
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APPENDIX C
SAMPLE PRINTOUT OF MAGNET

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MAGNET  -  VERSION VAX11/1.1                              MAGNAVOX NETWORK PROGRAM
                 MODEL : NWL-9D,     A=6378145 M,    1/F=298.25

SITE  NO. PIVT  LSS  OUT NSPT HYPR     PRINT OPTIONS         ......WINDOW........
   1 1059    1 1502   12    2    1      00000000             1  0: 0    366 23:59
UNIT PNUM SNUM SKIP                        ELEV     RMS
   0    0    0    0                        5.00     17.0

SITE     LATITUDE        CNST        LONGITUDE       CNST  ALTITUDE   CNST    MIN  MAX
 1    S 43 47  6.231   -1.00     E 138 41 32.897  -1.00    222.69  -1.00      1   73
 2    S 20 20 34.820   -1.00     E 139 12 21.630  -1.00    563.70  -1.00     74  157
 3    S 31 21 45.420   -1.00     E 136 52 54.583  -1.00    212.85  -1.00    158  237
 4    S 12 13  3.838   -1.00     E 136 51 49.355  -1.00    149.41  -1.00    238  299
 5    S 25 56 48.931   -1.00     E 133 12 33.890  -1.00    582.96  -1.00    300  364
 6    S 19 14 54.204   -1.00     E 134 10 18.396  -1.00    417.08  -1.00    365  422
 7    S 12 58  8.160   -1.00     E 131  2 31.329  -1.00    206.13  -1.00    423  484
 8    S 31 41  7.290   -1.00     E 129  0 44.697  -1.00     96.29  -1.00    485  690
 9    S 25 43 31.017   -1.00     E 126 10 26.582  -1.00    535.66  -1.00    691  874
10    S 18 17 24.856   -1.00     E 125 35 18.252  -1.00    161.68  -1.00    875 1058

SITE        T DELAY   CNST     FREQ   CNST   FDOT CNST     TROPO   CNST
 1          0.0001 0.0010      0.00 -1.00        -1.00      2.28   0.20
 2          0.0001 0.0010      0.00 -1.00        -1.00      2.19   0.20
 3          0.0001 0.0010      0.00 -1.00        -1.00      2.28   0.20
 4          0.0001 0.0010      0.00 -1.00        -1.00      2.30   0.20
 5          0.0001 0.0010      0.00 -1.00        -1.00      2.18   0.20
 6          0.0001 0.0010      0.00 -1.00        -1.00      2.23   0.20
 7          0.0001 0.0010      0.00 -1.00        -1.00      2.29   0.20
 8          0.0001 0.0010      0.00 -1.00        -1.00      2.32   0.20
 9          0.0001 0.0010      0.00 -1.00        -1.00      2.20   0.20
10          0.0001 0.0010      0.00 -1.00        -1.00      2.30   0.20

