GLOBAL POSITIONING SYSTEM DIFFERENTIAL POSITIONING SIMULATIONS

DEREK DAVIDSON
DEMITRIS DELIKARAOGLOU
RICHARD LANGLEY
BRADFORD NICKERSON
PETR VANICEK
DAVID WELLS

March 1983

TECHNICAL REPORT
NO. 90

PREFACE

In order to make our extensive series of technical reports more readily available, we have scanned the old master copies and produced electronic versions in Portable Document Format. The quality of the images varies depending on the quality of the originals. The images have not been converted to searchable text.

GLOBAL POSITIONING SYSTEM DIFFERENTIAL POSITIONING SIMULATIONS

Derek Davidson
Demitris Delikaraoglou
Richard Langley
Bradford Nickerson
Petr Vanicek
David Wells

Department of Surveying Engineering
University of New Brunswick
P.O. Box 4400
Fredericton, N.B.
Canada
E3B 5A3

March 1983

Latest Reprinting July 1992

PREFACE

This technical report is a revised version of the final report prepared for Geodetic Survey of Canada (GSC) contract OSU81-00314, "NAVSTAR/GPS Differential Positioning Preanalysis". The Scientific Authority at GSC for this contract was David Boal. The Principal Investigator at the University of New Brunswick for this contract was David Wells.

Part of the work contained herein was funded by three research grants from the Natural Sciences and Engineering Research Council of Canada. One of these, held by David Wells, is an operating grant entitled "Arctic Marine Navigation Aids". The second, held jointly by David Wells and Petr Vanicek, is a strategic grant entitled "Marine Geodesy". The third, held by Richard Langley, is entitled "Geodetic Applications of the Canadian VLBI System."

We thank Wayne Cannon of York University for the use of the program GEOAIM, developed there by Richard Langley, Derek Davidson and others. GEOAIM was the starting point for the development of the program DIGAP, as described in Chapters 8 and 11 of this report.

We thank Gerard Lachapelle, Norman Beck, Ray Banks, and their co-workers at Sheltech Canada (now Nortech Surveys (Canada) Inc., for the use of the GPS ephemerides in Table 5.4, and useful discussions on GPS.

We thank Mike Dyment and Patrick Hui of Canadian Marconi Company for comments on the mathematical models developed here, and suggestions as to useful simulations.

We thank Richard Nyarady for producing the polar plots of satellite azimuth and elevation in Chapter 12.

There are some significant changes between the simulation results presented in this report and those in the contract report prepared for GSC. The differences result from changing the satellite ephemerides to ones which are more consistent with the proposed satellite constellation and to a reformulation of the Doppler observable. The notation in equations (3.7) through (3.15) and (7.4) through (7.6) has also been corrected.

TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

NOTATIONAL CONVENTIONS

( )	functional relation (a function f of $t-t_o$ is written $f(t-t_o)$)
[ ]	mathematical relation (the product of f and $t-t_o$ is written f[t-to])
superscripted symbols	quantities associated with satellites
subscripted symbols	quantities associated with ground stations
super & subscripted symbols	quantities relating satellite and ground stations
τ	conventional GPS time
$T_j(\tau)$	jth ground station local time scale
$t^i(\tau)$	ith satellite local time scale
$\vec{R}_j = [X_j, Y_j, Z_j]^T$	jth ground station position vector and Cartesian coordinates
$\vec{r}^i(t^i(\tau)) = [x^i(t^i(\tau)), y^i(t^i(\tau)), z^i(t^i(\tau))]^T$	ith satellite position vector and Cartesian coordinates at $t^i(\tau)$
$\vec{\rho}^i_j = [\xi^i_j, \eta^i_j, \zeta^i_j]^T$	geometric range vector between ith satellite and jth ground station
ρ^i_j	length of $\vec{\rho}^i_j$
Δ or ∇ prefix	finite differences
δ prefix	correction terms
"simultaneous"	measurements referred to same satellite epoch
"difference"	one satellite position and two or more ground stations
"differential"	one satellite position and two or more ground stations

Chapter 1

INTRODUCTION

In this report we evaluate and compare various measurement schemes for using the Navigation Satellite Timing and Ranging (NAVSTAR) system, also known as the Global Positioning System (GPS), in the differential mode. A comprehensive bibliography on GPS is contained in Appendix A.

The differential mode presumes that simultaneous observations are made at two or more receivers, of the same GPS satellite signals. Differential GPS applications for navigation have been discussed elsewhere [Beser and Parkinson 1981; Cnossen et al. 1981; Mertikas and Wells 1982]. Here we consider the differential GPS techniques appropriate for geodetic and geodynamic applications. Some examples of such applications in the Canadian context are discussed in Chapter 2 and Appendix B.

There are four basic types of differential GPS measurements which have been suggested, and which are studied here: interferometric time delays, differential pseudoranges, differential carrier phases, and differential integrated Doppler measurements, called here integrated Doppler range differences. This study involved two major components: development of mathematical models to describe each of these four differential GPS measurement types and their associated errors, and development of computer software to implement these mathematical models and to perform simulations of differential GPS performance. The mathematical models developed are described in Chapters 3 to 7 and Appendix C of this report. The simulation software and results generated from it are described in Chapters 8 to 12 and Appendix D of this report.

Chapter 2

DIFFERENTIAL GPS APPLICATIONS IN GEODESY AND GEODYNAMICS

In this Chapter we specify five examples of the potential geodynamic and geodetic applications of differential GPS measurements in Canada. Required accuracies are defined and appropriate measurement schemes are suggested. First we discuss the reasons why differential GPS measurements may provide advantages. A supplemental discussion of the material in this chapter, from the viewpoint of potential markets for GPS equipment, is presented in Appendix B.

2.1 Advantages of Differential GPS Methods

Differential GPS methods potentially have advantages over other geodetic positioning techniques with respect to accuracy and with respect to cost.

Accuracy projections for interstation baseline vector determinations using the GPS interferometric or differential phase techniques range between a few millimetres and a few decimetres for baseline lengths up to 500 km and for observing periods of about one hour. The differential GPS Doppler technique should give decimetre accuracy after about eight hours of observations. Similar accuracies are achievable only with very precise terrestrial techniques and with some other extraterrestrial techniques, such as Transit differential integrated Doppler, mobile laser ranging, and mobile VLBI using quasars.

GPS provides cost advantages over terrestrial techniques since intervisibility between sites is not required. Very precise control surveys using terrestrial techniques require siting stations on hilltops, or erecting towers, and favourable observing weather, all involving extra time and expense. Intervisibility requirements usually limit terrestrial station separations to less than 50 km. Without the constraint of intervisibility, control points can be selected to optimize the point distribution geometry in the network. Rural surveys, while not as demanding in terms of accuracy, often involve cutting intervisibility lines through brush or forest, again involving extra time and expense.

Mobile laser ranging and mobile VLBI using quasars both use much bulkier and costlier equipment than GPS and require road access, site preparation, and much longer setup times. Laser ranging also requires favourable observing weather.

Transit differential integrated Doppler baseline determinations are at present accurate to a few decimetres and in principle should be determinable to within a few centimetres, with improvements in hardware and software [Kouba 1982]. Transit receivers are competative in cost and size with GPS receivers. However, differential GPS provides a cost advantage over Transit positioning due to the speed of positioning, requiring only one hour, rather than one or two days, of observations per baseline determination.

The combination of these speed, accuracy, cost, and intervisibility advantages of differential GPS techniques gives rise to a wide variety of potential applications in geodesy and geodynamics.

2.2 Vertical Crustal Movement Monitoring Network Near Point Sapin, New Brunswick

Project Outline

There are indications that there may have been recent dynamic activity in the central New Brunswick area in the form of a relative vertical displacement of the order of 1 cm per year. Recent seismic activity in the region suggests horizontal crustal compression. A monitoring network set up over the area could identify and quantify any such tectonic activity.

Project Description

Possible dynamic activity in the area of Point Sapin, on the eastern shore of New Brunswick, was first revealed by the sea level record of the tide gauge at Point Sapin during its period of operation 1967 to 1976 [Vaníček 1976]. The record shows a relative fall of sea level of the order of 90 cm per century. Unfortunately, the operation of this tide gauge was discontinued in 1976. A second sign of activity is a large (17 cm) misclosure of a first-order levelling loop that includes a coastal levelling line running through Point Sapin. This levelling line was levelled in two sections: in 1953, and in 1978. Thus the connecting bench mark was left sitting for 25 years during which time it might have undergone a sizeable vertical displacement. If this displacement is confined to a small geographical region, most of it would be directly translated into the loop misclosure. Finally there has been recent earthquake activity 100 km west of the area.

The aim of this project would be to verify whether there is any geodynamical activity in the area, and attempt to quantify any such uplift and/or compression.

Specifications

It is suggested that 8 points be positioned in the vicinity of Point Sapin using an available differential GPS technique. Point Sapin could be used as the permanent end of the baseline with a roving receiver (or receivers) visiting the other sites in a predetermined pattern of movement (Figure 2.1). The observations could be repeated every 6 months for a period of 5 years. If the accuracy of relative positions achieved is of the order of 2 cm or better, then any trend in either the vertical or horizontal positions should be discernable at the end of this period. It will be interesting to see if there is any horizontal crustal compression, which would provide a key toward possible explanations of the seismicity in the region.

Differential GPS Methods Applicable to this Problem

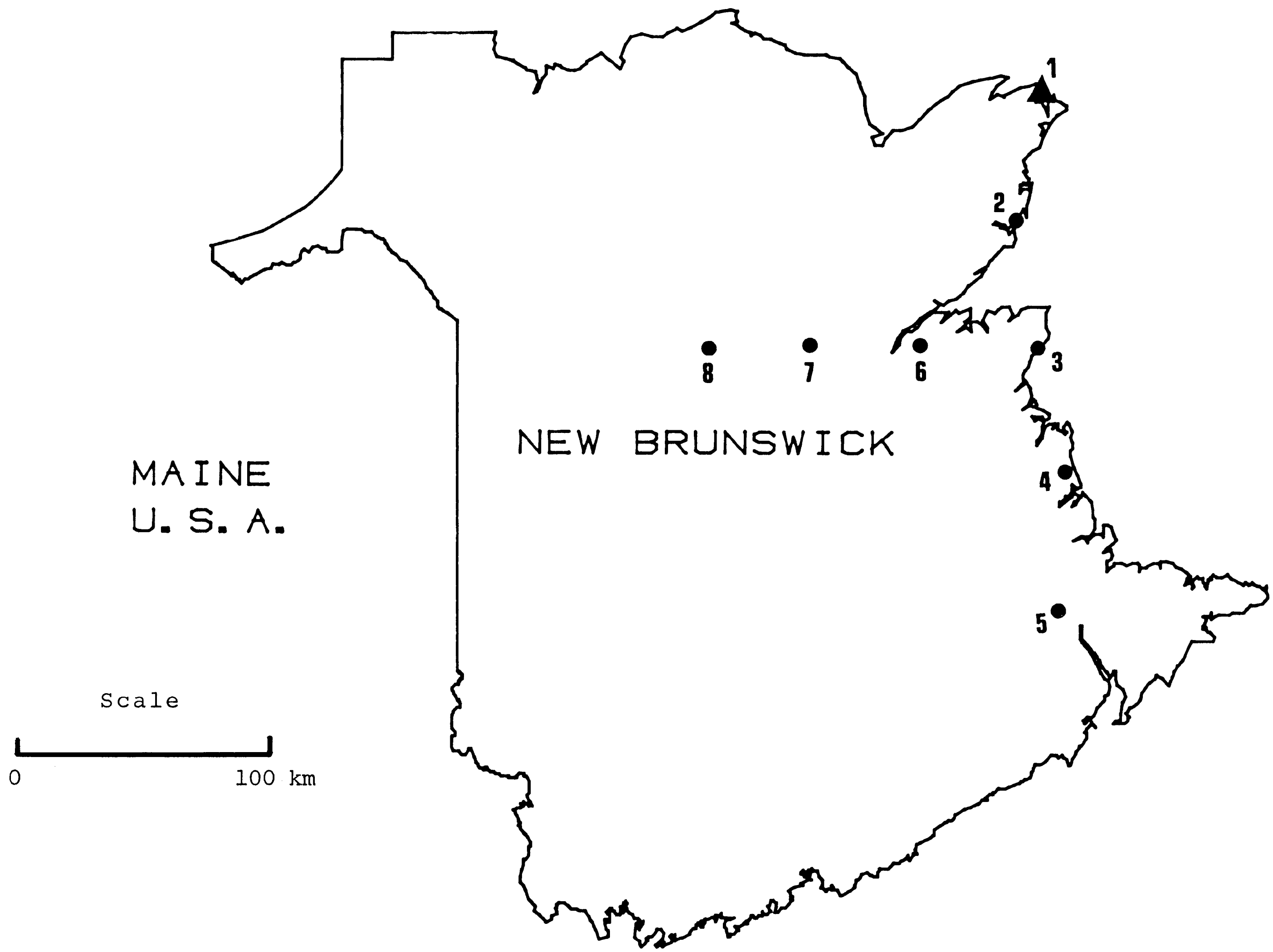
The accuracy requirement of 2 cm or better dictates that interferometry or carrier phase differential methods be used for this project.

Alternative Techniques

Bomford [1971] writes that high precision levelling can achieve accuracies of 2 cm over 200 km. Such levelling methods are expensive and time consuming, and would not be very practical for this project where measurements are to be repeated every six months. No terrestrial technique of sufficiently high accuracy exists.

FIGURE 2.1

POINT SAPIN TEST NETWORK



2.3 Three-Dimensional Crustal Movement Monitoring Network Near Whitehorse, Yukon Territory

Project Outline

The NASA Crustal Dynamics Project includes several Canadian sites which will be visited by mobile Very Long Baseline Interferometry (VLBI) systems. It is the responsibility of the Canadian geophysical and geodetic community to monitor any movements of the Canadian sites with respect to the surrounding terrain with an accuracy comparable to those anticipated for the VLBI observations, to distinguish between local and regional movements.

Project Description

As part of the Alaska campaign of the NASA Crustal Dynamics Project, several sites in Canada will be visited by NASA mobile VLBI systems in the time period 1984 to 1989 [NASA 1981]. These sites include Whitehorse in the Yukon Territory and Yellowknife in the Northwest Territories. VLBI quasar observations will be conducted at each site using a mobile system while observations are simultaneously made at one or more large fixed radio telescopes. The baselines between antennae will be determined with 2 cm to 3 cm accuracy. By annually repeating observations on the same baselines over the life of the project any significant relative motions will be detected.

The first observations with a mobile station in Canada are planned for the summer of 1984 at Whitehorse and Yellowknife. These sites will be used to determine motions occurring in the region of southeast Alaska. Earthquake fault plane solutions and the analysis of displaced terrains suggest that right lateral slip is occurring in the North American plate south of Yakutat at a rate of about 5 cm per year. A smaller rate of right lateral slip is believed to be occurring further inland on the Denali fault system and has been detected geodetically near the northwest end of the fault system south of Fairbanks. By making VLBI observations from a network of sites in Alaska (Fairbanks, Kodiak, Nome, Paxson, Yakutat, and Sand Point) in addition to Whitehorse, an accurate picture of the geodynamics of the region will be obtained (Figure 2.2).

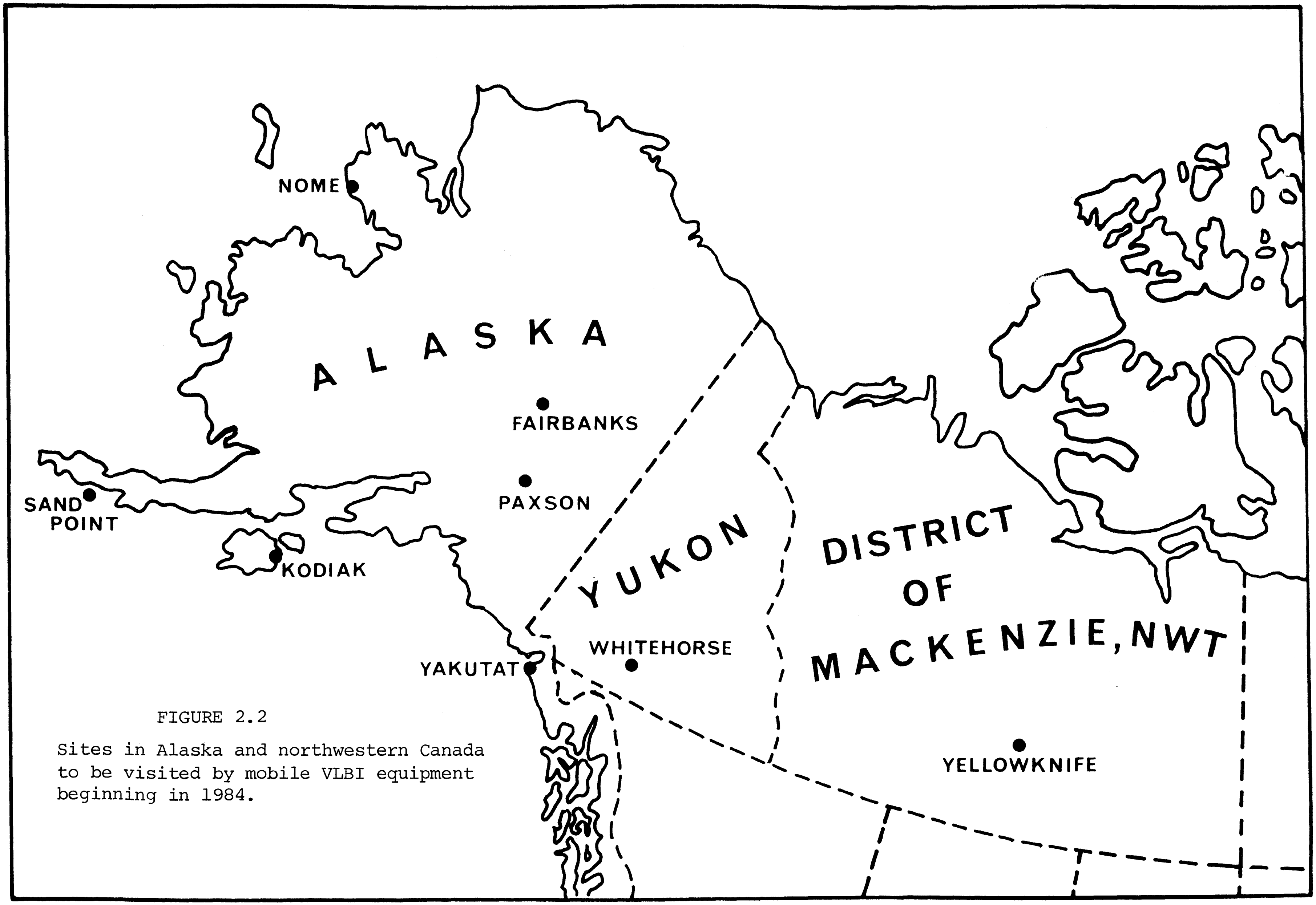


FIGURE 2.2

Sites in Alaska and northwestern Canada to be visited by mobile VLBI equipment beginning in 1984.

The interpretation of the VLBI baseline determinations in terms of the average strain across elements of the network requires that possible local movements of the observing sites be adequately modelled. This gives the need to establish the crustal movement monitoring network to detect vertical and horizontal movements of the VLBI sites with respect to the surrounding terrain.

Specifications

The local strains should be determined with an accuracy at least as good as that of the VLBI baseline determinations: 1 cm to 2 cm. These local networks should consist of at least eight survey markers, four of which would be located at least 10 km from the site and be distributed as evenly in azimuth as possible. Such a network should be adequate for determining displacement effects for those sites not likely to be subject to local earthquakes in excess of magnitude 6. This implies detecting movements of 1 cm [Lambert et al. 1981]. For sites close to active faults, a more elaborate network extending further out from the site is needed. As Whitehorse is situated in a high-risk seismic zone, such a network configuration may be appropriate for this site.

Differential GPS Method Applicable to this Problem

Accuracy requirements of 1 cm to 2 cm dictate the method to be selected for this network survey. Only the interferometric and carrier phase methods can provide this accuracy.

Alternative Techniques

Bomford [1971] writes that a zero-order local geodetic network using classical methods could attain the required accuracies: a relative accuracy of 10^{-6} over 10 km gives 1 cm position determination. These methods are, however, very much more expensive and time consuming. The possibly rugged and wooded terrain presents intervisibility problems which are of no concern in differential GPS methods.

2.4 Mining Subsidence

Project Outline

Monitoring of ground subsidence as a consequence of mining and mineral exploitation usually has been carried out with conventional surveys. In the last few years, new instrumentation has been developed and used [Chrzanowski and Faig 1981]. However, due to terrain difficulties in many mining areas and the necessity for continuous monitoring of the movements, the methods used have not been entirely adequate.

Project Description

There are various socio-economic reasons for monitoring subsidence in areas of underground exploitation: safety factors include warnings, and even prevention of, catastrophic land slides and caving-in of the surface; economic advantages such as developing more efficient methods of mining; and ecological phenomena such as water table changes and associated vegetation problems. According to estimates of the U.S. Bureau of Mines, at least $2 billion in property damage will occur by the year 2000 due to mining subsidence.

For mining depths greater than about 100 m the ground subsidence takes the form of a regular belt-shaped curve as shown in Figure 2.3 [Chrzanowski and Faig 1981] with a depression of (a) x (g) where

- a = subsidence coefficient which depends on the mining method and varies between 0.03 and 0.75.
- g = thickness of exploited deposit, with the same units as the result.

The full effect of the subsidence takes 2 to 3 years to reach the surface.

Specifications

This project requires permanently sited position monitors to be located in sensitive areas and able to provide continuous measurements at an accuracy of 1% of the subsidence. Subsidence of 5 m to 10 m thus requires an accuracy of 5 cm to 10 cm. On some sites the monitors are not accessible during the winter months, so automation and control from a remote site are added complications, together with the need for a battery supply to last at least half a year.

Differential GPS Technique Applicable to this Problem

The accuracy requirements suggest carrier phase or interferometry

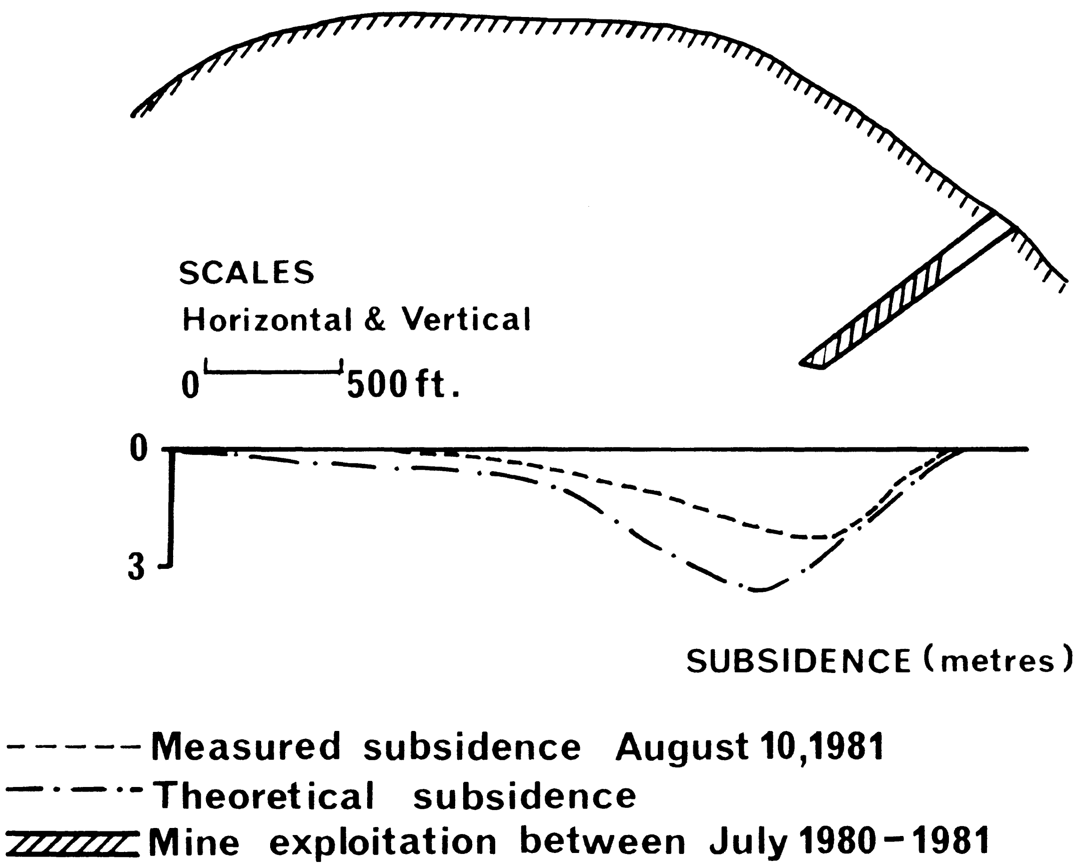


FIGURE 2.3

Mining subsidence. After Chrzanowski and Faig (1981).

techniques for this problem. The need for a short observation period to save power limits the use of pseudorange and Doppler methods. There are certain points about this application which can be used to simplify and lower the cost of the project. The receivers will be at well-known positions and closely spaced thus reducing the need for more than one receiving channel. Continuous measurements negate the need for a fast switching time between satellites. A single microprocessor for receiver control may suffice for a group of receivers.

Alternative Techniques

Field survey and photogrammetric techniques can provide the accuracy requirement, but are expensive in manpower, unable to provide continuous monitoring, and unusable for some projects in the winter months. Automated and continuous monitoring throughout the year is possible using an array of tiltmeters [Chrzanowski and Faig 1981]. Tiltmeters are sited along lines in the area to be monitored. Radio transmitters communicate with a single master microprocessor which controls the slave tiltmeter stations. Any subsidence depth is obtained by integrating the tilt times distance along the line of tiltmeters. The slave station's power lasts throughout the winter months whereas the master is connected to mains power. The master station can communicate with an external computer through a telephone link.

Problems with this system include the fact that subsidence is not well sampled using tiltmeters. Sudden cave-ins would likely cause large tilt variations which would be detected, but actual measurement of the cave-in would have to wait for a summer ground survey.

2.5. 1:50 000 Mapping Control on Ellesmere Island

Project Outline

Topographic surveys in isolated, mineral-bearing regions are of high economic importance. Accuracies required are not high compared with those attainable using differential GPS techniques, but a short field observing time with GPS has cost benefits which should be investigated.

Project Description

Ellesmere Island is an example of a possible resource area with a rugged, difficult terrain. It is situated in the Canadian Arctic 76°-83° North, 64°-88° West, approximately 780 km in north-south, and 330 km in east-west directions (Figure 2.4). It is expensive to conduct surveys in remote areas, with field time and transportation costs being significant factors. In other respects, this is a typical 1:50 000 mapping project. Control points are positioned around the perimeter of the area at a spacing of approximately ten models [Ontario Ministry of Natural Resources 1975]. Photography is flown at 1:80 000 scale, and aerial triangulation is carried out using the field control points, to give additional control to allow orientation for each model.

Specifications

Ontario Ministry of Natural Resources [1975] gives a horizontal control accuracy (1 sigma) requirement of better than 5 m. The standard deviation of vertical control is required to be better than 2.5 m. Additional requirements for this experiment involve as short a field time as possible to reduce expenses.

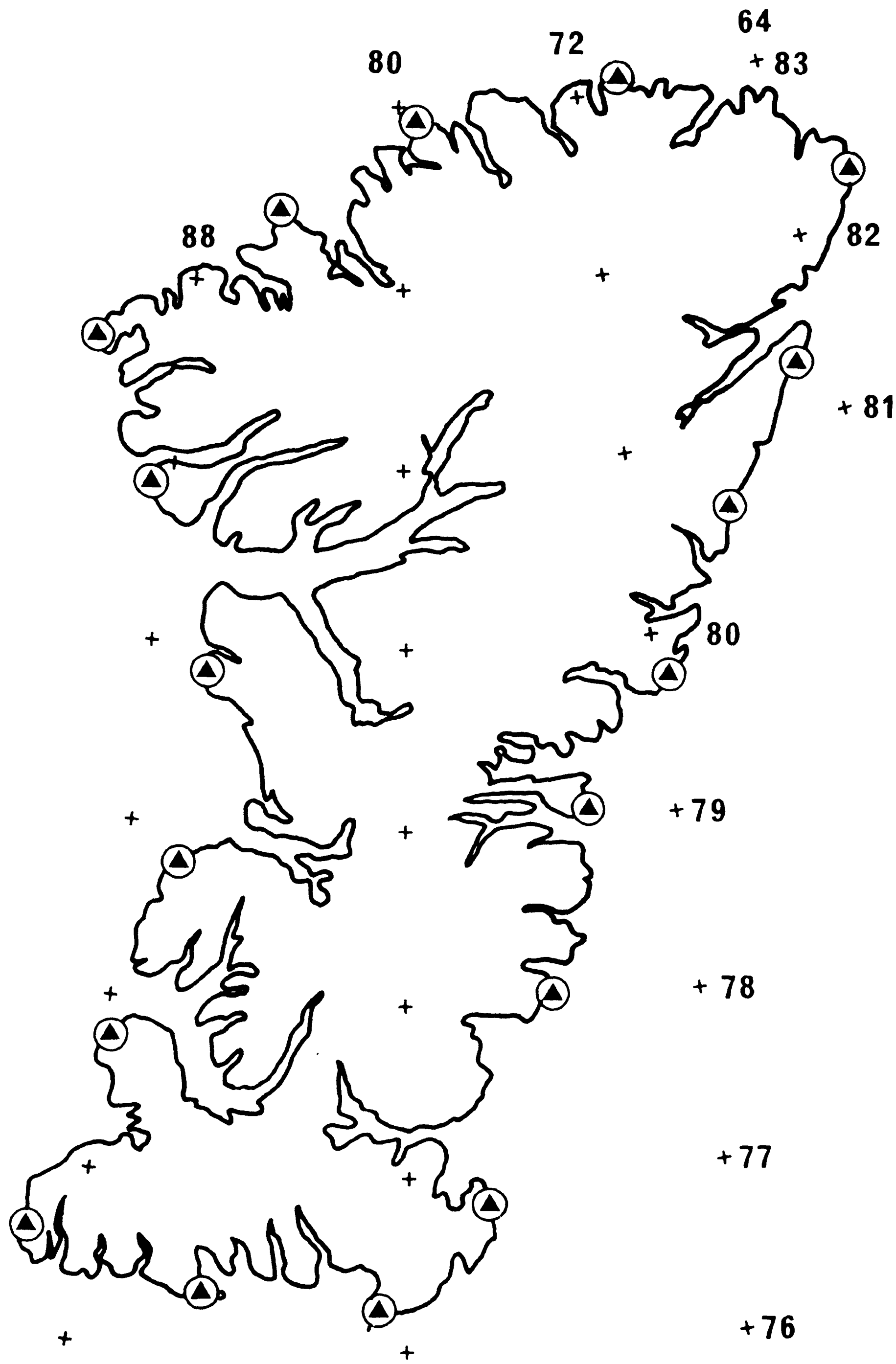
Differential GPS Method Applicable to this Problem

The method used will be determined by the field time required to give an accuracy below 2.5 m. Any of the four differential GPS methods could satisfy the accuracy requirement. Pseudoranges will achieve this accuracy after one hour of observation.

Alternative Techniques

Classical field survey techniques are time consuming and require intervisibility. Control stations must therefore be sited on high ground to allow long site lines. Time consumed thus involves reaching the point over difficult terrain as well as that required for the observations.

Transit Doppler requires about one day of observation to achieve 5 m accuracy, although control points can be placed in more accessible positions.



ELLESMERE ISLAND, CANADA

FIGURE 2.4
Mapping control on Ellesmere Island.

2.6 Rural Cadastral Survey used for Land Information Control

Project Outline

A land information system requires all data to be referenced to a single coordinate system. Currently there is a vast amount of boundary survey information available, but each survey has its own unique local coordinate system. None of these systems is referenced to another, or to a single universal coordinate system. A minimum of two control points for each local system would allow coordinate transformation to a common datum. A land information system requires detail on a single coordinate system. The numerous local systems can be tied to a single overall coordinate system referencing two points of detail. Coordinate transformation can then position all cadastral monuments in one unique system. The cost of clearing sight lines through forested terrain limit the use of conventional field survey methods for this project.

Project Description

A large proportion of survey boundaries in rural areas of New Brunswick had been set out before geodetic control was in place. Not every local area was, or has subsequently been, tied to the geodetic coordinate system. Survey methods for these boundaries would have typically used theodolite compass and tape. Scale and azimuth errors would be relatively constant within local areas. Markers in the form of wooden posts, metal survey markers, etc. exist in the field, and boundary details are stored as azimuths and distances [McLaughlin 1982, personal communication].

Specifications

An accuracy of 1 m for all detail is required for a land information system, thus semi-control points which are used to position this detail should be accurate to 25 cm to 50 cm. The cadastral monuments are to be used as the semi-control points, so the two points used for the coordinate transformation must be positioned with an accuracy of 25 cm.

An economically viable survey method must be capable of tying in two or three cadastral areas each day. Allowing 4 to 6 hours travel and search time leaves 1 to 2 hours for the observations. The instrumentation, to be practical, must be transportable over a few kilometres by back-pack. Reference geodetic control points are within 50 km of each cadastral area. A typical rural survey project is shown in Figure 2.5.

Differential GPS Methods Applicable to this Problem

The differential GPS method used for this project must give an accuracy of 25 cm over 10 km to 50 km after 1 to 2 hours observation. The interferometry or carrier phase methods, and possibly the pseudoranging method, should meet these specifications.

Alternative Technique #1: Field Survey Traverse

The classical survey technique for this problem is a theodolite and electronic distance measurement traverse from the geodetic control point to two points on the local cadastral survey. This involves five men, including the surveyor and the line cutting men. Progress rate through forest would be about two kilometres a day. Assuming a traverse accuracy of 1:20 000, 50 m is attainable over a 10 km distance.

Alternative Technique #2: Photogrammetry

Premarked photography at 1:25 000 can achieve 25 cm accuracy, but the pairs of points would have to be visited. To ensure the pre-marks do not deteriorate, this visit would have to be made immediately prior to the sortie. Subsequently aerotriangulation would have to be carried out. Since the visit to make the pre-mark would be as expensive as the differential GPS observations, the added costs of flying the photography and the aerotriangulation prohibit the use of photogrammetry as an alternative method.

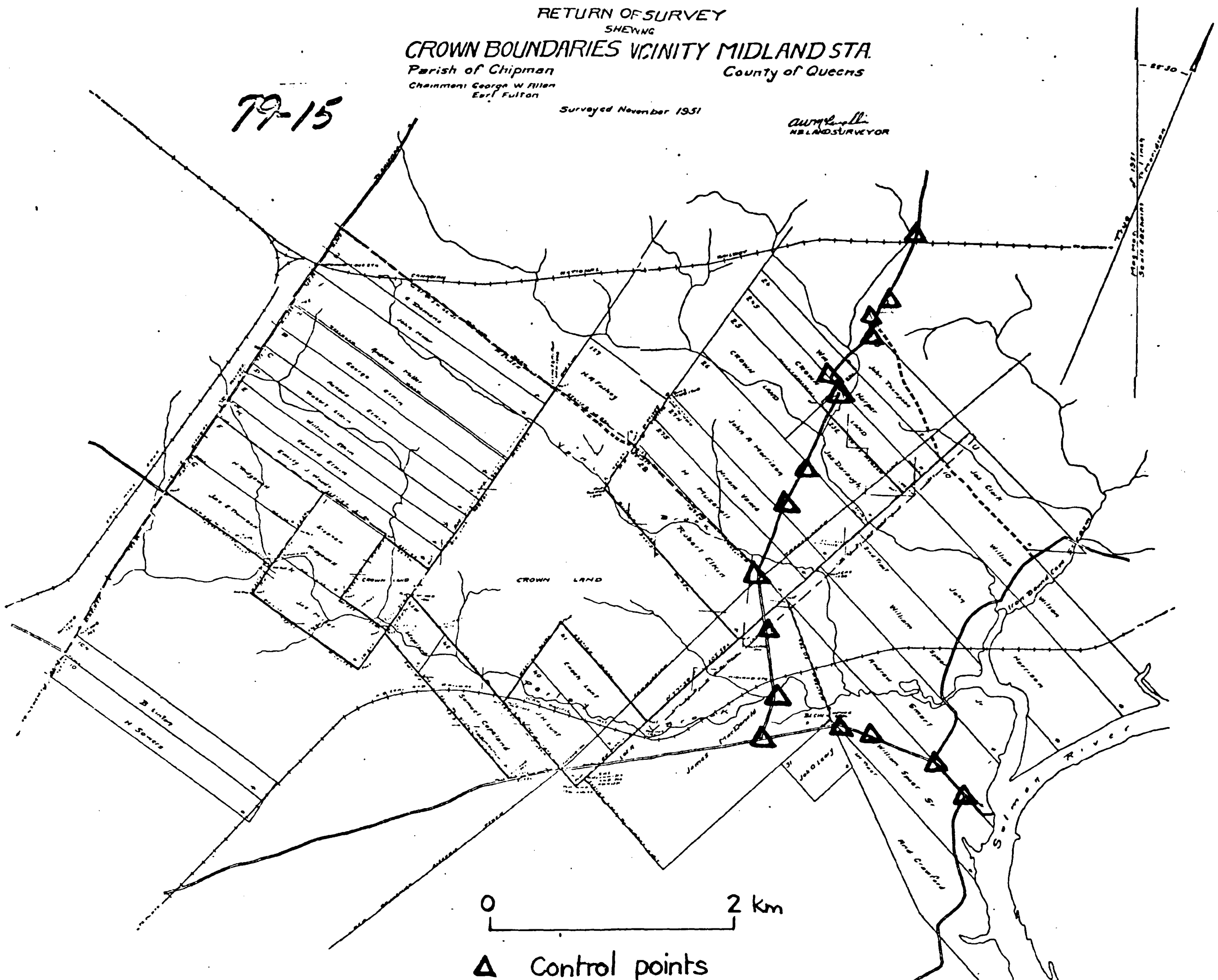


FIGURE 2.5
Rural Cadastral Survey Area

Chapter 3

MATHEMATICAL MODELS I

DIFFERENTIAL GPS MEASUREMENTS

3.1 Terminology and Notation

We will consider a network of n ground stations, which receive signals from m satellites. Quantities associated with the ground stations are denoted by uppercase letters and subscripts. Quantities associated with the satellites are denoted by lower case letters and superscripts. An earth-fixed coordinate system is used, so that the ground station positions are assumed to be time invariant, and the satellite positions to be time variable.

We assume that in general clocks at each ground station and in each satellite maintain independent local time scales, the lack of synchronization between them being only partially known or measured. The fundamental time scale, to which all satellite and ground station scales will be referred, we will call "conventional GPS time", and denote by τ. The local time scale of the j^{th} ground station is denoted T_j, and is functionally related to conventional GPS time as $T_j(\tau)$. Similarly, the local time scale of the i^{th} satellite is denoted t^i, and is functionally related to conventional GPS time as $t^i(\tau)$.