ORBITAL CONSTRAINTS- ALONG TRACK  HEIGHT  CROSS TRACK
                        26.00       5.00      10.00

SELECTED SITES  1   2   3   4   5   6   7   8   9  10

TIE  SAT PASS/S PASS/S PASS/S PASS/S PASS/S PASS/S PASS/S PASS/S PASS/S PASS/S
  1  480  75/ 2 469/ 8
  2  130  76/ 2 158/ 3 497/ 8
  3  190  77/ 2 159/ 3 498/ 8
  4  200  78/ 2 160/ 3
  5  140  79/ 2 161/ 3 499/ 8
  6  200  80/ 2 162/ 3 500/ 8
  7  140 163/ 3 501/ 8
  8  480  81/ 2 502/ 8
  9  480  82/ 2 503/ 8
 10  130  83/ 2 164/ 3
 11  190  85/ 2 165/ 3
 12  200  86/ 2 166/ 3
 13  140  87/ 2 167/ 3 504/ 8
 14  200  88/ 2 168/ 3 505/ 8
 15  140  89/ 2 169/ 3 506/ 8
 16  480  91/ 2 170/ 3 507/ 8 875/10
 17  130  92/ 2 171/ 3 508/ 8 876/10
 18  480 509/ 8 691/ 9 877/10
 19  130 172/ 3 238/ 4 300/ 5 423/ 7 510/ 8 692/ 9 878/10
 20  190   1/ 1  93/ 2 173/ 3 239/ 4 301/ 5 424/ 7 511/ 8
 21  190   2/ 1  94/ 2 174/ 3 240/ 4 302/ 5 365/ 6 425/ 7 512/ 8 693/ 9 879/10
 22  140   3/ 1  95/ 2 175/ 3 241/ 4 366/ 6
 23  200   4/ 1  96/ 2 176/ 3 242/ 4 303/ 5 367/ 6 426/ 7 513/ 8 694/ 9 880/10
 24  140   5/ 1  97/ 2 177/ 3 243/ 4 304/ 5 368/ 6 427/ 7 514/ 8 695/ 9 881/10
 25  200 178/ 3 305/ 5 428/ 7 515/ 8 696/ 9 882/10
 26  480   6/ 1  98/ 2 179/ 3
 27  480  99/ 2 244/ 4 306/ 5 369/ 6 429/ 7 883/ 8
 28  130   8/ 1 100/ 2 180/ 3 245/ 4 370/ 6 516/ 8 697/ 9 884/10
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29  190 101/ 2 246/ 4
30  190   9/ 1 102/ 2 181/ 3 247/ 4 307/ 5 371/ 6 430/ 7 517/ 8 698/ 9 885/10
31  140  10/ 1 182/ 3
32  200  11/ 1 103/ 2 248/ 4 308/ 5 372/ 6 431/ 7 699/ 9
33  140  12/ 1 104/ 2 183/ 3 249/ 4 309/ 5 373/ 6 432/ 7 518/ 8 700/ 9 886/10
34  200  13/ 1 105/ 2 184/ 3 250/ 4 310/ 5 374/ 6 433/ 7 519/ 8 701/ 9 887/10
35  480  14/ 1 106/ 2 185/ 3 251/ 4 311/ 5 375/ 6 434/ 7 520/ 8 702/ 9 888/10
36  480 521/ 8 703/ 9 889/10
37  130  15/ 1 107/ 2 186/ 3 252/ 4 376/ 6 435/ 7
38  190  16/ 1 187/ 3
39  190  17/ 1 108/ 2 188/ 3 253/ 4 312/ 5 377/ 6 436/ 7 522/ 8 704/ 9 890/10
40  200  18/ 1 109/ 2 189/ 3
41  190 705/ 9 891/10
42  140  19/ 1 110/ 2 190/ 3 254/ 4 313/ 5 378/ 6 437/ 7 523/ 8 706/ 9 892/10
43  200  20/ 1 111/ 2 191/ 3 255/ 4 314/ 5 379/ 6 438/ 7 524/ 8 707/ 9 893/10
44  140  21/ 1 315/ 5 380/ 6 525/ 8 708/ 9 894/10
45  480  23/ 1 192/ 3 256/ 4 316/ 5 381/ 6 439/ 7 709/ 9 895/10
46  130  24/ 1 112/ 2 193/ 3 257/ 4 317/ 5 382/ 6 440/ 7 526/ 8 710/ 9 896/10
47  480 527/ 8 711/ 9 897/10
48  130 712/ 9 898/10
49  190  25/ 1 113/ 2 194/ 3 258/ 4 318/ 5 383/ 6 411/ 7 713/ 9 899/10
50  190 195/ 3 319/ 5 442/ 7 714/ 9 900/10
51  140  27/ 1 114/ 2 196/ 3 259/ 4 320/ 5 385/ 6 443/ 7 528/ 8 715/ 9
52  140  28/ 1 196/ 3 260/ 4 321/ 5 385/ 6 444/ 7 529/ 8 716/ 9 901/10
53  480  29/ 1 115/ 2 198/ 3 261/ 4 322/ 5 386/ 6 445/ 7 530/ 8 717/ 9 902/10
54  130  30/ 1 116/ 2 199/ 3 262/ 4 323/ 5 387/ 6 446/ 7 531/ 8 718/ 9 903/10
55  130 324/ 5 448/ 7/532/ 8 719/ 9 904/10
56  190  31/ 1 117/ 2 200/ 3 263/ 4 325/ 5 388/ 6 449/ 7 533/ 8 720/ 9 905/10
57  190  32/ 1 264/ 4 326/ 5 389/ 6 450/ 7 534/ 8 721/ 9 906/10
58  140  33/ 1 118/ 2 201/ 3 265/ 4 327/ 5 390/ 6
59  140  34/ 1 119/ 2 202/ 3 266/ 4 328/ 5 391/ 6 451/ 7 536/ 8 722/ 9 907/10
60  480  35/ 1 120/ 2 203/ 3 267/ 4 329/ 5 392/ 6 452/ 7 537/ 8 723/ 9 908/10
61  130  36/ 1 121/ 2 204/ 3 268/ 4 330/ 5 393/ 6 453/ 7 538/ 8
62  480 205/ 3 331/ 5 394/ 6 454/ 7 539/ 8 724/ 9 909/10
63  130 122/ 2 206/ 4 395/ 6 455/ 7 910/10
64  190 123/ 2 269/ 4 332/ 5 396/ 6
65  190  37/ 1 124/ 2 207/ 3 270/ 4 333/ 5 397/ 6 456/ 7 540/ 8 725/ 9 911/10
66  200  38/ 1 334/ 5 541/ 8
67  200 125/ 2 208/ 3 271/ 4 335/ 5 398/ 6 457/ 7 726/ 9 912/10
68  480  40/ 1 126/ 2 272/ 4 336/ 5 458/ 7 542/ 8 727/ 9 913/10
69  130  41/ 1 127/ 2 209/ 3 273/ 4 337/ 5 399/ 6
70  480  42/ 1 128/ 2 210/ 3 274/ 4 338/ 5 400/ 6 459/ 7 544/ 8 728/ 9 914/10
71  130  43/ 1 129/ 2 211/ 3 275/ 4 339/ 5 545/ 8 729/ 9 915/10
72  190  44/ 1 130/ 2 212/ 3
73  190  45/ 1 131/ 2 213/ 3 276/ 4 340/ 5 401/ 6 460/ 7 730/ 9 916/10
74  200  46/ 1 132/ 2 214/ 3 277/ 4 341/ 5 402/ 6 461/ 7 546/ 8 731/ 9 917/10
75  200 547/ 8 732/ 9 918/10
76  480  47/ 1 133/ 2 215/ 3 278/ 4 343/ 5 403/ 6 462/ 7 548/ 8 733/ 9 919/10
77  480  48/ 1 135/ 2 216/ 3 279/ 4 344/ 5 404/ 6 463/ 7 549/ 8 734/ 9 920/10
78  130 136/ 2 280/ 4 405/ 6 464/ 7 921/10
79  190  49/ 1 137/ 2 217/ 3 281/ 4 345/ 5 406/ 6 465/ 7 735/ 9 923/10
80  190 346/ 5 466/ 7 736/ 9 924/10
81  200  50/ 1 138/ 2 218/ 3 282/ 4 347/ 5 407/ 6 467/ 7 550/ 8
82  140  51/ 1 219/ 3
83  200 220/ 3 348/ 5 551/ 8 737/ 9
84  480  52/ 1 139/ 2 221/ 3 350/ 5 408/ 6 468/ 7
85  480  54/ 1 140/ 2 222/ 3 283/ 4 351/ 5 409/ 6 468/ 7 552/ 8 738/ 9 925/10
86  130  55/ 1 141/ 2 223/ 3 284/ 4 352/ 5 410/ 6 470/ 7 553/ 8 739/ 9 926/10
87  130 554/ 8 740/ 9 927/10