The position vector and Cartesian coordinates of the j^{th} ground station are (Figure 3.1)

$$\vec{R}_j = [X_j,\ Y_j,\ Z_j]^T. \tag{3.1}$$

The position vector and Cartesian coordinates of the i^{th} satellite, at some epoch $t^i(\tau)$ of its local time scale is

$$\vec{r}^i(t^i(\tau)) = [x^i(t^i(\tau)),\ y^i(t^i(\tau)),\ z^i(t^i(\tau))]^T. \tag{3.2}$$

The geometric range vector between the i^{th} satellite and the j^{th} ground station, and its Cartesian coordinates are

$$\vec{\rho}^{\,i}_j = [\xi^i_j,\ \eta^i_j,\ \zeta^i_j]^T\ . \tag{3.3}$$

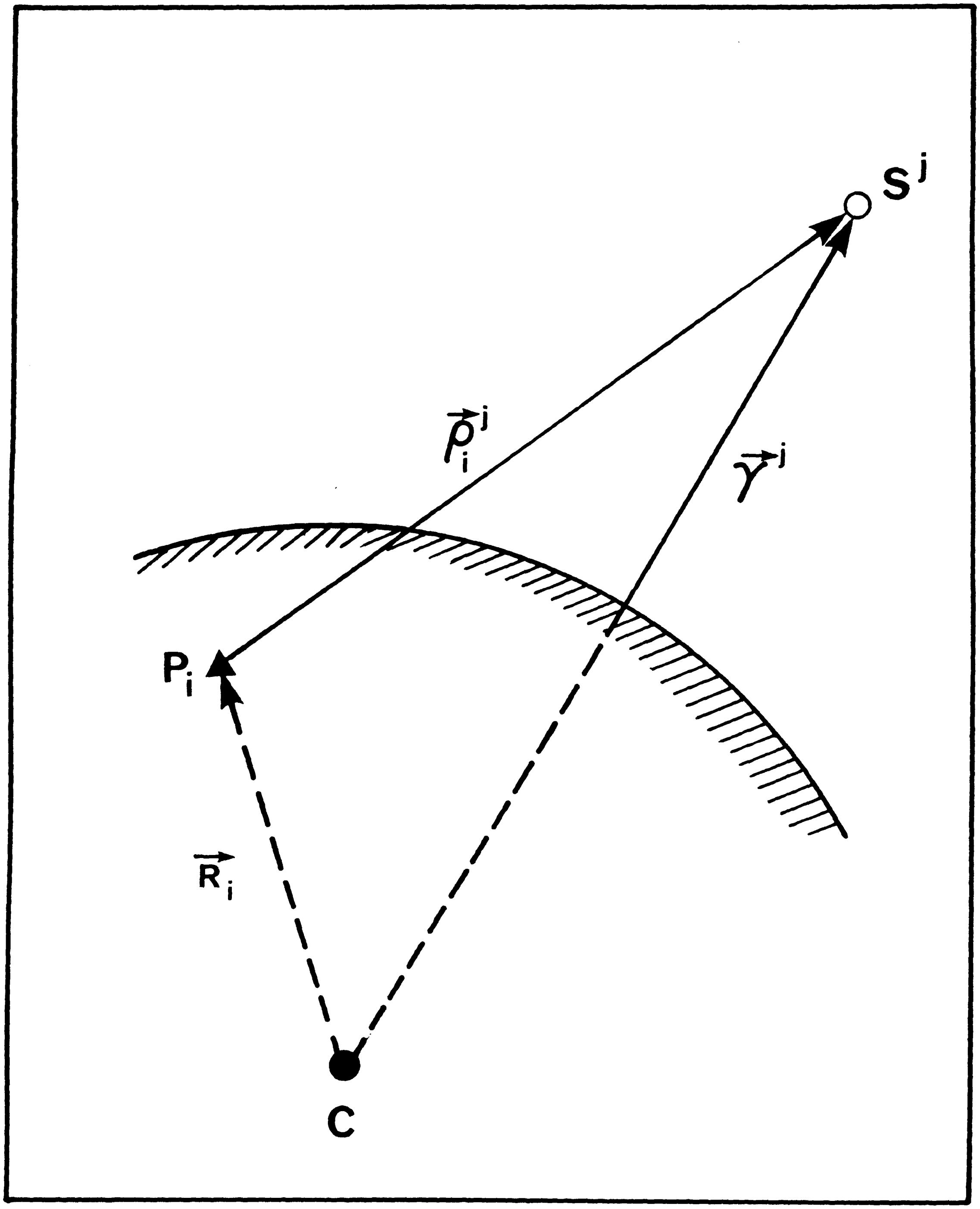


FIGURE 3.1

Ground to Satellite Range Vector.

The length of $\vec{\rho}^{\,i}_j$ is designated ρ^i_j. Under varying circumstances we express this range vector as a function of t^i, or of T_j, or of both. (NOTE: This notation differs from our earlier reports and papers [Wells et al. 1981; Wells et al. 1982], reversing the meanings of $\vec{r}$ and $\vec{\rho}$. We feel the change to this notation is worthwhile as it conforms with other conventions such as ρ-ρ LORAN-C.)

Measurements of satellite clock time marks (generated in the t^i time scale) as received at a ground station (thus measured with respect to the T_j time scale) are denoted by D^i_j, and are a function of t^i, T_j, and ρ^i_j. The term "simultaneous" refers exclusively to the satellite time scales. For example, a time mark from one satellite received at different times at two ground stations is taken to generate "simultaneous" measurements at those stations. Likewise, time marks from two satellites transmitted "simultaneously" and received at different times at one ground station are also taken as generating "simultaneous" measurements.

The adjectives "difference" and "differential" are used in a very specific way when they modify measurement times. Measurements which involve one ground station and two or more satellite positions (either simultaneous positions of different satellites, or positions of the same satellite at different times) are described by the term "difference". For example, measurements of

$$\rho^i_j(T_j) - \rho^k_j(T_j) \quad \text{or of} \quad \rho^i_j(t^i + \Delta t^i) - \rho^i_j(t^i)$$

are range difference measurements. Measurements which involve one satellite position and two or more ground stations (necessarily simultaneous) are described by the term "differential". For example, measurements of $\rho^i_j(t^i) - \rho^i_k(t^i)$ are differential range measurements.

Quantities prefixed by either Δ or ∇ denote finite differences, such as $\Delta\vec{R}_{ij} = \vec{R}_j - \vec{R}_i$, $\nabla\rho^{ij}_k(t^i) = \rho^j_k(t^i) - \rho^i_k(t^i)$. Quantities prefixed by the letter δ denote correction terms.

3.2 Measurement Types

We will consider four kinds of measurements: pseudoranges, interferometric differential ranges, integrated Doppler range differences, and carrier phase differential ranges.

The basic pseudorange observable denoted $\tilde{\rho}^i_j$ is the time of arrival (on the receiver time scale) of a particular signal transmitted by the satellite (Figures 3.2, 3.3):

$$\begin{aligned}\frac{\tilde{\rho}^i_j}{c} &= T_j(\tau_b) - t^i(\tau_a)\\ &= [\tau_b - (\tau_b - T_j(\tau_b))] - [\tau_a - (\tau_a - t^i(\tau_a))]\\ &= \tau_b - \tau_a + (\tau_a - t^i(\tau_a)) - (\tau_b - T_j(\tau_b))\\ &= \frac{\rho^i_j}{c} + (\tau_a - t^i(\tau_a)) - (\tau_b - T_j(\tau_b))\end{aligned} \tag{3.4}$$

where c is the speed of light. The term ρ^i_j is the true range to the satellite ignoring atmospheric effects. The second and third terms represent satellite and receiver clock errors respectively.

The basic interferometric differential range observable is the difference in this time of arrival at two different stations:

$$\frac{\Delta\tilde{\rho}^i_{jk}}{c} = \frac{\tilde{\rho}^i_k}{c} - \frac{\tilde{\rho}^i_j}{c} \quad . \tag{3.5}$$

If the satellite signal is periodic (as are the GPS carriers L_1 and L_2) then we can denote by f^i the frequency of this signal measured at the satellite. If the signal is coherent with the satellite time base t^i, f^i will depend on t^i. The frequency of the signal from the i^{th} satellite measured at the j^{th} receiver is denoted F^i_j, and is dependent on both t^i and T_j. A comparison signal generated and used solely within the receiver has frequency denoted F_j. The instantaneous phase of the satellite signal, measured at the satellite, is simply $\phi^i = f^i t^i$. The instantaneous phase of the signal from

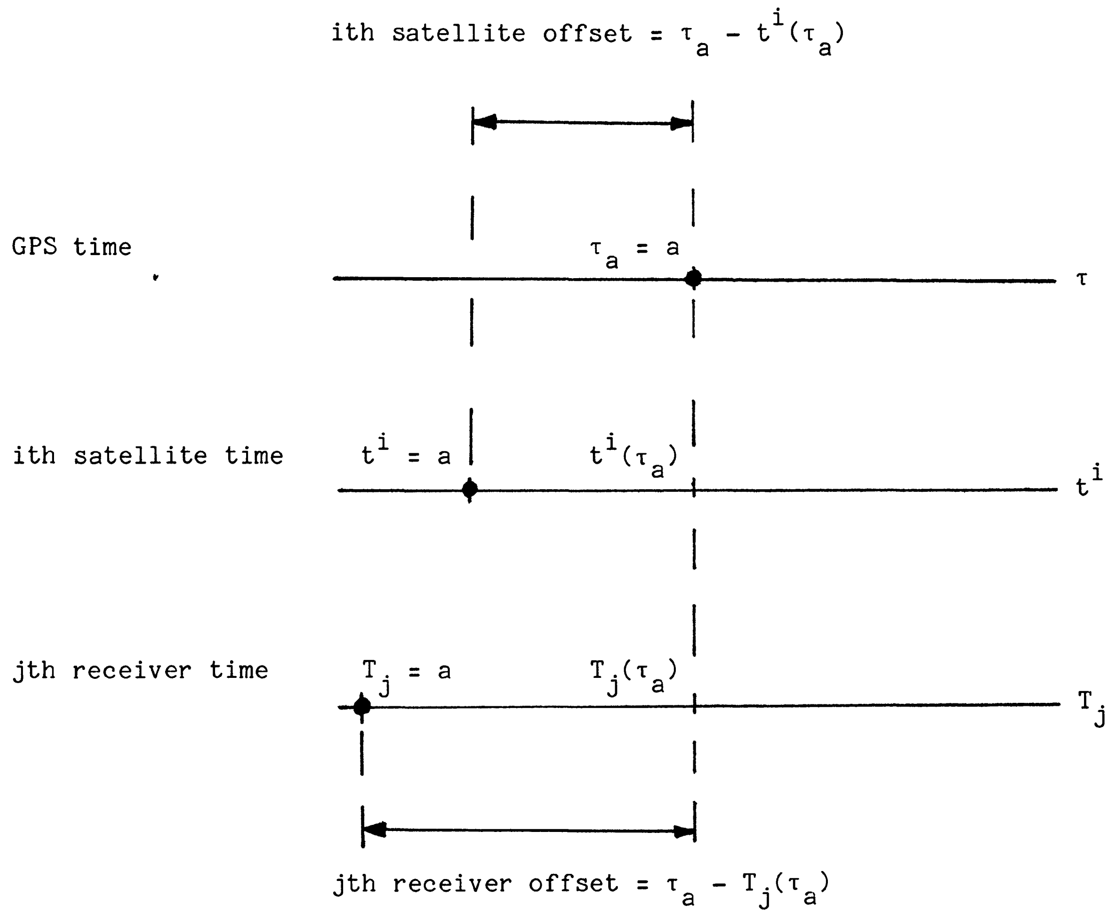


FIGURE 3.2

Satellite and Receiver Time Scales, and Their Differences From Conventional GPS Time. Here a = a real number expressing the GPS time of the week. In general, $\tau_a \neq t^i(\tau_a)$, $\tau_a \neq T_j(\tau_a)$.

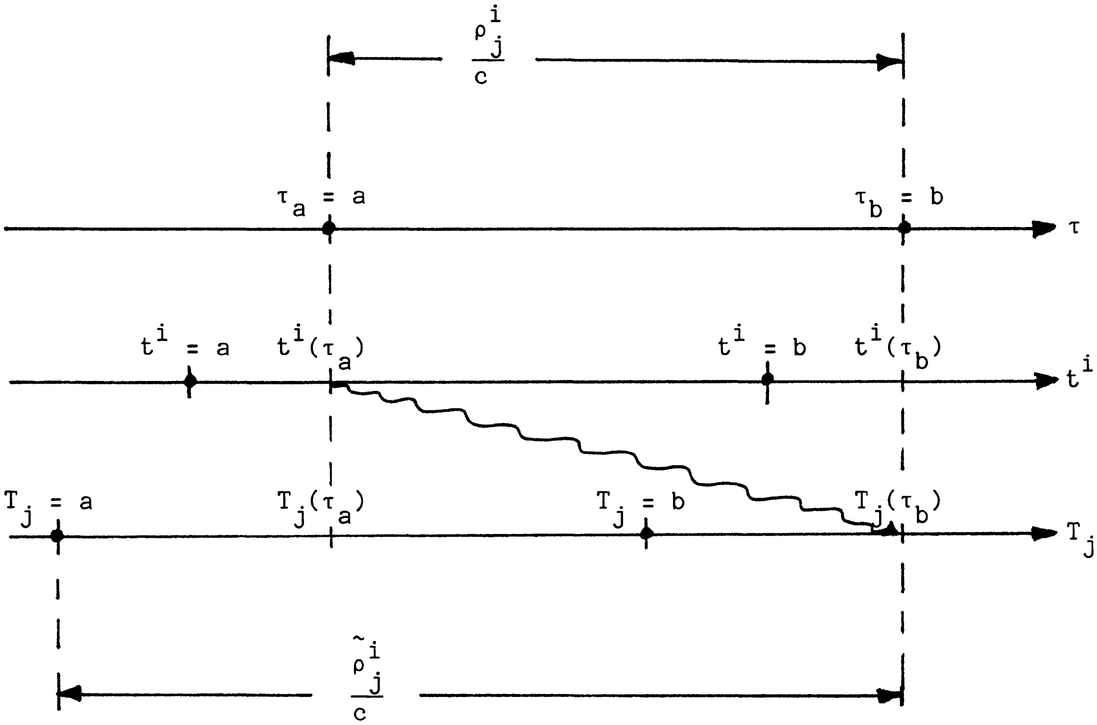


FIGURE 3.3

The Pseudorange Observation (from Ward [1981]).

Here, c = speed of light, assuming a neutral atmosphere and perfect instrument,

$\frac{\tilde{\rho}^i_j}{c}$ = measured pseudorange including satellite and receiver clock offsets,

$\frac{\rho^i_j}{c}$ = true (GPS) signal travel time between satellite and receiver.

the i^{th} satellite, measured at the j^{th} receiver is

$$\Phi_j^i = F_j^i \frac{\tilde{\rho}_j^i}{c} \quad . \tag{3.6}$$

The basic integrated Doppler range difference observable is the integral (see Figure 6.1)

$$N_j^i(\tau_b, \tau_d) = \int_{T_j(\tau_b)}^{T_j(\tau_d)} (F_j - F_j^i)\, dT_j \quad . \tag{3.7}$$

The number of cycles of a signal transmitted between $t^i(\tau_a)$ and $t^i(\tau_c)$ must equal the number of cycles of the same signal received between $T_j(\tau_b)$ and $T_j(\tau_d)$ if the epochs are related by (3.4). That is, if

$$\begin{aligned} T_j(\tau_b) &= t^i(\tau_a) + \tilde{\rho}_j^i(\tau_a, \tau_b)/c \\ T_j(\tau_d) &= t^i(\tau_c) + \tilde{\rho}_j^i(\tau_c, \tau_d)/c \end{aligned} \tag{3.4a}$$

then

$$\int_{t^i(\tau_a)}^{t^i(\tau_c)} f^i dt^i = \int_{T_j(\tau_b)}^{T_j(\tau_d)} F_j^i dT_j \quad .$$

Assuming f^i and F_j are constant, the basic integrated Doppler observation equation is

$$N_j^i(\tau_a, \tau_b, \tau_c, \tau_d) = F_j(T_j(\tau_d) - T_j(\tau_b)) - f^i(t^i(\tau_c) - t^i(\tau_a)) \quad . \tag{3.8}$$

Using (3.4a) we can either express t^i in terms of T_j

$$N_j^i(\tau_b, \tau_d) = F_j(T_j(\tau_d) - T_j(\tau_b))$$

$$- f^i(T_j(\tau_d) - \frac{\tilde{\rho}_j^i}{c}(\tau_c, \tau_d) - T_j(\tau_b) + \frac{\tilde{\rho}_j^i}{c}(\tau_a, \tau_b))$$

$$= (F_j - f^i)(T_j(\tau_d) - T_j(\tau_b)) - \frac{f^i}{c}(\tilde{\rho}_j^i(\tau_a, \tau_b) - \tilde{\rho}_j^i(\tau_c, \tau_d)) \qquad (3.9)$$

or we can express T_j in terms of t^i

$$N_j^i(\tau_a, \tau_c) = F_j(t^i(\tau_c) + \frac{\tilde{\rho}_j^i}{c}(\tau_c, \tau_d) - t^i(\tau_a) - \frac{\tilde{\rho}_j^i}{c}(\tau_a, \tau_b))$$

$$- f^i(t^i(\tau_c) - t^i(\tau_a))$$

$$= (F_j-f^i)(t^i(\tau_c)-t^i(\tau_a)) + \frac{F_j}{c}(\tilde{\rho}_j^i(\tau_c,\tau_d) - \tilde{\rho}_j^i(\tau_a,\tau_b)). \qquad (3.10)$$

The basic carrier phase differential observable is the difference in the phase of the same satellite signal, as measured at two different ground stations. This also describes the interferometric phase observable. Only the fractional part of the differential carrier phase is observed:

$$\Delta\Phi_{jk}^i = \Phi_k^i - \Phi_j^i - 2\pi n, \qquad (3.11)$$

where n is the unknown number of full cycles of differential phase.

From (3.4), (3.5), (3.10), and (3.11) we can develop more familiar forms. The relationship between ρ_j^i, $\vec{r}^i$ and $\vec{R}_j$ is given by

$$\rho_j^i = |\vec{r}^i - \vec{R}_j| \qquad (3.12)$$

Multiplying (3.4) and (3.5) by c we obtain the pseudorange observation equation

$$\boxed{\tilde{\rho}^i_j = |\vec{r}^i - \vec{R}_j| + c[(\tau_a - t^i(\tau_a)) - (\tau_b - T_j(\tau_b))]} \tag{3.13}$$

and the interferometric differential range observation equation

$$\boxed{\Delta\tilde{\rho}^i_{jk} = |\vec{r}^i - \vec{R}_k| - |\vec{r}^i - \vec{R}_j| + c[(\tau_b - T_j(\tau_b)) - (\tau_c - T_k(\tau_c))]}\,. \tag{3.14}$$

Setting $t^i(\tau_c) - t^i(\tau_a) = \Delta t^i$, and substituting from (3.12), we obtain from (3.10) the Doppler observation equation

$$\boxed{N^i_j(\tau_a,\tau_c) = \Delta t^i(F_j - f^i) + \frac{F_j}{c}|\vec{r}^i(t^i(\tau_c)) - \vec{R}_j| - \frac{F_j}{c}|\vec{r}^i(t^i(\tau_a)) - \vec{R}_j|} \tag{3.15}$$

For differential carrier phase and interferometric phase from (3.4) and (3.6), (3.11) becomes:

$$\boxed{\Delta\Phi^i_{jk} = \frac{F^i_k}{c}|\vec{r}^i - \vec{R}_k| - \frac{F^i_j}{c}|\vec{r}^i - \vec{R}_j| + F^i_j(\tau_b - T_j(\tau_b)) - F^i_k(\tau_c - T_k(\tau_c)) - 2\pi n} \tag{3.16}$$

In this chapter we have not dealt with the influence of imperfect clocks in the satellite and receivers. That is discussed in Chapter 6. Appendix C examines the practical problem of determining n in (3.16).

Chapter 4

MATHEMATICAL MODELS II

DIFFERENTIAL GPS GEOMETRY

4.1 Geometry of a Tetrahedron

A tetrahedron is formed by two ground stations P_1, P_2 and two satellite positions S^j, S^l (Figure 4.1). A tetrahedron is the main geometrical "building block" in any investigation of differential positioning by satellites. To facilitate the setting up of observation equations, we introduce here the vector quantities one is likely to need in describing geometrical relations within a tetrahedron.

We begin with the four basic unit vectors $\vec{u}_1^j$, $\vec{u}_2^j$, $\vec{u}_1^l$, $\vec{u}_2^l$. Everything else can then be expressed in terms of these unit vectors. The mean station or satellite vectors are defined as

$$\begin{aligned}
\vec{u}_1^m &= \frac{1}{2}(\vec{u}_1^j + \vec{u}_1^l) \\
\vec{u}_2^m &= \frac{1}{2}(\vec{u}_2^j + \vec{u}_2^l) \\
\vec{u}_m^j &= \frac{1}{2}(\vec{u}_1^j + \vec{u}_2^j) \\
\vec{u}_m^l &= \frac{1}{2}(\vec{u}_1^l + \vec{u}_2^l) \quad .
\end{aligned} \tag{4.1}$$

The total mean vector $\vec{u}$ is defined as

$$\vec{u} = \frac{1}{4}(\vec{u}_1^j + \vec{u}_2^j + \vec{u}_1^l + \vec{u}_2^l) \quad . \tag{4.2}$$

Through elementary operations, it can be shown that

$$\vec{u} = \frac{1}{2}(\vec{u}_m^j + \vec{u}_m^l) = \frac{1}{2}(\vec{u}_1^m + \vec{u}_2^m) \quad . \tag{4.3}$$

This completes the definition of vectors; we note that except for the four basic unit vectors, none of the others is a unit vector.

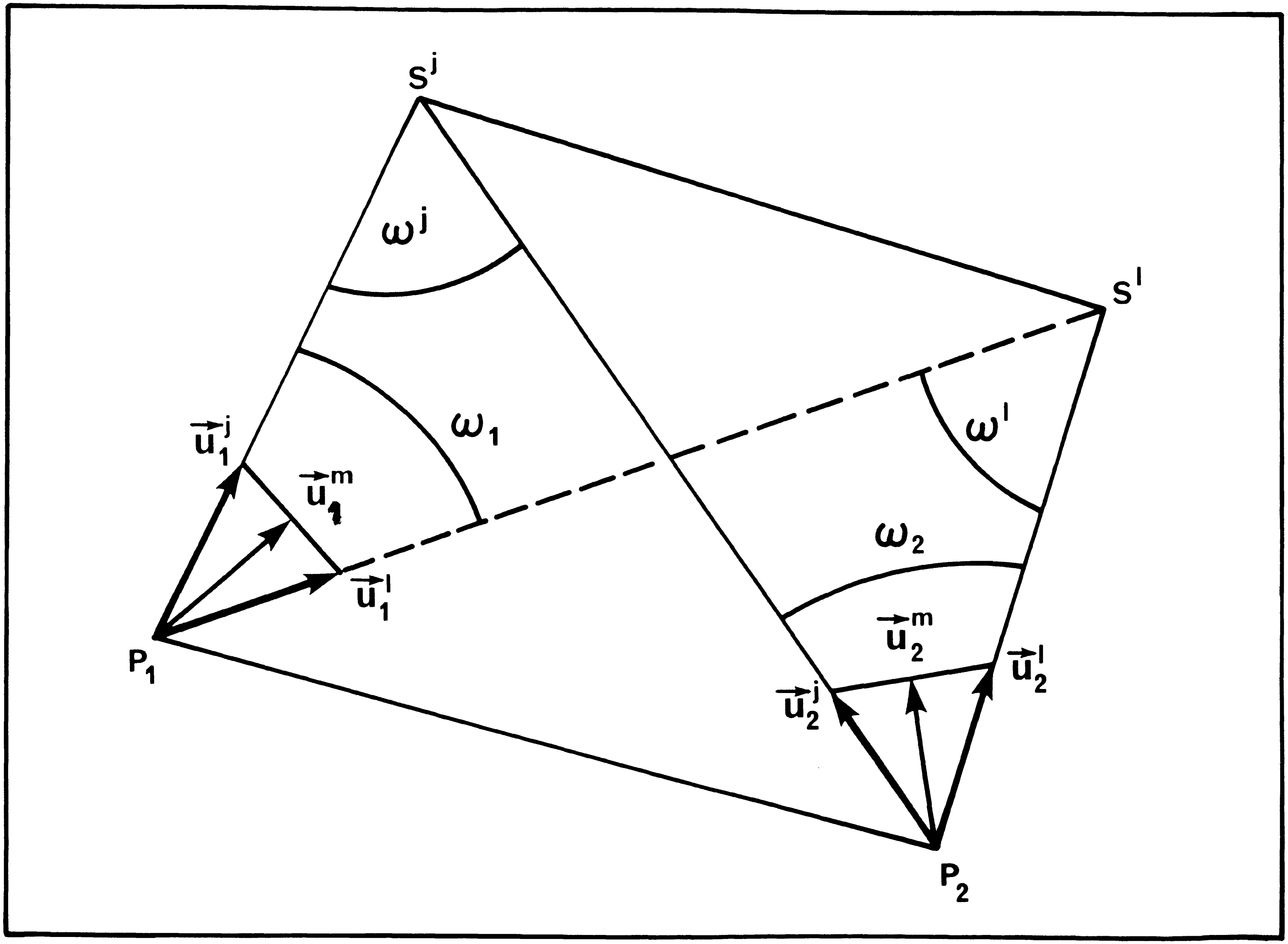


FIGURE 4.1

Differential GPS Tetrahedron.

Next, we define the following vector differences:

$$\begin{aligned}
\Delta\vec{u}^{j} &= \vec{u}^{j}_{2} - \vec{u}^{j}_{1} \\
\Delta\vec{u}^{l} &= \vec{u}^{l}_{2} - \vec{u}^{l}_{1} \\
\Delta\vec{u}_{1} &= \vec{u}^{l}_{1} - \vec{u}^{j}_{1} \\
\Delta\vec{u}_{2} &= \vec{u}^{l}_{2} - \vec{u}^{j}_{2} \quad .
\end{aligned} \tag{4.4}$$

From these we can construct the mean differences

$$\begin{aligned}
\Delta\vec{u}^{m} &= \frac{1}{2}(\Delta\vec{u}^{j} + \Delta\vec{u}^{l}) \\
\Delta\vec{u}_{m} &= \frac{1}{2}(\Delta\vec{u}_{1} + \Delta\vec{u}_{2}) \quad .
\end{aligned} \tag{4.5}$$

Through elementary means, we can show that

$$\begin{aligned}
\Delta\vec{u}^{m} &= \vec{u}^{m}_{2} - \vec{u}^{m}_{1} = \frac{1}{2}(-\vec{u}^{j}_{1} + \vec{u}^{j}_{2} - \vec{u}^{l}_{1} + \vec{u}^{l}_{2}) \\
\Delta\vec{u}_{m} &= \vec{u}^{l}_{m} - \vec{u}^{j}_{m} = \frac{1}{2}(-\vec{u}^{j}_{1} - \vec{u}^{j}_{2} + \vec{u}^{l}_{1} + \vec{u}^{l}_{2}) \quad .
\end{aligned} \tag{4.6}$$

The total mean difference can be defined as

$$\Delta\vec{u} = \frac{1}{2}(\Delta\vec{u}^{m} + \Delta\vec{u}_{m}) \quad . \tag{4.7}$$

A symmetric quantity would be

$$\nabla\vec{u} = \frac{1}{2}(\Delta\vec{u}^{m} - \Delta\vec{u}_{m}) \quad . \tag{4.8}$$

The last two can also be written as

$$\begin{aligned}
\Delta\vec{u} &= \frac{1}{2}(\vec{u}^{l}_{2} - \vec{u}^{j}_{1}) \\
\nabla\vec{u} &= \frac{1}{2}(\vec{u}^{j}_{2} - \vec{u}^{l}_{1}) \quad .
\end{aligned} \tag{4.9}$$

Second differences are

$$\Delta^2\vec{u}^m = \Delta\vec{u}^l - \Delta\vec{u}^j$$

$$\Delta^2\vec{u}_m = \Delta\vec{u}_2 - \Delta\vec{u}_1 \quad . \tag{4.10}$$

It is easily shown that

$$\Delta^2\vec{u}^m = \Delta^2\vec{u}_m = \vec{u}_1^j - \vec{u}_2^j - \vec{u}_1^l + \vec{u}_2^l \quad . \tag{4.11}$$

We shall call this quantity $\Delta^2\vec{u}$. It is interesting to note that the four basic unit vectors can be expressed as linear combinations of the four main derived quantites, $\vec{u}$, $\Delta\vec{u}$, $\nabla\vec{u}$, $\Delta^2\vec{u}$ from (4.2), (4.9), and (4.11) as follows:

$$\boxed{\begin{aligned} \vec{u}_1^j &= \vec{u} - \Delta\vec{u} + \tfrac{1}{4}\Delta^2\vec{u} \\ \vec{u}_2^j &= \vec{u} + \nabla\vec{u} - \tfrac{1}{4}\Delta^2\vec{u} \\ \vec{u}_1^l &= \vec{u} - \nabla\vec{u} - \tfrac{1}{4}\Delta^2\vec{u} \\ \vec{u}_2^l &= \vec{u} + \Delta\vec{u} + \tfrac{1}{4}\Delta^2\vec{u} \end{aligned}} \; . \tag{4.12}$$

Finally, the following relations involving first differences can also be derived:

$$\begin{aligned} \vec{u}\Delta\vec{u}^m &= \tfrac{1}{4}(\vec{u}_2^j\ \vec{u}_2^l - \vec{u}_1^j\ \vec{u}_1^l) \\ \vec{u}\Delta\vec{u}_m &= \tfrac{1}{4}(\vec{u}_1^l\ \vec{u}_2^l - \vec{u}_1^j\ \vec{u}_2^j) \\ \vec{u}\Delta\vec{u} &= \tfrac{1}{8}(\vec{u}_1^l + \vec{u}_2^j)(\vec{u}_2^l - \vec{u}_1^j) \\ \vec{u}\nabla\vec{u} &= \tfrac{1}{8}(\vec{u}_1^j + \vec{u}_2^l)(\vec{u}_2^j - \vec{u}_1^l) \\ \Delta\vec{u}_m\ \Delta\vec{u}^m &= \tfrac{1}{2}(\vec{u}_1^l\ \vec{u}_2^j - \vec{u}_2^l\ \vec{u}_1^j) \\ \Delta\vec{u}\ \nabla\vec{u} &= \tfrac{1}{4}(\vec{u}_2^l - \vec{u}_1^j)(\vec{u}_2^j - \vec{u}_1^l) \quad . \end{aligned} \tag{4.13}$$

Second differences satisfy the following equations:

$$
\begin{aligned}
\vec{u}\ \Delta^2\vec{u} &= -\ \Delta\vec{u}_m\ \Delta\vec{u}^m \\
\Delta\vec{u}\ \Delta^2\vec{u} &= -\ 4\vec{u}\ \Delta\vec{u} \\
\Delta\vec{u}^m\ \Delta^2\vec{u} &= -\ 4\vec{u}\ \Delta\vec{u}_m \\
\Delta\vec{u}_m\ \Delta^2\vec{u} &= -\ 4\vec{u}\ \Delta\vec{u}^m \\
\nabla\vec{u}\ \Delta^2\vec{u} &= 4\vec{u}\ \nabla\vec{u} \quad .
\end{aligned}
\tag{4.14}
$$

4.2 Range Difference Observation Equation.

In this section we shall look for an equation relating the baseline vector to observed range differences, while neglecting all timing and refraction errors. Writing the range vector between ground station P_i and satellite position S^j as

$$\vec{r}^{\,j} - \vec{R}_i = \vec{\rho}_i^{\,j} \quad , \tag{4.15}$$

we obtain for its length

$$|\vec{r}^{\,j} - \vec{R}_i| = \rho_i^j \quad . \tag{4.16}$$

The difference in the length of the two range vectors from ground station P_i to satellite positions S^j and S^l, called here the range difference $\nabla\rho_i$, is

$$|\vec{r}^{\,l} - \vec{R}_i| - |\vec{r}^{\,j} - \vec{R}_i| = \rho_i^l - \rho_i^j = \nabla\rho_i^{jl} = \nabla\rho_i \quad . \tag{4.17}$$

To avoid the necessity of linearizing this equation, we rewrite it in vector notation:

$$\vec{u}_i^{\,l}(\vec{r}^{\,l} - \vec{R}_i) - \vec{u}_i^{\,j}(\vec{r}^{\,j} - \vec{R}_i) = \nabla\rho_i \quad . \tag{4.18}$$

Rearranging the terms we get

$$- \Delta\vec{u}_i \; \vec{R}_i = \nabla\rho_i - \vec{u}_i^{\,l} \; \vec{r}^{\,l} + \vec{u}_i^{\,j} \; \vec{r}^{\,j} \quad . \tag{4.19}$$

This would be an observation equation for the position $\vec{R}_i$. To determine the baseline

$$\Delta\vec{R} = \Delta\vec{R}_{12} = \vec{R}_2 - \vec{R}_1 \quad , \tag{4.20}$$

we shall assume that two range differences, $\nabla\rho_1$, $\nabla\rho_2$ were observed simultaneously from P_1 and P_2. We can then write two equations (4.19) and subtract one from another, obtaining

$$\Delta\vec{u}_1 \; \vec{R}_1 - \Delta\vec{u}_2 \; \vec{R}_2 = \nabla\rho_2 - \nabla\rho_1 - (\vec{u}_2^{\,l} - \vec{u}_1^{\,l})\vec{r}^{\,l} + (\vec{u}_2^{\,j} - \vec{u}_1^{\,j})\vec{r}^{\,j} \quad . \tag{4.21}$$

Using the geometry of a so-defined tetrahedron, we get

$$\begin{aligned} &\Delta\vec{u}_m \; \vec{R}_1 - \tfrac{1}{2}\Delta^2\vec{u} \; \vec{R}_1 - \Delta\vec{u}_m \; \vec{R}_2 - \tfrac{1}{2}\Delta^2\vec{u} \; R_2 = \\ &= \nabla\rho_2 - \nabla\rho_1 - \Delta\vec{u}^{\,m} \; \vec{r}^{\,l} - \tfrac{1}{2}\Delta^2\vec{u} \; \vec{r}^{\,l} + \Delta\vec{u}^{\,m} \; \vec{r}^{\,j} - \tfrac{1}{2}\Delta^2\vec{u} \; \vec{r}^{\,j} \quad . \end{aligned} \tag{4.22}$$

Rearranging this equation we get

$$-\Delta\vec{u}_m \; \Delta\vec{R} = \nabla\rho_2 - \nabla\rho_1 - \Delta\vec{u}^{\,m}(\vec{r}^{\,l} - \vec{r}^{\,j}) + \tfrac{1}{2}\Delta^2\vec{u}(\vec{R}_1 + \vec{R}_2 - \vec{r}^{\,l} - \vec{r}^{\,j}) \; . \tag{4.23}$$

Defining

$$\begin{aligned} \nabla^2\rho &= \nabla\rho_2 - \nabla\rho_1 \quad , \\ \Delta\vec{r} &= \vec{r}^{\,l} - \vec{r}^{\,j} \quad , \\ \vec{R}_m &= \tfrac{1}{2}(\vec{R}_1 + \vec{R}_2) \quad , \\ \vec{r}^{\,m} &= \tfrac{1}{2}(\vec{r}^{\,l} + \vec{r}^{\,j}) \quad , \end{aligned} \tag{4.24}$$

the sought equation becomes:

$$\boxed{-\,\Delta\vec{u}_m\,\Delta\vec{R} = \nabla^2\rho - \Delta\vec{u}^m\,\Delta\vec{r} + \Delta^2\vec{u}\,(\vec{R}_m - \vec{r}^m)} \quad . \tag{4.25}$$

We note that this equation is (geometrically) exact as well as linear in the unknowns ($\Delta\vec{R}$) and observations ($\nabla^2\rho$). The knowledge of $\Delta\vec{r}$, $\vec{R}_m$, $\vec{r}^m$ and all the involved direction cosines is also required.

4.3 Differential Range Observation Equation.

From Figure 4.2 we can readily see that

$$\Delta\vec{R} + \rho_2^j\,\Delta\vec{u}^j = -\,\vec{u}_1^j\,\Delta\rho_{12}^j \quad . \tag{4.26}$$

Multiplication by $\vec{u}_m^j$ results in

$$\vec{u}_m^j\,\Delta\vec{R} + \vec{u}_m^j\,\Delta\vec{u}^j\,\rho_2^j = -\,\vec{u}_m^j\,\vec{u}_1^j\,\Delta\rho_{12}^j \quad . \tag{4.27}$$

Rewriting the coefficient of ρ_2^j as

$$\vec{u}_m^j\,\Delta\vec{u}^j = \frac{1}{2}(\vec{u}_1^j + \vec{u}_2^j)(\vec{u}_2^j - \vec{u}_1^j) = \frac{1}{2}(\vec{u}_2^j\,\vec{u}_2^j - \vec{u}_1^j\,\vec{u}_1^j) \quad , \tag{4.28}$$

it is easy to see that it is identically equal to zero. The second coefficient can be rewritten as

$$\vec{u}_m^j\,\vec{u}_1^j = \frac{1}{2}(\vec{u}_1^j + \vec{u}_2^j)\vec{u}_1^j = \frac{1}{2}(1 + \vec{u}_2^j\,\vec{u}_1^j) \quad , \tag{4.29}$$

and

$$\vec{u}_m^j\,\vec{u}_1^j = \frac{1}{2}(1 + \cos\omega^j) = 1 - \sin^2\frac{\omega^j}{2} = \cos^2\frac{\omega^j}{2} \quad . \tag{4.30}$$

Thus, denoting $\Delta\rho_{12}^j$ by $\Delta\rho^j$, we have:

$$\boxed{\vec{u}_m^j\,\Delta\vec{R} = -\,\cos^2\frac{\omega^j}{2}\,\Delta\rho^j} \quad . \tag{4.31}$$

This equation was derived, along different lines, by Bossler et al. [1981]. It represents an exact linear relation between observed differential range

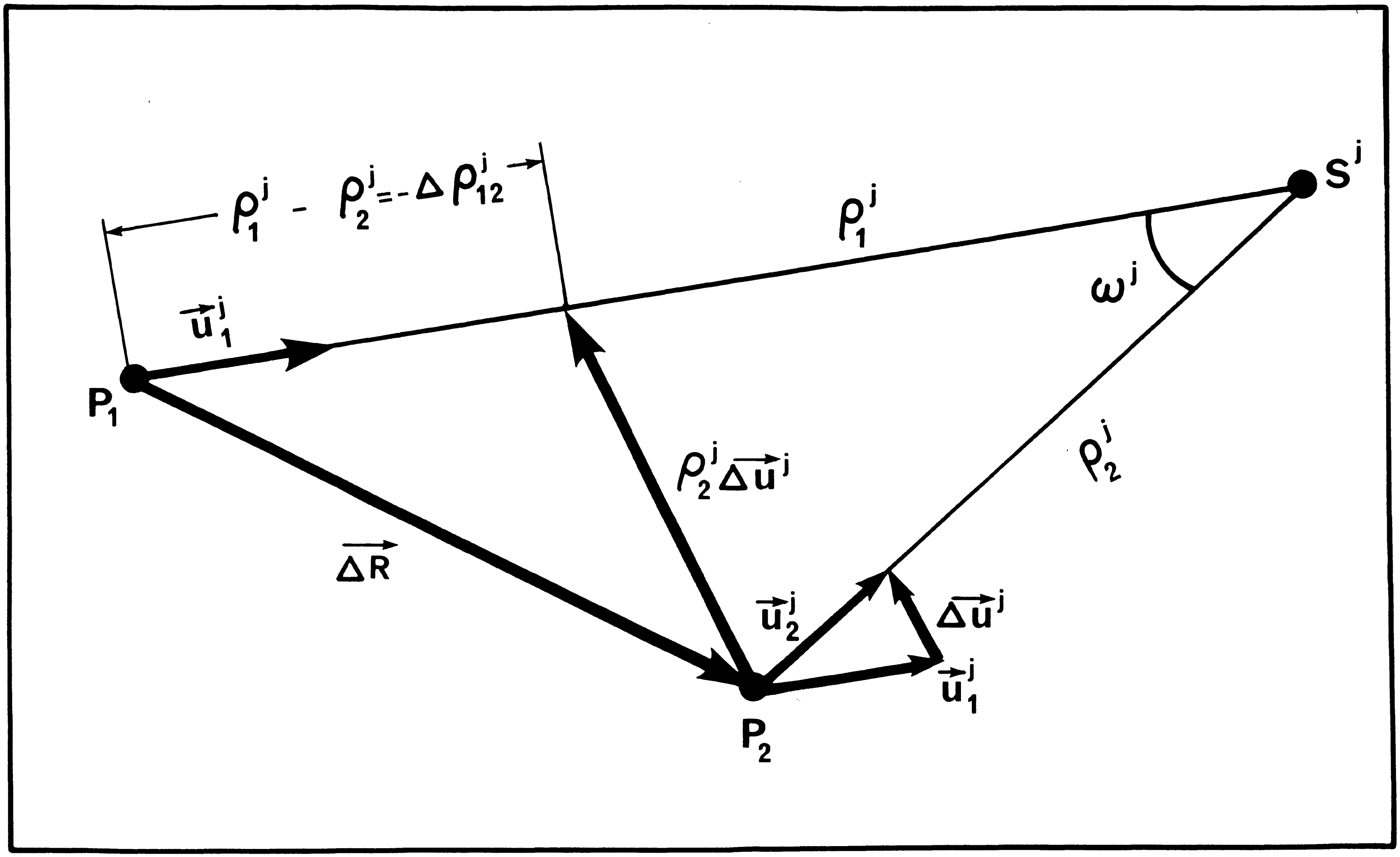


FIGURE 4.2

Differential Range Geometry.

($\Delta\rho^j$) and the baseline vector ($\Delta\vec{R}$). It is curious to see how simple this relation is.

Let us now see, if we can take advantage of two simultaneously observed differential ranges ($\Delta\rho^j$, $\Delta\rho^l$), i.e., to see if there is any improvement in the geometry of such a configuration. We can write an equation similar to (4.31) for satellite position S^l as

$$\vec{u}^{\,l}_m \, \Delta\vec{R} = - \cos^2 \frac{\omega^l}{2} \, \Delta\rho^l \quad . \tag{4.32}$$

Differencing equations (4.32) and (4.31) we get

$$- \Delta\vec{u}_m \, \Delta\vec{R} = \cos^2 \frac{\omega^l}{2} \, \Delta\rho^l - \cos^2 \frac{\omega^j}{2} \, \Delta\rho^j \quad . \tag{4.33}$$

(It can be shown that this equation is exactly equivalent to (4.25).) A few manipulations and the following substitution,

$$\Delta\rho^m = \frac{1}{2}(\Delta\rho^l + \Delta\rho^j) = 2(\rho^m_2 - \rho^m_1), \; \Delta^2\rho = \Delta\rho^l - \Delta\rho^j \quad , \tag{4.34}$$

yield

$$\boxed{- \Delta\vec{u}_m \, \Delta\vec{R} = (1 - \frac{1}{2}\Delta\vec{u} \, \nabla\vec{u}) \, \Delta^2\rho + 2\vec{u} \, \Delta\vec{u}_m \, \Delta\rho^m} \quad . \tag{4.35}$$

This equation is almost exact, since it involves some approximations.

4.4 A Closer Look at the Observation Equations

All three observation equations for the baseline vector, using the range difference differences (4.25), differential ranges (4.31) or differential range differences (4.35) are practically exact and linear in both the unknowns and observables. There is however a considerable difference between the three equations.

While in (4.25) (differential Doppler), the satellite points are along the same satellite trajectory, and are hence separated by, say, 10^5 m (for 30-second Doppler integration), in (4.35) the satellite points are from different satellite trajectories, and will typically be separated by

4×10^7 m. The ranges ρ will have typical values of 2×10^7 m. For a baseline ΔR of 10^5 m, the angles ω^j and ω^1 in Figure 1 will then have typical values of 5×10^{-3} radians. For the case of (4.25), so also will the angles ω_1 and ω_2, but not so for (4.35). In all three equations, the coefficient of the observations is close to unity. In (4.25) and (4.35) the unknowns are multiplied by $\Delta\vec{u}_m$; in (4.31) the multiplier is $\vec{u}_m^j$. Hence in (4.25)--but not in (4.35)--the components of $\Delta\vec{u}_m$ are all smaller than 5×10^{-3}, while in (4.31) $\vec{u}_m^j$ is close to being a unit vector. Thus the range difference differences ($\nabla^2\rho$) have to be known 200 times more accurately than differential ranges ($\Delta\rho$) to compete with those (disregarding the geometry of vectors $\vec{u}_m^j$ and $\Delta\vec{u}_m$ vis-a-vis $\Delta\vec{R}$). These results indicate that Doppler observations are less attractive, from the geometrical point of view, than the other observations, at least for Doppler integration intervals of 30 seconds. Hence in the rest of this chapter, we shall concentrate solely on the treatment of differential ranges.

Assuming $\Delta\vec{R} < 10^5$ m, to ensure an accuracy in $\Delta\vec{R}$ of 1 cm, $\vec{u}_m^j$ must be known to a relative accuracy of at least 10^{-7}. This, in turn, implies a required accuracy of at least 1 m in $\vec{r}^j$, $\vec{R}_1$, $\vec{R}_2$. This accuracy appears achievable only in an iterative fashion.

Finally we observe that the coefficient $\cos^2 \frac{\omega^i}{2}$ of the observable $\Delta\rho^j$ is of the order of

$$1 - \sin^2 \frac{\omega^j}{2} = 1 - \left(\frac{\omega^j}{2} - \frac{\omega^{j^2}}{4.2!} + \ldots\right)^2 \doteq 1 - \frac{\omega^{j^2}}{4} \backsim 1 - 3.2 \times 10^{-6}. \quad (4.36)$$

If an accuracy of 1 cm is required, this coefficient cannot be replaced by 1.

4.5 Repeated Differential Ranging

Clearly, at least three differential ranges are needed for the determination of the baseline vector. In practice many more ranges (n) will be observed so that one will end up with redundant observations:

$$\left.\begin{aligned}\vec{u}_m^{\,j}\,\Delta\vec{R} &= \left(1 - \frac{\omega^{j^2}}{4}\right)\Delta\rho^j \\ &= (1 - \Omega_j)\,\Delta\rho^j\end{aligned}\right\}\qquad j = 1,2,\ldots,n \quad . \tag{4.37}$$

In matrix form, one has

$$\begin{bmatrix}\vec{u}_m^{\,1} \\ \vec{u}_m^{\,2} \\ \cdot \\ \cdot \\ \cdot \\ \vec{u}_m^{\,n}\end{bmatrix}\Delta\vec{R} = \begin{bmatrix}1-\Omega_1 & & & 0 \\ & 1-\Omega_2 & & \\ & & \ddots & \\ 0 & & & 1-\Omega_n\end{bmatrix}\begin{bmatrix}\Delta\rho^1 \\ \Delta\rho^2 \\ \cdot \\ \cdot \\ \cdot \\ \Delta\rho^n\end{bmatrix} \quad , \tag{4.38}$$

or simply

$$\underline{A}\ \underline{\Delta R} = \underline{B}\ \underline{\Delta} \quad . \tag{4.39}$$

Here $\underline{A}$ may be written as

$$\underline{A} = \frac{1}{2}(\underline{U}_1 + \underline{U}_2) \quad , \tag{4.40}$$

where $\underline{U}_1 = [\vec{u}_1^{\,1}, \vec{u}_1^{\,2}, \ldots, \vec{u}_1^{\,n}]^T$, $\underline{U}_2 = [\vec{u}_2^{\,1}, \vec{u}_2^{\,2}, \ldots, \vec{u}_2^{\,n}]^T$, and

$$\underline{B} = \underline{I} - \mathrm{diag}(\Omega_j) = I - \underline{\delta B} \quad . \tag{4.41}$$

Hence

$$\underline{A}\ \underline{\Delta R} = \underline{\Delta} - \underline{\delta B}\ \underline{\Delta} \quad . \tag{4.42}$$

It is usual to seek the least-squares solution $\underline{\widehat{\Delta\vec{R}}}$ to this system of equations with the understanding that the covariance matrix $\underline{C}_\Delta$ of the vector $\underline{\Delta}$ of differential ranges is known. We get

$$\underline{A}^T C_\Delta^{-1} \underline{A}\ \underline{\widehat{\Delta\vec{R}}} = \underline{A}^T \underline{C}_\Delta^{-1} (\underline{I} - \underline{\delta B})\ \underline{\Delta} \quad , \tag{4.43}$$

a linear relation between the vector of observations $\underline{\Delta}$ and the unknown baseline vector $\underline{\Delta R}$. The transformation matrix

$$\underline{T} = (\underline{A}^T \underline{C}_\Delta^{-1} \underline{A})^{-1} \underline{A}^T \underline{C}_\Delta^{-1} (\underline{I} - \underline{\delta B}) \tag{4.44}$$

depends only on the geometry ($\underline{A}$ and $\delta\underline{B}$) and the accuracy ($\underline{C}_\Delta$) of the observations. It can easily be investigated for optimum geocentric design, minimization of various effects, etc.

Chapter 5

MATHEMATICAL MODELS III

GPS SATELLITE EPHEMERIDES

In this chapter we first review the contents of the GPS message, and the equations used to determine satellite coordinates from the message parameters. The model used in this study to represent ephemeris errors is then presented. Finally, message parameter values used to represent the present (1982) GPS constellation and the proposed (1988) constellation are given.

5.1 GPS Satellite Positions

The GPS satellite message is structured into a 1500 bit frame, containing five subframes of 300 bits each. Each subframe consists of ten words, each 30 bits long.

The content of these subframes was, until September 1982, formatted according to the GPS Phase I Message Format [van Dierendonck 1978]. This format was scheduled to be replaced by the GPS Phase III Message Format in September 1982 [Payne 1982]. While the two formats differ substantially, there is only one change directly affecting the computation of satellite positions (the addition of a rate of change of inclination angle parameter to the GPS Phase III Message Format).

Table 5.1 lists the message parameters used to represent the satellite ephemeris in the GPS Phase I Message Format. For the Phase III message, $\dot{i}$ (rate of change of i_o) should be added to this list.

Table 5.2 lists the constants and equations used to convert the message parameters of Table 5.1 into Conventional Terrestrial Cartesian coordinates (x^k, y^k, z^k). An equation correcting i_o by $\dot{i} \cdot t_k$ must be added for the Phase III message.

For the present study, the Phase I message and its associated equations were used.

5.2 Ephemeris Error Models

For this study, the influence of errors in satellite ephemerides on computed positions was of interest. Ephemeris errors are the result of intentional or unintentional errors in the values of the GPS message parameters. The message parameter values are predictions based on observations made at the GPS control segment ground stations. A simple model to represent ephemeris errors was developed and used in the generation of simulated observations.

This ephemeris error model is based on three simplifying assumptions:

(a) The error in each Cartesian coordinate for each satellite is statistically independent from the error in other Cartesian coordinates of the same satellite, and all coordinates of other satellites.

(b) The error in each Cartesian coordinate is constant in time, at least for the duration of a simulated observing period (up to five hours), resulting in biases to each coordinate over an entire simulated observing period. Note from Figure 5.1 that a bias in the Cartesian coordinates is not equivalent to a bias in the orbit elements, or to a parallel shift in the orbit from its nominal position.

(c) The biases in all Cartesian coordinates for all satellites over a simulated observing period are samples from the same normal distribution, with zero mean and a standard deviation which is specified by an input parameter for that simulation run.

This ephemeris error is implemented in program DIFGPS (Chapter 9). A single input parameter, σ_{POS}, represents the standard deviation of GPS satellite Cartesian coordinates computed from the satellite message as in Table 5.2. For each satellite the simulated Cartesian coordinates incorporating these modelled ephemeris errors ($\tilde{x}^i$, $\tilde{y}^i$, $\tilde{z}^i$) are computed from

$$\begin{aligned}
\tilde{x}^i &= x^i + \phi_n(0,\ 1;\ \xi)\ \sigma_{POS} \\
\tilde{y}^i &= y^i + \phi_n(0,\ 1;\ \xi)\ \sigma_{POS} \qquad (5.1) \\
\tilde{z}^i &= z^i + \phi_n(0,\ 1;\ \xi)\ \sigma_{POS}
\end{aligned}$$

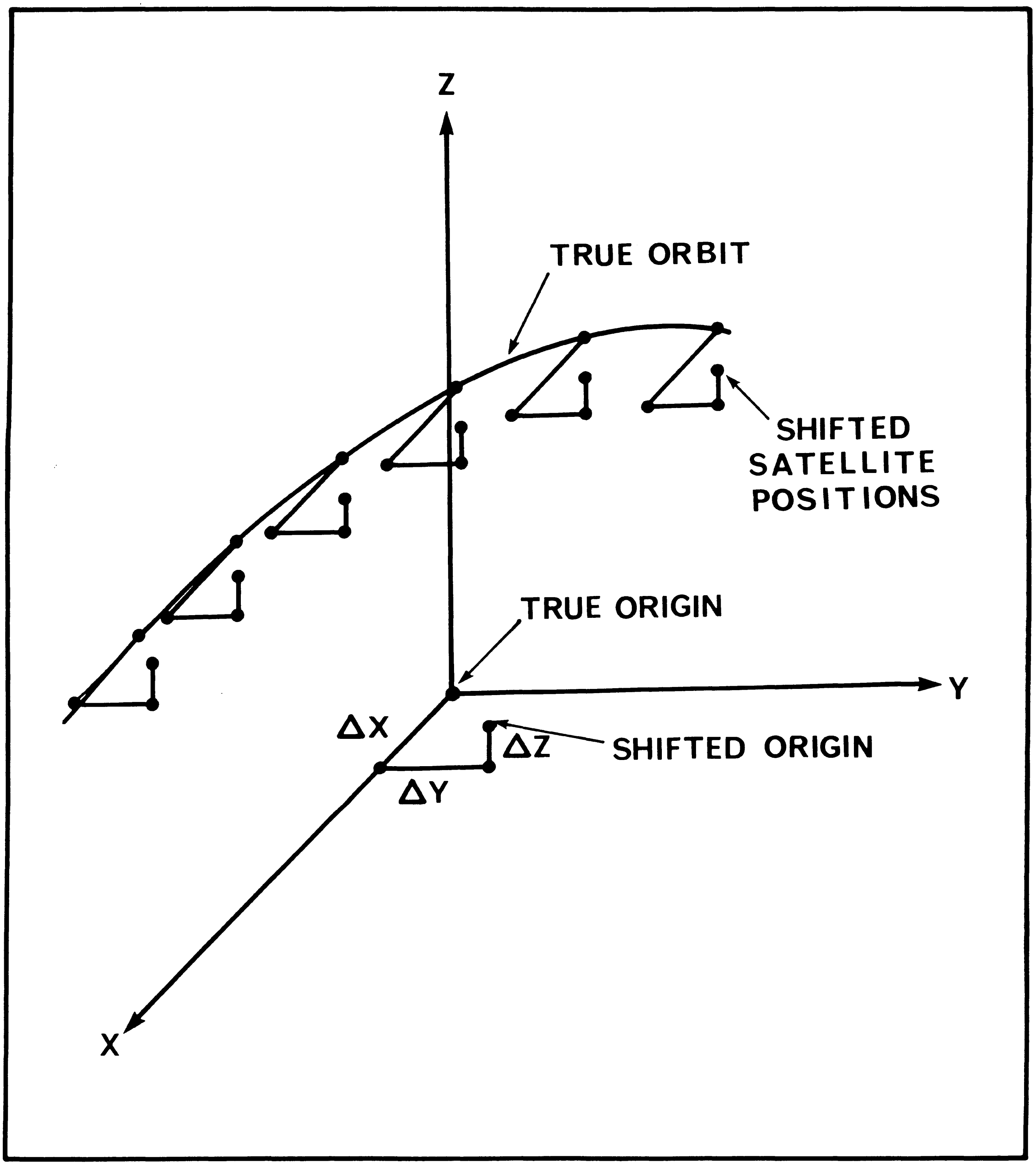


FIGURE 5.1

Perturbed Satellite Orbit.

where (x^i, y^i, z^i) are the Cartesian coordinates for the ith satellite position, computed from the equations in Table 5.2, and $\phi_n(0, 1; \xi)$ represents an abscissa value from the standard normal distribution, computed once for each simulation run for each Cartesian coordinate of each satellite.

Such ephemeris errors can be propagated into an equivalent user range error (which is simply the projection of the satellite ephemeris error vector onto the satellite-receiver range vector). To the extent that these equivalent range errors are similar at both ends of a baseline, their effect will be largely eliminated when applying differential GPS techniques to measure the baseline. The similarity of these equivalent range errors will decrease the longer the baseline.

Two values of σ_{POS} were used in these simulations. To represent the errors contained in the ephemerides for the present 4-satellite GPS constellation and in the undegraded ephemerides for the planned 18-satellite GPS constellation, σ_{POS} was set to 1.5 m (see Sections 12.1 and 12.2). To represent the errors in degraded ephemerides for the planned 18-satellite GPS constellation, σ_{POS} was set to 200 m (see Section 12.3).

5.3 GPS Constellations Used

The GPS message parameters used to represent the satellite orbits are shown in Table 5.3. The values for these parameters used to represent the present 4-satellite constellation are shown in Table 5.4. These values were obtained from actual tracked data on 12 November 1981, and were provided by Sheltech Canada. The values for these parameters used to represent the planned 18-satellite constellation are shown in Table 5.5. These values were chosen to simulate the uniform six-plane constellation with a Walker constellation index 18/6/2 [Walker, 1977].

M_o	Mean anomaly at reference time.
$\Delta\eta$	Mean motion difference from computed value.
e	Eccentricity.
$\sqrt{a}$	Square root of semi-major axis.
Ω_o	Right ascension at reference time.
i_o	Inclination angle at reference time.
ω	Argument of the perigee.
$\dot{\Omega}$	Rate of right ascension.
C_{uc}, C_{us}	Cosine and sine harmonic correction terms to the argument of latitude.
C_{rc}, C_{rs}	Cosine and sine harmonic correction terms to the orbit radius.
C_{ic}, C_{is}	Cosine and sine harmonic correction terms to the inclination.
t_{oe}	Ephemeris reference time.
$\dot{i}$	Rate of inclination (not included in Phase I message)

TABLE 5.1

GPS Message Parameters Representing the Ephemeris.

$\mu = 3.986008 \cdot 10^{14}\ m^3/sec^2$	Universal Gravitational Constant (WGS 72).
$\omega_e = 7.292115147 \cdot 10^{-5}$ rad/sec	Earth's mean rotation rate (WGS 72).
$a = (\sqrt{a})^2$	Semi-major axis.
$\eta_o = \sqrt{\mu/a^3}$	Computed mean motion.
$t_k = t - t_{oe}$	Time from reference epoch.
$\eta = \eta_o + \Delta n$	Corrected mean motion.
$M_k = M_o + \eta t_k$	Mean anomaly.
$M_k = E_k - e \sin E_k$	Kepler's equation for eccentric anomaly.
$\cos V_k = (\cos E_k - e)/(1 - e \cos E_k)$ $\sin V_k = \sqrt{1-e^2} \sin E_k/(1-e \cos E_k)$	True anomaly.
$\phi_k = V_k + \omega$	Argument of latitude.
$\delta u_k = C_{uc} \cos 2\phi_k + C_{us} \sin 2\phi_k$	J_2 correction to the argument of latitude.
$\delta r_k = C_{rc} \cos 2\phi_k + C_{rs} \sin 2\phi_k$	J_2 correction to the orbit radius.
$\delta i_k = C_{ic} \cos 2\phi_k + C_{is} \sin 2\phi_k$	J_2 correction to the inclination angle.
$u_k = \phi_k + \delta u_2$	Corrected argument of latitude.
$r_k = a(1 - e \cos E_k) + \delta r_k$	Corrected orbit radius.
$i_k = i_o + \delta i_k + (\dot{i} t_k)$	Corrected inclination ($\dot{i}$ not in Phase I).
$x_k = r_k \cos u_k$ $y_k = r_k \sin u_k$	Position in orbital plane.
$\Omega_k = \Omega_o + (\dot{\Omega} - \omega_e)t_k - \omega_e t_{oe}$	Corrected longitude of ascending node.
$x^k = x_k \cos \Omega_k - y_k \cos i_k \sin \Omega_k$ $y^k = x_k \sin \Omega_k + y_k \cos i_k \cos \Omega_k$ $z^k = y_k \sin i_k$	Earth fixed coordinates.

TABLE 5.2

GPS Satellite Position Computation From the Broadcast Ephemeris.

EPH(1)	=	age of ephemeris in seconds.
EPH(2)	=	amplitude of the sine harmonic correction term to the orbit radius (m).
EPH(3)	=	mean motion difference from computed value (rad/sec).
EPH(4)	=	mean anomaly at reference time (radians).
EPH(5)	=	amplitude of the cosine harmonic correction term to the argument of latitude (radians).
EPH(6)	=	orbital eccentricity.
EPH(7)	=	amplitude of the sine harmonic correction term to the argument of latitude (radians)
EPH(8)	=	semi-major axis of orbital ellipse (metres).
EPH(9)	=	ephemeris reference time in seconds.
EPH(10)	=	amplitude of the cosine harmonic correction term to the angle of inclination (radians).
EPH(11)	=	right ascension at reference time (radians).
EPH(12)	=	amplitude of the sine harmonic correction term to the angle of inclination.
EPH(13)	=	inclination angle at reference time (radians).
EPH(14)	=	amplitude of the cosine harmonic correction term to the orbit radius (m).
EPH(15)	=	argument of perigee.
EPH(16)	=	rate of right ascension (radians/second).
EPH(17)	=	satellitie ID #.
EPH(18)	=	corrected mean motion (radians/second).

TABLE 5.3

Parameter Array EPH Used to Represent a Satellite Orbit.

EPH #	SAT #5	SAT #6	SAT #8	SAT #9
1	1433.6000	2048.0000	86016.000	2048.0000
2	-18.312500	-54.062500	-16.687500	-58.312500
3	.15779229D-08	.12914824D-08	.21879483D-08	.12889823D-08
4	-2.6430540	-.11616932	.76583056	.33562735
5	-.81770122D-06	-.29560179D-05	-.81956387D-06	-.32205113D-05
6	.20666615D-02	.16592914D-02	.20113677D-02	.80549773D-02
7	.94622374D-05	.14064834D-04	.94752759D-05	.14137477D-04
8	26560867.	26560516.	26560746.	26560813.
9	421488.00	407088.00	403488.00	410688.00
10	-.31478703D-06	.48987567D-06	.61094761D-06	.15273690D-06
11	2.4304594	.31357057	2.4276097	.31877875
12	.82328916D-06	-.21792948D-06	-.15571713D-05	-.41164458D-06
13	1.1122619	1.1067821	1.1032779	1.1033115
14	271.71875	179.15625	263.62500	178.68750
15	-1.9668020	2.0639462	-.14931060	1.3890641
16	-.60284654D-08	-.62427600D-08	-.74749542D-08	-.62827617D-08
17	5.0000000	6.0000000	8.0000000	9.0000000
18	.14585133D-03	.14585394D-03	.14585295D-03	.14585149D-03

TABLE 5.4
Values of EPH Array Used to Represent the Present (1982) 4-Satellite Constellation.

SAT #	EPH(4)	EPH(11)
1	.0	.0
2	2.0940000	.0
3	4.1890000	.0
4	.69800000	1.0470000
5	2.7930000	1.0470000
6	4.8870000	1.0470000
7	1.3960000	2.0940000
8	3.4910000	2.0940000
9	5.5850000	2.0940000
10	2.0940000	3.1420000
11	4.1890000	3.1420000
12	0.0	3.1420000
13	2.7930000	4.1890000
14	4.8870000	4.1890000
15	.69800000	4.1890000
16	3.4910000	5.2360000
17	5.5850000	5.2360000
18	1.3960000	5.2360000

Those not changing

EPH(1)	1433.6000	EPH(10)	.0
EPH(2)	.0	EPH(12)	.0
EPH(3)	.0	EPH(13)	.95990000
EPH(5)	.0	EPH(14)	.0
EPH(6)	.30000000D-02	EPH(15)	0.0
EPH(7)	.0	EPH(16)	.62620000D-08
EPH(8)	26560400.	EPH(17)	1.0000000 to 18.0000000
EPH(9)	585728.00	EPH(18)	.14585360D-03

TABLE 5.5
Values of EPH Array Used to Represent Proposed
(1988) 18/6/2 Constellation.

Chapter 6

MATHEMATICAL MODELS IV

GPS CLOCKS AND OBSERVATIONS

This chapter deals with the characterization of typical errors associated with atomic clock scales. This information provides the general background required for the discussion related to the simulation of GPS observables in the present development.

6.1 Atomic Clocks

Consider a typical atomic clock whose frequency is subject to error with respect to some nominal frequency f. In modelling these errors we make three assumptions:

(1) The frequency of this imperfect clock is subject only to two kinds of variations with time--a frequency drift which is linear in time, and random fluctuations.

(2) The frequency drift rate $\dot{f}$ is constant.

(3) The random fluctuations $\tilde{f}(t)$ can be modelled by a white noise random process having a constant standard deviation.

At some arbitrary epoch, t, the frequency of the clock may be expressed by a model of the form

$$f(t) = f + \Delta f + \dot{f}[t - t_o] + \tilde{f}(t) \quad , \qquad (6.1)$$

where t_o is some initial time of synchronization with a primary frequency standard, and Δf is the frequency offset between $f(t_o)$ and the nominal frequency f.

The phase accumulated since t_o is

$$\phi(t) - \phi(t_o) = \int_{t_o}^{t} f(\tau)\, d\tau \qquad (6.2)$$

or

$$\phi(t) = \phi(t_o) + f[t-t_o] + \Delta f[t-t_o] + \frac{\dot{f}}{2}[t-t_o]^2 + \int_{t_o}^{t} \tilde{f}(\tau)\, d\tau \qquad (6.3)$$

where $\phi(t_o)$ is the phase error at synchronization.

Equations (6.1) to (6.3) will be used to represent both a receiver oscillator clock and a satellite oscillator clock. In the absence of frequency variation terms, the time argument will represent conventional GPS time as kept by the Master Control Station. That is, a clock keeping perfect GPS time will be represented by a phase function

$$\phi(\tau) = f\,\tau \qquad (6.4)$$

where this "perfect" clock is assumed to have zero phase at $\tau = 0$.

Similarly a time interval will be represented by the difference in phase at two epochs τ_1, τ_2

$$\tau_2 - \tau_1 = \frac{1}{f}[\phi(\tau_2) - \phi(\tau_1)] = \frac{N}{f} \qquad (6.5)$$

where N is the number of cycles (not necessarily an integer) recorded by the clock in the interval $[\tau_1, \tau_2]$.

Because of the frequency variations and synchronization errors, the phase of the "imperfect" clock (given by (6.3)) differs from the phase of the "perfect" clock (given by (6.4)) by

$$\Delta\phi(t) = \phi(t_o) + \Delta f[t-t_o] + \frac{\dot{f}}{2}[t-t_o]^2 + \int_{t_o}^{t} \tilde{f}(\tau)\, d\tau \qquad (6.6)$$

Dividing this phase error by the nominal frequency f gives us the error in time

$$\boxed{\begin{aligned} \Delta t(t) &= \frac{\phi(t_o)}{f} + \frac{\Delta f}{f}[t-t_o] + \frac{\dot{f}}{2f}[t-t_o]^2 + \frac{1}{f}\int_{t_o}^{t} \tilde{f}(\tau)\, d\tau \\ &= a_o + a_1[t-t_o] + a_2[t-t_o]^2 + \tilde{x}(t) \end{aligned}} \qquad (6.7)$$

where

$$a_o = \frac{\phi(t_o)}{f} \tag{6.8a}$$

is the time error at synchronization,

$$a_1 = \frac{\Delta f}{f} \tag{6.8b}$$

is the fractional frequency offset,

$$a_2 = \frac{\dot{f}}{2f} \tag{6.8c}$$

is the aging (fractional drift) rate of the clock, and

$$\tilde{x}(t) = \frac{1}{f}\,\tilde{\phi}(t) = \frac{1}{f}\int_{t_o}^{t} \tilde{f}(\tau)\,d\tau \quad = \quad \sigma_{CLK}\,\phi_n(0,1;\xi) \tag{6.8d}$$

represents random fluctuations in clock time, where σ_{CLK} is the standard deviation of $\tilde{x}(t)$, and $\phi_n(0,1;\xi)$ represents the abscissa value from the standardized normal distribution.

Hence by specifying values for t_o, a_o, a_1, a_2, and σ_{CLK} we can characterize the behavior of a clock, using (6.7).

We have ignored the effect of errors other than those modelled here (for example, $\dot{f}$ may not be constant, and $\tilde{f}(t)$ may not be a white noise process). The model could be extended to explicitly include these effects, if we are sure of their form. Otherwise, it may well be preferable to attach some "age" to the model itself, and to represent its reliability as a function of its age, through some kind of weighting scheme. These possibilities are not pursued further in this report.

6.2 Pseudoranges

Let a signal from the ith satellite be transmitted at some epoch $t^i = t^i(\tau_a)$ and received at the jth receiver at some later time $T_j = T_j(\tau_b)$ (see Figure 6.1). The pseudorange observable is essentially the time of arrival of the signal

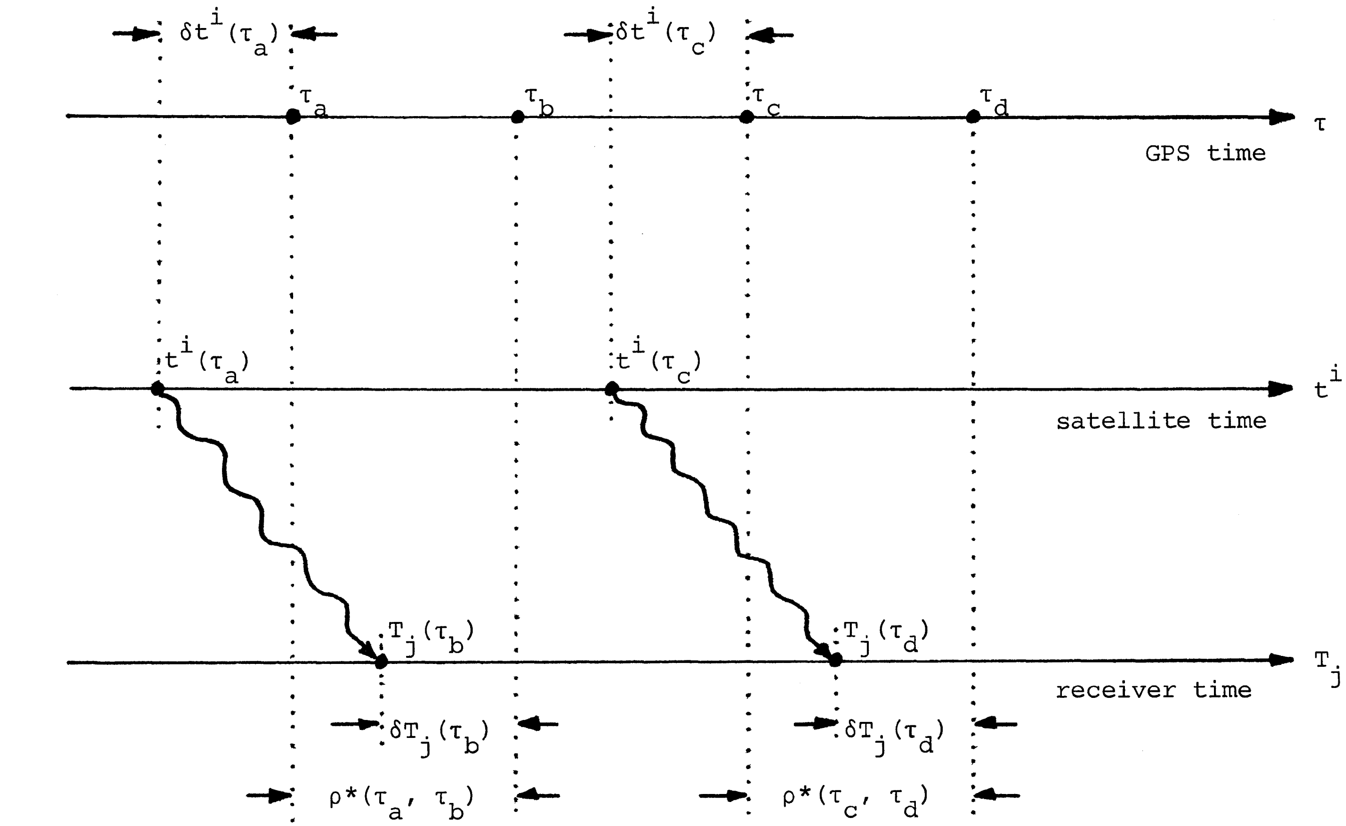


FIGURE 6.1

Geometry of GPS Measurements.

$$\frac{\tilde{\rho}_j^i}{c} = T_j(\tau_b) - t^i(\tau_a)$$

$$= [\tau_b - \tau_b + T_j(\tau_b)] - [\tau_a - \tau_a + t^i(\tau_a)]$$

$$= [\tau_b - \tau_a] + [\tau_a - t^i(\tau_a)] - [\tau_b - T_j(\tau_b)] \tag{6.9}$$

where c is the speed of light.

The first term in (6.9) represents the total propagation delay of the signal (delays in the receiver are not considered separately from receiver clock errors here, but see Appendix C):

$$\tau_b - \tau_a = [\rho_j^i + (\delta\rho_j^i)_{ion} + (\delta\rho_j^i)_{trop}]/c \tag{6.10}$$

where ρ_j^i is the true range to the satellite

$$\rho_j^i = |\vec{r}^i(t^i) - \vec{R}_j| \quad . \tag{6.11}$$

The second and third terms in (6.9) represent the satellite and receiver clock errors with respect to GPS time. These may be expressed in the form of (6.7), henceforth replacing $t-t_o$ by t, as

$$\delta t^i = \delta t^i(\tau_a) = a_o + a_1\, t^i + a_2\, [t^i]^2 + \tilde{x}(t^i) \tag{6.12}$$

and

$$\delta T_j = \delta T_j(\tau_b) = A_o + A_1\, T_j + A_2\, T_j^2 + \tilde{X}(T_j) \quad . \tag{6.13}$$

In view of (6.10) to (6.13) the pseudorange observation equation (6.9) may be written as

$$\boxed{\begin{aligned} \tilde{\rho}_j^i &= |\vec{r}^i(t^i) - \vec{R}_j| + (\delta\rho_j^i)_{ion} + (\delta\rho_j^i)_{trop} + c\ \delta t^i - c\ \delta T_j && (6.14a) \\ &= \rho^*(\tau_a, \tau_b) + c\ \delta t^i(\tau_a) - c\ \delta T_j(\tau_b) && (6.14b) \end{aligned}}$$

where

$$\rho^*(\tau_a, \tau_b) = |\vec{r}^i(\tau_a) - \vec{R}_j| + (\delta\rho_j^i)_{ion} + (\delta\rho_j^i)_{trop}$$

is the total apparent propagation path of the signal. The total propagation delay is ρ^*/c.

6.3 Carrier Phase and Doppler

At some epoch $t^i = t^i(\tau_a)$ let the phase of a signal transmitted by the ith satellite be expressed in cycles as

$$\phi^i(t^i) = \phi^i(t^i(\tau_a)) = \phi(t_o) + [f + \delta f(t^i)]\ t^i + \tilde{\phi}(t^i) \tag{6.15a}$$

$$= f\ [t^i + \delta t^i] + \tilde{\phi}(t^i) \quad . \tag{6.15b}$$

At reception time $T_j = T_j(\tau_b)$ let a similar signal in the jth receiver derived from the local clock be expressed as

$$\Phi_j(T_j) = \Phi_j(T_j(\tau_b)) = \Phi(T_o) + [F + \delta F(T_j)]\ T_j + \tilde{\Phi}(T_j) \tag{6.16a}$$

$$= F\ [T_j + \delta T_j] + \tilde{\Phi}(T_j) \quad . \tag{6.16b}$$

The phase of the signal transmitted from the ith satellite and measured in the jth receiver is then

$$\boxed{\begin{aligned} \Phi_j^i(\tau_a,\tau_b) &= \Phi_j(T_j(\tau_b)) - \phi^i(t^i(\tau_a)) && (6.17a)\\ &= [F+\delta F(T_j)]T_j - [f+\delta f(t^i)]t^i + \tilde{\Phi}(T_j) - \tilde{\phi}(t^i) + \Phi(T_o) - \phi(t_o) && (6.17b)\\ &= F\ [T_j + \delta T_j] - f\ [t^i + \delta t^i] + \tilde{\Phi}(T_j) - \tilde{\phi}(t^i) \quad . && (6.17c) \end{aligned}}$$

Using the relation of the satellite and receiver time scales with respect to the GPS time, from (6.9) to (6.14)

$$T_j + \delta T_j = t^i + \delta t^i + \frac{\rho^*(\tau_a, \tau_b)}{c} \quad , \tag{6.18}$$

we can express in equation (6.17c) either T_j in terms of t^i, so that

$$\Phi^i_j(\tau_a, \tau_b) = F\,[t^i + \delta t^i + \frac{\rho^*(\tau_a, \tau_b)}{c}]$$

$$- f\,[t^i + \delta t^i] + \tilde{\Phi}(T_j(t^i)) - \tilde{\phi}(t_i) \qquad (6.19a)$$

$$= [F - f]\;\; [t^i + \delta t^i] + F\;\frac{\rho^*(\tau_a, \tau_b)}{c}$$

$$+ \tilde{\Phi}(T_j(t^i)) - \tilde{\phi}(t^i) \qquad (6.19b)$$

or t^i in terms of T_j, so that

$$\Phi^i_j(\tau_a, \tau_b) = [F - f]\;\; [T_j + \delta T_j] + f\,\frac{\rho^*(\tau_a, \tau_b)}{c}$$

$$+ \tilde{\Phi}(T_j) - \tilde{\phi}(t^i(T_j)) \quad . \qquad (6.20)$$

The basic "Doppler" observable is essentially the measurement of the phase Φ^i_j at two different times (see Figure 6.1),

$$N^i_j(\tau_a, \tau_b, \tau_c, \tau_d) = \Phi^i_j(\tau_c, \tau_d) - \Phi^i_j(\tau_a, \tau_b) \qquad (6.21)$$

which in view of (6.19b) may be written as

$$N^i_j(\tau_a, \tau_b, \tau_c, \tau_d) = [F - f][t^i(\tau_c) - t^i(\tau_a)]$$

$$+ [F - f]\;[\delta t^i(t^i(\tau_c)) - \delta t^i(t^i(\tau_a))]$$

$$+ \frac{F}{c}\,[\rho^*(\tau_c, \tau_d) - \rho^*(\tau_a, \tau_b)]$$

$$+ \tilde{\Phi}(T_j(t^i(\tau_c))) - \tilde{\Phi}(T_j(t^i(\tau_a)))$$

$$- [\tilde{\phi}(t^i(\tau_c)) - \tilde{\phi}(t^i(\tau_a))] \qquad (6.22a)$$

$$= [F - f]\;[\Delta t^i + \Delta\delta t^i]$$

$$+ \frac{F}{c}\,\Delta\rho^* + \Delta\tilde{\Phi} - \Delta\tilde{\phi} \qquad (6.22b)$$

where

$$\Delta t^i = t^i(\tau_c) - t^i(\tau_a) \tag{6.23a}$$

$$\Delta\delta t^i = \delta t^i(t^i(\tau_c)) - \delta t^i(t^i(\tau_a)) \tag{6.23b}$$

$$\Delta\rho^* = \rho^*(\tau_c, \tau_d) - \rho^*(\tau_a, \tau_b) \tag{6.23c}$$

$$\Delta\tilde{\Phi} = \tilde{\Phi}(T_j(\tau_d)) - \tilde{\Phi}(T_j(\tau_b)) \tag{6.23d}$$

$$\Delta\tilde{\phi} = \tilde{\phi}(t^i(\tau_c)) - \tilde{\phi}(t^i(\tau_a)) \quad . \tag{6.23e}$$

Expressing N_j^i in the receiver time scale, (6.21) may similarly be written as

$$\boxed{\begin{aligned} N_j^i(\tau_a, \tau_b, \tau_c, \tau_d) = {} & [F - f]\,[\Delta T_j + \Delta\delta T_j] \\ & + \frac{f}{c}\,\Delta\rho^* + \Delta\tilde{\Phi} - \Delta\tilde{\phi} \end{aligned}} \tag{6.24}$$

where

$$\Delta T_j = T_j(\tau_d) - T_j(\tau_b) \tag{6.25a}$$

$$\Delta\delta T_j = \delta T_j(T_j(\tau_d)) - \delta T_j(T_j(\tau_b)) \quad . \tag{6.25b}$$

The basic Doppler measurement is the received number of carrier cycles between two epochs, τ_b and τ_d. A Doppler data set consists of a series of such measurements corresponding to different epoch pairs. The relationships among these epoch pairs will determine the processing technique required to correctly interpret the data. There are three possibilities. If the Doppler count is recorded for a short interval of time, the counter reset to zero and sometime later another Doppler count is recorded and so on, we have the case of intermittently integrated Doppler. This approach is not efficient as many potential data are lost. A second approach is to reset the counter to zero after the integration interval and immediately start integrating again. In this case the end of the integration period of one datum coincides with the beginning of the subsequent integration period. These data are known as consecutive Doppler counts. A problem with these data is that consecutive counts are serially correlated with a correlation coefficient of -0.5 (see, e.g., Krakiwsky et al. [1972]; Brown [1976]). The third approach, however, produces quantities that are uncorrelated. Here one simply sums the consecutive Doppler counts throughout a satellite pass and interprets the partial sums as range differences between some initial epoch τ_o (satellite "lock-on") and all subsequent epochs. These data are known as continuously integrated Dopplers (CIDs) [Brown 1976]. This technique requires that the range to the satellite at τ_o be estimated as a "nuisance parameter" along with the other unknowns. In our present work we have simulated CID data.

6.4 Interferometric Delay and Phase

The basic interferometric delay observable is the difference in the time of arrival of the same satellite signal as measured at two different stations.

From (6.14a) for a signal from the ith satellite to the jth receiver

$$\tilde{\rho}^i_j(\tau_a,\tau_b) = |\vec{r}^i(\tau_a) - \vec{R}_j| + (\delta\rho^i_j)_{ion} + (\delta\rho^i_j)_{trop} + c\delta t^i - c\delta T_j \qquad (6.26)$$

and for the same signal to the kth receiver

$$\tilde{\rho}^i_k(\tau_a,\tau_c) = |\vec{r}^i(\tau_a) - \vec{R}_k| + (\delta\rho^i_k)_{ion} + (\delta\rho^i_k)_{trop} + c\delta t^i - c\delta T_k \qquad (6.27)$$

so that the interferometric range observable equation is

$$\boxed{\begin{aligned}
\Delta\tilde{\rho}^i_{jk} &= |\vec{r}^i(\tau_a) - \vec{R}_k| - |\vec{r}^i(\tau_a) - \vec{R}_j| \\
&\quad + (\delta\rho^i_k)_{ion} - (\delta\rho^i_j)_{ion} + (\delta\rho^i_k)_{trop} - (\delta\rho^i_j)_{trop} \\
&\quad - c\,[\delta T_k(\tau_c) - \delta T_j(\tau_b)] && (6.28a) \\
&= |\vec{r}^i(\tau_a) - \vec{R}_k| - |\vec{r}^i(\tau_a) - \vec{R}_j| \\
&\quad + (\delta\rho^i_{jk})_{ion} + (\delta\rho^i_{jk})_{trop} - c\,\delta T_{jk} && (6.28b)
\end{aligned}}$$

where

$$(\delta\rho^i_{jk})_{ion} = (\delta\rho^i_k)_{ion} - (\delta\rho^i_j)_{ion} \tag{6.29a}$$

$$(\delta\rho^i_{jk})_{trop} = (\delta\rho^i_k)_{trop} - (\delta\rho^i_j)_{trop} \tag{6.29b}$$

are differential ionospheric and tropospheric terms and

$$\delta T_{jk} = \delta T_k(\tau_c) - \delta T_j(\tau_b) \tag{6.29c}$$

is the differential correction of the receiver time scales with respect to GPS time.