88  190  56/ 1 142/ 2 224/ 3 285/ 4 353/ 5 411/ 6 471/ 7 555/ 8 741/ 9 928/10
89  190 427/ 7 556/ 8 742/ 9 929/10
90  200  57/ 1 143/ 2 286/ 4
91  140  58/ 1 144/ 2 225/ 3 287/ 4 354/ 5 412/ 6 473/ 7 557/ 8
92  200  59/ 1 145/ 2 226/ 3 288/ 4 355/ 5 413/ 6 474/ 7 558/ 8 743/ 9 930/10
93  140  60/ 1 146/ 2 227/ 3 289/ 4 356/ 5 414/ 6 475/ 7 559/ 8 744/ 9 931/10
94  480  61/ 1 147/ 2 228/ 3 290/ 4 357/ 5 415/ 6 476/ 7 560/ 8
95  130  62/ 1 148/ 2 229/ 3 358/ 5 416/ 6 561/ 8 745/ 9
96  480 291/ 4 477/ 7 932/10
97  130  63/ 1 230/ 3 359/ 5 417/ 6 478/ 7 746/ 9 933/10
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 98  190  64/ 1 149/ 2 292/ 4 360/ 5 418/ 6 479/ 7
 99  190  65/ 1 150/ 2 293/ 4 419/ 6 480/ 7 562/ 8 747/ 9 934/10
100  200  66/ 1 231/ 3
101  140  67/ 1 151/ 2 232/ 3 294/ 4 361/ 5
102  200  68/ 1 152/ 2 233/ 3 295/ 4 362/ 5 420/ 6 481/ 7 563/ 8 748/ 9 935/10
103  140  69/ 1 153/ 2 234/ 3 296/ 4 363/ 5 421/ 6 482/ 7 564/ 8 749/ 9 936/10
104  480  70/ 1 154/ 2 235/ 3 297/ 4
105  480  71/ 1 155/ 2 236/ 3 298/ 4 364/ 5 422/ 6 483/ 7 565/ 8 750/ 9 937/10
106  130  72/ 1 156/ 2 237/ 3 299/ 4 484/ 7 566/ 8 751/ 9 938/10
107  190  73/ 1 157/ 2
108  190 567/ 8 752/ 9 939/10
109  200 568/ 8 753/ 9 940/10
110  140 754/ 9 941/10
111  200 569/ 8 755/ 9 942/10
112  140 570/ 8 756/ 9 943/10
113  480 571/ 8 757/ 9 944/10
114  130 572/ 8 756/ 9 945/10
115  190 573/ 8 759/ 9 946/10
116  190 574/ 8 760/ 9 947/10
117  140 575/ 8 761/ 9
118  200 576/ 8 762/ 9 948/10
119  140 577/ 8 763/ 9 949/10
120  480 578/ 8 764/ 9 950/10
121  130 579/ 8 765/ 9 951/10
122  130 766/ 9 953/10
123  190 580/ 8 767/ 9 954/10
124  190 581/ 8 768/ 9 955/10
125  200 583/ 8 769/ 9 956/10
126  140 584/ 8 770/ 9 957/10
127  480 585/ 8 772/ 9 958/10
128  130 586/ 8 773/ 9
129  480 774/ 9 959/10
130  130 587/ 8 960/10
131  190 588/ 8 775/ 9 961/10
132  190 776/ 9 962/10
133  140 591/ 8 963/10
134  200 592/ 8 777/ 9 964/10
135  480 593/ 8 778/ 9 965/10
136  130 594/ 8 779/ 9 966/10
137  480 595/ 8 780/ 9 967/10
138  130 596/ 8 781/ 9
139  190 598/ 8 782/ 9 968/10
140  140 600/ 8 783/ 9 969/10
141  200 601/ 8 784/ 9 970/10
142  140 785/ 9 971/10
143  480 786/ 9 972/10
144  480 602/ 8 787/ 9 973/10
145  190 603/ 8 788/ 9 975/10
146  140 604/ 8 790/ 9
147  200 791/ 9 976/10
148  140 605/ 8 792/ 9 977/10
149  480 606/ 8 793/ 9 978/10
150  130 607/ 8 794/ 9 979/10
151  190 608/ 8 795/ 9 980/10
152  190 796/ 9 981/10
153  140 610/ 8 798/ 9 982/10
154  480 611/ 8 799/ 9 983/10
155  130 800/ 9 985/10
156  190 801/ 9 986/10
157  190 613/ 8 802/ 9 987/10
158  140 615/ 8 803/ 9 988/10
159  480 616/ 8 804/ 9 989/10
160  130 617/ 8 805/ 9 990/10
161  190 618/ 8 806/ 9 991/10
162  190 619/ 8 807/ 9 992/10
163  200 620/ 8 808/ 9
164  480 621/ 8 809/ 9 993/10
165  480 622/ 8 810/ 9 994/10
166  130 623/ 8 995/10
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167  190 624/ 8 811/ 9 996/10
168  200 625/ 8 812/ 9
169  480 813/ 9 998/10
170  130 626/ 8 814/ 9 999/10
171  190 627/ 8 815/ 9
172  200 628/ 8 816/ 9
173  200 629/ 8 817/ 91001/10
174  480 631/ 8 818/ 91003/10
175  130 632/ 8 819/ 91004/10
176  130 633/ 8 820/ 9
177  190 634/ 81005/10
178  200 637/ 8 821/ 91007/10
179  480 638/ 8 822/ 91009/10
180  130 639/ 8 823/ 91010/10
181  130 640/ 8 824/ 91011/10
182  190 641/ 8 825/ 91012/10
183  190 642/ 8 826/ 91013/10
184  200 643/ 8 827/ 91014/10
185  140 644/ 8 828/ 91015/10
186  480 645/ 8 829/ 91016/10
187  130 646/ 8 830/ 91017/10
188  190 648/ 8 831/ 91018/10
189  200 832/ 91019/10
190  140 649/ 8 833/ 91020/10
191  200 650/ 81021/10
192  480 651/ 8 834/ 91022/10
193  130 652/ 8 835/ 9
194  480 653/ 8 836/ 91023/10
195  130 654/ 8 837/ 91024/10
196  190 655/ 8 838/ 91025/10
197  140 839/ 91026/10
198  200 656/ 8 840/ 91027/10
199  140 657/ 8 841/ 91028/10
200  480 658/ 8 842/ 91029/10
201  130 659/ 8 843/ 91030/10
202  190 660/ 8 844/ 91031/10
203  140 663/ 8 845/ 91031/10
204  480 846/ 91033/10
205  480 66/ 8 847/ 91034/10
206  190 665/ 8 849/ 91035/10
207  190 666/ 8 850/ 91036/10
208  200 667/ 8 851/ 91037/10
209  140 668/ 8 852/ 9
210  200 669/ 8 853/ 91038/10
211  480 670/ 8 854/ 91039/10
212  130 671/ 81040/10
213  480 672/ 8 855/ 91041/10
214  130 674/ 81042/10
215  190 674/ 81043/10
216  190 675/ 8 856/ 91044/10
217  200 676/ 8 857/ 9
218  140 858/ 91045/10
219  200 677/ 8 859/ 91046/10
220  130 678/ 8 860/ 91047/10
221  480 861/ 91048/10
222  130 679/ 8 862/ 91049/10
223  190 680/ 8 863/ 9
224  190 681/ 8 864/ 91050/10
225  140 682/ 8 865/ 91051/10
226  200 866/ 91052/10
227  140 683/ 8 867/ 91053/10
228  480 684/ 8 868/ 91054/10
229  480 685/ 8 869/ 91055/10
230  190 870/ 91056/10
231  140 688/ 8 872/ 9
232  480 689/ 8 873/ 91057/10
233  130 690/ 8 874/ 91058/10
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ITERATION MOVEMENT 1