The basic interferometric phase observable is similarly the difference in phase of the same satellite signal as measured at two different stations. In practice only the fractional part of the differential phase is observed,

$$\Delta\Phi^i_{jk} = \Phi^i_k - \Phi^i_j - n \tag{6.30}$$

where n is the unknown number of full cycles of differential phase. Using (6.19b)

$$\boxed{\Delta\Phi^i_{jk} = \frac{F}{c}\,[\rho^*(\tau_a, \tau_b) - \rho^*(\tau_a, \tau_c)] + \tilde{\Phi}(T_j(\tau_c)) - \tilde{\Phi}(T_j(\tau_b))\ .} \tag{6.31}$$

The problem of determining n in (6.31) was not considered for the simulations in this report, but is discussed in Appendix C.

6.5 Implementation of Clock Models for GPS Simulations

Each of the satellite and receiver clocks in the simulations reported here was assigned values for the clock model parameters as in (6.7). For each clock, a set of values different from those for the other clocks was arbitrarily selected. The range of these assigned values, for each parameter, was

(1) for a_o (synchronization error) $\pm\ \{10^{-11},\ 10^{-8}\}$ seconds

(2) for a_1 (fractional frequency offset) $\pm\ \{10^{-14},\ 10^{-11}\}$

(3) for a_2 (fractional drift rate) $\pm \{10^{-17}, 10^{-14}\}$ per second

(4) for σ_{CLK} (random fluctuation standard deviation) 2×10^{-10} seconds

(5) for $\phi_n(0,1;\xi)$ (sample from the standard normal distribution), values were computed independently for each clock, for each observation epoch.

Chapter 7
MATHEMATICAL MODELS V
GPS REFRACTION

Transmission at 1.575 42 GHz and 1.2276 GHz puts GPS carrier waves in the UHF, or microwave, region of the electromagnetic spectrum. Propagation delays due to wave travel through the atmosphere are conveniently split into frequency dependent (ionospheric) and frequency independent (neutral atmosphere) effects.

7.1 Ionosphere

The ionosphere is generally considered to be that region of the atmosphere from approximately 50 to 1000 km altitude where ionization of the gases found there occurs. Conductivity of an ionized gas is dependent primarily on the density of free electrons liberated by ionization and is related to a characteristic frequency of the plasma called the plasma angular frequency [Lorrain and Corson 1970]. The plasma angular frequency is defined as

$$\omega_P = \left[\frac{N_e \, e^2}{m \, \varepsilon_o} \right]^{1/2} \tag{7.1}$$

where N_e = electron density (electrons $\cdot$ m^{-3}),
e = the electron charge (1.6021×10^{-19} C),
m = the electron mass (9.11×10^{-31} kg),
ε_o = permittivity of free space (8.859×10^{-12} $C^2kg^{-1}m^{-3}s^{-2}$).

Evaluating the expression in (7.1) gives a plasma frequency in Hz of

$$f_P = \frac{\omega_P}{2\pi} = 8.984 \sqrt{N_e} \quad , \tag{7.2}$$

Electron densities of the ionosphere normally range from about 1×10^9 to about 3×10^{12} electrons per m^3 [Meeks 1976]. This leads to a maximum plasma frequency of approximately 15 MHz.

GPS transmissions are at frequencies approximately 100 times higher than this, which allows one to use the following approximate formula for index of refraction in the ionosphere:

$$n \simeq 1 - \frac{40.28\ N_e}{f^2} \quad , \tag{7.3}$$

where f is the transmitted carrier frequency in Hz.

The total phase delay experienced by a wave propagating through the ionosphere is

$$\delta\phi = \frac{f}{c} \int (n - 1) ds \quad ,$$

$$\delta\phi = - \frac{40.28}{f\ c} \int N_e ds \quad , \tag{7.4a}$$

where c is the speed of light, 299 792 458 ms^{-1}, and $\delta\phi$ is in cycles or turns of phase. The integrated electron density along the signal path is the total electron content, N_T. Using N_T, (7.4a) can be evaluated (multiplying by 2π) to give

$$\delta\phi = - \frac{8.442}{f} N_T \quad , \tag{7.4b}$$

where N_T is in units of 10^{16} electrons $\cdot$ m^{-2}, f is in GHz, and $\delta\phi$ is in radians.

The phase delay is negative; i.e., the phase of a pure sine wave of frequency f is decreased by the presence of the plasma. In other words, the phase velocity is greater than the velocity of light.

The ionosphere is a dispersive medium. Therefore the group refractive index does not equal the phase refractive index. The group refractive index is given by

$$n_g = n + f \frac{dn}{df} \quad ,$$

$$n_g \simeq 1 + \frac{40.28\ N_e}{f^2} \tag{7.5a}$$

and the group delay of a signal is therefore

$$\delta\tau = \frac{40.28}{f^2 c} \int N_e ds \quad . \tag{7.5b}$$

Equation (7.5b) may be re-written in terms of N_T as

$$\delta\tau = \frac{1.3436\ N_T}{f^2} \quad , \tag{7.5c}$$

where, as before, N_T is in units of 10^{16} electrons $\cdot$ m^{-2}, and f is in GHz. With this choice of units, $\delta\tau$ is in nanoseconds.

The group delay increases the measured range between satellite i and station j by an amount

$$(\delta\rho_j^i)_{ion} = c\delta\tau = \frac{40.28\ N_T}{f^2} \quad , \tag{7.6}$$

for $(\delta\rho_j^i)_{ion}$ in metres.

The only independent variable in the above equations is the total electron content, N_T. In the zenith direction, this quantity normally varies from approximately 5×10^{16} el/m^2 at night to 5×10^{17} el/m^2 during the day. At a frequency of 1.6 GHz, this corresponds to a group delay of 2.6 to 26 ns. Figure 7.1 [Spilker 1980] shows results of measurements of ionospheric delay made at three sites in North America in 1958.

Total electron content increases significantly for ray paths not in the zenith direction. The ratio of slant content to zenith content, the obliquity factor, increases roughly as cosec(E), where E is the elevation angle (see Figure 7.2). From Figures 7.1 and 7.2, it is seen that N_T can be as high as 2.8×10^{18} el/m^2. For the L1 and L2 frequencies of GPS, this amounts to 151 ns (45 m) and 250 ns (75 m) maximum delays, respectively. Corresponding maximum phase delays are −1500 radians and −1925 radians.

The ionospheric delay effects may be removed by using both frequencies simultaneously. The range difference is calculated as

$$\Delta\rho = (\tilde{\rho}_j^i)^{L1} - (\tilde{\rho}_j^i)^{L2} \quad , \tag{7.7}$$

where $(\tilde{\rho}_j^i)$ indicates that the range includes the ionospheric effect, and L1, L2 indicate the frequencies 1.575 42 GHz and 1.2276 GHz, respectively.

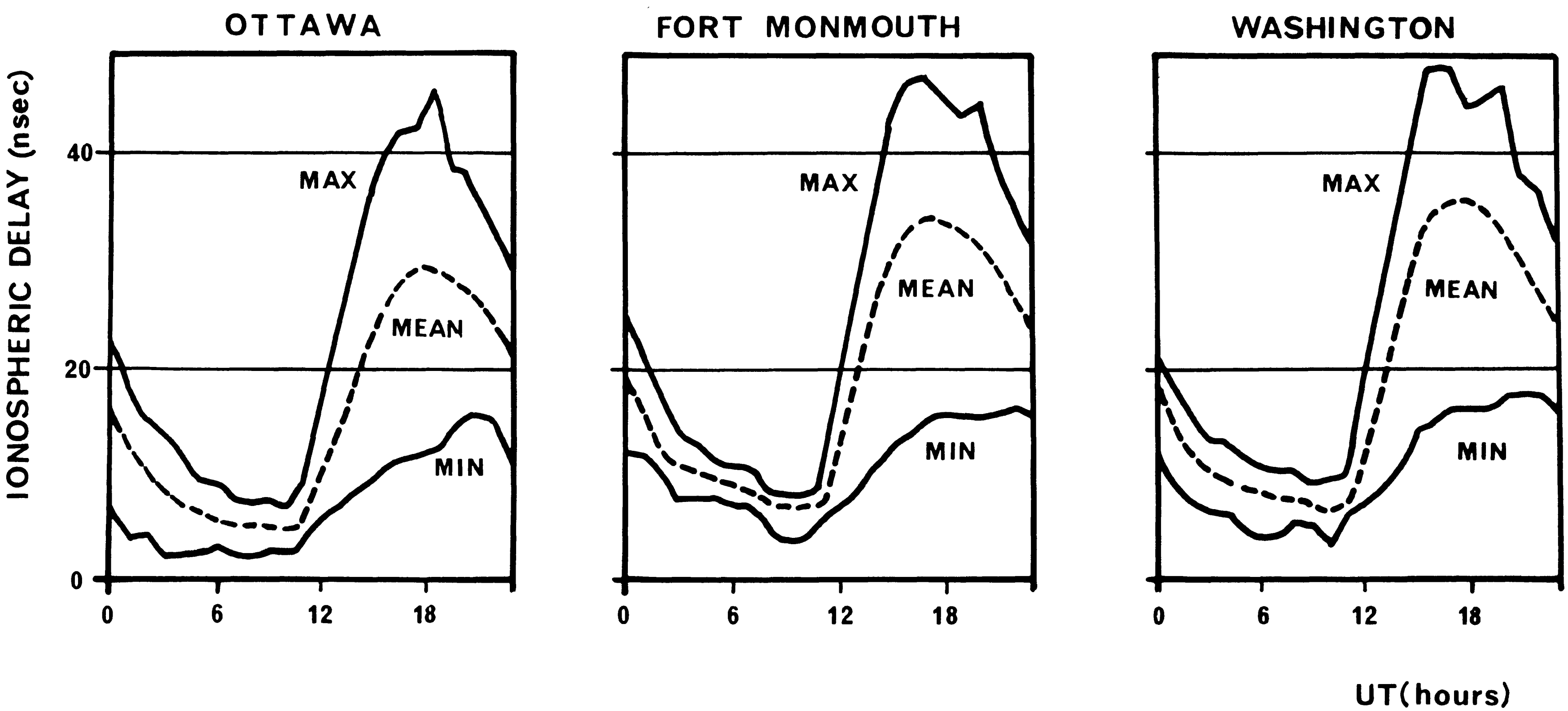


FIGURE 7.1

Ionospheric Delay Observations.
Observed ionospheric delay for a satellite at zenith and
a frequency of 1.6 GHz (from Spilker (1980)).

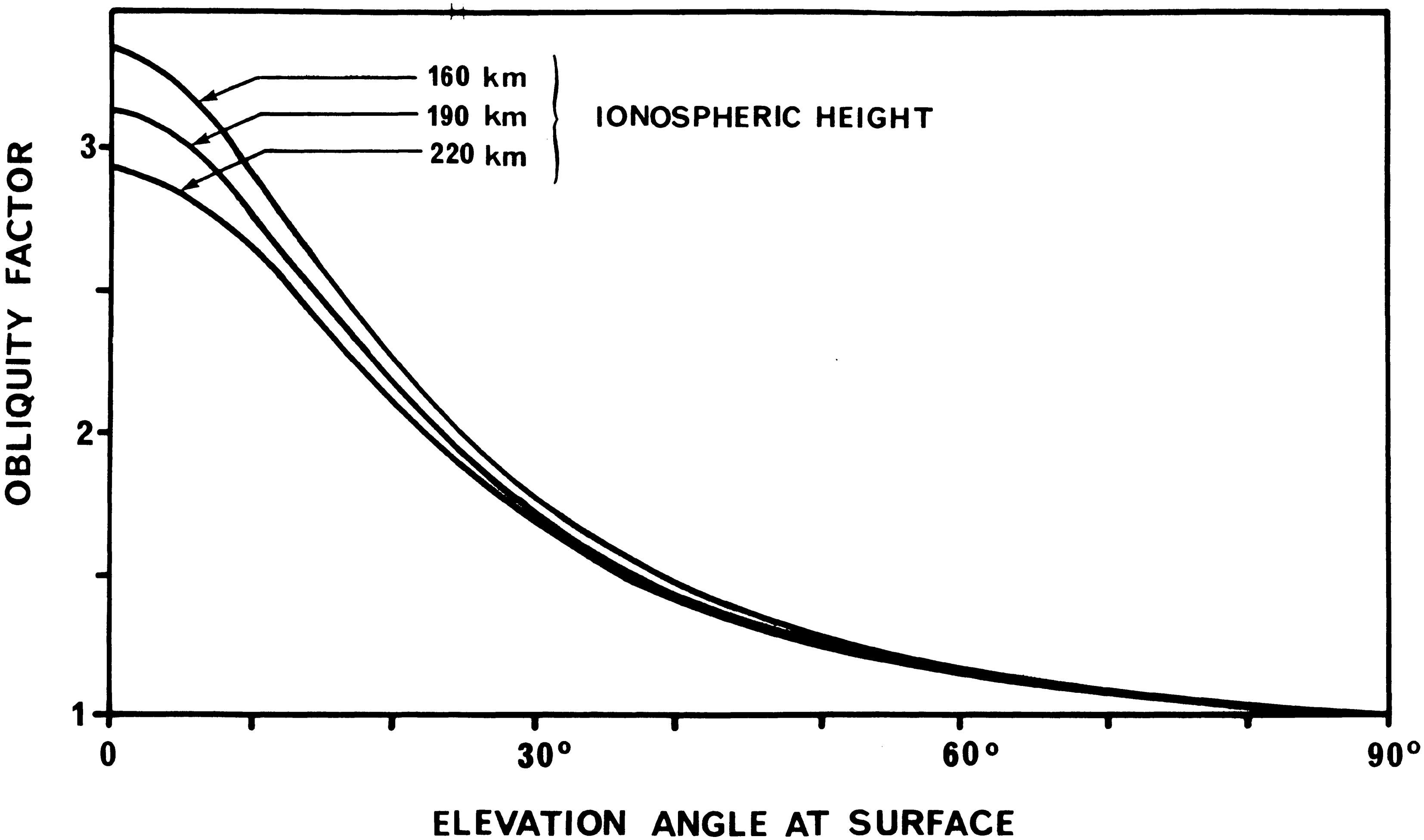


FIGURE 7.2

Obliquity Factor for the Ionosphere (from Spilker (1980)).

From the formula (7.6) above

$$(\tilde{\rho}^i_j)^{L1} = \rho^i_j + (\delta\rho^i_j)^{L1}_{ion} \quad , \tag{7.8}$$

$$(\tilde{\rho}^i_j)^{L2} = \rho^i_j + (\delta\rho^i_j)^{L1}_{ion} \left[\frac{f_1}{f_2}\right]^2 , \tag{7.9}$$

where ρ^i_j here indicates the range from satellite i to station j corrected for the ionospheric effect. Subtracting (7.9) from (7.8) leaves

$$\Delta\rho = (\delta\rho^i_j)^{L1}_{ion} \left[1 - \frac{f_1^2}{f_2^2}\right] = (\delta\rho^i_j)^{L1}_{ion} \left[\frac{f_2^2 - f_1^2}{f_2^2}\right] \quad ,$$

or $$(\delta\rho^i_j)^{L1}_{ion} = \Delta\rho \left[\frac{f_2^2}{(f_2^2 - f_1^2)}\right] \quad . \tag{7.10}$$

The true range ρ^i_j is then calculated from (7.8). For a maximum electron content of 2.8×10^{18} el/m^2 and GPS frequencies, the expected maximum $\Delta\rho$ would be approximately -29 m.

A similar technique is used to correct the phase delay. From (7.4b)

$$(\tilde{\phi}^i_j)^{L1} = (\phi^i_j)^{L1} + (\delta\phi^i_j)^{L1}_{ion} \quad , \tag{7.11}$$

$$(\tilde{\phi}^i_j)^{L2} = (\phi^i_j)^{L2} + (\delta\phi^i_j)^{L1}_{ion} \frac{f_1}{f_2} \quad . \tag{7.12}$$

Multiplying (7.12) by $\frac{f_1}{f_2}$, and subtracting it from (7.11) gives

$$(\tilde{\phi}^i_j)^{L1} - \frac{f_1}{f_2}(\tilde{\phi}^i_j)^{L2} = (\delta\phi^i_j)^{L1}_{ion} - (\delta\phi^i_j)^{L1}_{ion} \frac{f_1^2}{f_2^2} = (\delta\phi^i_j)^{L1}_{ion} \left[1 - \frac{f_1^2}{f_2^2}\right] . \tag{7.13}$$

Solving for the unknown correction $(\delta\phi^i_j)^{L1}_{ion}$ gives

$$(\delta\phi_j^i)_{ion}^{L1} = \left[(\tilde{\phi}_j^i)^{L1} - \frac{f_1}{f_2}(\tilde{\phi}_j^i)^{L2} \right] \frac{f_2^2}{(f_2^2 - f_1^2)} \quad , \tag{7.14}$$

and the corrected phase is computed from (7.11) as

$$(\phi_j^i)^{L1} = (\tilde{\phi}_j^i)^{L1} - (\delta\phi_j^i)_{ion}^{L1} \; .$$

Doppler counts are simply phases accumulated between two time epochs, and divided by 2π. Equation (7.14) can also be used for the Doppler observations if the integration interval is known, and the assumption is made that the spatial gradient of the total electron content N_T along the paths to the satellite during the integration interval is zero.

The above techniques can only be applied to two-frequency receivers. Users of single-frequency receivers must rely on the ionospheric model parameters transmitted as part of the broadcast message by the GPS satellites [van Dierendonck et al. 1980]. Presently, this ionospheric delay model is being evaluated by the Control Segment. Initial studies indicate that it should account for 50% to 75% of the actual ionospheric group delay [Martin 1980; Geckle and Feen 1980], with near real-time parametric data. A study using actual data [Lachapelle and Wade 1982] has shown that using the current broadcast ionospheric correction actually makes the results worse than not applying the correction.

For differential observations, the difference in ionospheric effects at each end of the baseline is important. The above formulae are also applicable when the observables are differential. Herring et al. [1981] show ionospheric group delay corrections calculated for two VLBI baselines (one 832 km, and one 5591 km). Using combinations of X-band ($\backsim$ 8.4 GHz, $\lambda \simeq$ 3.6 cm, one cycle $\simeq$ 0.12 ns) and S-band ($\backsim$ 2.3 GHz, $\lambda \simeq$ 13 cm, one cycle $\simeq$ 0.44 ns) group and phase delay measurements, they calculate the difference in ionospheric delay at the baseline ends (see Figure 7.3). Figure 7.3 shows that there are significant differences in the ionospheric delays of the signals reaching each end of the baseline. Assuming a total electron

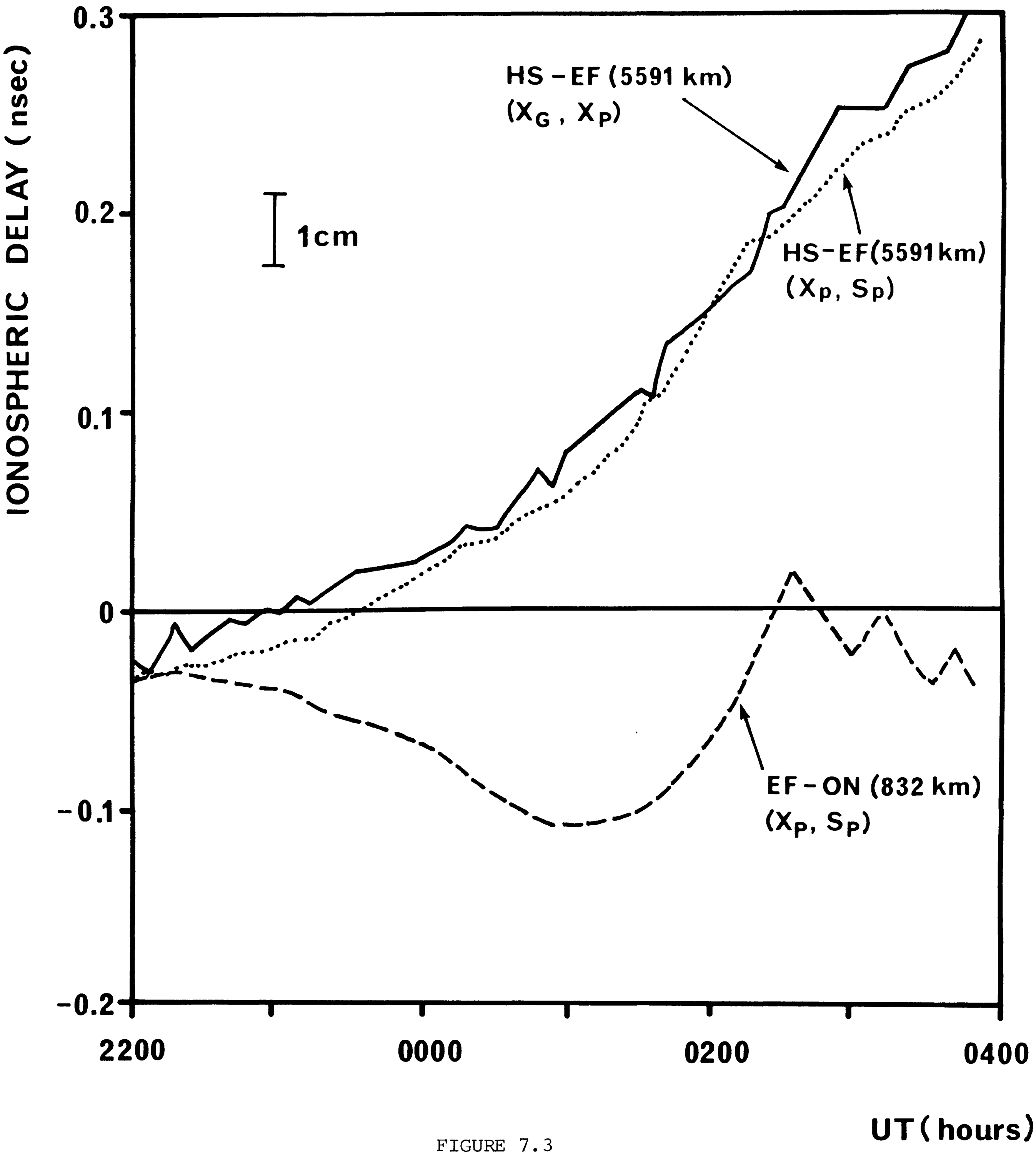


FIGURE 7.3

Relative Ionospheric Delay for VLBI Baselines.
Shown are the differences in ionospheric delay for two baselines; Haystack-Effelsberg (HS-EF), and Effelsberg-Onsala (EF-ON) along signal paths in the direction of $\alpha \simeq 16^{h}\ 40^{m}$, $\delta \simeq 39^{o}\ 53'$. Both X-band and S-band observations were used, with either group delay (G) or phase delay (P) combinations from Herring et al. (1981)).

content $N_T = 1 \cdot 10^{17}$ electrons $\cdot$ m^{-2}, the expected ionospheric delay at 8.4 GHz is 0.19 ns. The maximum ionospheric delay differences shown in Figure 7.3 are -0.12 ns and 0.35 ns for the 832 km and 5591 km baselines, respectively. This points out that there is significant spatial variation in the ionosphere.

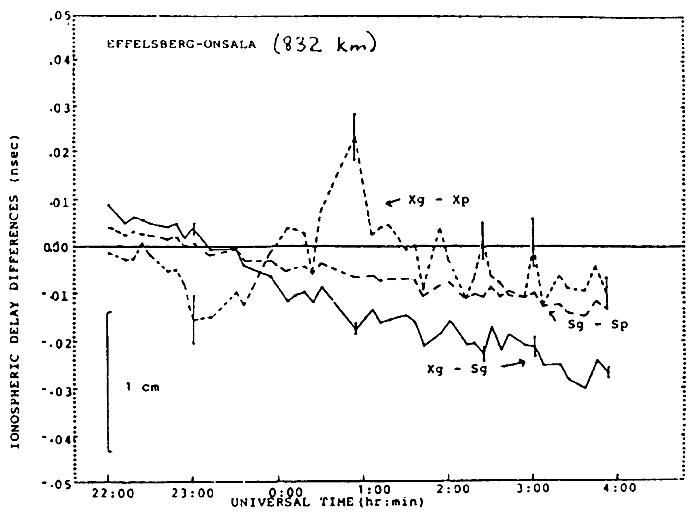
Figure 7.4 shows the differences between the different measurement types for calculating the ionospheric delay. The methods differ by less than the X- or S-band phase delay ambiguities, which implies that the "phase delay ambiguities should be able to be eliminated using the group-delay observations, without the need for spacing the observations closely in time" [Herring et al. 1981]. Further discussion of the phase delay ambiguity is contained in Appendix C.

Another atmospheric disturbance to be considered is ionospheric scintillation. Ionospheric scintillation effects are prominent near the geomagnetic equator ($\pm$ 15°), and in arctic regions beyond about 60° geomagnetic latitude [Meeks 1976]. Using an STI 5010 GPS receiver at Kwajalein, Marshall Islands (9.4°N, 167.5°E), Rino et al. [1981] observed the phase scintillations shown in Figure 7.5. These scintillation effects are thought to be caused by atmospheric gravity waves related to heating effects or hydromagnetic interactions in the auroral zone [Meeks 1976]. For relatively short baselines, this effect will be minimal since both ends are affected similarly. The scintillation effect may not affect both ends of a longer baseline by the same amount, and should be kept in mind as a possible problem.

7.2 Neutral Atmosphere

Refraction in the neutral atmosphere (which includes the troposphere and other regions up to 80 km altitude) is essentially independent of frequency over the entire radio spectrum. It is a function of the atmospheric pressure due to dry gases, temperature, and the partial pressure of water vapour. Refraction in the neutral atmosphere may be conveniently separated into "dry" and "wet" components. The dry component is approximated by

$$\Delta R_D \simeq 2.27 \times 10^{-3} P_o \quad , \tag{7.16}$$



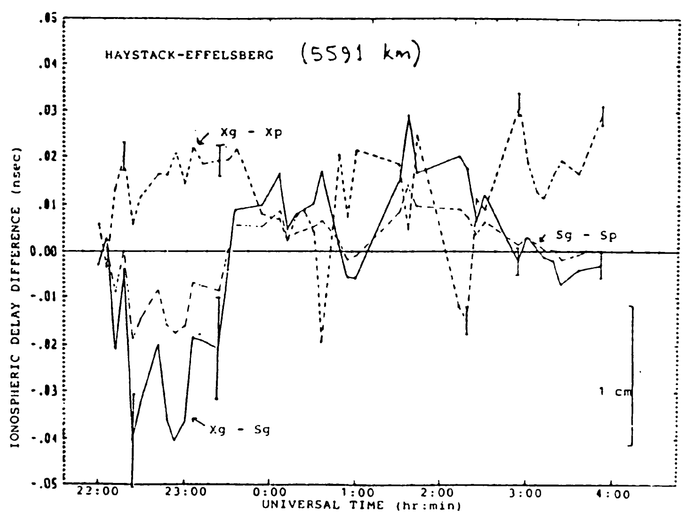


FIGURE 7.4

Comparison of different methods for determining ionospheric delay. Different combinations of X-band and S-band phase delay(p) and group delay (g), used to determine ionospheric delay, lead to slightly different results. The maximum difference between these results is less than the phase delay ambiguity, indicating that group delay observations can be used to compute the phase delay ambiguity (from Herring et al. (1981)).

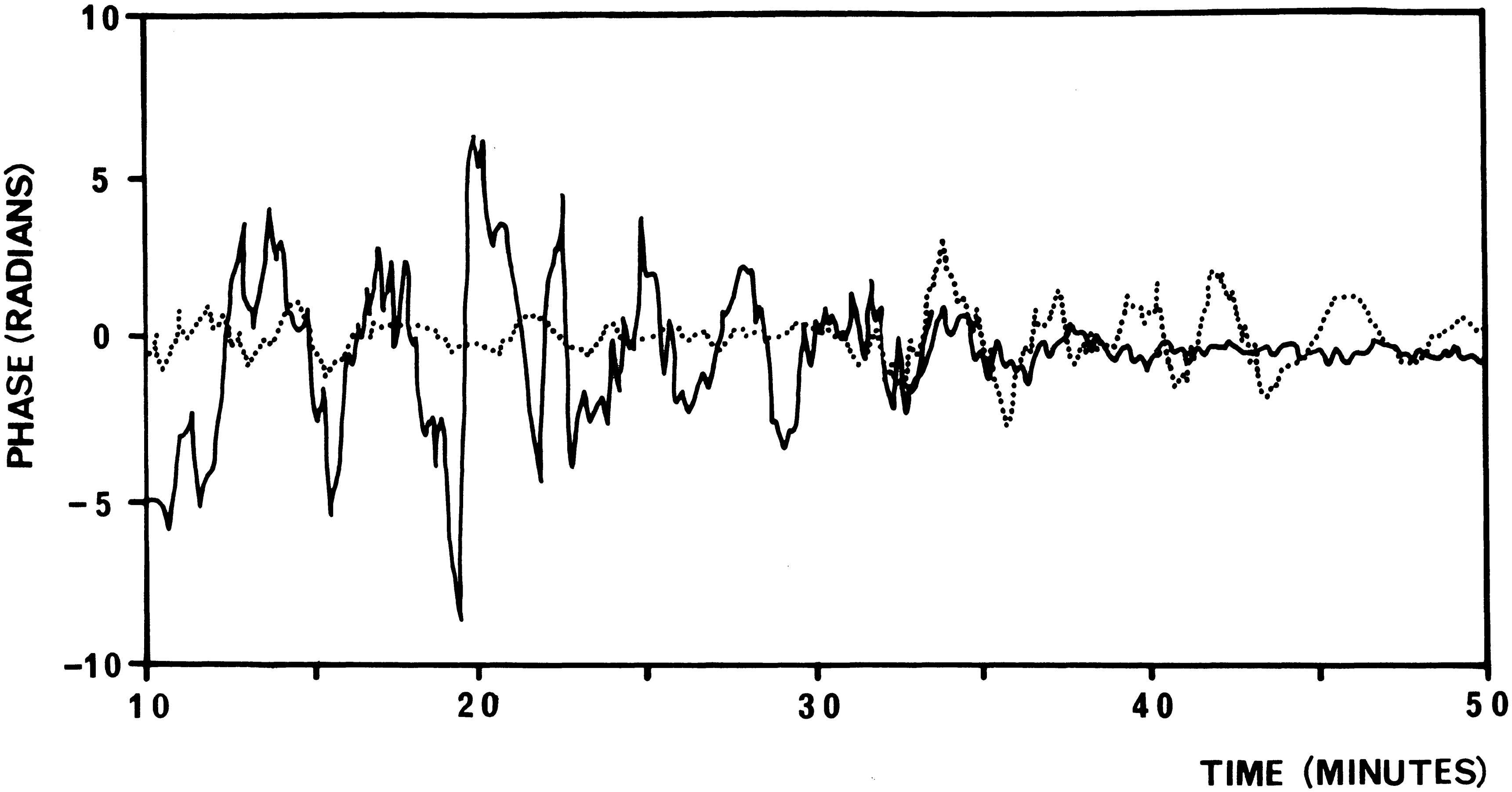


FIGURE 7.5

Phase Scintillation.
The figure shows both moderate (dotted line maximum 5 radians peak-to-peak) and strong (solid line maximum 15 radians peak-to-peak) L-band phase scintillations near the geomagnetic equator (from Rino et al. (1981)).

where ΔR_D is the dry term range contribution (m) in the zenith direction, and P_o is the surface pressure (mbar) [Meeks 1976]. For an average atmospheric pressure of 1013 mbar, this corresponds to a range contribution of 2.3 m. The dry term constitutes approximately 90% of the total zenith range error, and may be estimated from surface pressure data with an accuracy of 0.2% ($\approx$ 0.5 cm) [Hopfield 1971].

The wet term depends on the conditions along the ray path, which are not necessarily well correlated with surface conditions. Figure 7.6 [Meeks 1976] shows the relative range error due to changes in humidity in clouds. For a zenith angle of 0^o, a range difference of 9 cm due to variability of water vapour occurs over a distance of less than 1 km.

A study of 22 days of data from 7 radiosonde balloons launched nearly simultaneously at 3-hour intervals from 1000 to 2200 local time in west Texas [Coco and Clynch 1982] showed that the horizontal variation in partial water vapour pressure was less different for stations 50 to 100 km apart than for stations 100 to 200 km apart (see Figure 7.7). Only 10% as many occurrences of zero differences were noted for the 50 to 100 km station separations. This shows that even for west Texas, where the climate is semi-arid with infrequent weather disturbances, correlations due to water vapour content are very hard to predict. (In addition, their study showed that the Hopfield model [Hopfield 1969] for wet tropospheric range correction agreed best with the actual data compared with models of Berman, Chao and Saastamoinen.)

7.3 Implementation of Atmospheric Models for GPS Simulation

Four parameters are used to control the modelling of atmospheric effects. Both random and systematic effects are modelled by these parameters. Using simulation program DIFGPS (see Chapter 9), the effects of the atmosphere are added to the theoretical ranges. Then the adjustment program DIGAP (see Chapter 11) corrects for the recoverable effects using the two-frequency approach for ionospheric refraction, and an assumed constant atmosphere for the tropospheric refraction.

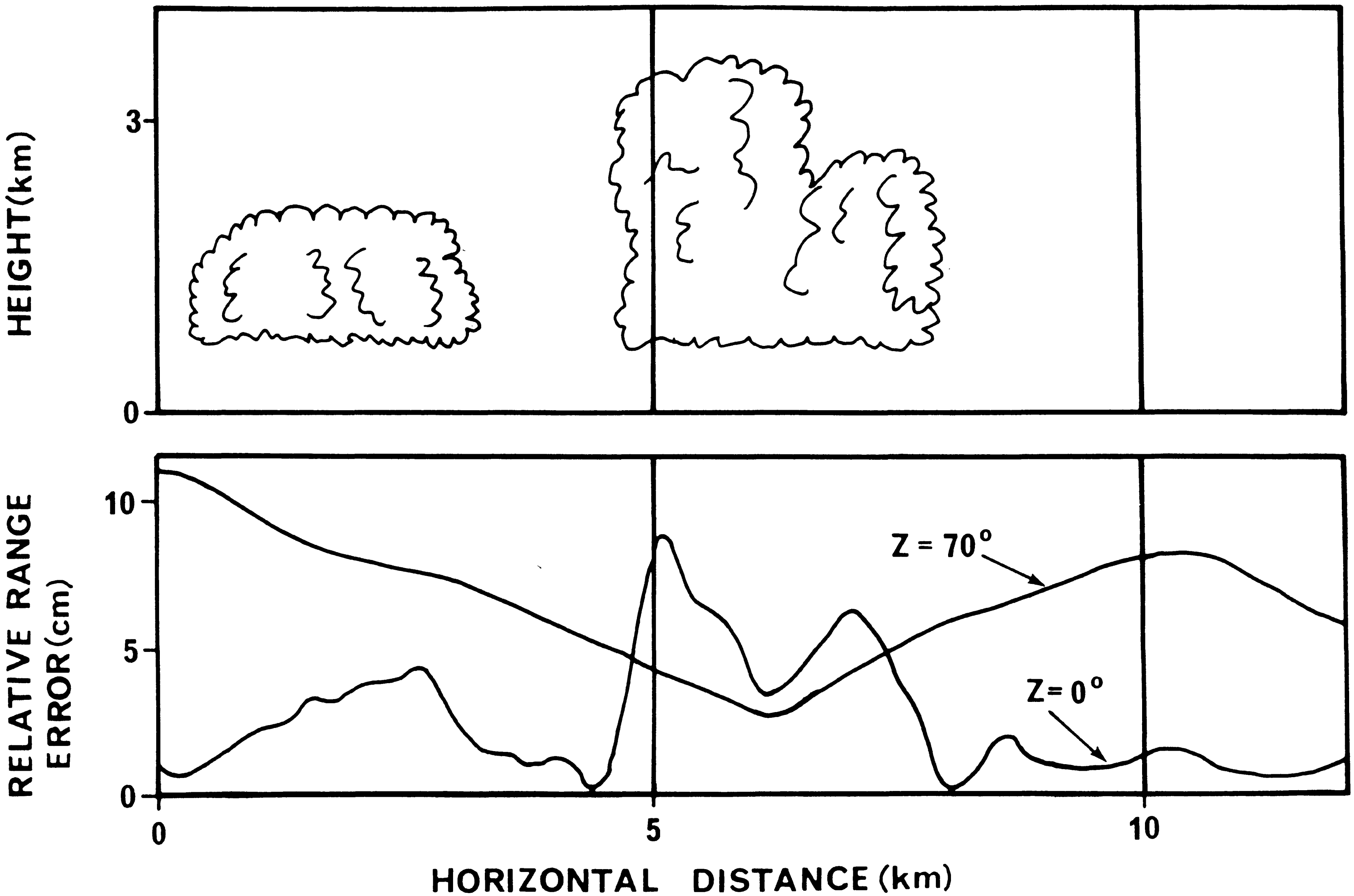


FIGURE 7.6

Range Error Variations due to the Wet Component of Refraction. Passage of radio waves through cumulus clouds results in a range difference of up to 9 cm in the vertical direction (from Meeks (1976)).

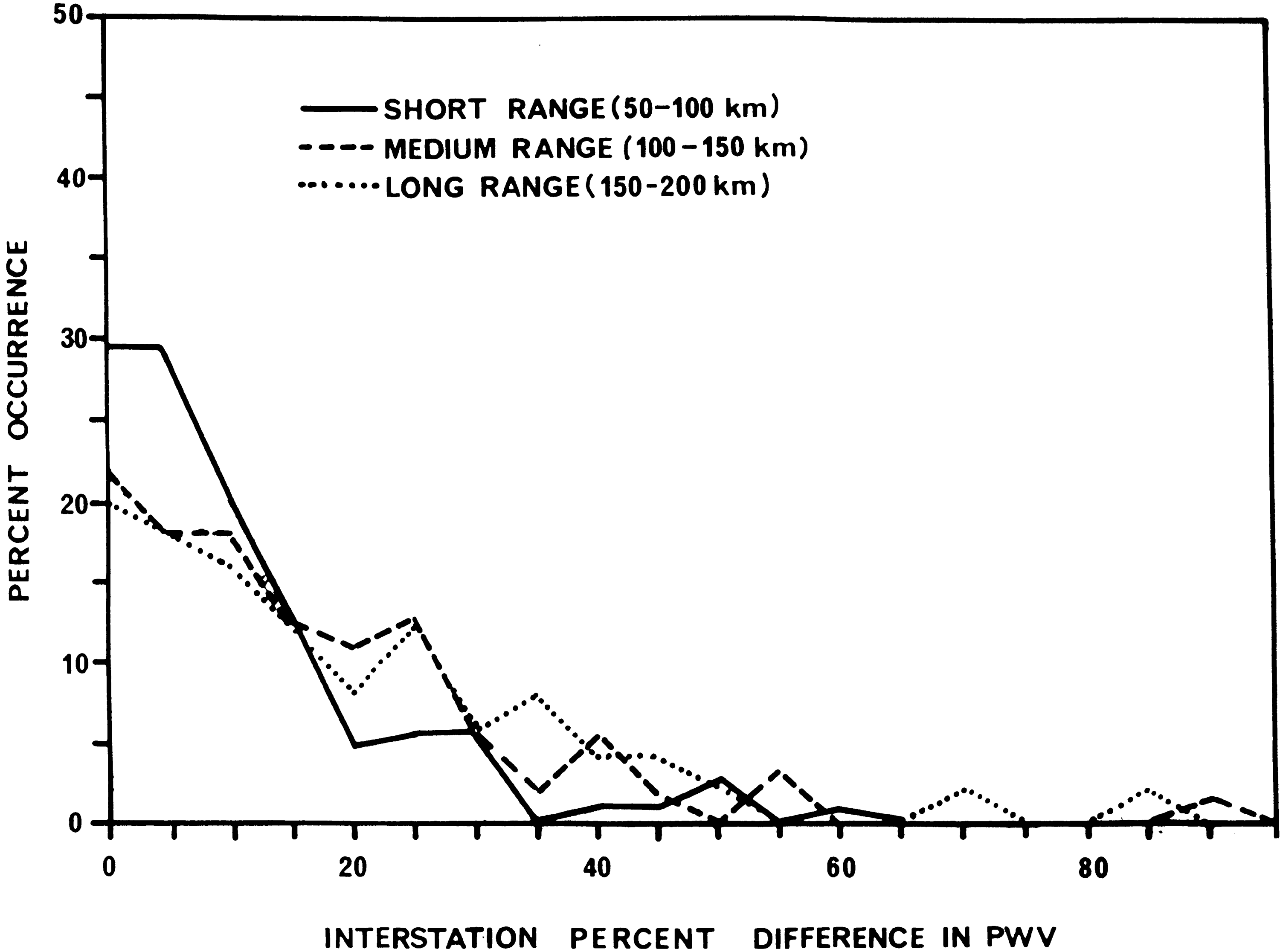


FIGURE 7.7

Spatial Variation of Water Vapour.
Partial water vapour (PWV) content of the troposphere was measured at 7 sites simultaneously in west Texas using radiosonde balloons. For 3 categories of different distances between stations, the percent occurrence of differences in PWV for the 2 end stations are plotted (from Coco and Clynch (1982)).

A constant zenith electron content of 1×10^{17} el/m^2 is assumed for the model ionosphere. The delay for the L1 frequency is calculated as in Martin [1980]; i.e.,

$$(\delta\rho^i_j)^{L1}_{ion} = \frac{1.6 \times 10^3}{4\pi^2 \, f_1^2} \, (1 \times 10^{17}) \, \csc[(E^2 + 20.3^2)^{1/2}] \quad , \tag{7.17}$$

where E = elevation angle to the satellite in degrees,

f_1 = carrrier frequency = 1.57542×10^9 Hz for L1,

$(\delta\rho^i_j)^{L1}_{ion}$ = ionospheric delay for frequency L1 between satellite i and station j in metres.

Equation (7.17) is equivalent to the delay given by (7.6), except that the elevation angle E is now accounted for. The L2 frequency delay in metres is then computed as

$$(\delta\rho^i_j)^{L2}_{ion} = (\delta\rho^i_j)^{L1}_{ion} \left[\frac{f_1}{f_2} \right]^2 \quad , \tag{7.18}$$

which follows from (7.6). The complete ionospheric effect $(\tilde{\delta\rho}^i_j)_{ion}$ is modelled by adding the random and systematic errors as follows:

$$(\tilde{\delta\rho}^i_j)_{ion} = (\delta\rho^i_j)_{ion} + k_{ion}(\delta\rho^i_j)_{ion} + \phi_n(0,\ 1;\ \xi)\ \sigma_{ion} \quad , \tag{7.19}$$

where k_{ion} = input factor defining the amount of the actual modelled effect to be added as a systematic error,

σ_{ion} = input estimated standard deviation of the two-frequency ionospheric correction,

$\phi_n(0,\ 1;\ \xi)$ = abscissa value from the standard normal Gaussian distribution (the same value is used for both L1 and L2).

This ionospheric term is added to the actual range as in (6.26) in program DIFGPS. The simulations generated for this report used .002 (0.2%) and 0 cm as the values for k_{ion} and σ_{ion}, respectively. Program DIGAP recovers the $(\delta\rho^i_j)_{ion}$ portion of the ionospheric effect using the following expressions (see equations (7.7 to 7.10)):

$$(\delta\rho^i_j)^{L1}_{ion} = \left[(\tilde{\rho}^i_j)^{L1} - (\tilde{\rho}^i_j)^{L2} \right] \left[\frac{f_2^2}{(f_2^2 - f_1^2)} \right] \quad , \tag{7.20}$$

and $(\rho^i_j)^{L1} = (\tilde{\rho}^i_j)^{L1} - (\delta\rho^i_j)^{L1}_{ion}$, (7.21)

where $(\rho^i_j)^{L1}$ = L1 range corrected for the ionospheric effect,

$(\tilde{\rho}^i_j)^{L1}$ = L1 range affected by refraction.

Although these expressions are given for ranges, they also apply for range differences as used in DIGAP.

For the carrier phase and Doppler observable types, DIFGPS converts the range ionospheric effect calculated according to (7.19) into the appropriate units. For example, the phase correction is calculated as

$$(\tilde{\delta\phi}^i_j)^{L1}_{ion} = \frac{-\,2\pi\ f_1(\tilde{\delta\rho}^i_j)^{L1}_{ion}}{c} \quad , \qquad (7.22)$$

where c is the speed of light, and f_1 is equal to 1.575 42 GHz. This corresponds to (7.4b) given earlier. Recovery of the ionospheric effect in DIGAP is done as outlined in (7.11) to (7.14) above.

The interferometric observable is differential by definition. Calculation of the random component of ionospheric refraction is performed in program FOROBS (see Chapter 10) as follows:

$$(\tilde{\delta\rho}^i_{jk})_{ion} = (\delta\rho^i_k)_{ion}(1+k_{ion}) - (\delta\rho^i_j)_{ion}(1+k_{ion}) + \phi_n(0,1;\xi)\sigma_{ion}\ , \qquad (7.22a)$$

where $(\tilde{\delta\rho}^i_{jk})_{ion}$ is the ionospheric effect on interferometric delay (see (6.29a)), and the other elements are defined above. Note that only one abscissa value for the normal Gaussian distribution is required for the interferometric observable, whereas for the other observable types two are required.

Tropospheric or neutral atmospheric effects are computed using a constant atmosphere defined as

temperature = 5.85 °C,
pressure = 1020 mbar,
relative humidity = 100%.

The simplified Hopfield model for tropospheric corrections [Hopfield 1971] is used to calculate the tropospheric effect. It is given by [Wells 1974]

$$(\delta\rho_j^i)_{trop} = \frac{k_d}{\sin(E^2 + 6.25)^{1/2}} + \frac{k_w}{\sin(E^2 + 2.25)^{1/2}} \quad , \tag{7.23}$$

where $k_d = 1.552 \times 10^{-5} \frac{P}{T} ((148.72\ T - 488.3552) - h_{stn})$,

$k_w = 7.46512 \times 10^{-2} \frac{e}{T^2} (11000 - h_{stn})$,

T = temperature in Kelvins,

P = pressure in mbar,

E = elevation angle to the satellite in degrees,

e = water vapour pressure in mbar,

h_{stn} = height of the station above the geoid in metres.

The total tropospheric effect $(\tilde{\delta}\rho_j^i)_{trop}$ to be added to the true range is calculated by adding the random and systematic components of the model as

$$(\tilde{\delta}\rho_j^i)_{trop} = (\delta\rho_j^i)_{trop} + k_{trop}(\delta\rho_j^i)_{trop} + \phi_n(0,\ 1;\ \xi)\ \sigma_{trop} \quad , \tag{7.24}$$

where k_{trop} = input factor defining the amount of the actual effect to be added to the tropospheric correction as a systematic error,

σ_{trop} = input estimated standard deviation of Hopfield's simplified correction,

$\phi_n(0,\ 1;\ \xi)$ = abscissa value from the standard normal Gaussian distribution.

This tropospheric correction is added to the actual range (as depicted in (6.26)) in program DIFGPS. Values of k_{trop} = 0.04 (4%) and σ_{trop} = 5 cm were used for the simulation runs. Program DIGAP (see Chapter 9) recovers the $(\delta_j^i)_{trop}$ portion of the correction using (7.23).

The interferometric observable is treated differently as it is for the ionospheric disturbance. Program FOROBS is used to calculate the random component of the tropospheric refraction which is added to the other components as follows:

$$(\tilde{\delta\rho}^{i}_{jk})_{trop} = (\delta\rho^{i}_{k})_{trop}(1+k_{trop}) - (\delta\rho^{i}_{j})_{trop}(1+k_{trop}) + \phi_n(1,0;\xi)\sigma_{trop}, \quad (7.24a)$$

where $(\tilde{\delta}^{i}_{jk})_{trop}$ is the tropospheric effect on interferometric delay (see (6.29b)).

Chapter 8
GPS DIFFERENTIAL SOFTWARE I
SPECIFICATIONS AND FLOWCHART

The software developed in this study was based on three perceptions:

(1) Development of GPS receivers available to civilian users and capable of being used for precise differential GPS measurements, is advancing rapidly (e.g., Counselman et al. [1982]; Ward [1982]; MacDoran et al. [1982]; Hui [1982]). It is likely that observations may be available from up to five different receiver types over the next one to three years. It makes sense, then, to invest time in developing software that would be capable not only of differential GPS simulation analyses now, but of processing actual differential GPS observations of whatever type is available, and in any combination, in the near future. Hence we decided to develop a full simulation software package, rather than a package limited to preanalysis, or covariance analysis, from simulated error models.

(2) Baseline determination from differential measurements is a proven technique, using the Very Long Baseline Interferometry (VLBI) observations of quasar radio signals. Software relating the determined baseline to the VLBI delay and fringe frequency observations has been developed by several groups. One such package is GEOAIM, developed by the Canadian VLBI group centred at York University [Cannon 1978; Langley 1979; Davidson 1980].

(3) Differential GPS measurements can be categorized as interferometric delay and differential pseudorange (which are "analogous" to quasar VLBI group delay measurements), differential carrier phase (which is "analogous" to quasar VLBI phase-delay measurements), and differential Doppler (which is "analogous" to quasar VLBI fringe frequency measurements).

As a result of these perceptions, we decided to modify GEOAIM, which is a proven package familiar to us, to accept all four differential GPS measurement types. The modifications were not trivial, requiring the modelling of satellite rather than quasar sources, the addition of ionospheric and changes to tropospheric refraction models, and revisions throughout to handle all four differential GPS measurement types in any combination on any baselines. The revised version of GEOAIM, renamed "DIfferential GPS Adjustment Program" (DIGAP) is described in Chapter 11.

It should be noted that the development of this software proceeded in parallel with the development of the mathematical models described in Chapters 3 to 7. In particular DIGAP and the analysis of differential GPS geometry in Chapter 4, can be considered independent investigations. DIGAP was developed to build on proven, familiar software, and to that extent its development was expedient. Chapter 4 represents a unified development of differential GPS models, and an adjustment program based on this unified approach may well differ significantly from DIGAP. We return to this point in Chapter 13.

In addition to DIGAP, we developed software to generate the simulated differential GPS measurements to be adjusted by DIGAP. This is done in two stages. Program DIFGPS (described in Chapter 9) generates a sequence of simulated GPS observations, as they would be observed at each station of a differential GPS network. Program FOROBS (described in Chapter 10) combines these single station observations into differential measurements for each baseline to be determined, formatted to be read by DIGAP.

8.1 Specifications

The software developed in this study was designed to meet two goals:

(1) analysis of the performance of differential GPS under a wide variety of conditions, using artificial observations generated to simulate these conditions;

(2) analysis of actual differential GPS observations of any type, once such data becomes available.

The requirements imposed on the software design by these goals can be stated as a set of specifications. The software shall be capable of:

(1) operating in a simulation or actual data analysis mode,

(2) accepting data from any network of n GPS receiving stations,

(3) accepting data from any set of m GPS satellites,

(4) accepting any combination of the four basic types of differential GPS measurements observed throughout the network,

(5) testing the sensitivity of the performance of differential GPS (in the simulation mode) to a wide variety of factors (clock errors, ephemeris errors, refraction errors, receiver design, GPS code type).

8.2 Flowcharts

Figure 8.1 is a flowchart showing the relationships between the three programs in the software package.

Figure 8.2 is a block diagram showing the input and output information flow in a typical simulation run.

Table 8.1 lists the information contained in the simulated observation data set produced by program DIFGPS.

Table 8.2 lists the information contained in the differential observation data set produced by program FOROBS.

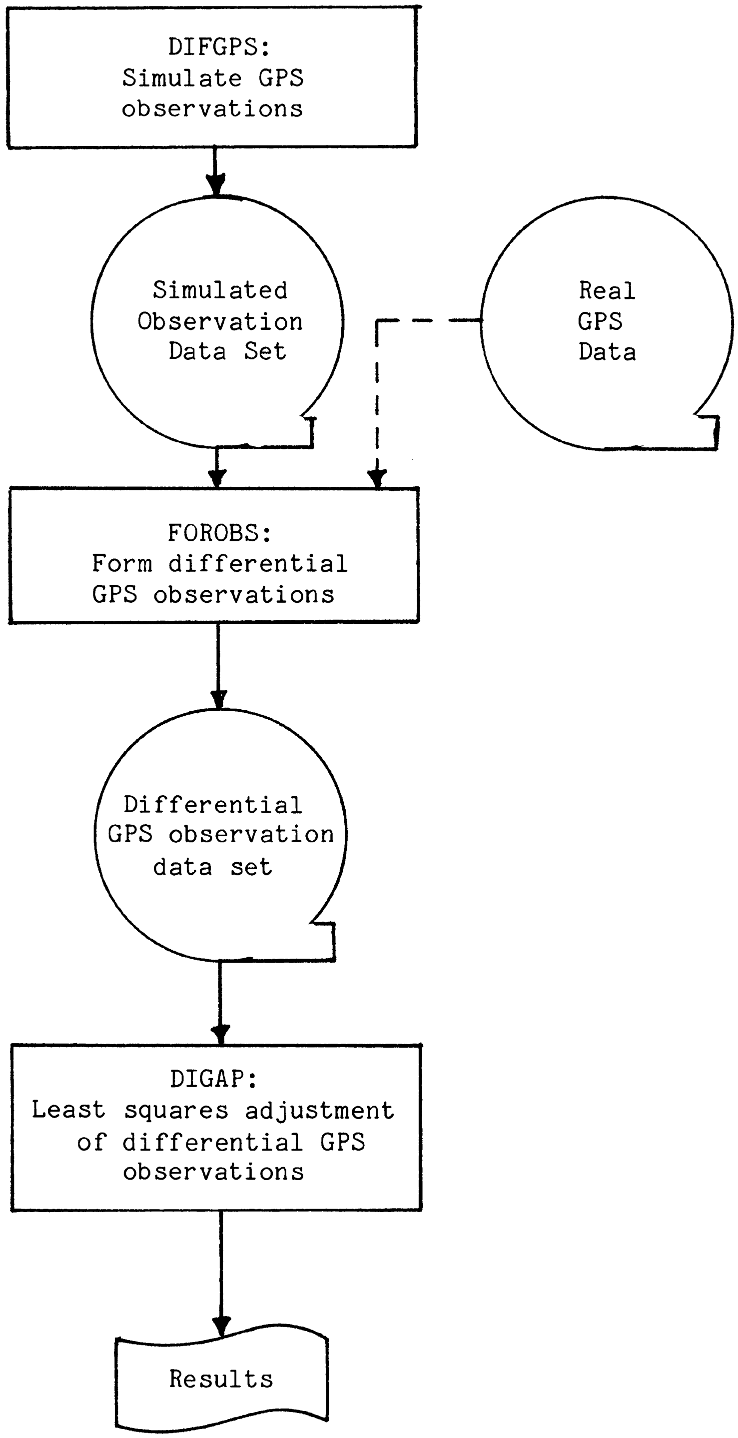


FIGURE 8.1

Simulation Flowchart.

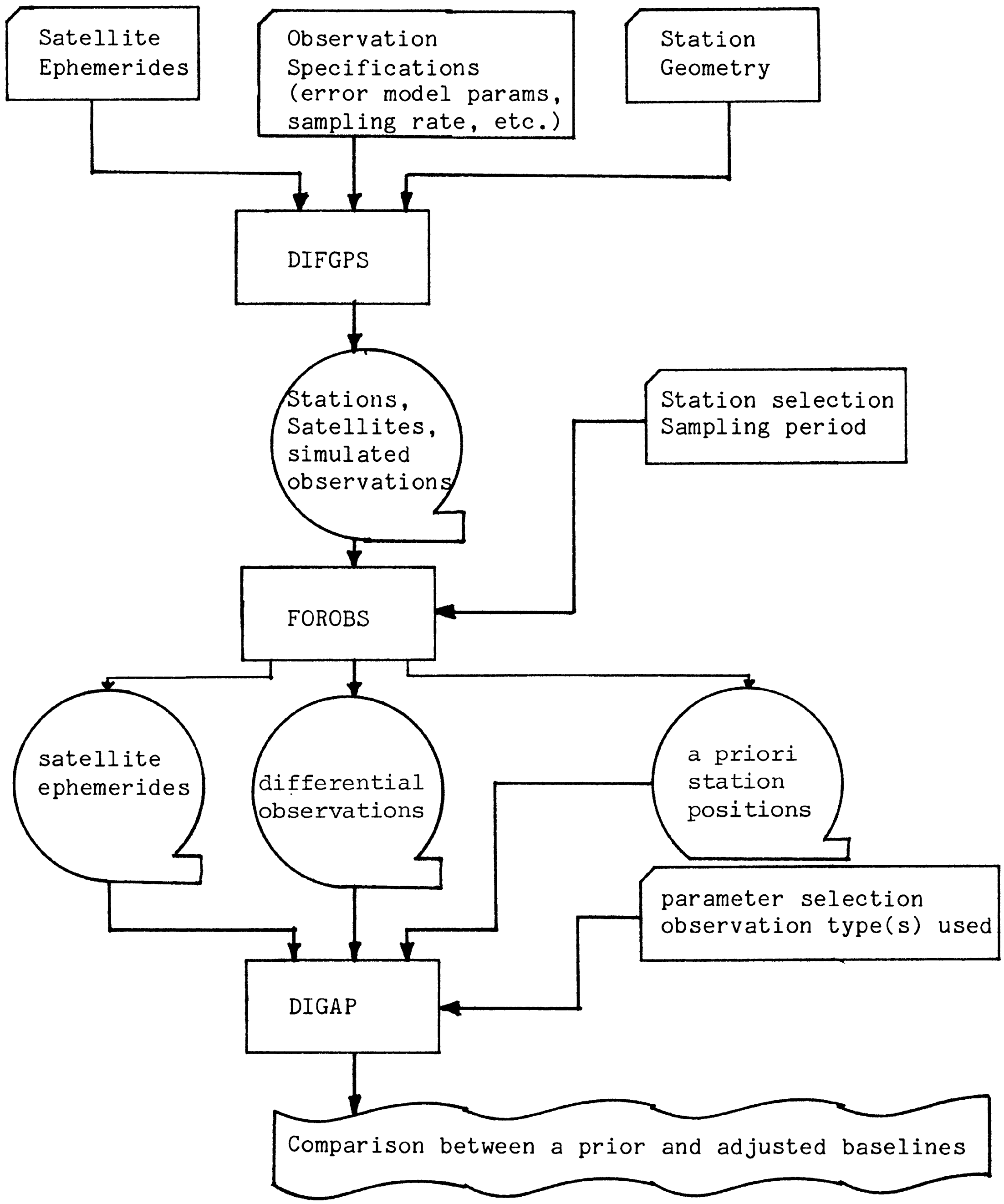


FIGURE 8.2

Simulation Block Diagram.

TABLE 8.1

Simulated Single-Station Observation Data Set.

Variable #	Name	Description
HEADER RECORD 1: (one record only)		
		80 characters describing origin and content of file
HEADER RECORD 2: (one record only)		
1	IYR(1)	observation starting year
2	IDAY(1)	observation starting day
3	IHR(1)	observation starting hour
4	IMIN(1)	observation starting minute
5	IYR(2)	observation ending year
6	IDAY(2)	observation ending day
7	IHR(2)	observation ending hour
8	IMIN(2)	observation ending minute
9	ZCNT1	start zcnt
10	ZCNT2	end zcnt
11	NSTN	# stations observing
12	MXSAT	# satellites tracked
13-17	RX(1)-RX(5)	receiver options
18-26	ERRSPC	error specifications
27-33	DTM	datum parameters
HEADER RECORD 3: (one record per station)		
1	JSTN	station # in network
2-4	XR,YR,ZR	x,y,z coordinates
5-10	CLKRX	clock parameters
HEADER RECORD 4: (one record per satellite)		
1 -18	EPH	orbital parameters
19-24	CLK	clock parameters
OBSERVATION RECORD: (one record per station per visible satellite per observation epoch)		
1	TIME	time of observation (GPS time)
2	ISAT	satellite being observed
3	JSTN	station observing
4	ELEV	elevation
5	AZ	azimuth
6 - 8	XS,YS,ZS	satellite coordinates
9	RANGE	theoretical range (m)
10-11	PRNG(1)-(2)	pseudorange L1 (P- , C/A-code)
12-13	PRNG(3)-(4)	pseudorange L2 (P- , C/A-code)
14-21		range equivalent errors (m)
14		receiver clock error
15		satellite ephemeris error
16		P-code measurement noise
17		C/A-code measurement noise
18		satellite clock error

19	ionospheric error on L1
20	ionospheric error on L2
21	tropospheric error
22	theoretical Doppler count on L1
23	simulated Doppler count on L1
24	noise
25-27	same for Doppler count on L2
28	theoretical phase on L1(RAD)
29	simulated phase on L1(RAD)
30	noise
31-33	same for phase on L2

TABLE 8.2

Differential GPS Observation Data Set.

HEADER RECORD 1: (one record)
Same as header type 1 on file produced by DIFGPS.

HEADER RECORD 2: (one record)
Indexes name of file, characteristics, and when created.

OBSERVATION RECORDS: (6 records per observation;
one set of observation records per baseline
per visible satellite
per observation epoch)

Record 1
M,IYR,IDY,IHR,MIN,ISEC,K,L,ISAT,FREQ1,FREQ2
Format ('*',I5,5I3,1X,I1,'P',I1,'P',1X,'GPS',I2,2(1X,F8.3))

M - observation number
IYR - year of observation
IDY - UTC day of observation
IHR - UTC hour of observation
MIN - UTC minute of observation
ISEC - UTC second of observation
K - ID number of first station of baseline pair
L - ID number of second station of baseline pair
ISAT - satellite ID number
FREQ1 - L1 frequency in MHz
FREQ2 - L2 frequency in MHz

Record 2
M,DPRCA1,SIGMA1,DPRP1,SIGMA2,DPRCA2,SIGMA3,DPRP2,SIGMA4
Format ('2',I5,1X,4(1X,F11.3,1X,F5.2)

M - observation number
DPRCA1 - differential pseudorange from C/A-code reception on L1 (metres)
SIGMA1 - uncertainty in DPRCA1 (metres)
DPRP1 - differential pseudorange from P-code reception on L1 (metres)
SIGMA2 - uncertainty in DPRP1 (metres)
DPRCA2 - differential pseudorange from C/A-code reception on L2 (metres)
SIGMA3 - uncertainty in DPRCA2 (metres)
DPRP2 - differential pseudorange from P-code reception on L2 (metres)
SIGMA4 - uncertainty in DPRP2 (metres)

Record 3
M,DCPHS1,SIGMA9,DCPHS2,SIGMA0
Format ('3',I5,2(1X,F16.6,1X,F10.6))

M - observation number
DCPHS1 - differential carrier phase on L1 (radians)
SIGMA9 - uncertainty in DCPHS1 (radians)
DCPHS2 - differential carrier phase on L2 (radians)
SIGMA0 - uncertainty in DCPHS2 (radians)

Record 4
M,DDOPP1,SIGMA5,DDOPP2,SIGMA6
Format ('4',I5,2(1X,F13.6,1X,F10.6))

M - observation number
DDOPP1 - 6-second differential Doppler count on L1
SIGMA5 - uncertainty in DDOPP1
DDOPP2 - 6-second differential Doppler count on L2
SIGMA6 - uncertainty in DDOPP2

Record 5
M,DELAY1,SIGMA7,DELAY2,SIGMA8
Format ('5',I5,2(1X,F13.6,1X,F10.6))

M - observation number
DELAY1 - VLBI group delay from L1 observations (microseconds)
SIGMA7 - uncertainty in DELAY1 (microseconds)
DELAY2 - VLBI group delay from L2 observations (microseconds)
SIGMA8 - uncertainty in DELAY2 (microseconds)

Record 6
M,T1,P1,RH1,T2,P2,RH2
Format ('6',I5,6(1X,F7.2))

M - observation number
T1 - surface air temperature at station 1 (Kelvins)
P1 - surface barometric pressure at station 1 (mbar)
RH1 - surface relative humidity at station 1 (%)
T2 - surface air temperature at station 2 (Kelvins)
P2 - surface barometric pressure at station 2 (mbar)
RH2 - surface relative humidity at station 2 (%)

Chapter 9

GPS DIFFERENTIAL SOFTWARE II

PROGRAM DIFGPS

Program DIFGPS is a set of FORTRAN routines which generates simulated GPS observations of various types: pseudorange, carrier phase, integrated Doppler count, and interferometric delay.

9.1 Program Hierarchy

Program DIFGPS consists of a main program and 24 subroutines. The calling hierarchy of these routines is illustrated in Figure 9.1.

9.2 Summary of Routines

One sentence summaries of each routine, arranged alphabetically, follow.

ANMLY	Computes satellite eccentric and true anomalies from mean anomaly.
CLKAN	Applies corrections for secular relativistic effects on the broadcast satellite clock correction coefficients.
CLKERR	Simulates clock errors due to bias, drift, aging, and random frequency fluctuations.
DASET	Performs input/output buffer operations.
DATUM	Defines reference ellipsoid parameters.
DERIV	Computes range to satellite, its derivatives with respect to latitude and longitude, and satellite elevation and azimuth.
DIFGPS	The main program.
DTEPOC	Generates a sequence of time epochs for which observables are simulated according to specified sampling, switching, and re-acquisition time rates.
ERRBDG	Defines the error budget for simulation.
GAUSS	Computes a normally distributed random number with a given mean and standard deviation.
HPFLD	Computes tropospheric refraction using Hopfield's model.
IONDLY	Computes ionospheric delay for two frequencies in terms of the maximum possible ionospheric delay error (i.e., maximum vertical electron content).
NCLOK	Extracts satellite clock coefficients from the ephemeris record.

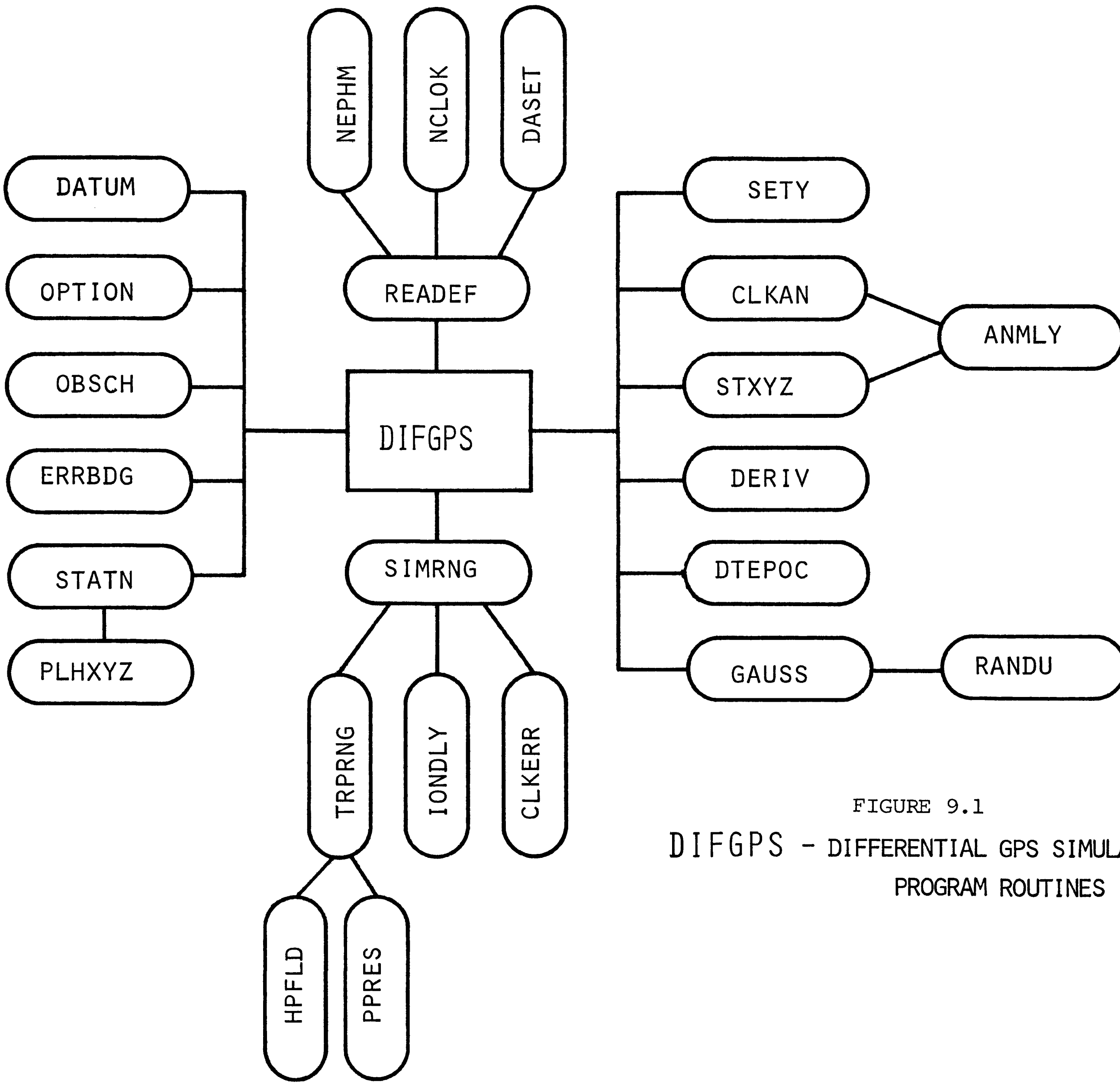


FIGURE 9.1

DIFGPS - DIFFERENTIAL GPS SIMULATION PROGRAM ROUTINES

NEPHM	Extracts satellite orbital parameters from the ephemeris record.
OBSCH	Defines the observing scenario for simulation.
OPTION	Defines various simulation options.
PLHXYZ	Converts ϕ, λ, h coordinates into Cartesian x, y, z coordinates.
PPRES	Computes partial vapour pressure based on Hopfield's model from relative humidity and temperature.
RANDU	Computes a uniformly distributed random number with zero mean and unit variance.
READEF	Reads input satellite ephemeris.
SETY	Initializes the vector of six Keplerian elements.
SIMRNG	Simulates equivalent range errors due to satellite, receiver, and atmospheric errors and corresponding pseudoranges.
STATN	Reads input station coordinates and their associated covariances.
STXYZ	Computes GPS satellite earth-fixed Cartesian coordinates from broadcast ephemeris parameters.
TRPRNG	Selects tropospheric refraction correction model.

Chapter 10

GPS DIFFERENTIAL SOFTWARE III

PROGRAM FOROBS

Program FOROBS forms the differential observations for one pair of stations (one baseline) at a time. The output from program DIFGPS is used as input for program FOROBS. The output from program FOROBS is used as input for program DIGAP. Figure 10.1 is a block diagram of FOROBS.

10.1 Input Data

FOROBS takes as input the unformatted magnetic tape file created by the program DIFGPS. Also input as in-stream data is information on the observations that are not included in the tape file. This ancillary information consists of the name of the observing network (e.g., PTSEPIN), and the name of the reference surface to which the station coordinates refer. Also read is a descriptor "card" which gives the name of the disc or tape file onto which the observations will be written and any additional information. Finally the station numbers (a "station select list") and the sampling period to be used in extracting data from the data tape are read.

10.2 Output Data

Subroutine XYZ2EL is called to convert the x, y, z coordinates of the station position to geodetic coordinates (ϕ, λ, h). These coordinates together with information on the reference datum are written as a separate formatted disc file in a format readable by the program DIGAP.

The four differential observation types are created by differencing and scaling the ranges and Doppler counts for all pairs of stations from the "select" list that can "see" a given satellite. Differential observations are created for times specified by the initial observation and the specified sampling period.

The time-tagged "observations" are written on a disc or tape file as six 80-column records of information. Each set of six records is for one station pair and one satellite, and includes data for all four observation

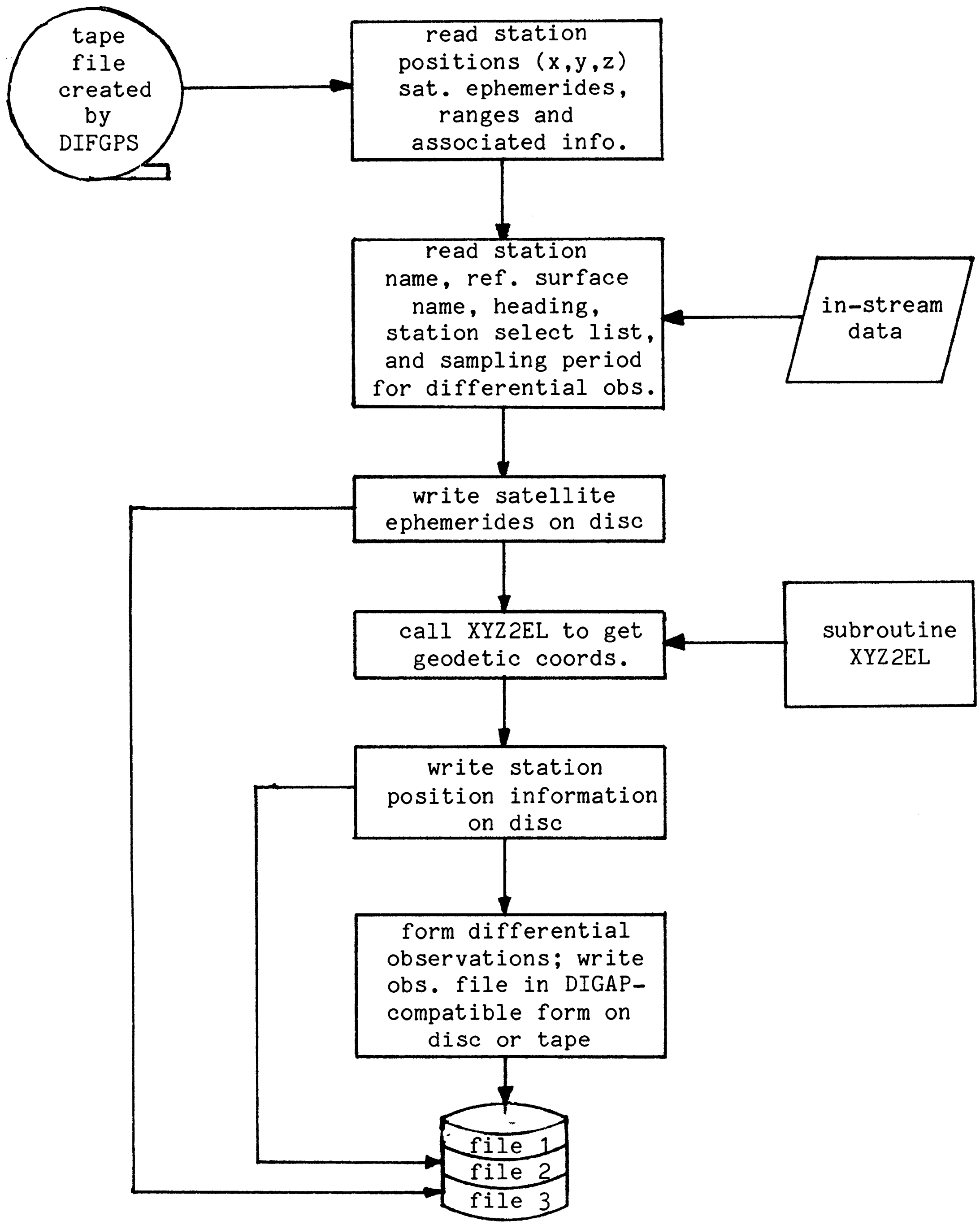


FIGURE 10.1 Block Diagram of Program FOROBS.

types. Also included are the carrier frequencies observed and temperature, pressure, and relative humidity at the two sites at the time of observation.

Chapter 11

GPS DIFFERENTIAL SOFTWARE IV

PROGRAM DIGAP

Program DIGAP (Differential GPS Adjustment Program) is a set of FORTRAN routines which will allow various options for the adjustment of differential GPS observations: pseudorange, carrier phase, Doppler, and interferometric. The package is an extension of the existing GEOAIM program, produced for long baseline interferometry at York University and UNB, revised to include the GPS model routines developed as part of the present study at UNB.

11.1 Program Hierarchy

Figure 11.1 shows the calling hierarchy of the 33 routines included in program DIGAP.

11.2 Summary of Routines

Short summaries of each routine, arranged alphabetically, follow.

ANGLES — This entry to routine DIFFER computes the elevation angles to the satellites from each station, and then forms the tropospheric correction for each observation type by calling TROP and HPFLD.

ANMLY — Computes satellite eccentric and true anomalies from mean anomaly (same as in program DIFGPS).

BLKCON — Block data routine to define global constants for the DIGAP program.

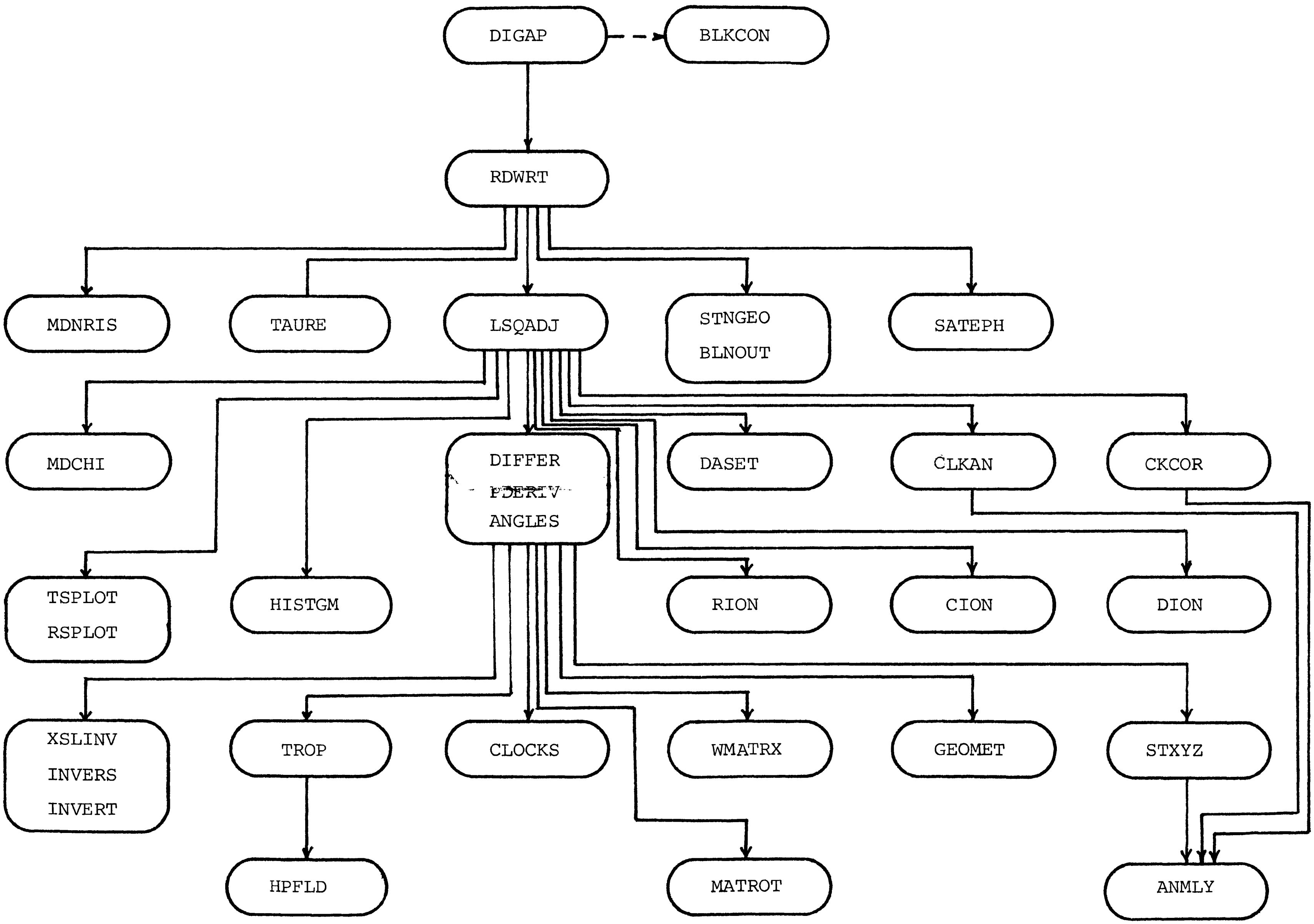
BLNOUT — This entry to routine STNGEO is used to print out both the a priori and adjusted components of the vectors between each station.

CION — Makes the ionospheric correction to the dual frequency carrier phase observation.

CKCOR — Converts GPS time measured from Saturday/Sunday midnight to time from reference epoch, and applies the ephemeris satellite clock correction parameter.

CLKAN — Applies corrections for secular relativistic effects on the broadcast satellite clock correction coefficients (same as in program DIFGPS).

FIGURE 11.1 DIGAP - DIFFERENTIAL GPS ADJUSTMENT PROGRAM ROUTINES



CLOCKS Computes the contribution of the parameterized station clocks to each observation type.

DASET Performs input/output buffer operations (same as in program DIFGPS).

DIFFER Computes the model of the differential observations (see entries PDERIV and ANGLES).

DIGAP The main program. Used to define vectors and arrays of variable dimension. It initiates the program by calling subroutine RDWRT.

DION Makes the ionospheric correction to the dual frequency Doppler observation.

GEOMET Computes the range and partial derivatives between a ground station and a satellite position when both are given in three-dimensional, earth-fixed Cartesian coordinates.

HISTGM Produces the histogram of residuals for each observation type.

HPFLD Computes tropospheric refraction using Hopfield's model (same as in program DIFGPS).

INVERS This entry to routine XSLINV performs the Choleski inversion of the normal matrix.

INVERT This entry to routine XSLINV forms the Choleski inversion of the normal matrix if XSLINV has been previously called to give the solution.

LSQADJ Performs the least squares adjustment. Within a loop for each observation point, the normal matrix and constant vector are incremented. The solution is resolved, and the parameter covariance matrix is calculated. Statistical checks are made on the resulting parameters which are printed, together with differences from the a priori estimates, and their standard errors.

MATROT Orthogonally transforms a position vector.

MDCHI This IMSL (International Mathematical and Statistical Library) routine computes the chi-squared statistic.

MDNRIS This IMSL routine computes rejection criteria using the normal distribution.

PDERIV This entry to routine DIFFER computes the partial derivatives of the observations with respect to the estimated parameters.