SITE    TDLAY      DRIFT     DEL LAT    DEL LON    DEL ANT       RADIAL
  1      0.10       0.00       -5.52      -3.05      -8.91        10.92
  2      0.10       0.00      -10.10      -0.45     -15.74        18.71
  3      0.10       0.00       -3.90      -4.55     -10.26        11.88
  4      0.10       0.00       -3.60       6.35     -24.08        25.16
  5      0.10       0.00      -11.58       2.29     -15.02        19.11
  6      0.10       0.00       -2.96       2.74     -14.54        15.09
  7      0.10       0.00       -6.13      -0.18     -21.62        22.47
  8      0.10       0.00       -3.94      -0.45     -30.77        31.02
  9      0.10       0.00       -3.95       2.76     -13.70        14.52
 10      0.10       0.00       -4.19       3.38       4.43         6.97

ITERATION MOVEMENT 2

SITE    TDLAY      DRIFT     DEL LAT    DEL LON    DEL ANT       RADIAL
  1      0.10      -0.04       -0.14      -0.20       0.11         0.27
  2      0.10       0.00       -0.15      -0.19       0.11         0.26
  3      0.10      -0.15       -0.08       0.02      -0.25         0.26
  4      0.10      -0.04       -0.55       0.03      -0.54         0.77
  5      0.10       0.11        0.06       0.03       0.22         0.22
  6      0.10       0.04       -0.07      -0.15       0.42         0.45
  7      0.10       0.05       -0.39      -0.26       0.93         1.04
  8      0.10       0.02       -0.15      -0.26      -0.05         0.31
  9      0.10       0.05       -0.18      -0.35       0.06         0.40
 10      0.10       0.00       -0.29       0.31      -0.37         0.56