RDWRT Reads and echoes the titles and options for the adjustment, including observation types, numbers of stations, and arrangements of station clock polynomials. It derives statistical rejection criteria, and sets up the parameter vectors for the adjustment. After calling subroutine LSQADJ to perform the adjustment, the derived inter-station baseline components and standard errors are printed by calling BLNOUT.

RION Ionospheric correction to range and interferometric dual freqency observations is computed in this subroutine.

RSPLOT This entry to routine TSPLOT plots the residual for each observation time point.

SATEPH Reads the GPS satellite ephemeris for all observed satellites, storing the values in an ephemeris vector.

STNGEO Reads the a priori station coordinates, and transforms from geodetic coordinates to three-dimensional Cartesian geocentric coordinates (see entry BLNOUT).

STXYZ Computes GPS satellite earth-fixed Cartesian coordinates from broadcast ephemeris parameters (same as in program DIFGPS).

TAURE Computes rejection criteria using the tau distribution function.

TROP Computes the tropospheric refraction correction by calling subroutine HPFLD with atmospheric and geometric parameters for the observation.

TSPLOT Initializes values used for the time series plot of the residuals (see entry RSPLOT).

WMATRX Computes the polar motion transformation matrix relating instantaneous to average terrestrial positions.

XSLINV Computes the Cholesky solution for the adjustment (see entries INVERS and INVERT).

Chapter 12

DIFFERENTIAL GPS SOFTWARE V

SIMULATION RESULTS FOR POINT SAPIN NETWORK

The differential GPS software described in Chapters 8 to 11 was tested using the Point Sapin network of Figure 2.1 and Figure 12.1.

12.1 Simulation Conditions

The object of these tests was to evaluate the performance of differential GPS, as modelled by our software, under various conditions. In order to limit the computer runs to a manageable number (and cost), the variations in the conditions were limited to the following:

(a) five kinds of differential GPS observations
   - interferometric delay
   - differential carrier phase
   - differential P-code pseudorange
   - differential C/A-code pseudorange
   - differential integrated Doppler

(b) three GPS satellite constellations (see Chapter 5.3)
   - present (1982) 4-satellite constellation
   - proposed (1988) 18-satellite constellation, undegraded
   - proposed (1988) 18-satellite constellation, degraded

(c) two intervals between observations (observations on all visible satellites were assumed to be taken simultaneously)
   - six seconds
   - thirty seconds

(d) two total time spans of the observations
   - one hour
   - five hours.

All eight stations in the Point Sapin network were used for some of the runs. However, to limit the computer usage, stations 1, 3, 4 and 8 (see Figure 12.1) were used for most of the runs. Station 1 was used as the base station, and its coordinates were held fixed in all runs.

The observations were generated from the "true" satellite and ground

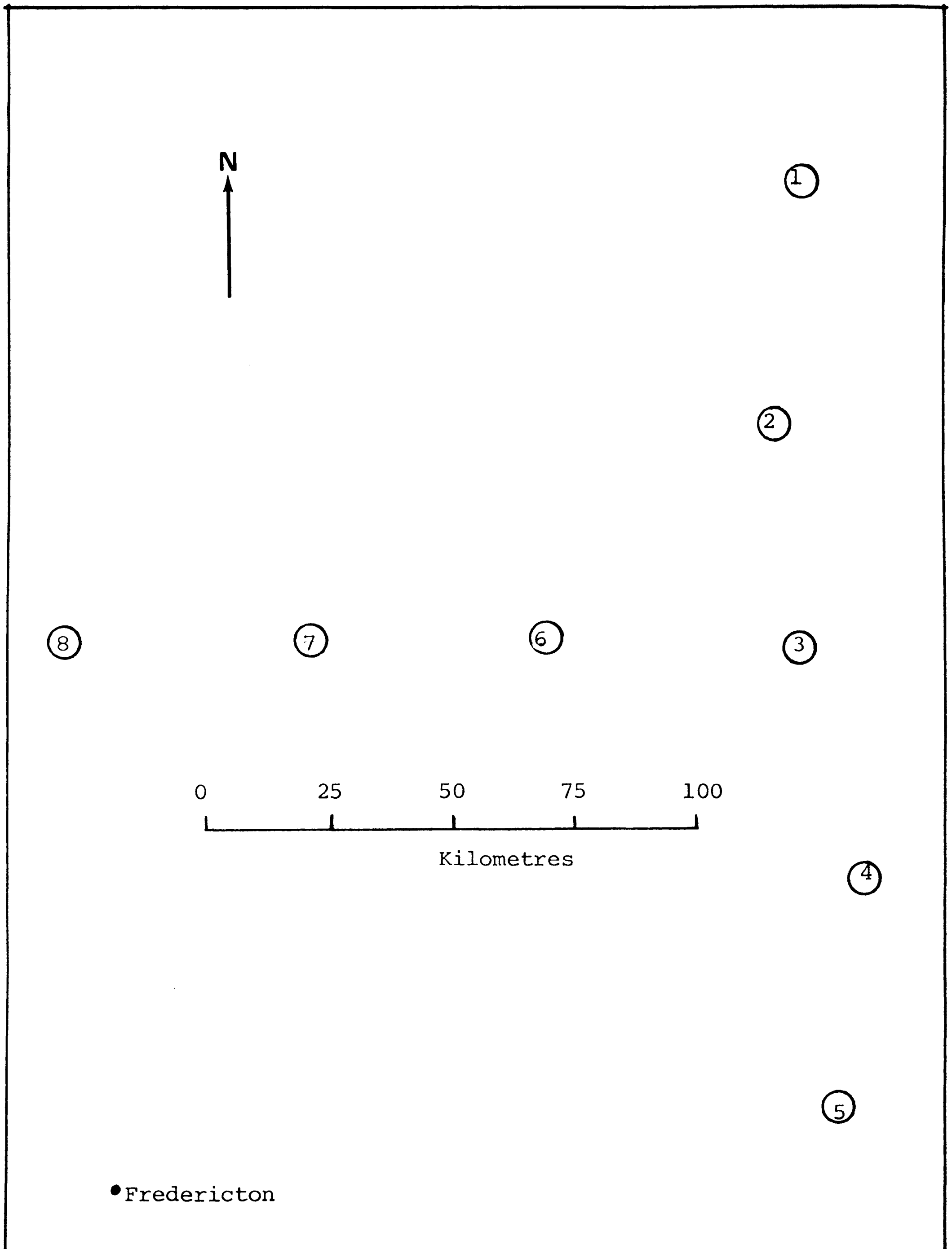


Figure 12.1
Point Sapin Network used for Simulations

station coordinates, and then corrupted to account for clock and atmospheric effects and for measurement noise. The clock model is described in Chapter 6.5, and the atmospheric model in Chapter 7.3. The measurement noise was applied from a sample of normally-distributed random values with the following standard deviations:

(a) for P-code pseudoranges, 1 m,

(b) for C/A-code pseudoranges, 10 m,

(c) for interferometric delay, 3 cm,

(d) for phase and Doppler measurements, the carrier tracking loop noise was assumed to be negligible compared with the clock noise, and the satellite and receiver clock noise contributions were as given in (6.17c) and (6.24), respectively.

The "true" satellite coordinates were corrupted to account for ephemeris errors, as described in Chapter 5.2, before being used in the least squares adjustment in program DIGAP.

In order to test the software, before performing the simulations reported here, test runs were made with errorless observations (all the above error models being disabled). The discrepancies between the "true" and adjusted station coordinates were in all cases (for all types of observation) less than 1 mm, as were the estimated standard deviations of the adjusted coordinates.

For the simulations reported here, the "true" station coordinates were used as a priori coordinates in the least squares adjustment of program DIGAP. This was done so that the discrepancies between the a priori and adjusted coordinates could be directly interpreted as errors in the recovery of the "true" coordinates by the differential GPS technique being tested.

However, in order to test the effect of errors in the a priori coordinates, test runs were made with a priori coordinates offset from the "true" values by over one kilometre. With errorless observations, the "true" coordinates were recovered to better than 1 mm. With corrupted observations, the discrepancies between the adjusted and "true" coordinates were similar to the results presented here.

12.2 Simulation Computer Runs

Four runs were made of program DIFGPS (to vary the GPS satellite constellation), as tabulated in Table 12.1(a). All runs were made for 12 November 1981, 1700-2200 UT. The 4-satellite constellation was based on actual ephemerides. The 18-satellite constellation was simulated. Polar plots of the satellite azimuth and elevation, as seen from station 6 of Figure 12.1 for the 4-satellite constellation and the 18-satellite constellation respectively, are shown in Figures 12.2 and 12.3.

Program Run	Simulated Errors	No. Sats	No. Stn	Time Span (hr)	Sample Interval (sec)	Tape File Number (slot #)
DIFGPS-1	Random + Bias	4	8	5	6	File 8 (3757)
DIFGPS-2	Random + Bias	18	8	5	6	File 1 (3722)
DIFGPS-3	Random	18	8	5	6	File 3 (3722)
DIFGPS-4	Random + Bias	18(DOA)	8	5	6	File 2 (3722)

TABLE 12.1(a)
DIFGPS Runs.

Ten runs were made of program FOROBS (to vary the interval between observations, the total time span of the observations, and the number of ground stations used), as tabulated in Table 12.1(b).

Program Run	Input Data	No. Sats	No. Stn	Time Span (hr)	Sample Interval (sec)	Tape File Name	Total No Observ's
FOROBS-1	DIFGPS-1	4	8	1	30	OBSERV 30	12574
FOROBS-2	DIFGPS-1	4	4	1	6	OBSERV 31	13369
FOROBS-3	DIFGPS-1	4	4	5	30	OBSERV 32	10112
FOROBS-4	DIFGPS-2	18	8	1	30	OBSERV 43	18666
FOROBS-5	DIFGPS-2	18	4	1	6	OBSERV 44	20010
FOROBS-6	DIFGPS-2	18	4	5	30	OBSERV 45	19527
FOROBS-7	DIFGPS-3	18	4	5	30	OBSERV 46	19527
FOROBS-8	DIFGPS-4	18(DOA)	8	1	30	OBSERV 47	18666
FOROBS-9	DIFGPS-4	18(DOA)	4	1	6	OBSERV 48	20010
FOROBS-10	DIFGPS-4	18(DOA)	4	5	30	OBSERV 49	19527

TABLE 12.1(b)
FOROBS Runs.

Fifty runs were made of program DIGAP (to vary the kind of differential GPS observation used), as tabulated in Table 12.1(c).

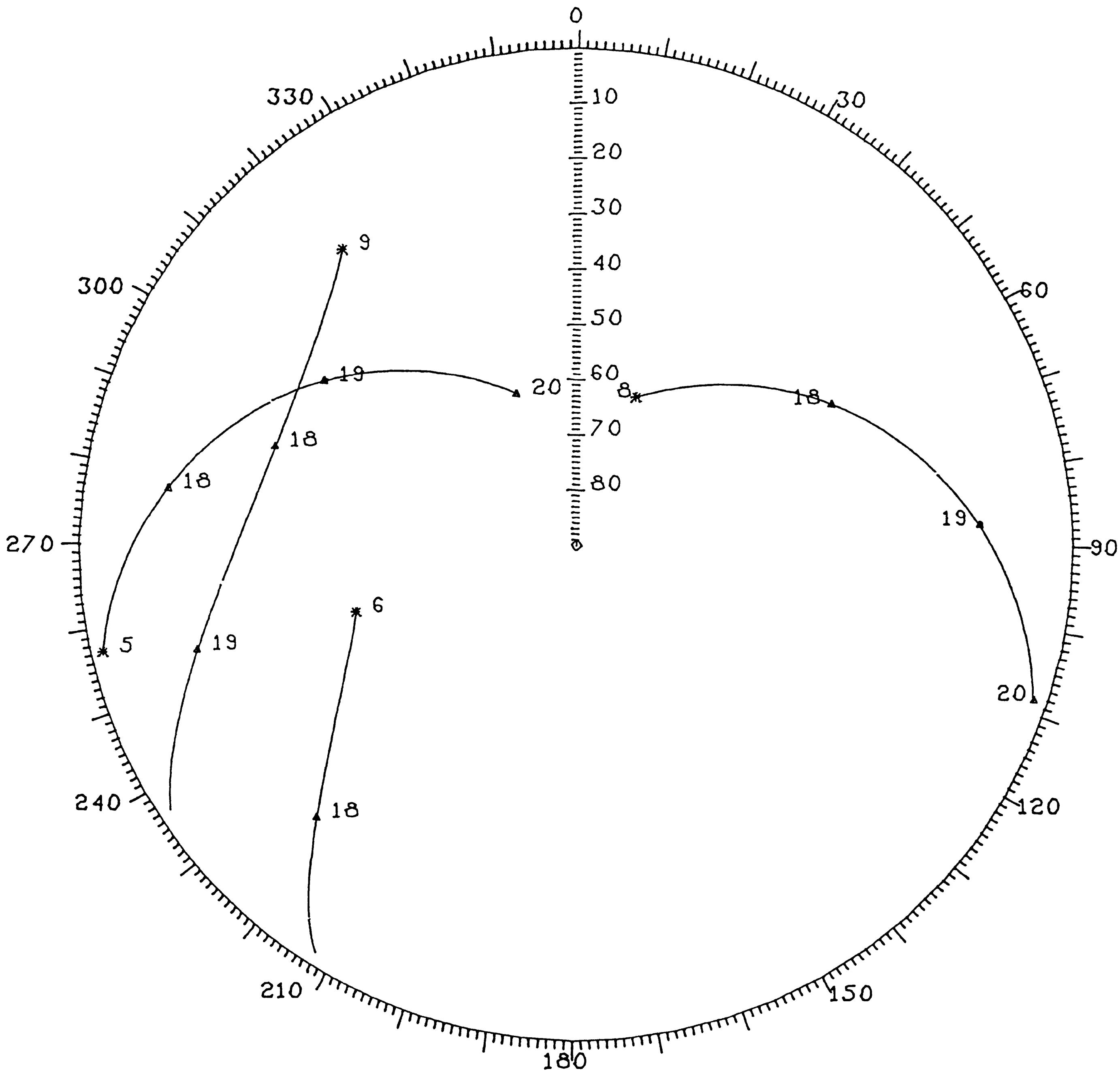


FIGURE 12.2

Polar Plots of Satellite Azimuth and Elevation
as seen from Point Sapin Network Station 6,
for the Period 1700 to 2200 UT, 12 November 1981,
for the Present Four-Satellite Constellation.

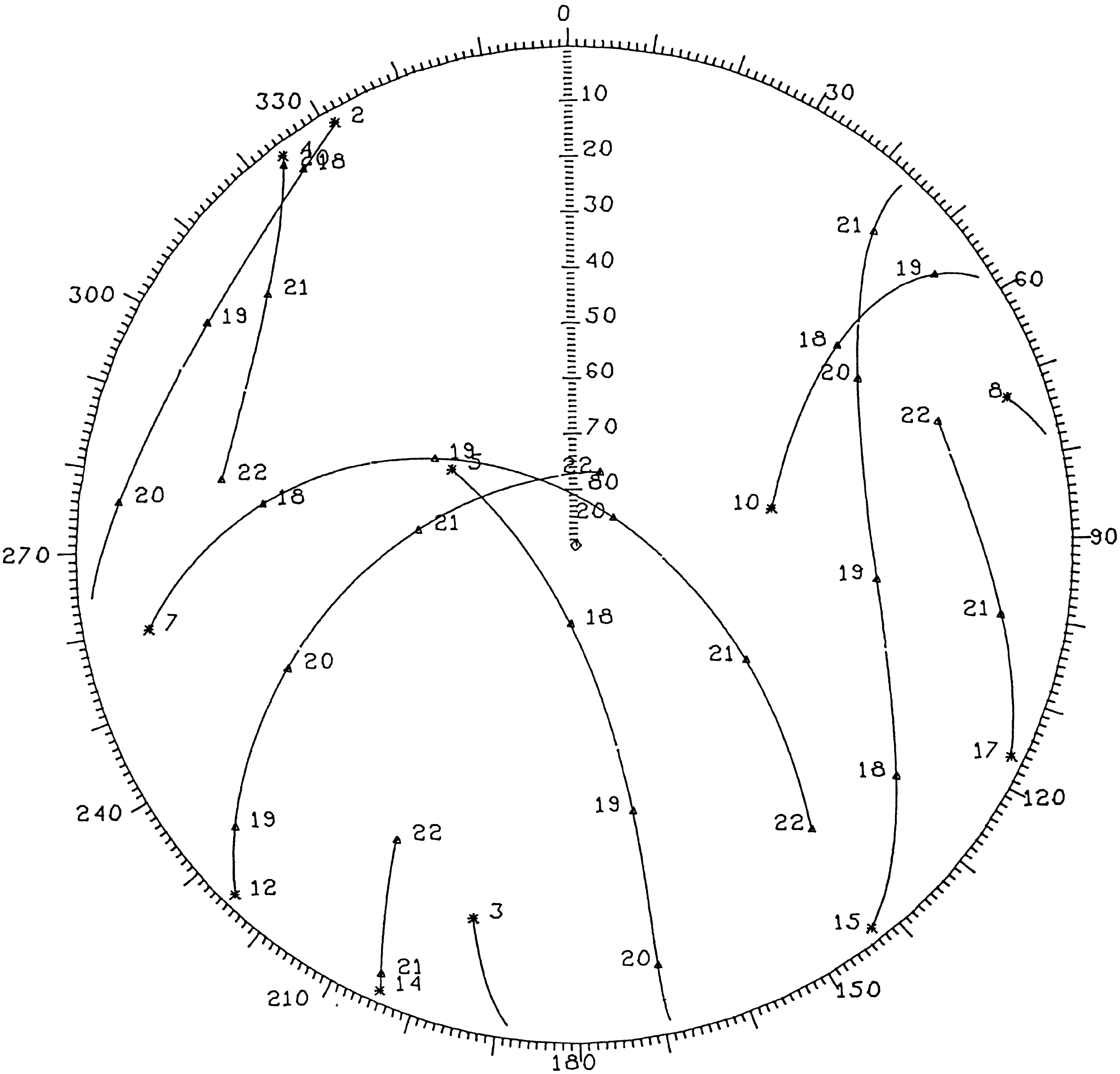


FIGURE 12.3

Polar Plots of Satellite Azimuth and Elevation
as seen from Point Sapin Network Station 6,
for the Period 1700 to 2200 UT, 12 November 1981,
for the Proposed 18-Satellite Constellation.

Program Run	Input Data	No. Sats	No. Stn	Time Span (hr)	Sample Interval (sec)	Observation Type
DIGAP-1	FOROBS-1	4	8	1	30	Interferometric
DIGAP-2	FOROBS-2	4	4	1	6	Delay
DIGAP-3	FOROBS-3	4	4	5	30	
DIGAP-4	FOROBS-4	18	8	1	30	
DIGAP-5	FOROBS-5	18	4	1	6	
DIGAP-6	FOROBS-6	18	4	5	30	
DIGAP-7	FOROBS-7	18	4	5	30	
DIGAP-8	FOROBS-8	18(DOA)	8	1	30	
DIGAP-9	FOROBS-9	18(DOA)	4	1	6	
DIGAP-10	FOROBS-10	18(DOA)	4	5	30	
DIGAP-11	FOROBS-1	4	8	1	30	Differential
DIGAP-12	FOROBS-2	4	4	1	6	Carrier
DIGAP-13	FOROBS-3	4	4	5	30	Phase
DIGAP-14	FOROBS-4	18	8	1	30	
DIGAP-15	FOROBS-5	18	4	1	6	
DIGAP-16	FOROBS-6	18	4	5	30	
DIGAP-17	FOROBS-7	18	4	5	30	
DIGAP-18	FOROBS-8	18(DOA)	8	1	30	
DIGAP-19	FOROBS-9	18(DOA)	4	1	6	
DIGAP-20	FOROBS-10	18(DOA)	4	5	30	
DIGAP-21	FOROBS-1	4	8	1	30	P-Code
DIGAP-22	FOROBS-2	4	4	1	6	Differential
DIGAP-23	FOROBS-3	4	4	5	30	Pseudorange
DIGAP-24	FOROBS-4	18	8	1	30	
DIGAP-25	FOROBS-5	18	4	1	6	
DIGAP-26	FOROBS-6	18	4	5	30	
DIGAP-27	FOROBS-7	18	4	5	30	
DIGAP-28	FOROBS-8	18(DOA)	8	1	30	
DIGAP-29	FOROBS-9	18(DOA)	4	1	6	
DIGAP-30	FOROBS-10	18(DOA)	4	5	30	
DIGAP-31	FOROBS-1	4	8	1	30	C/A-Code
DIGAP-32	FOROBS-2	4	4	1	6	Differential
DIGAP-33	FOROBS-3	4	4	5	30	Pseudorange
DIGAP-34	FOROBS-4	18	8	1	30	
DIGAP-35	FOROBS-5	18	4	1	6	
DIGAP-36	FOROBS-6	18	4	5	30	
DIGAP-37	FOROBS-7	18	4	5	30	
DIGAP-38	FOROBS-8	18(DOA)	8	1	30	
DIGAP-39	FOROBS-9	18(DOA)	4	1	6	
DIGAP-40	FOROBS-10	18(DOA)	4	5	30	
DIGAP-41	FOROBS-1	4	8	1	30	Differential
DIGAP-42	FOROBS-2	4	4	1	6	Doppler
DIGAP-43	FOROBS-3	4	4	5	30	
DIGAP-44	FOROBS-4	18	8	1	30	
DIGAP-45	FOROBS-5	18	4	1	6	

DIGAP-46	FOROBS-6	18	4	5	30
DIGAP-47	FOROBS-7	18	4	5	30
DIGAP-48	FOROBS-8	18(DOA)	8	1	30
DIGAP-49	FOROBS-9	18(DOA)	4	1	6
DIGAP-50	FOROBS-10	18(DOA)	4	5	30

TABLE 12.1(c)
DIGAP Runs.

12.3 Simulation Results

The results of each DIGAP run are contained in Appendix D. Typical DIGAP results, for each of the five observation types, are shown in Tables 12.2 to 12.6.

The information in these tables is divided into four sections: a header section, and three sections giving the discrepancies in station coordinates.

The header information consists of a title line, with the date and time of the DIGAP computer run; header records for each of the three programs, DIFGPS, FOROBS, and DIGAP, describing the characteristics of that run; a summary of the number and time span of the observations; and the GPS satellites used.

All the discrepancies, and their standard deviations, are given in millimetres in the form "discrepancy (standard deviation)".

The first two discrepancy sections resolve the three-dimensional discrepancy vector (the vector from the a priori to the adjusted station position) into (in the first section) geocentric Cartesian components DX, DY, DZ, and into (in the second section) local geodetic Cartesian components (DLAT, DLON, DHGT); that is, northing, easting, and height components. The length of the discrepancy vector and the standard deviation of the length are also shown.

The third discrepancy section resolves the discrepancy vector into components in a coordinate system whose axes are aligned as follows:

SUMMARY OF DIFFERENTIAL GPS RESULTS   TUE. OCT. 19. 1982 19:31:11

DIFGPS HEADER = OCT. 11,1982:DIFTAP:S002256:F10:DD:ALL RANDOM ERRORS NONZERO (4 SAT. ABER. IN)
FOROBS HEADER = FILE: LANGLEY.GPS.OBSERV12.DATA:4 STATIONS;OBS CREATED:TUE. OCT. 19. 1982 023229
DIGAP HEADER = INTERFEROMETRIC   FOUR STATIONS

TOTAL OBSERVATIONS = 13369 ON DAY 316 , 1981 FROM 18: 0: 6 TO 18:59:36. SPAN= 0 HR(S). 59 MIN.
SATELLITES USED = 6 8 9 5

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX	(SD-DX)	DY	(SD-DY)	DZ	(SD-DZ)	DR	(SD-DR)
1	1PTSAPIN	F I X E D		S T A T I O N					
2	3PTSAPIN	0(	4)	-13(	8)	12(	10)	18(	12)
3	4PTSAPIN	1(	4)	-26(	8)	10(	10)	28(	11)
4	8PTSAPIN	-17(	4)	71(	9)	-94(	10)	120(	12)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT	(SD-DLAT)	DLON	(SD-DLON)	DHGT	(SD-DHGT)	DR	(SD-DR)
1	1PTSAPIN	F I X E D		S T A T I O N					
2	3PTSAPIN	0(	5)	-6(	5)	17(	12)	18(	12)
3	4PTSAPIN	-10(	5)	-10(	5)	24(	12)	28(	11)
4	8PTSAPIN	-11(	5)	12(	4)	-118(	12)	120(	12)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN	(SD-DLEN)	DAZ	(SD-DAZ)	DELEV	(SD-DELEV)	BASELINE (IN
1	1PTSAPIN	F I X E D		S T A T I O N				
2	3PTSAPIN	1(	5)	7(	4)	17(	12)	92429
3	4PTSAPIN	10(	5)	12(	4)	24(	12)	142000
4	8PTSAPIN	-2(	3)	-16(	6)	-118(	12)	154584

TABLE 12.2

DIGAP-2

SUMMARY OF DIFFERENTIAL GPS RESULTS   TUE, OCT. 19, 1982   19:10:48

DIFGPS HEADER = OCT. 11,1982:DIFTAP:S002256:F10:DD:ALL RANDOM ERRORS NONZERO (4 SAT, ABER. IN)
FOROBS HEADER = FILE: LANGLEY.GPS.OBSERV12.DATA:4 STATIONS;OBS CREATED:TUE, OCT. 19, 1982 023229
DIGAP HEADER = CARRIER PHASE   FOUR STATIONS

TOTAL OBSERVATIONS = 13369 ON DAY 316 , 1981 FROM 18: 0: 6 TO 18:59:36. SPAN= 0 HR(S), 59 MIN.
SATELLITES USED = 6 8 9 5

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	11(4)	-18(9)	-5(11)	23(6)
3	4PTSAPIN	20(4)	-36(9)	-4(11)	43(7)
4	8PTSAPIN	1(4)	45(9)	-94(11)	105(13)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	-19(5)	2(5)	11(12)	23(6)
3	4PTSAPIN	-33(5)	2(5)	26(12)	43(7)
4	8PTSAPIN	-34(5)	19(5)	-96(12)	105(13)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	20(5)	0(5)	11(12)	92429
3	4PTSAPIN	35(6)	1(4)	25(12)	142000
4	8PTSAPIN	5(4)	-38(6)	-97(12)	154584

TABLE 12.3

DIGAP-12

SUMMARY OF DIFFERENTIAL GPS RESULTS   TUE, OCT. 19, 1982   18:40:56

DIFGPS HEADER = OCT. 11,1982:DIFTAP:S002256:F10:DD:ALL RANDOM ERRORS NONZERO (4 SAT, ABER. IN)
FOROBS HEADER = FILE: LANGLEY.GPS.OBSERV12.DATA:4 STATIONS;OBS CREATED:TUE, OCT. 19, 1982 023229
DIGAP HEADER = PSEUDO RANGE   FOUR STATIONS

TOTAL OBSERVATIONS = 13369 ON DAY 316 , 1981 FROM 18: 0: 6 TO 18:59:36. SPAN= 0 HR(S), 59 MIN.
SATELLITES USED =   6   8   9   5

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	-136(50)	85(109)	124(134)	204(75)
3	4PTSAPIN	-80(50)	132(109)	-69(135)	170(135)
4	8PTSAPIN	-196(50)	248(109)	14(134)	317(92)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	184(68)	-87(59)	-1(156)	204(75)
3	4PTSAPIN	63(68)	-16(59)	-156(156)	170(135)
4	8PTSAPIN	233(67)	-80(57)	-198(156)	317(92)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	-187(69)	77(57)	0(156)	92429
3	4PTSAPIN	-65(70)	10(56)	-155(156)	142000
4	8PTSAPIN	-82(45)	234(76)	-197(156)	154584

TABLE 12.4

DIGAP-22

```
SUMMARY OF DIFFERENTIAL GPS RESULTS          TUE. OCT. 19. 1982  18:27:45
-----------------------------------

DIFGPS HEADER = OCT. 11,1982:DIFTAP:S002256:F10:DD:ALL RANDOM ERRORS NONZERC (4 SAT.  ABER. IN)
FOROBS HEADER = FILE: LANGLEY.GPS.OBSERV12.DATA:4 STATIONS;CBS CREATED:TUE. OCT. 19. 1982 023229
DIGAP  HEADER = C/A PSEUDO RANGE       FOUR STATIONS

TOTAL OBSERVATIONS =  13369 ON DAY 316 , 1981 FROM 18: 0: 6  TO 18:59:36. SPAN=  0 HR(S), 59 MIN.
SATELLITES USED =   6   8   9   5

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)
STN     NAME                 DX (SD-DX)          DY (SD-DY)          DZ (SD-DZ)          DR (SD-DR)

 1    1PTSAPIN                F   I   X   E   D      S   T   A   T   I   O   N
 2    3PTSAPIN            -1365(   499)        980(  1088)       1129(  1338)       2025(   705)
 3    4PTSAPIN             -812(   499)       1559(  1087)       -788(  1340)       1927(  1372)
 4    8PTSAPIN            -1803(   497)       1849(  1081)        992(  1332)       2767(   681)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)
STN     NAME               DLAT (SD-DLAT)      DLON (SD-DLON)      DHGT (SD-DHGT)        DR (SD-DR)

 1    1PTSAPIN                F   I   X   E   D      S   T   A   T   I   O   N
 2    3PTSAPIN             1844(   673)       -818(   587)       -175(  1557)       2025(   705)
 3    4PTSAPIN              732(   678)        -68(   589)      -1780(  1556)       1927(  1372)
 4    8PTSAPIN             2441(   665)       -917(   567)       -923(  1558)       2767(   681)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)
STN     NAME               DLEN (SD-DLEN)      DAZ  (SD-DAZ )    DELEV (SD-DELEV)      BASELINE (IN

 1    1PTSAPIN                F   I   X   E   D      S   T   A   T   I   O   N
 2    3PTSAPIN            -1888(   685)        713(   569)       -161(  1558)            92429
 3    4PTSAPIN             -754(   701)         -7(   555)      -1772(  1558)           142000
 4    8PTSAPIN             -802(   448)       2486(   755)       -913(  1556)           154584
```

TABLE 12.5

DIGAP-32

SUMMARY OF DIFFERENTIAL GPS RESULTS   TUE, FEB. 15, 1983 10:28:32

DIFGPS HEADER = FEB. 09,1983:DIFTAP:S003757:F06:DD:ALL BIASES NONZERO (4 SAT, ABER. IN)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV31.DATA:4 STNS;6 S   CREATED:SAT, FEB. 12, 1983 140351
DIGAP HEADER = FOUR STATIONS CONTINUOUSLY INTEGRATED DOPPLER   4 SATS,WITH NOISE

TOTAL OBSERVATIONS = 13460 ON DAY 316 , 1981 FROM 18: 0: 0 TO 19: 0: 0. SPAN= 1 HR(S), 0 MIN.
SATELLITES USED =   6   8   9   5

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	-1547(32)	-572(71)	4967(87)	5234(91)
3	4PTSAPIN	1737(32)	1087(71)	1180(87)	2365(26)
4	8PTSAPIN	905(32)	385(70)	-782(87)	1257(77)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	3492(82)	-1644(71)	3535(43)	5234(91)
3	4PTSAPIN	987(68)	2035(69)	691(65)	2365(26)
4	8PTSAPIN	-539(47)	984(32)	-566(101)	1257(77)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	-3552(28)	1444(102)	3562(49)	92429
3	4PTSAPIN	-758(44)	-2127(102)	699(37)	142000
4	8PTSAPIN	-443(29)	-1032(93)	-560(63)	154584

TABLE 12.6

DIGAP-42

(a) one axis aligned to the true baseline from the fixed station to the adjusted station,

(b) one axis in the direction of increasing azimuth for the baseline,

(c) one axis in the direction of increasing elevation for the baseline (note that this is almost identical to the local geodetic height component). The baseline length is also shown in this section.

12.4 Analysis of Results

The simulation results in Appendix D are summarized in Figures 12.4 to 12.15.

Figure 12.4 shows the discrepancy vector components for each station for run DIGAP-1 (interferometric delay observable; 4-satellite constellation; 8-station network; one hour data span, sampled every 30 seconds). Figure 12.5 shows similar results for run DIGAP-4 (differing only from DIGAP-1 in the use of the 18-satellite constellation). From Figures 12.4(b) and 12.5(b) we see that latitude and longitude are determined in each case to better than 20 mm for all stations. However, the height errors range up to 150 mm. The structure of the height errors differs between the two figures. In the first case (present 4-satellite constellation), heights are poorly determined for stations 3, 6, 7 and 8, which form the east-west leg of the Point Sapin network (see Figure 12.1). In the second case (proposed 18-satellite constellation), heights are poorly determined for stations 4, 5 and 8 which are those furthest from the fixed station. These differences in the structure of the height discrepancies are attributed to differences between the geometry of the 4-satellite and 18-satellite constellations (see Figures 12.2 and 12.3). In particular it should be noted that for the 18-satellite constellation no satellites were in the southern half of the sky during the period used for the one hour runs (1800 to 1900 UT).

These results indicate that

a) the height component is not as well determined as the horizontal components;

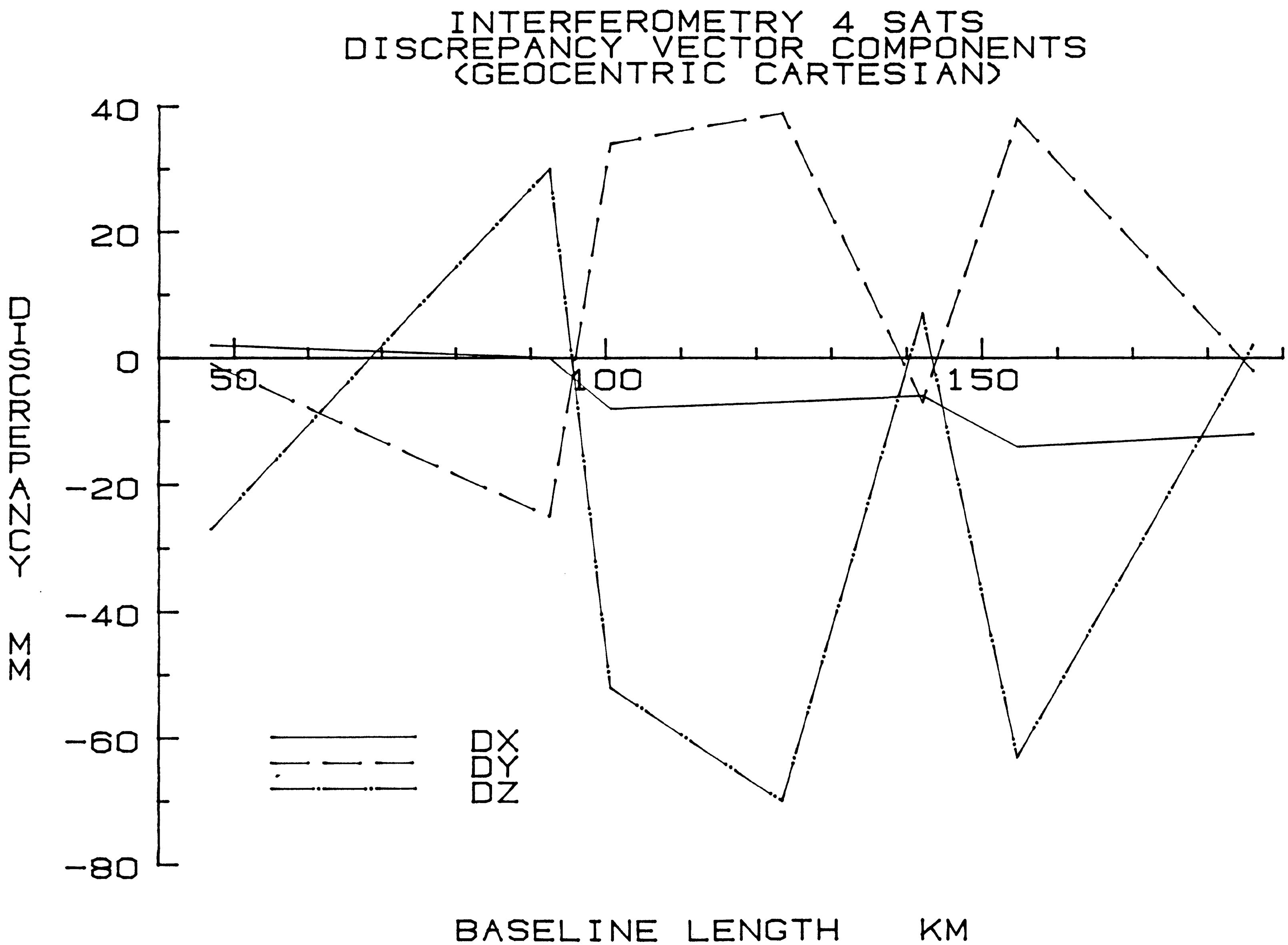


FIGURE 12.4(a)
Discrepancy Vector Components for Run DIGAP-1.

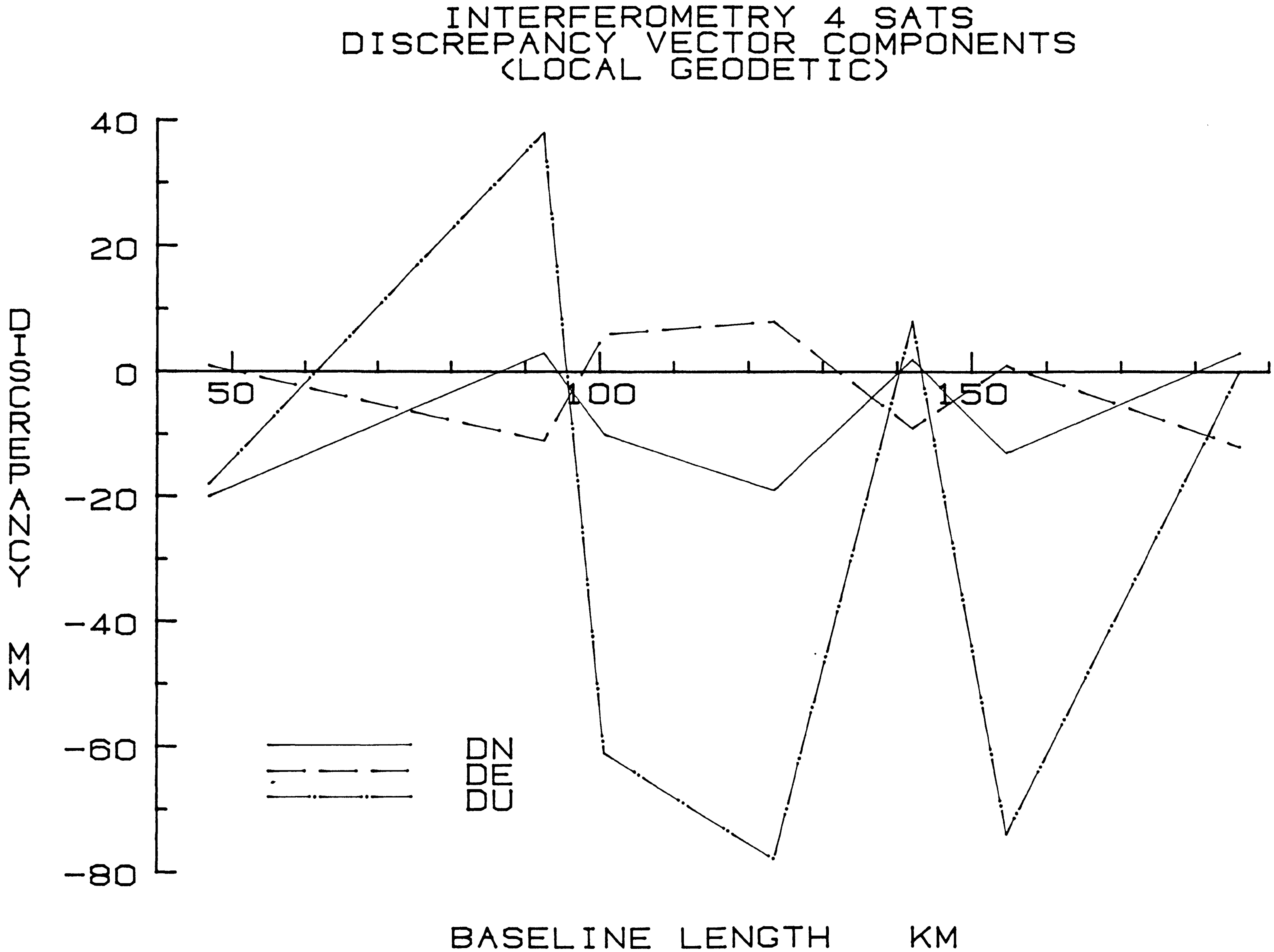


FIGURE 12.4(b)
Discrepancy Vector Components for Run DIGAP-1.

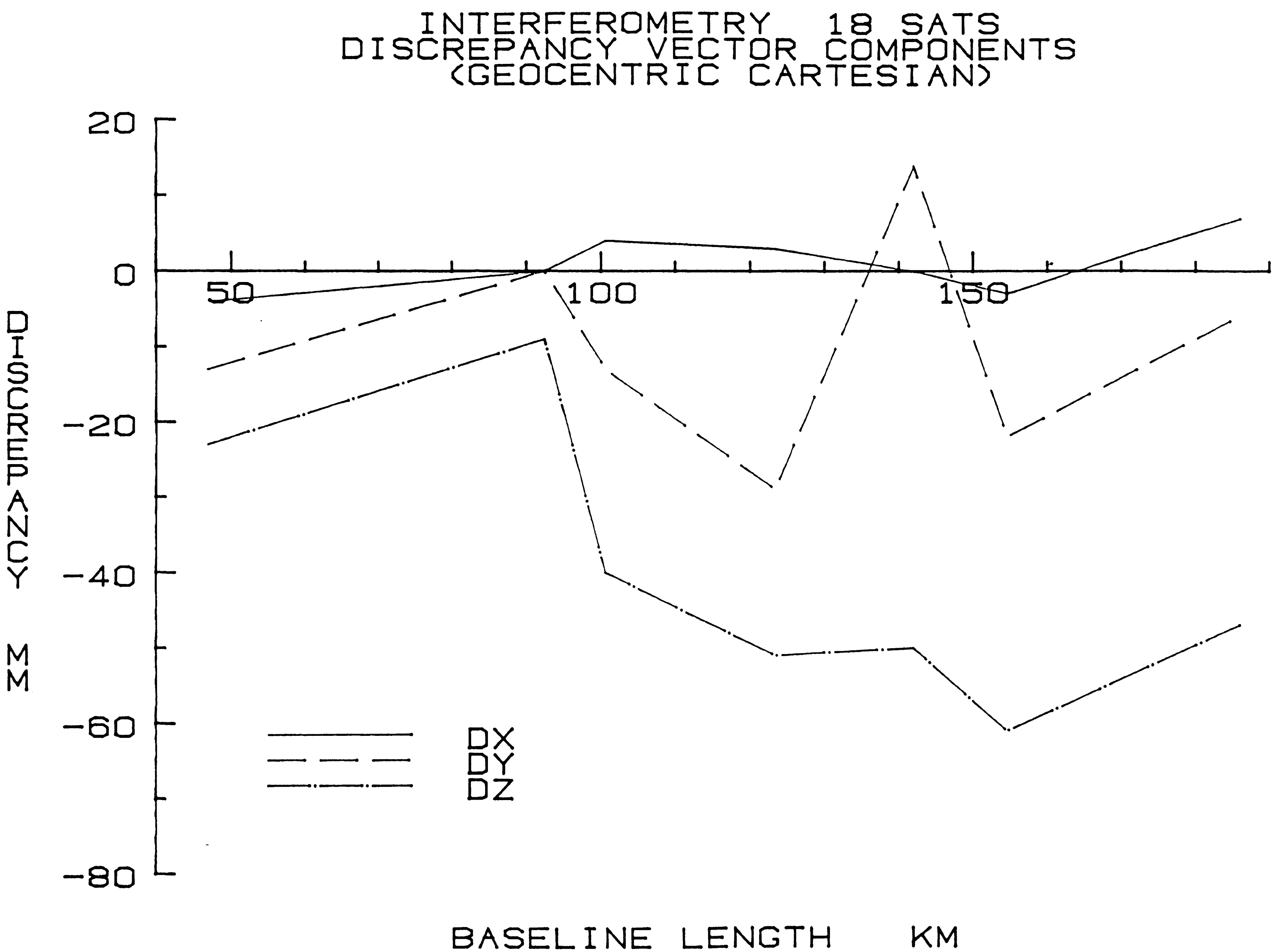


FIGURE 12.5(a)
Discrepancy Vector Components for Run DIGAP-4.

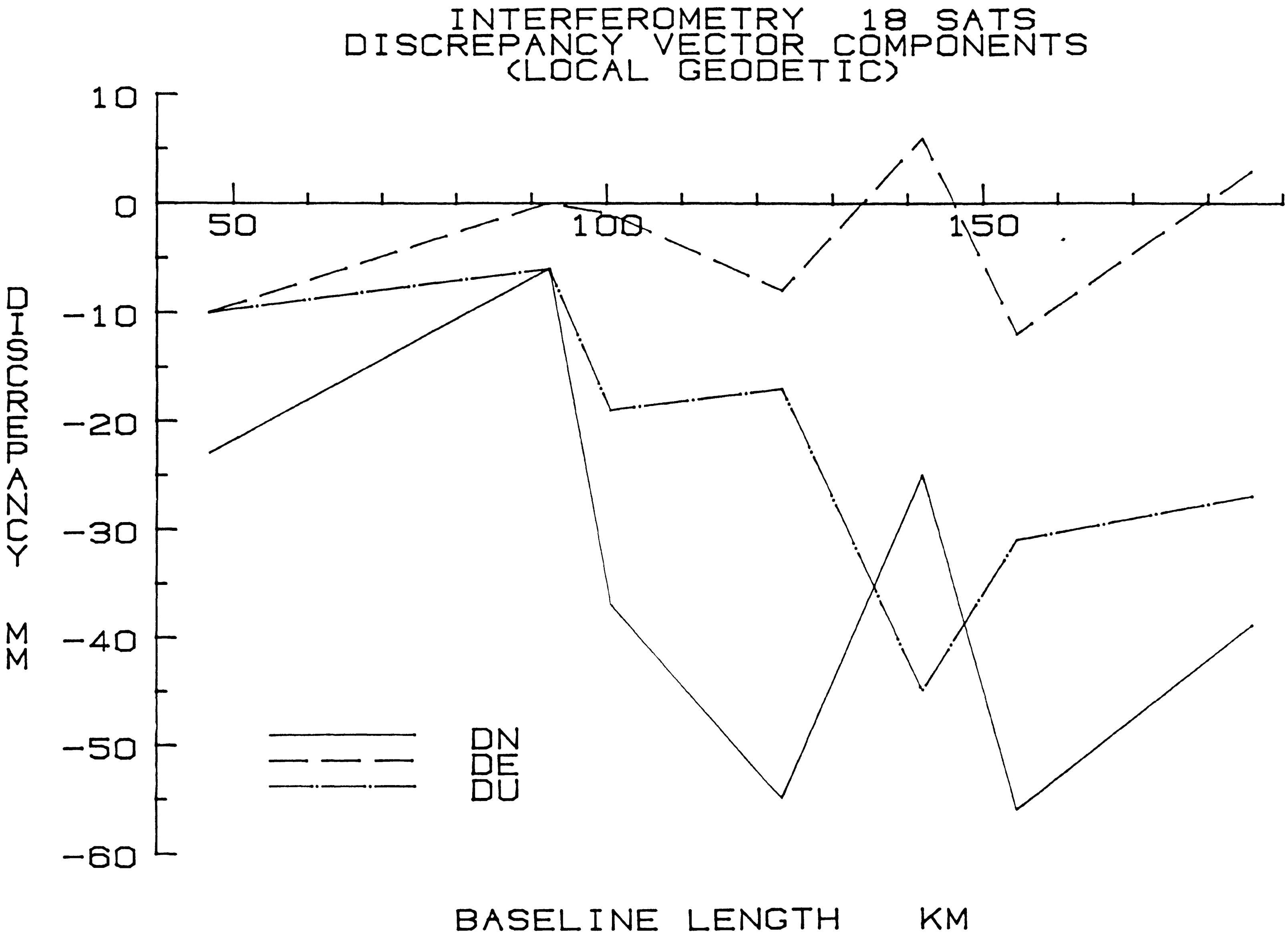


FIGURE 12.5(b)
Discrepancy Vector Components for Run DIGAP-4.

b) the present 4-satellite constellation provides comparably useful satellite geometry to the eventual 18-satellite constellation, although only for part of each day.

Figures 12.6 to 12.15 show the discrepancy vector lengths and consistencies for all 50 DIGAP runs. The discrepancy vector length is as defined in the previous section and is a measure of how well the network positions were recovered. The discrepancy vector consistency is defined as the discrepancy vector length divided by its estimated standard deviation, and is a measure of how well the estimated standard deviation models the actual discrepancy, that is, how consistent the estimated standard deviations and the actual discrepancies are. Perfect consistency would result in uniform values of one for this measure.

Comparison between different FOROBS runs yields measures of different features of differential GPS performance. As can be seen from the last column in Table 12.1(b), the total number of observations was kept roughly constant for all runs, in order that the following comparisons not be clouded by variations in redundancy of the observations. The effect of spreading the same number of observations over different numbers of stations is measured by comparing results from FOROBS-1 and FOROBS-2. The effect of spreading the same number of observations over different time spans (different total satellite geometry variations) is measured by comparing results from FOROBS-2 and FOROBS-3.

The difference between GPS performance today (the present 4-satellite constellation) and when the system is complete (the 18-satellite constellation) is measured by comparing results from FOROBS-1 to FOROBS-3 with results from FOROBS-4 to FOROBS-6. FOROBS-7 is a special run in which the bias terms in the simulated errors for ionospheric and tropospheric refraction and satellite position were suppressed. Comparison between results from FOROBS-6 and FOROBS-7 measures the effect of including (more realistically) or excluding these bias terms. The influence that the proposed Denial of Access degradation of GPS performance will have on differential GPS performance is measured by comparing results from FOROBS-4 to FOROBS-6 with results from FOROBS-8 to FOROBS-10.

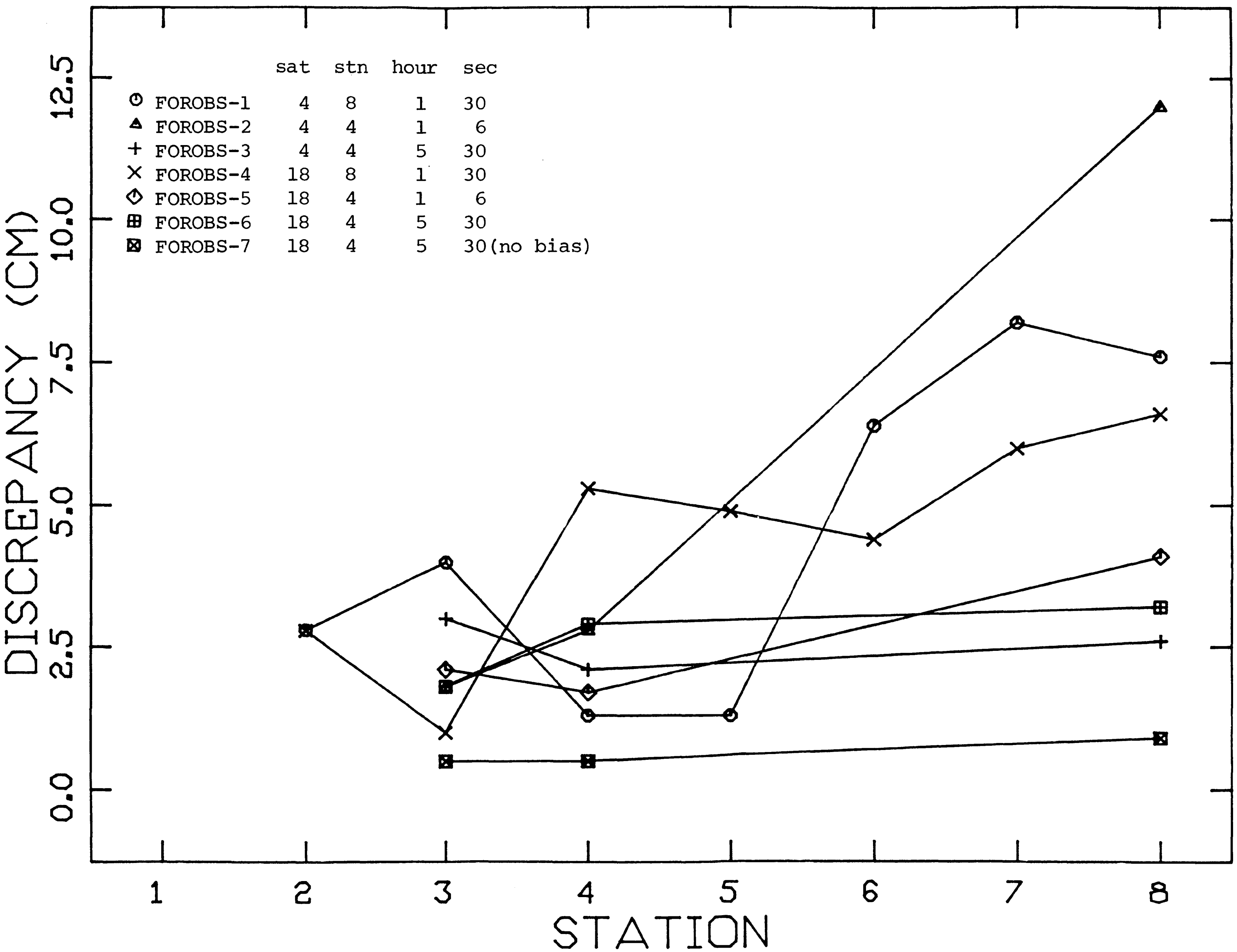


FIGURE 12.6(a)
Discrepancy Vector Lengths for Interferometric Delay Observable.
(DIGAP Runs 1-7; Undegraded Ephemeris.)

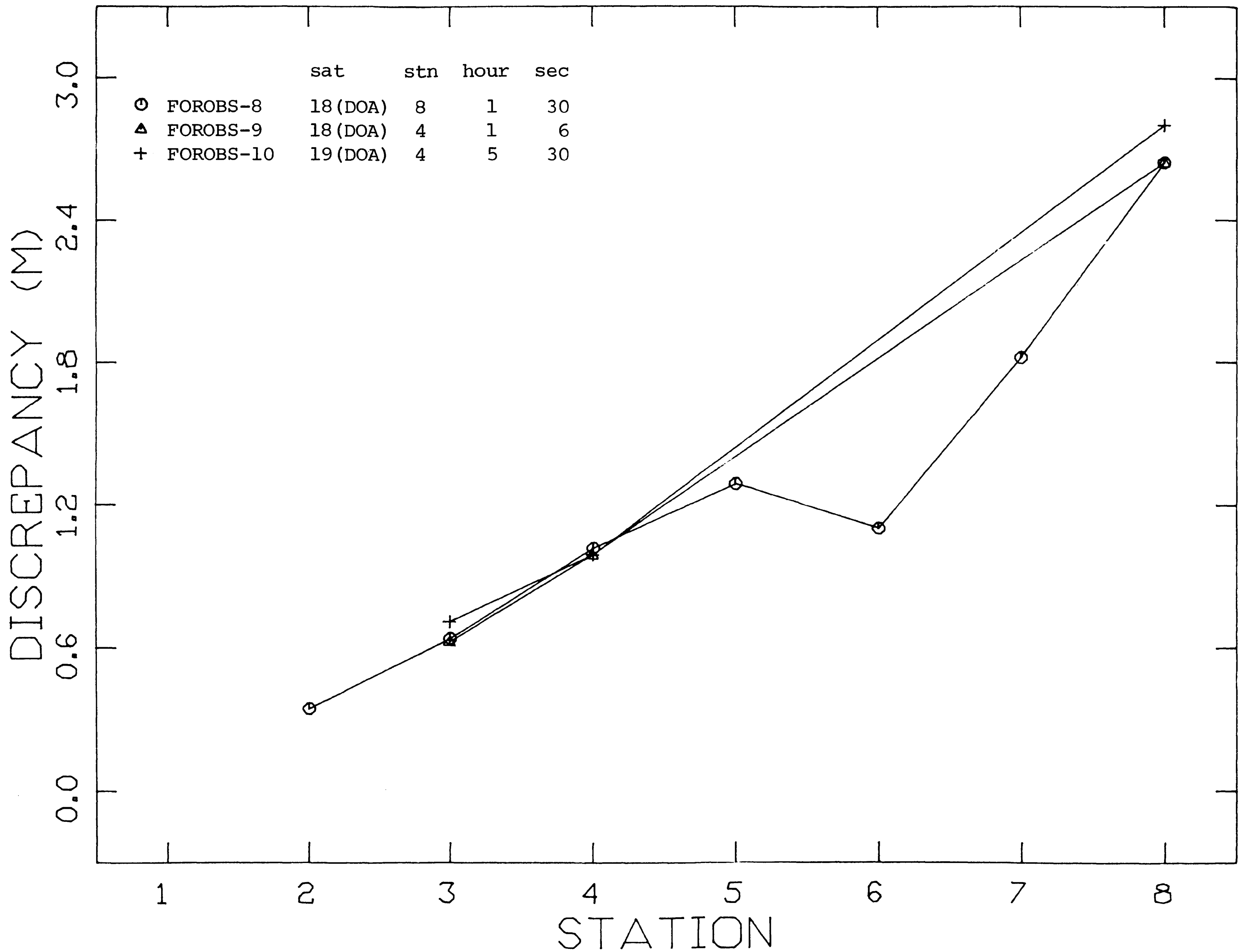


FIGURE 12.6(b)
Discrepancy Vector Lengths for Interferometric Delay Observable.
(DIGAP Runs 8-10; Degraded Ephemeris.)

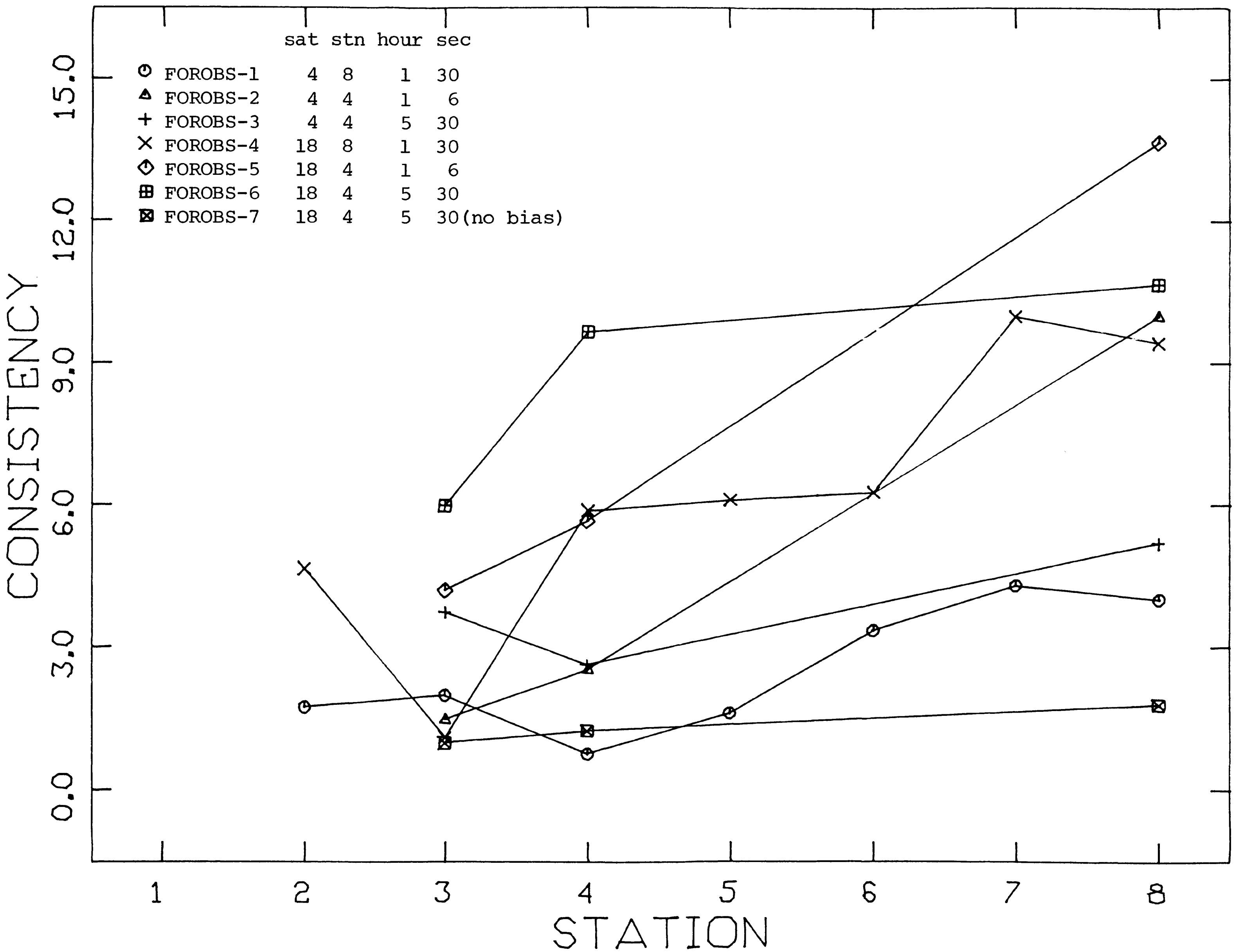


FIGURE 12.7(a)
Discrepancy Vector Consistency for Interferometric Delay Observable.
(DIGAP Runs 1-7; Undegraded Ephemeris.)

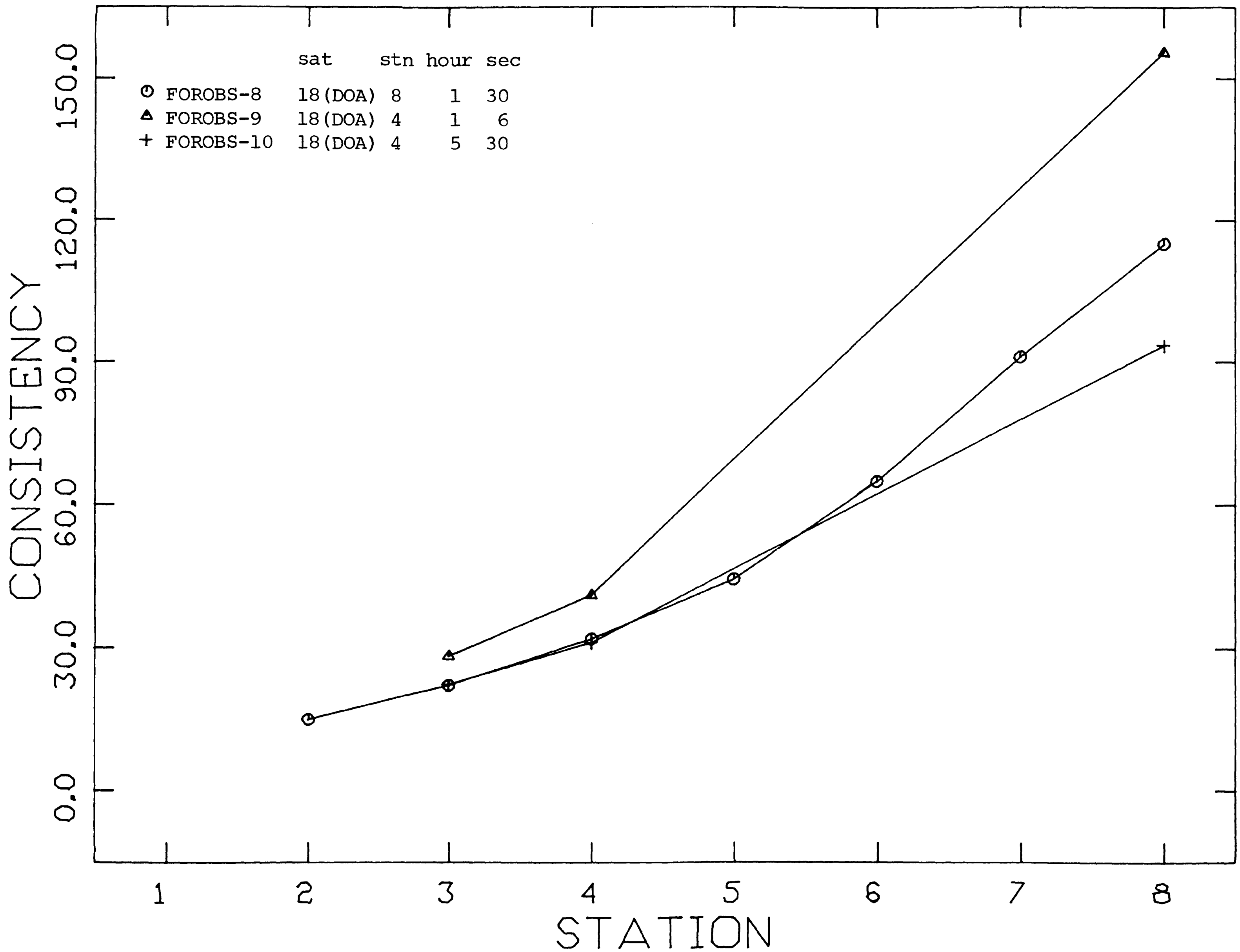


FIGURE 12.7(b)
Discrepancy Vector Consistency for Interferometric Delay Observable.
(DIGAP Runs 8-10; Degraded Ephemeris.)

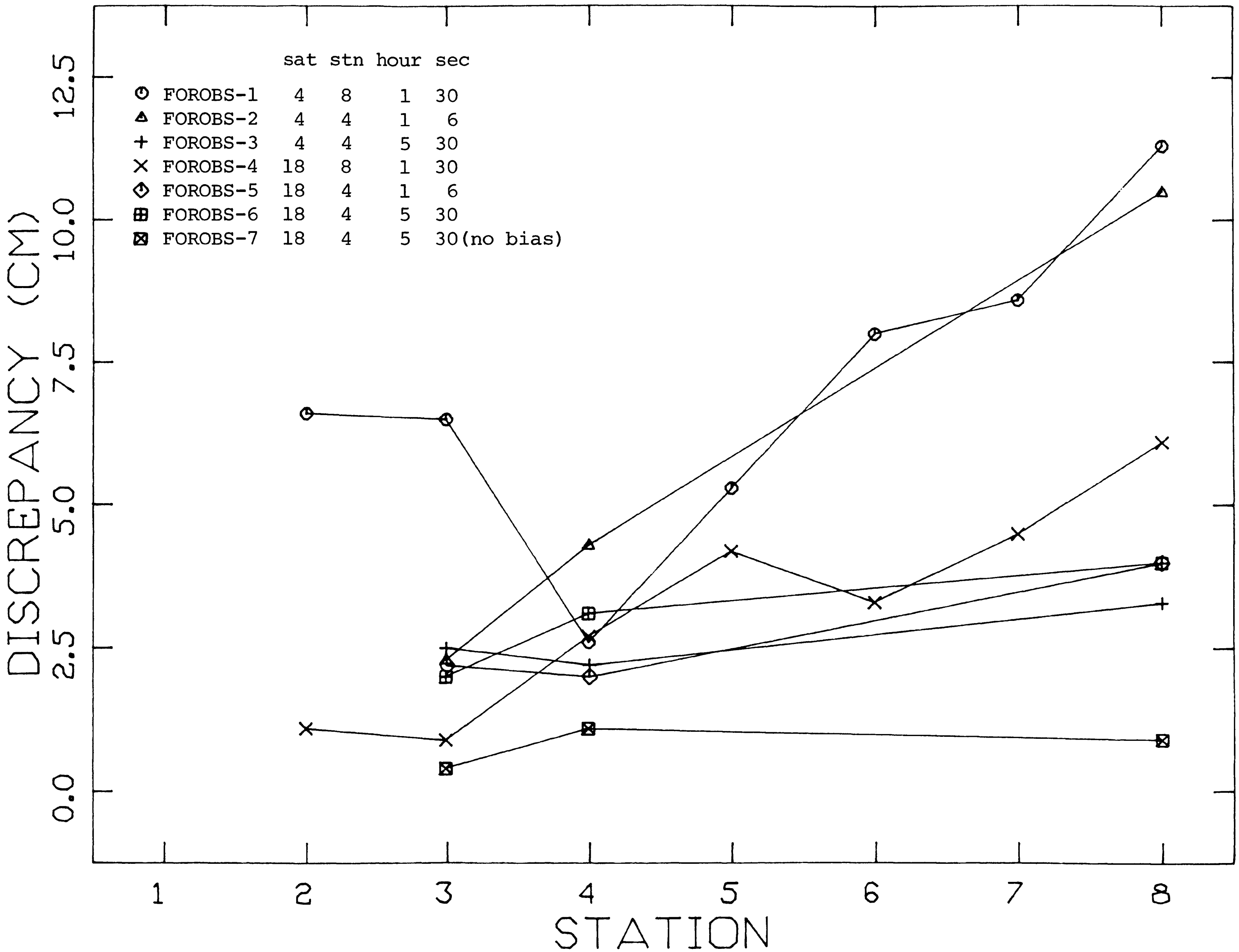


FIGURE 12.8(a)
Discrepancy Vector Lengths for Differential Carrier Phase Observable.
(DIGAP Runs 11-17; Undegraded Ephemeris.)

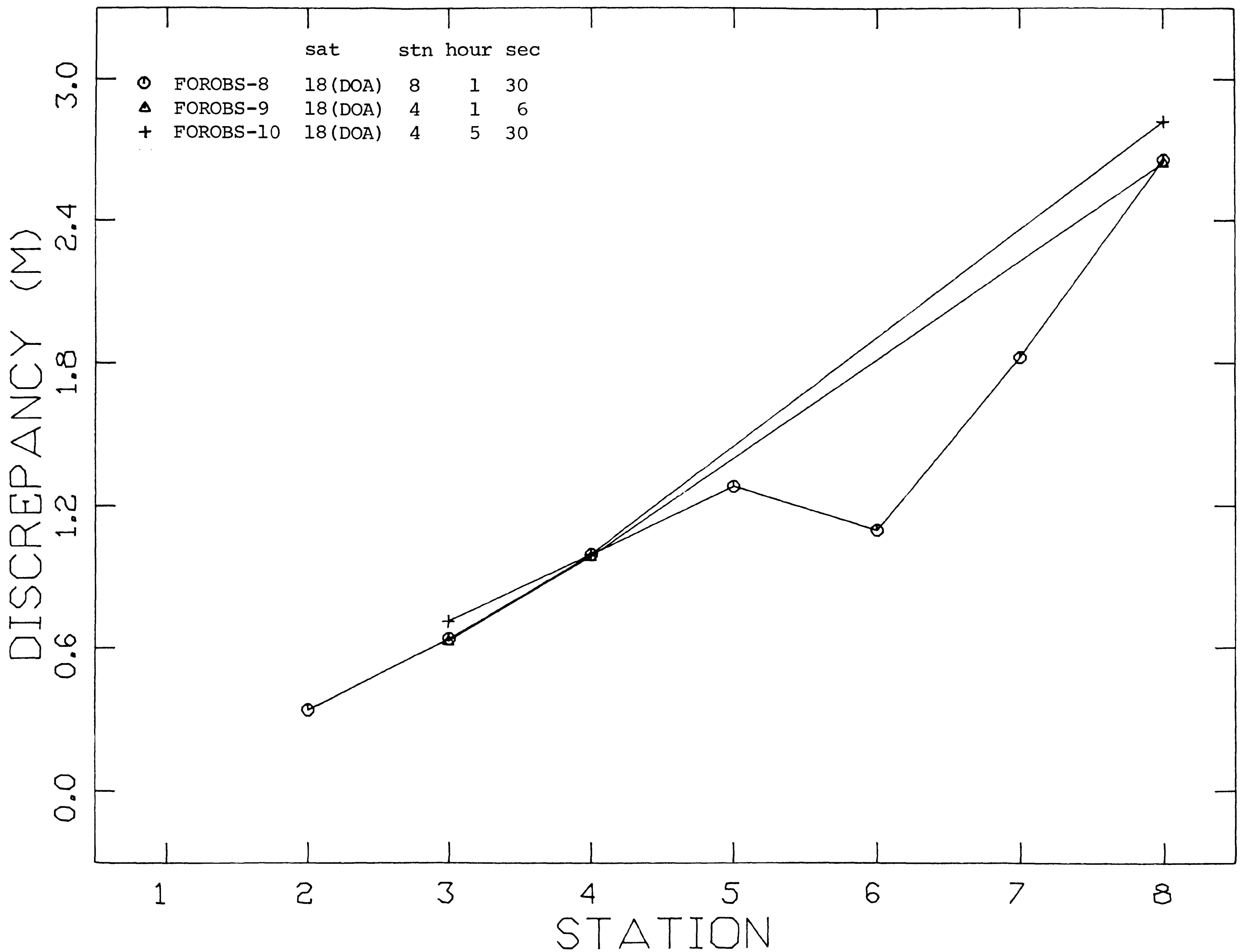


FIGURE 12.8(b)

Discrepancy Vector Lengths for Differential Carrier Phase Observable.
(DIGAP Runs 18-20; Degraded Ephemeris.)

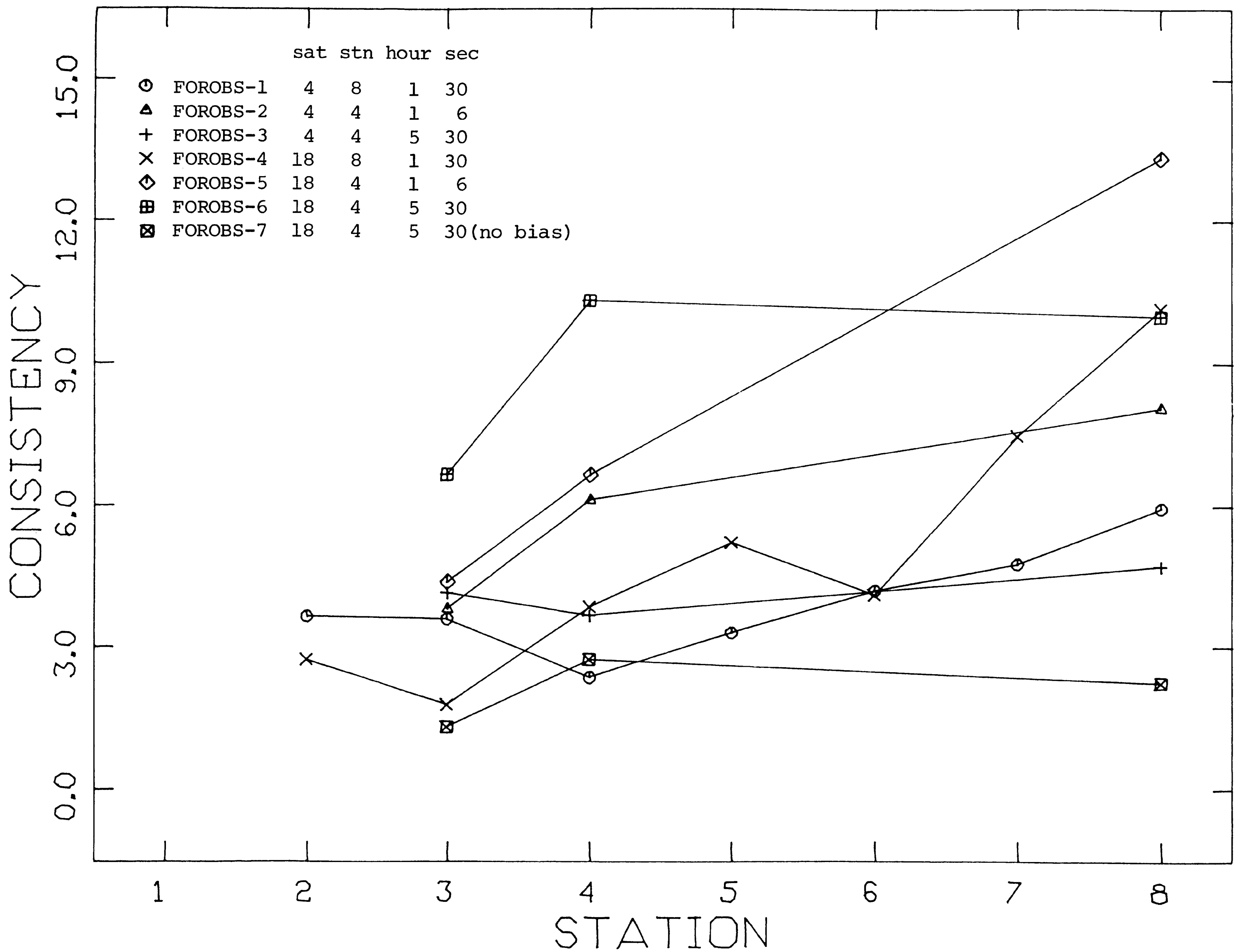


FIGURE 12.9(a)
Discrepancy Vector Consistency for Differential Carrier Phase Observable.
(DIGAP Runs 11-17; Undegraded Ephemeris.)

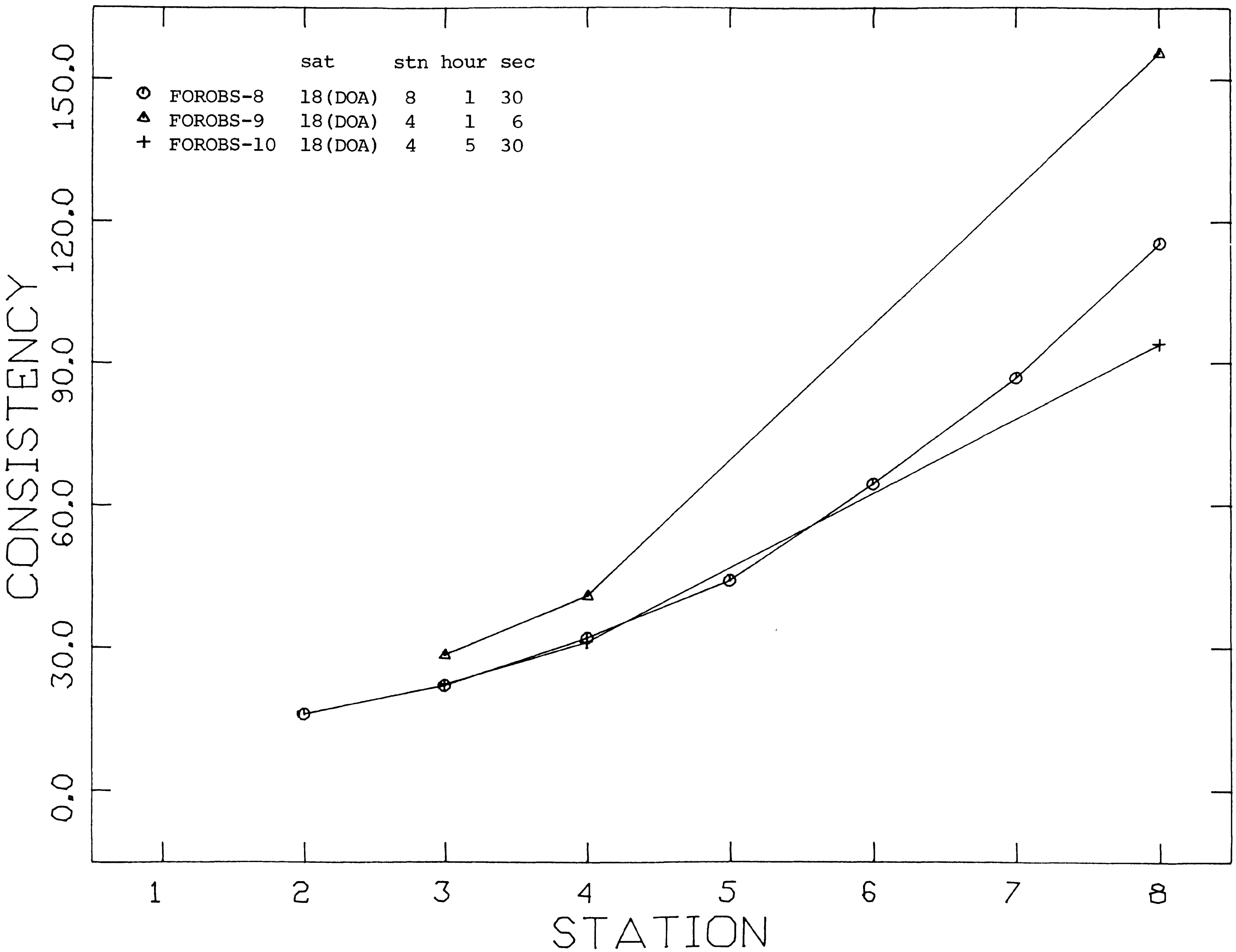


FIGURE 12.9(b)
Discrepancy Vector Consistency for Differential Carrier Phase Observable.
(DIGAP Runs 18-20; Degraded Ephemeris.)