ITERATION MOVEMENT 3

SITE    TDLAY      DRIFT     DEL LAT    DEL LON    DEL ANT       RADIAL
  1      0.10      -0.04       -0.10       0.18      -0.31         0.37
  2      0.10       0.00       -0.14       0.29       0.03         0.32
  3      0.10      -0.15        0.07       0.01      -0.25         0.26
  4      0.10      -0.04       -0.05      -0.07      -0.11         0.14
  5      0.10       0.11        0.01      -0.06      -0.26         0.27
  6      0.10       0.04       -0.07       0.21      -0.02         0.22
  7      0.10       0.05        0.08       1.08       1.65         1.97
  8      0.10       0.02       -0.03       0.04       0.02         0.05
  9      0.10       0.05        0.00       0.01       0.00         0.01
 10      0.10       0.00        0.02       0.06      -0.05         0.08

ITERATION MOVEMENT 4

SITE    TDLAY      DRIFT     DEL LAT    DEL LON    DEL ANT       RADIAL
  1      0.10      -0.04        0.01       0.00      -0.04         0.04
  2      0.10       0.00       -0.05       0.04      -0.12         0.14
  3      0.10      -0.15        0.10      -0.02       0.26         0.28
  4      0.10      -0.04        0.03      -0.01      -0.01         0.03
  5      0.10       0.11        0.06      -0.05      -0.08         0.11
  6      0.10       0.04        0.05      -0.03      -0.01         0.05
  7      0.10       0.05       -0.04      -0.03       0.06         0.08
  8      0.10       0.02        0.03       0.02       0.01         0.04
  9      0.10       0.05        0.05       0.04      -0.04         0.07
 10      0.10       0.00        0.04       0.00      -0.01         0.04

ITERATION MOVEMENT 5

SITE    TDLAY      DRIFT     DEL LAT    DEL LON    DEL ANT       RADIAL
  1      0.10      -0.04        0.00       0.00       0.00         0.00
  2      0.10       0.00        0.00       0.00       0.00         0.00
  3      0.10      -0.15        0.00       0.00       0.00         0.00
  4      0.10      -0.04        0.00       0.00       0.00         0.00
  5      0.10       0.11        0.00       0.00       0.00         0.00
  6      0.10       0.04        0.00       0.00       0.00         0.00
  7      0.10       0.05        0.00       0.00       0.00         0.00
  8      0.10       0.02        0.00       0.00       0.00         0.00
  9      0.10       0.05        0.00       0.00       0.00         0.00
 10      0.10       0.00        0.00       0.00       0.00         0.00
```

```
10 STATION SOLUTION USING  14044. DOPPLER COUNTS   RMS =    7.24
SIGMA-CROSS CORRELATION MATRIX
 0.52
-0.06  0.50
 0.06  0.05  0.35
 0.00  0.00  0.00  0.00

 0.94 -0.05  0.05  0.00    0.53
-0.04  0.37  0.03  0.00   -0.03  0.50
 0.03  0.04  0.38  0.00    0.04  0.05  0.38
 0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00

 0.94 -0.05  0.05  0.00    0.94 -0.05  0.03  0.00    0.52
-0.03  0.45  0.10  0.00   -0.03  0.39  0.08  0.00   -0.32  0.48
 0.05  0.01  0.44  0.00    0.05 -0.01  0.40  0.00    0.05  0.09  0.35
 0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00

 0.92 -0.06  0.05  0.00    0.92 -0.05  0.02  0.00    0.92 -0.04  0.05  0.00
 0.54
-0.02  0.30  0.06  0.00   -0.02  0.32  0.06  0.00   -0.02  0.31  0.03  0.00
-0.04  0.53
 0.02  0.01  0.31  0.00    0.02 -0.02  0.34  0.00    0.02  0.03  0.31  0.00
-0.05  0.02  0.42
 0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00
 0.00  0.00  0.00  0.00

 0.94 -0.07  0.04  0.00    0.93 -0.06  0.02  0.00    0.94 -0.05  0.05  0.00
 0.92 -0.03  0.02  0.00    0.53
 0.01  0.33  0.12  0.00    0.01  0.31  0.12  0.00    0.01  0.35  0.07  0.00
 0.01  0.32  0.08  0.00    0.00  0.50
 0.04 -0.06  0.33  0.00    0.04 -0.06  0.30  0.00    0.04 -0.05  0.33  0.00
 0.04 -0.03  0.31  0.00    0.05 -0.07  0.36
 0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00
 0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00

 0.93 -0.07  0.05  0.00    0.93 -0.06  0.02  0.00    0.94 -0.05  0.05  0.00
 0.92 -0.03  0.02  0.00    0.94  0.00  0.04  0.00    0.53
 0.00  0.31  0.08  0.00    0.00  0.34  0.09  0.00   -0.01  0.33  0.05  0.00
-0.01  0.33  0.05  0.00   -0.02  0.34  0.00  0.00   -0.02  0.51
 0.03 -0.05  0.33  0.00    0.03 -0.06  0.34  0.00    0.03 -0.02  0.34  0.00
 0.02 -0.02  0.35  0.00    0.03  0.04  0.35  0.00    0.05  0.06  0.37
 0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00
 0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00

 0.92 -0.07  0.04  0.00    0.92 -0.06  0.02  0.00    0.92 -0.06  0.05  0.00
 0.91 -0.04  0.01  0.00    0.92 -0.01  0.04  0.00    0.92 -0.02  0.02  0.00
 0.53
 0.03  0.27  0.10  0.00    0.03  0.25  0.12  0.00    0.02  0.28  0.08  0.00
 0.02  0.31  0.10  0.00    0.02  0.32  0.05  0.00    0.01  0.32  0.08  0.00
 0.02  0.51
 0.01 -0.08  0.23  0.00    0.01 -0.07  0.22  0.00    0.01 -0.07  0.24  0.00
 0.01 -0.06  0.26  0.00    0.02 -0.02  0.30  0.00    0.02 -0.03  0.30  0.00
-0.03 -0.03  0.42
 0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00
 0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00
 0.00  0.00  0.00  0.00

 0.94 -0.08  0.04  0.00    0.94 -0.06  0.01  0.00    0.94 -0.06  0.05  0.00
 0.92 -0.04  0.01  0.00    0.94 -0.02  0.04  0.00    0.94 -0.02  0.02  0.00
 0.93  0.00  0.02  0.00    0.52
 0.04  0.31  0.16  0.00    0.04  0.29  0.16  0.00    0.03  0.36  0.15  0.00
 0.03  0.03  0.13  0.00    0.02  0.37  0.07  0.00    0.02  0.31  0.09  0.00
 0.01  0.34  0.02  0.00    0.01  0.38
 0.07 -0.10  0.26  0.00    0.07 -0.08  0.24  0.00    0.07 -0.10  0.31  0.00
 0.07 -0.06  0.24  0.00    0.08 -0.06  0.33  0.00    0.08 -0.06  0.30  0.00
 0.07 -0.02  0.28  0.00    0.07  0.03  0.27
 0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00
 0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00
 0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00
```

```
 0.94 -0.09  0.04  0.00    0.94 -0.07  0.01  0.00    0.94 -0.07  0.04  0.00
 0.92 -0.04  0.01  0.00    0.94 -0.03  0.04  0.00    0.94 -0.03  0.02  0.00
 0.93 -0.01  0.02  0.00    0.97  0.00  0.08  0.00    0.52
 0.07  0.25  0.15  0.00    0.07  0.23  0.15  0.00    0.07  0.28  0.14  0.00
 0.06  0.25  0.14  0.00    0.06  0.32  0.11  0.00    0.06  0.28  0.13  0.00
 0.05  0.33  0.06  0.00    0.05  0.57  0.06  0.00    0.04  0.39
 0.04 -0.14  0.20  0.00    0.04 -0.02  0.17  0.00    0.04 -0.15  0.23  0.00
 0.05 -0.11  0.19  0.00    0.05 -0.12  0.30  0.00    0.05 -0.11  0.27  0.00
 0.05 -0.08  0.28  0.00    0.05 -0.13  0.56  0.00    0.06 -0.04  0.27
 0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00
 0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00
 0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00

 0.93 -0.09  0.04  0.00    0.93 -0.07  0.01  0.00    0.94 -0.07  0.04  0.00
 0.92 -0.05  0.01  0.00    0.94 -0.03  0.04  0.00    0.94 -0.03  0.02  0.00
 0.93 -0.01  0.02  0.00    0.96 -0.01  0.08  0.00    0.97  0.04  0.05  0.00
 0.52
 0.06  0.22  0.13  0.00    0.06  0.20  0.13  0.00    0.06  0.25  0.12  0.00
 0.06  0.22  0.12  0.00    0.06  0.27  0.09  0.00    0.06  0.25  0.12  0.00
 0.05  0.30  0.05  0.00    0.05  0.49  0.06  0.00    0.04  0.55 -0.02  0.00
 0.04  0.42
 0.02 -0.13  0.16  0.00    0.02 -0.11  0.14  0.00    0.02 -0.13  0.19  0.00
 0.02 -0.10  0.16  0.00    0.03 -0.11  0.25  0.00    0.03 -0.10  0.22  0.00
 0.02 -0.09  0.25  0.00    0.03 -0.11  0.46  0.00    0.03 -0.05  0.55  0.00
 0.03 -0.03  0.31
 0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00
 0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00
 0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00    0.00  0.00  0.00  0.00
 0.00  0.00  0.00  0.00

SITE  DOP  NW   NE   SW   SE   S1   S2   S3   S4   S5   S6   S7   S8   S9   S10
  1   1032  17   16   15   20   68   58   57   50   53   52   47   45   44   42
  2   1189  22   20   18   19   58   79   64   54   50   52   47   52   40   43
  3   1131  18   18   21   20   57   64   77   45   50   48   47   51   43   44
  4    805  15   14   16   12   50   54   45   57   48   47   45   40   40   42
  5    912  14   16   17   15   53   50   50   48   62   52   51   47   48   46
  6    879  16   16   14   12   52   52   48   47   52   58   49   41   43   44
  7    860  16   13   14   16   47   47   47   45   51   49   59   44   46   49
  8   2492  44   36   50   41   45   52   51   40   47   41   44  171  144  138
  9   2436  42   40   43   44   44   40   43   40   48   43   46  144  169  151
 10   2308  44   42   39   41   42   43   44   42   46   44   49  138  151  166

SITE    LATITUDE        LONGITUDE      ANTENNA     GEO X        GEO Y        GEO Z
  1   S 34 47  6.417  E 138 41 32.777   213.54  -3939356.89  3461730.90  -3618439.45
  2   S 20 20 35.158  E 139 12 21.619   547.97  -4529707.91  3909110.54  -2203543.24
  3   S 31 21 45.543  E 136 52 54.411   202.35  -3979187.91  3726032.25  -3300401.75
  4   S 12 13  3.973  E 136 51 49.563   124.66  -4549676.02  4262911.26  -1340984.81
  5   S 25 56 49.302  E 133 12 33.969   567.82  -3929585.87  4183203.14  -2774037.59
  6   S 19 14 54.303  E 134 10 18.491   402.94  -4197713.01  4320855.47  -2089465.17
  7   S 12 58  8.369  E 131  2 31.349   187.15  -4081950.36  4688793.77  -1422106.00
  8   S 31 41  7.422  E 129  0 44.672    65.91  -3419713.65  4221125.11  -3330835.27
  9   S 25 43 31.149  E 126 10 26.670   521.98  -3393926.66  4641617.99  -2751908.70
 10   S 18 17 24.999  E 125 35 18.380   165.69  -3525546.46  4926531.10  -1988969.40

SITE    TDLAY      DRIFT     DEL LAT    DEL LON    DEL ANT      RADIAL
  1      0.10      -0.04       -5.74      -3.06      -9.15       11.22
  2      0.10       0.00      -10.44      -0.31     -15.73       18.88
  3      0.10      -0.15       -3.80      -4.54     -10.50       12.06
  4      0.10      -0.04       -4.18       6.30     -24.75       25.88
  5      0.10       0.11      -11.46       2.21     -15.14       19.12
  6      0.10       0.04       -3.05       2.78     -14.14       14.73
  7      0.10       0.05       -6.47       0.61     -18.98       20.06
  8      0.10       0.02       -4.08      -0.66     -30.78       31.06
  9      0.10       0.05       -4.08       2.45     -13.68       14.48
 10      0.10       0.00       -4.42       3.75       4.01        7.04
```

```
CHORD MEASUREMENTS

SITE          1          2          3          4          5          6          7
              8          9
   2 1597057.97
   3  415439.15 1240841.86
   4 2490216.67  932513.12 2110215.75
   5 1110689.95  872202.40  698945.50 1563491.43
   6 1772739.48  541080.68 1366724.29  829131.08  747983.77
   7 2519900.16 1191233.35 2113164.64  637749.05 1451397.89  770809.86
   8  964066.81 1612522.15  747699.53 2288682.13  755930.83 1468410.32 2073769.24
   9 1562211.00 1458516.67 1217239.75 1862761.82  705382.63 1089858.94 1497991.12
      715985.48
  10 2229809.70 1445519.54 1834895.87 1381707.89 1154173.45  910357.20  829119.09
     1519671.74  824970.08
```

APPENDIX D
SAMPLE PRINTOUT OF GEODOP3

```
                               DEPT./ENERGY MINES & RESOURCES
                               GEODETIC SURVEY OF CANADA
                               PROGRAM GEODOP(VERSION APR/80)
                               MODIFIED BY SHI AT UNSW SEP/81
                               ==============================
                                           84/09/04.


 ADJUSTMENT OPTOPNS
 ------------------
   APRIORI VARIANCE FACTOR=   1.00
   REFRACTION MODEL       =   1    <=1  HOPFIELD REFRACTION MODEL
                                    =2  SAASTAMOINEN MODEL
                                    >2  NO REFRACTION APPLIED
   CORRELATION COEFFICIENT=   0.00
   ORBIT CONSTRAINTS ALONG=  26.00
                    ACROSS=  10.00
              OUT OF PLANE=   5.00
   PASS ELEVATION CUTOFF  =  14.50
   MINIMUM HORIZON        =   7.50

 ELLIPSOID PARAMETERS
                SEM.MAJ.A= 6378145.000
                    MIN.B= 6356759.800
                      DX=       0.000
                      DY=       0.000
                      DZ=       0.000

 CONVERGE LIMITATION      =  1.00

   FIGURE                 =PHASE W1
   EPHEMERIS SOURCE       =BROADCAST*

 RECEIVER COORDINATES
 ====================
   STATION          X          S.D.        Y          S.D.        Z           S.D.
   ------------------------------------------------------------------------------------
  1 PF0400    -3939359.569   .927    3461732.633    .943  -3618436.777     .707
  2 PF0499    -4529710.451   .871    3909116.650    .905  -2203543.935     .721
  3 PF0611    -3979191.325   .881    3726034.870    .874  -3300400.483     .687
  4 PF0870    -4549677.324   .992    4262917.667   1.030  -1340987.366     .808
  5 PF0010    -3929588.335   .901    4183207.311    .874  -2774037.207     .721
  6 PF0686    -4197715.374   .928    4302861.370    .927  -2089466.154     .758
  7 PF0838    -4081952.762   .977    4688799.096    .933  -1422108.379     .789
  8 PF1140    -3419715.810   .652    4221128.419    .613  -3330834.667     .547
  9 PF1005    -3393927.325   .668    4641623.446    .626  -2751909.359     .569
 10 PF1698    -3525546.373   .684    4926540.028    .648  -1988970.940     .613


 STATION COORDINATES REDUCED TO CENTRE
 -------------------------------------
   STATION  CODE  WEIGHT   LATITUDE       S.D.   LONGITUDE      S.D.  HEIGHT  S.D.
   -------------------------------------------------------------------------------
  1 PF0400    0      1.00  S 34 47  6.2860  .7  E 138 41 32.7951  1.1   214.60  .7
  2 PF0499    0      1.00  S 20 20 35.1115  .7  E 139 12 21.5171  1.0   553.76  .7
  3 PF0611    0      1.00  S 31 21 45.4346  .7  E 136 52 54.4268  1.0   205.34  .7
  4 PF0870    0      1.00  S 12 13  4.0173  .8  E 136 51 49.4383  1.2   130.41  .8
  5 PF0010    0      1.00  S 25 56 49.2224  .7  E 133 12 33.9314  1.0   571.89  .7
  6 PF0686    0      1.00  S 19 14 54.2692  .8  E 134 10 18.4085  1.1   408.81  .7
  7 PF0838    0      1.00  S 12 58  8.4035  .8  E 131  2 31.2931  1.1   193.13  .8
  8 PF1140    0      1.00  S 31 41  7.3374  .6  E 129  0 44.6564   .7    68.93  .5
  9 PF1005    0      1.00  S 25 43 31.0997  .6  E 126 10 26.5737   .7   526.59  .5
 10 PF1698    0      1.00  S 18 17 24.9722  .6  E 125 35 18.2002   .8   173.01  .5
```

```
CHORD DISTANCES
---------------
FROM TO  DISTANCES
   1  2 1597056.160
   1  3  415438.715
   2  3 1240840.253
   1  4 2490213.052
   2  4  932511.485
   3  4 2110212.590
   1  5 1110689.796
   2  5  872201.134
   3  5  698945.918
   4  5 1563488.389
   1  6 1772738.299
   2  6  541080.572
   3  6 1366723.555
   4  6  829129.171
   5  6  747982.804
   1  7 2519897.489
   2  7 1191231.796
   3  7 2113162.582
   4  7  637747.502
   5  7 1451395.717
   6  7  770808.376
   1  8  964067.720
   2  8 1612520.958
   3  8  747700.952
   4  8 2288679.018
   5  8  755930.826
   6  8 1468409.265
   7  8 2073767.028
   1  9 1562212.672
   2  9 1458517.794
   3  9 1217242.336
   4  9 1862760.586
   5  9  705384.797
   6  9 1089859.871
   7  9 1497990.384
   8  9  715985.773
   1 10 2229811.871
   2 10 1445523.226
   3 10 1834898.859
   4 10 1381709.649
   5 10 1154176.104
   6 10  910360.967
   7 10  829121.212
   8 10 1519672.303
   9 10  824970.341
```

```
                          DEPT./ENERGY MINES & RESOURCES
                          GEODETIC SURVEY OF CANADA
                          PROGRAM GEODOP(VERSION APR/80)
                          MODIFIED BY SHI AT UNSW SEP/81
                          ==============================
                                     84/09/04.

P H A S E   S O L U T I O N - S U M M A R Y
===========================================

      NUMBER OF STATIONS          =  10
      UNKNOWN STATIONS            =  10
      PROCESSED PASSES            = 300
      ACCEPTED PASSES             = 298
      REJECTED PASSES             =   2
          EXCEEDING 99 PERCENT    =   2
```

```
            ZERO DEG. FREEDOM         =  0
            LESS THAN 14.5 DEG ELEV   =  0
       DOPPLERS REJECTED > 99         = 158

       DEGREES OF FREEDOM                     =    23704
       SQUARE SUM OF RESIDUALS (VPV)          =     3795.200
       ESTIMATED STD. DEVIATION OF UNIT WEIGHT (SO)      =     .400

VARIANCE-COVARIANCE MATRIX OF X Y Z(SQ-METRES)

  .85998
  .29340       .88928
 -.27603E-01  .76943E-02  .49966
  .45331      .11266      .14285E-02   .75851
  .10665      .42256     -.11584E-01   .25144      .81934
 -.59600E-02  .32122E-01  .29956       .49554E-02  .98346E-02  .51996
  .44050      .80700E-01 -.34355E-02   .43524      .72421E-01  .28463E-03  .77654
                     AND SO ON AND SO ON...
```

THIS SAMPLE IS PRECEEDED BY A SUMMARY OF EACH INDIVIDUAL PASS AND FOLLOWED BY A SUMMARY OF EACH STATION INCLUDING ACCUMULATED PASS INFORMATION AND A PLOT OF DF(FREQUENCY OFFSET), DX(CHANGES IN X-COORDINATE), DY(CHANGES IN Y-COORDINATE), DZ(CHANGES IN Z-COORDINATE) AND DR(CHANGES IN ELLIPSOIDAL RADIUS). THE TOTAL PRINTED OUTPUT AMOUNTING TO 246 PAGES.

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