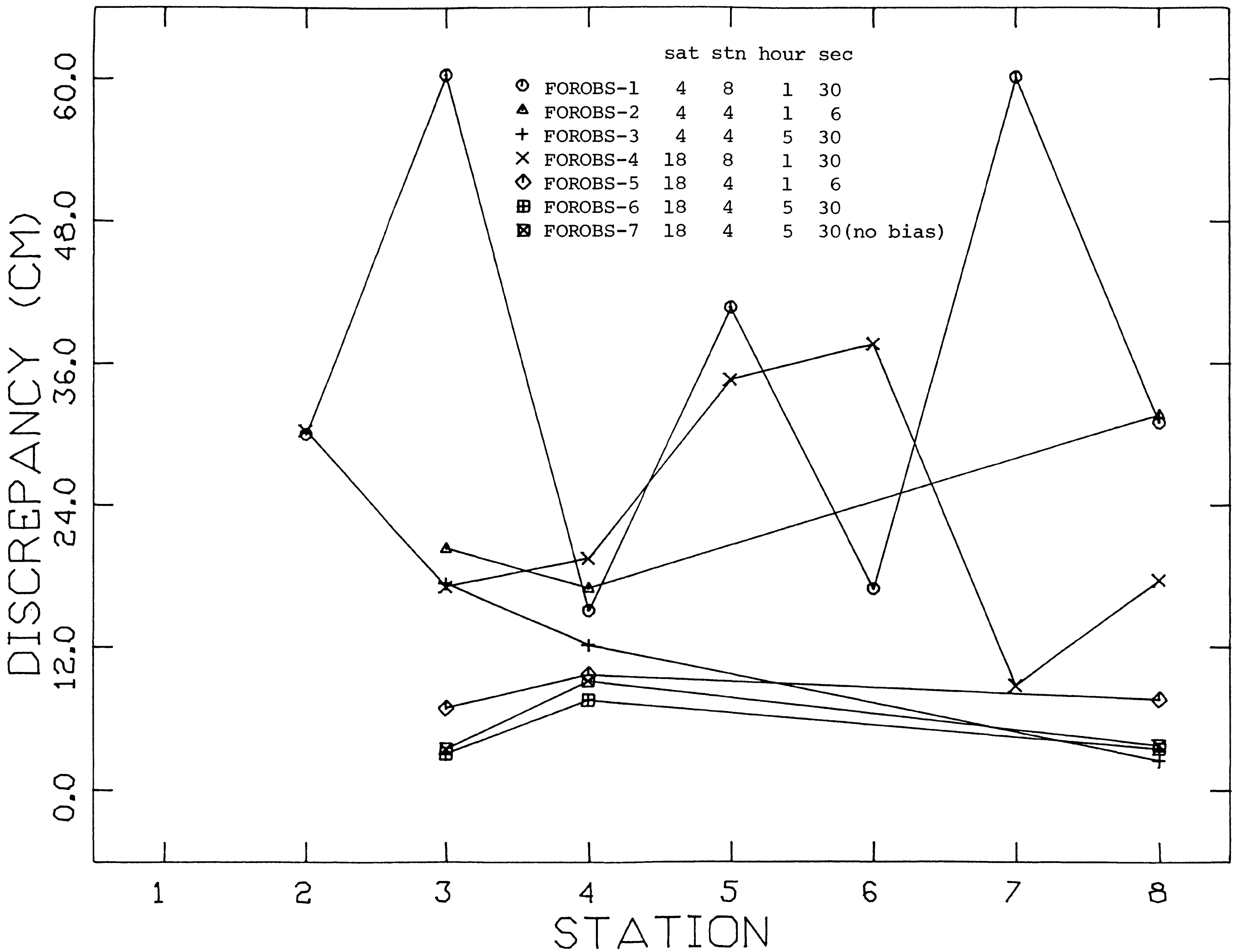


FIGURE 12.10(a)
Discrepancy Vector Lengths for P-Code Differential Pseudorange Observable.
(DIGAP Runs 21-27; Undegraded Ephemeris.)

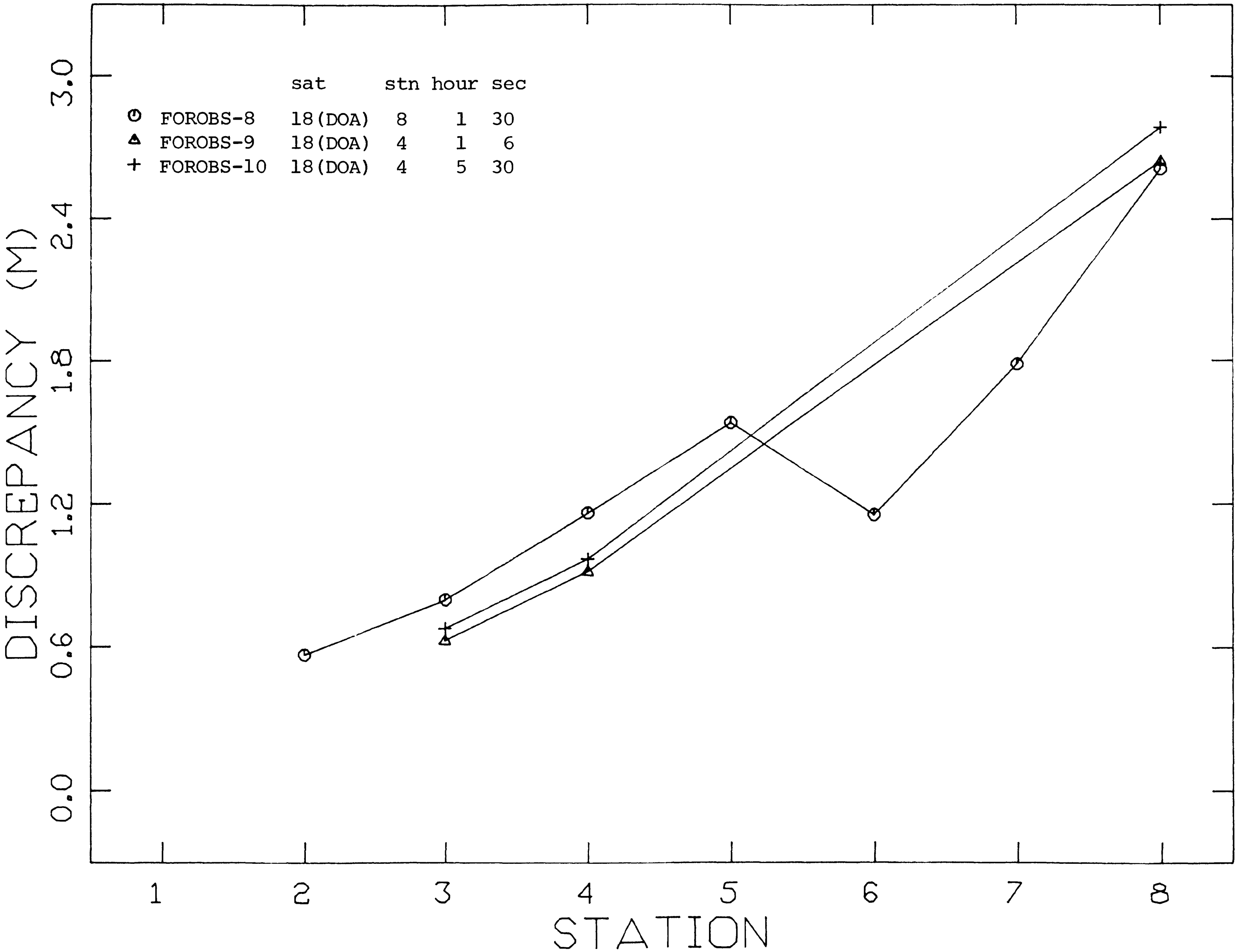


FIGURE 12.10(b)
Discrepancy Vector Lengths for P-Code Differential Pseudorange Observable.
(DIGAP Runs 28-30; Degraded Ephemeris.)

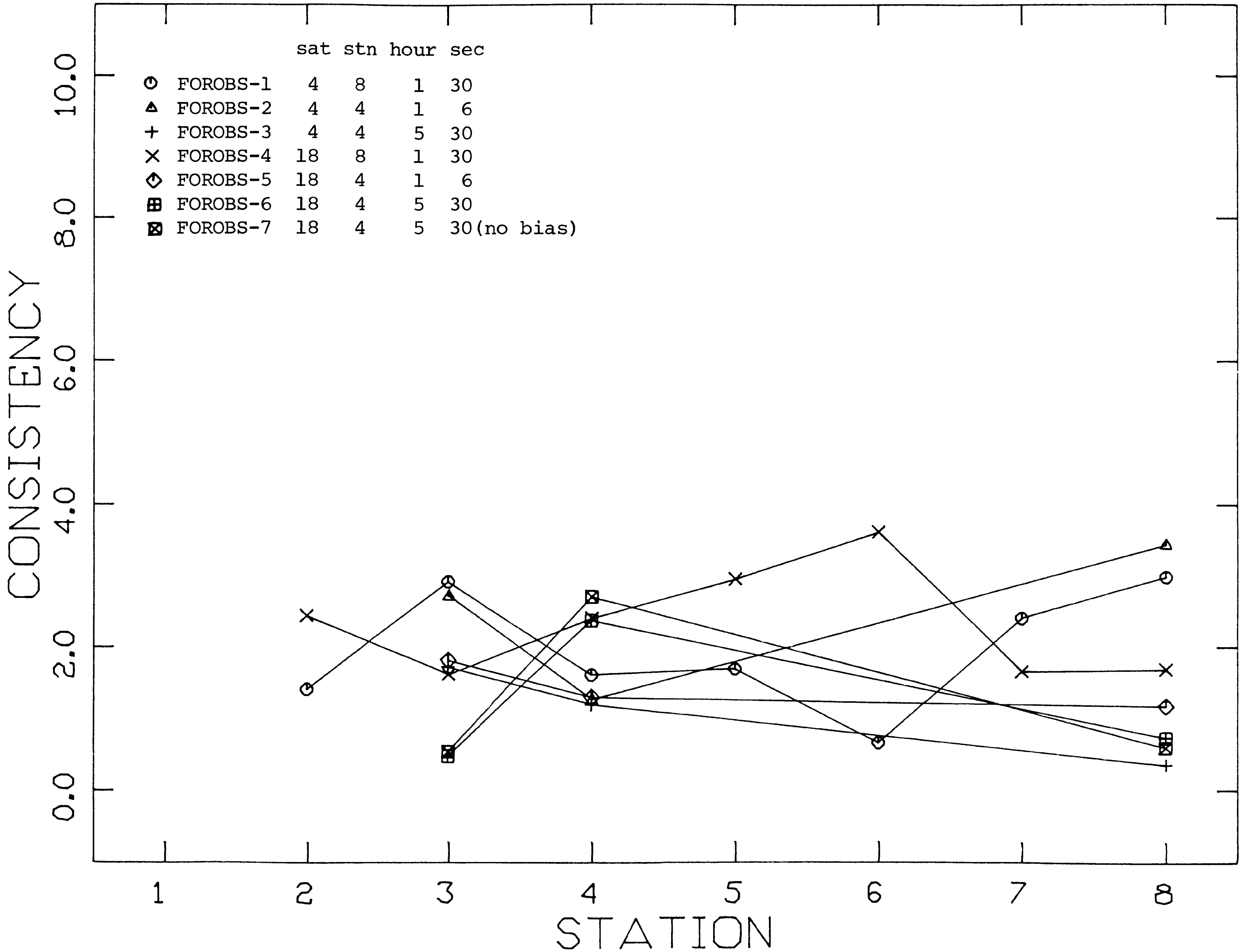


FIGURE 12.11(a)
Discrepancy Vector Consistency for P-Code Differential Pseudorange Observable.
(DIGAP Runs 21-27; Undegraded Ephemeris.)

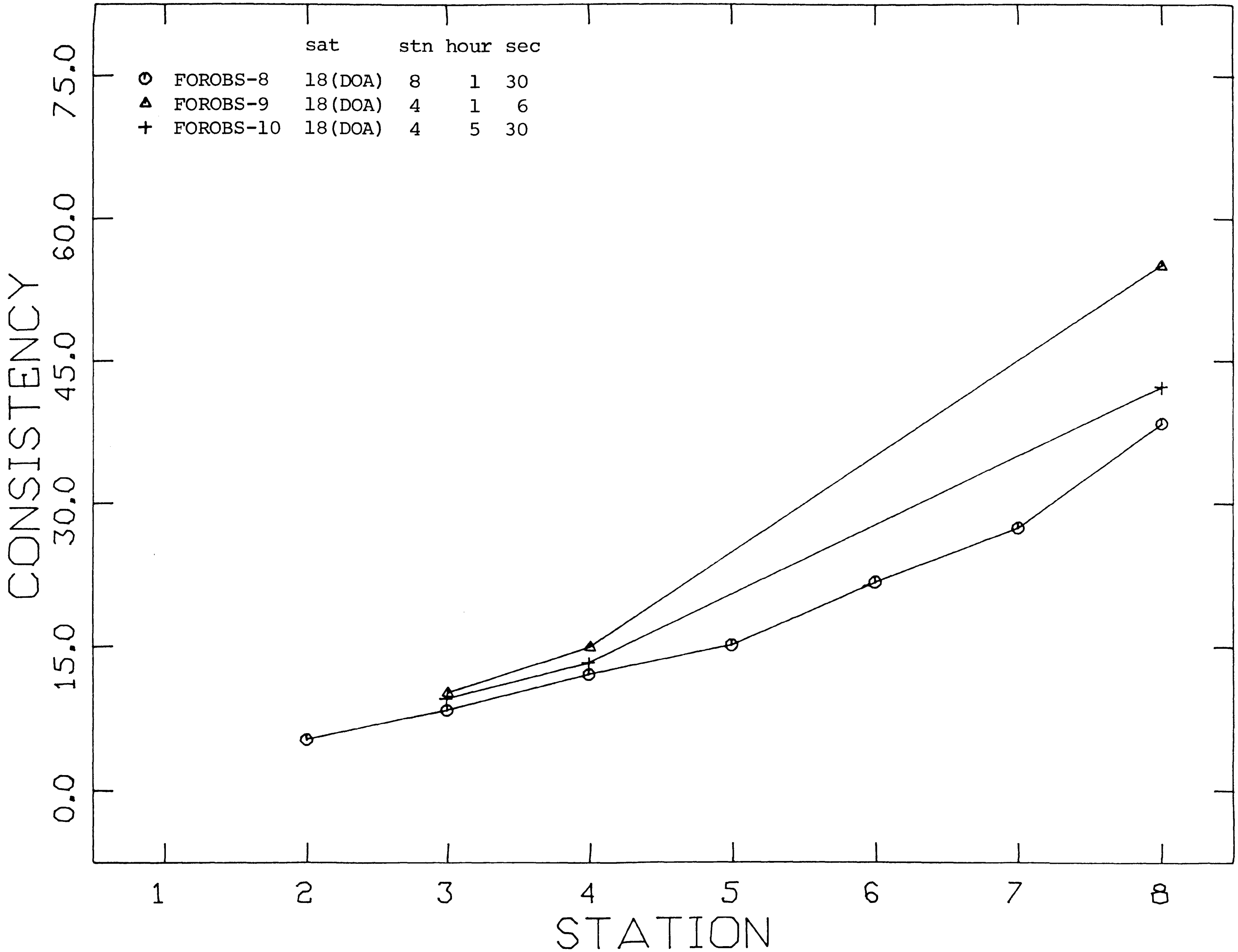


FIGURE 12.11(b)
Discrepancy Vector Consistency for P-Code Differential Pseudorange Observable.
(DIGAP Runs 28-30; Degraded Ephemeris.)

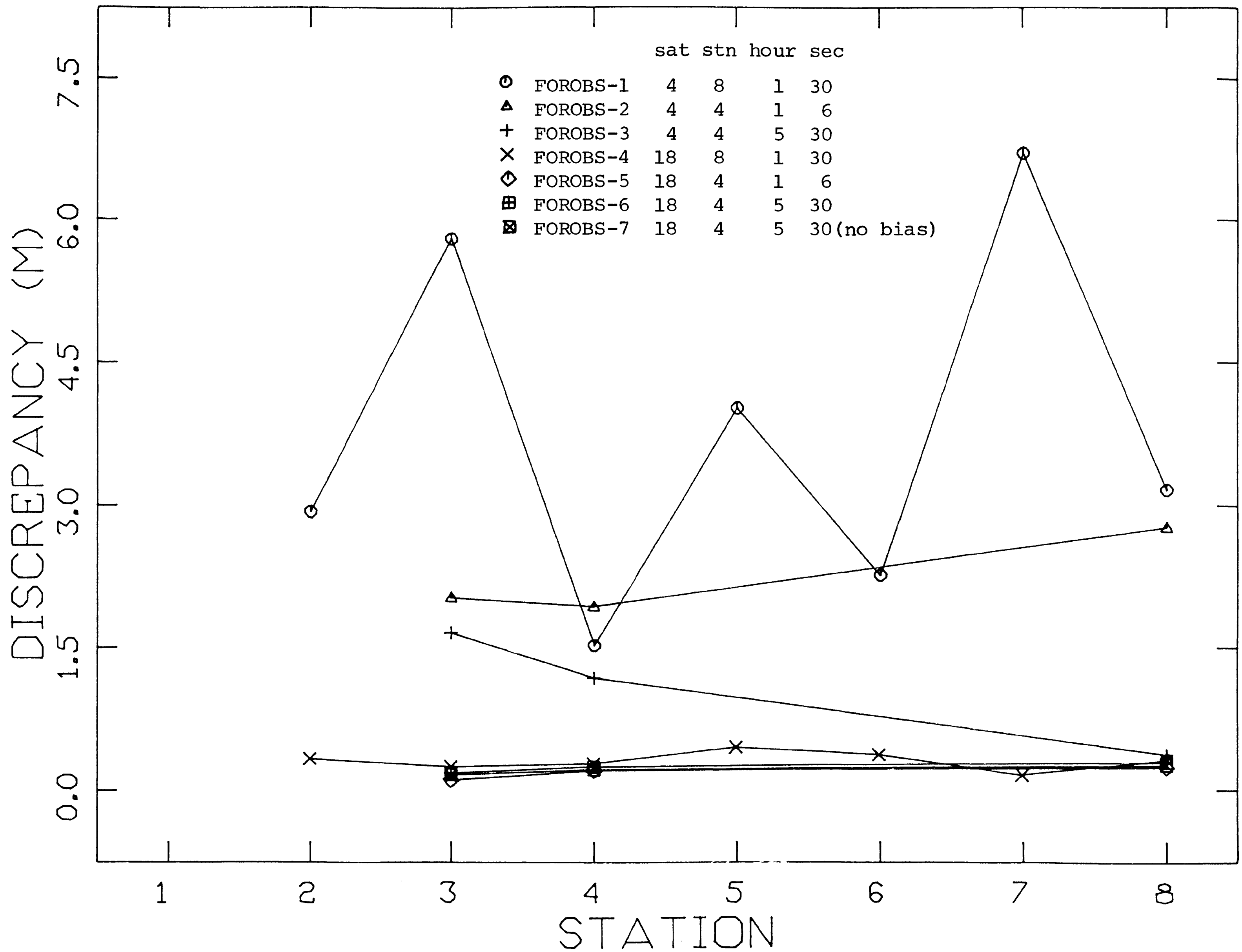


FIGURE 12.12(a)

Discrepancy Vector Lengths for C/A-Code Differential Pseudorange Observable.
(DIGAP Runs 31-37; Undegraded Ephemeris.)

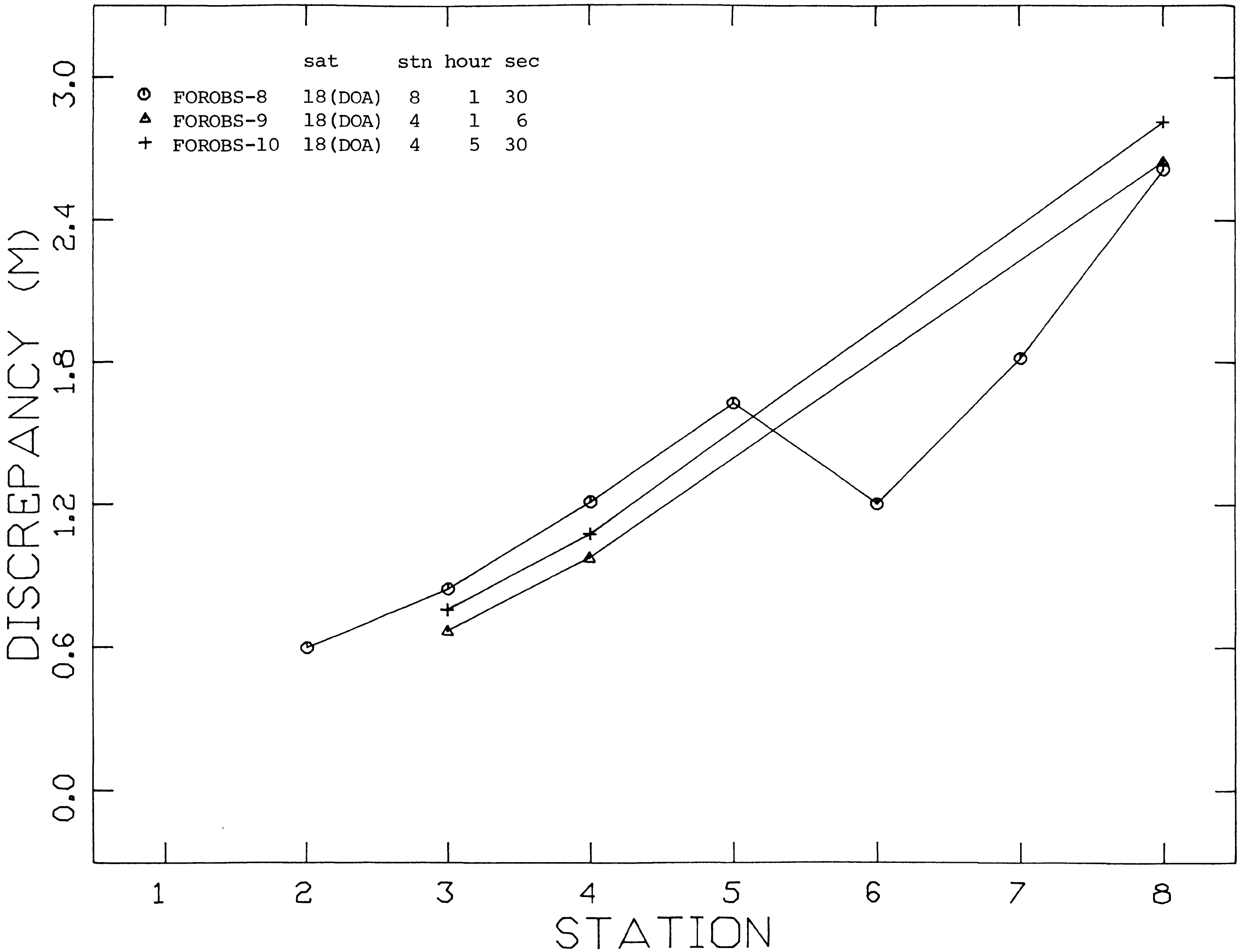


FIGURE 12.12(b)
Discrepancy Vector Lengths for C/A-Code Differential Pseudorange Observable.
(DIGAP Runs 38-40; Degraded Ephemeris.)

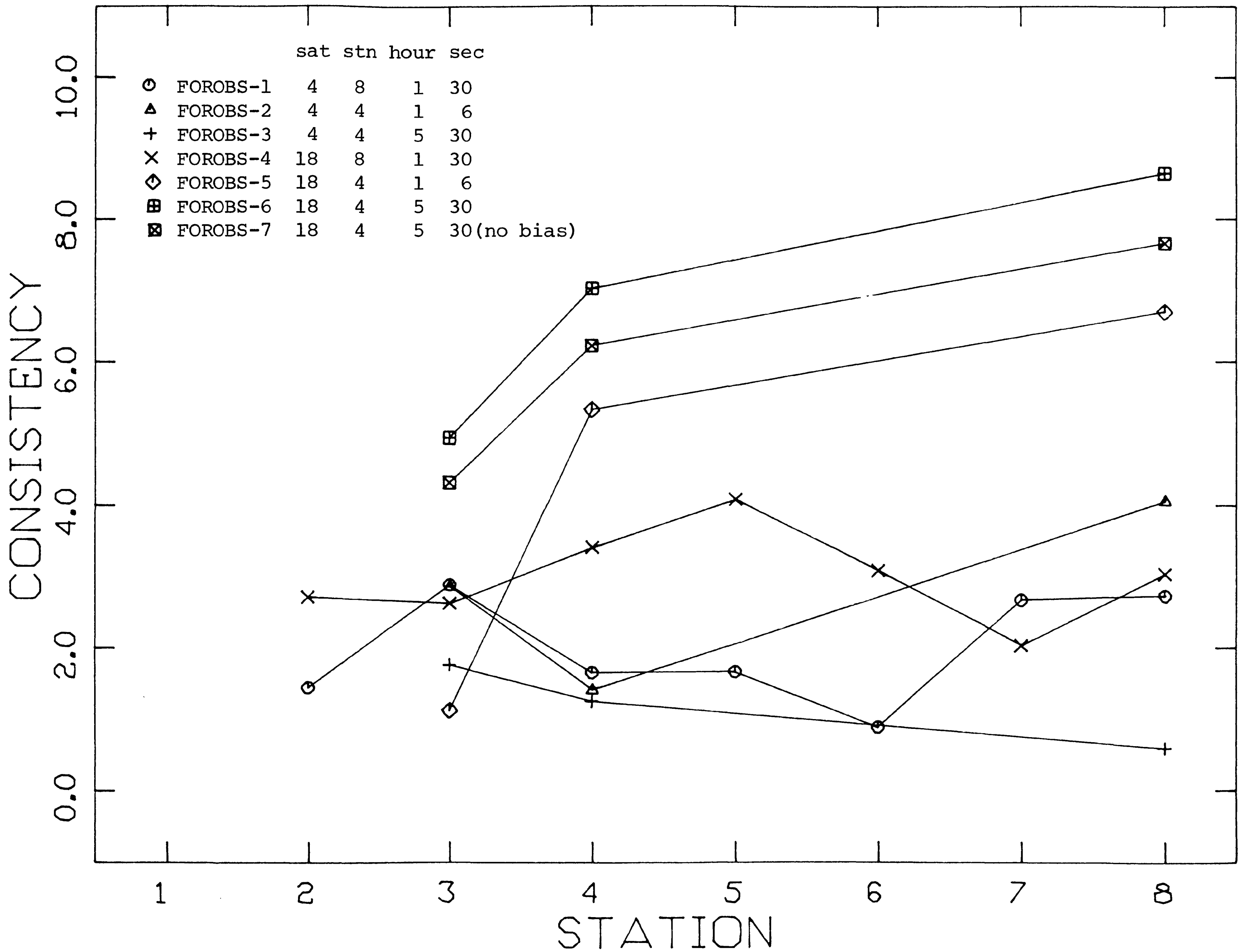


FIGURE 12.13(a)

Discrepancy Vector Consistency for C/A-Code Differential Pseudorange Observable.
(DIGAP Runs 31-37; Undegraded Ephemeris.)

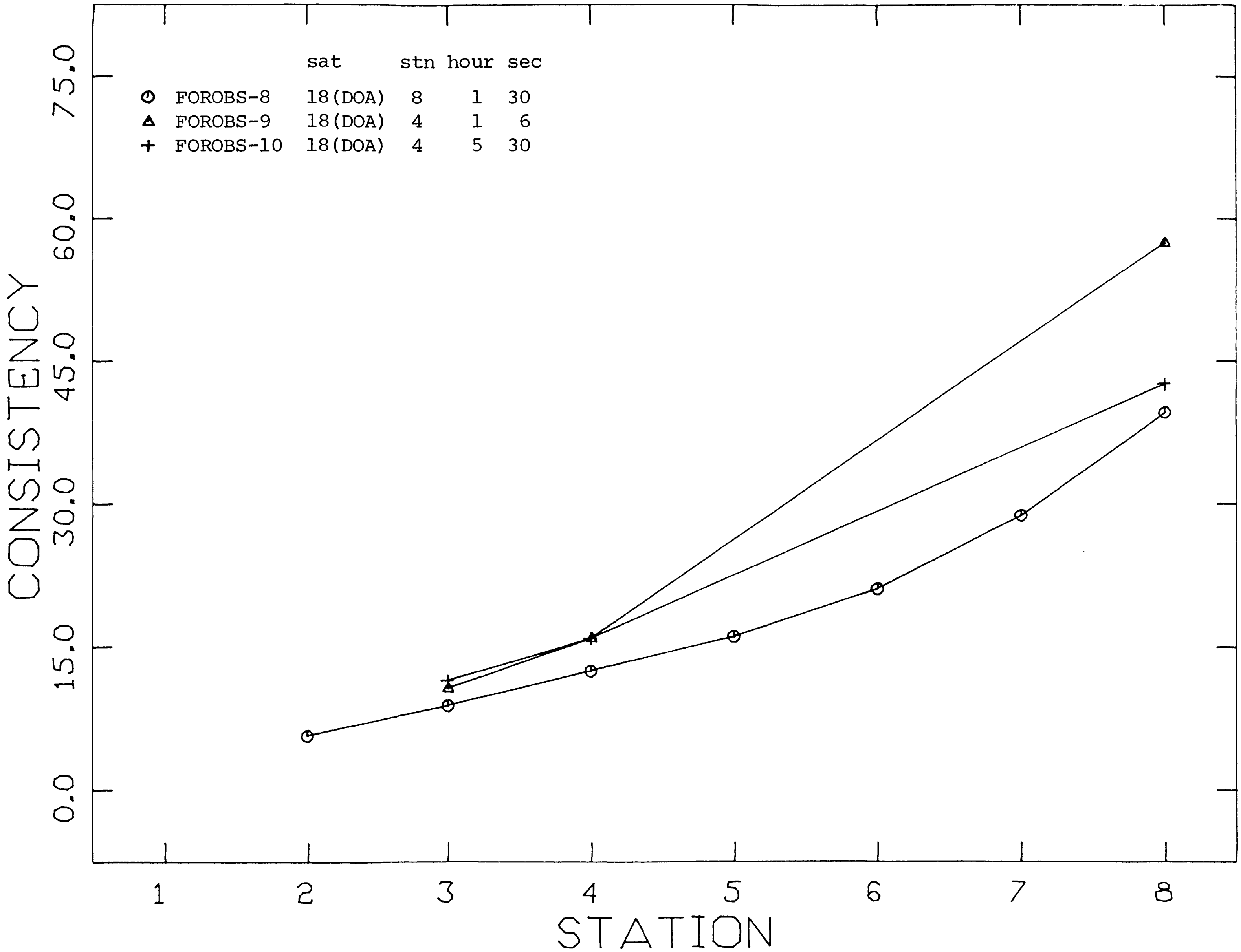


FIGURE 12.13(b)

Discrepancy Vector Consistency for C/A-Code Differential Pseudorange Observable.
(DIGAP Runs 38-40; Degraded Ephemeris.)

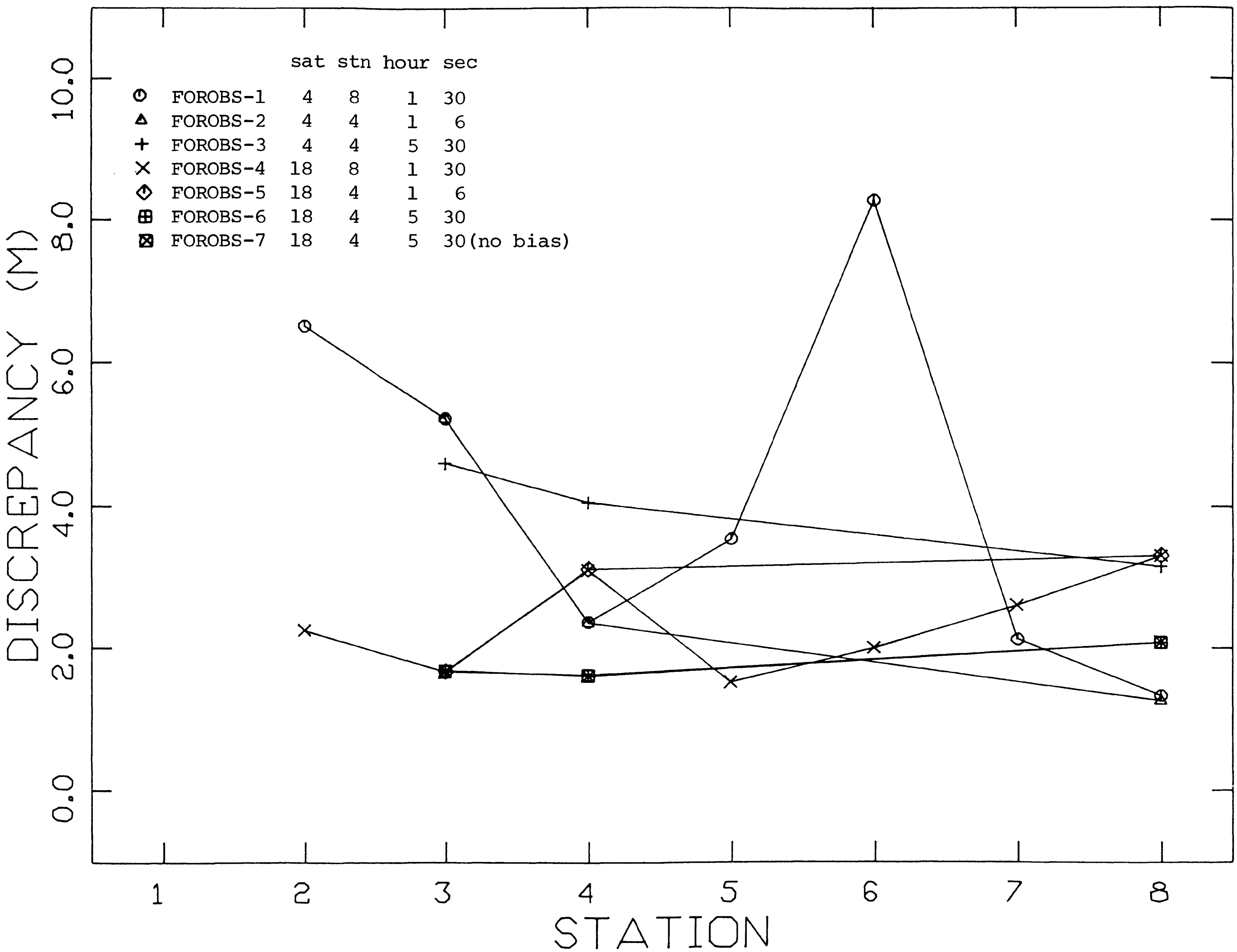


FIGURE 12.14(a)
Discrepancy Vector Lengths for Differential Doppler Observable.
(DIGAP Runs 41-47; Undegraded Ephemeris.)

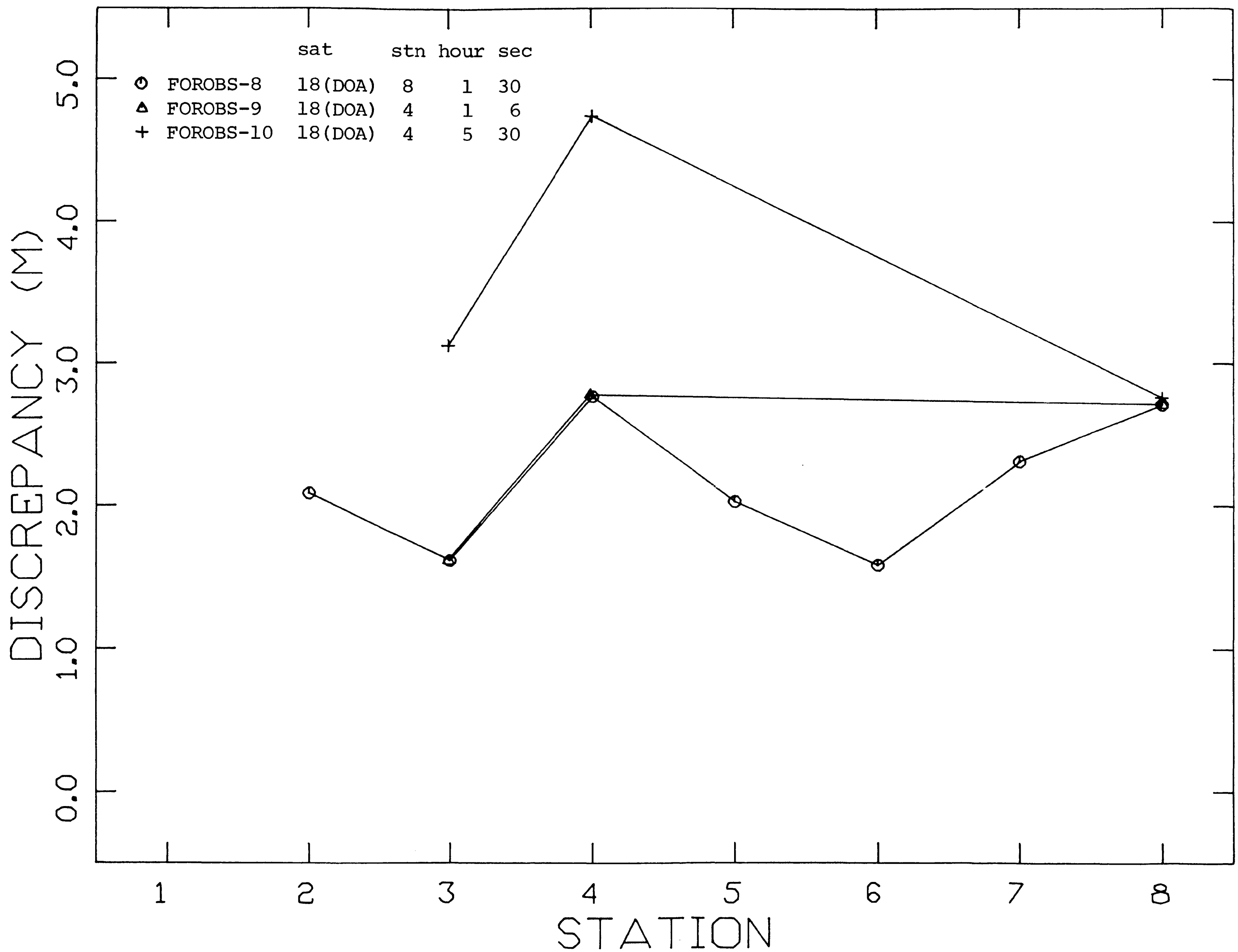


FIGURE 12.14(b)
Discrepancy Vector Lengths for Differential Doppler Observable.
(DIGAP Runs 48-50; Degraded Ephemeris.)

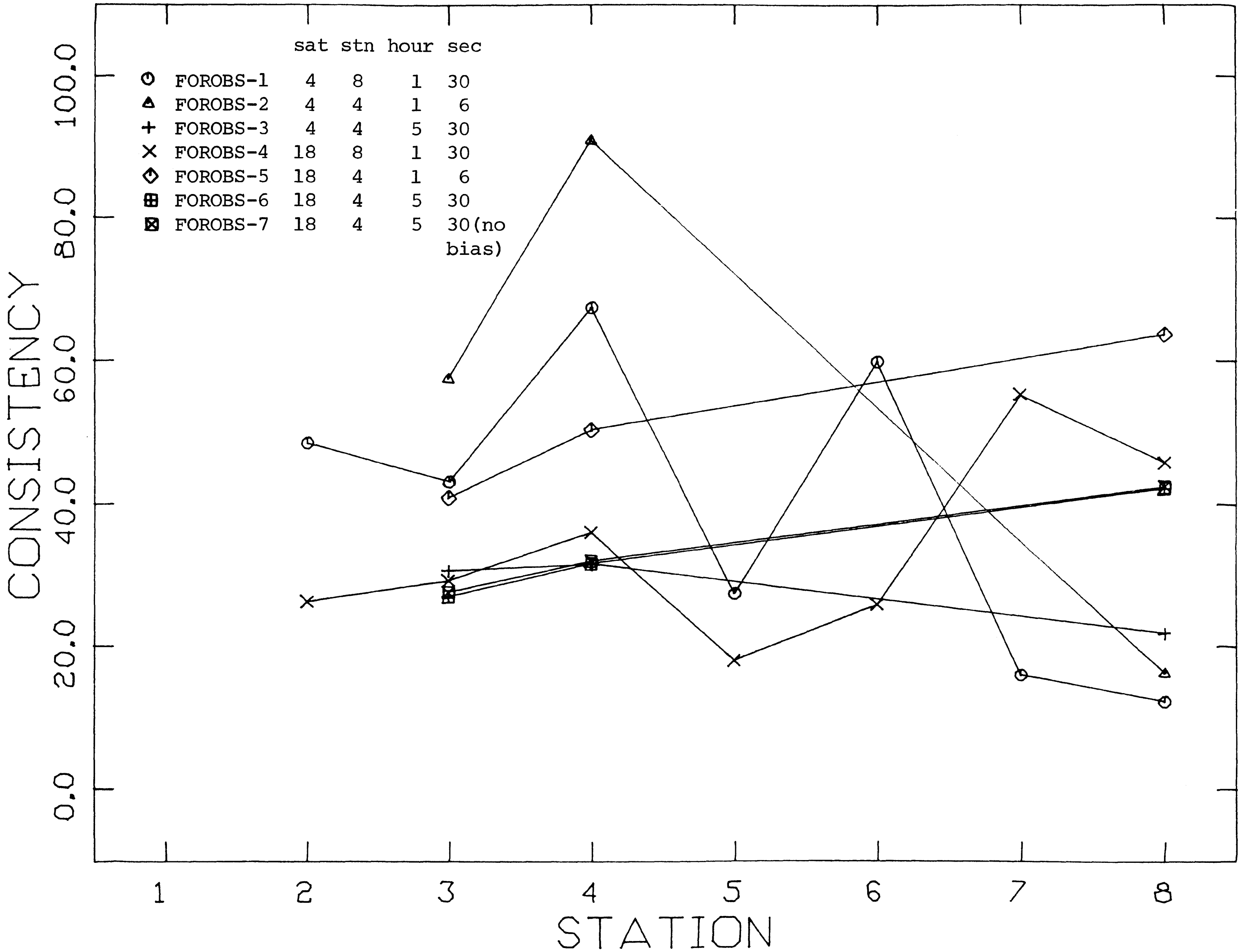


FIGURE 12.15(a)
Discrepancy Vector Consistency for Differential Doppler Observable.
(DIGAP Runs 41-47; Undegraded Ephemeris.)

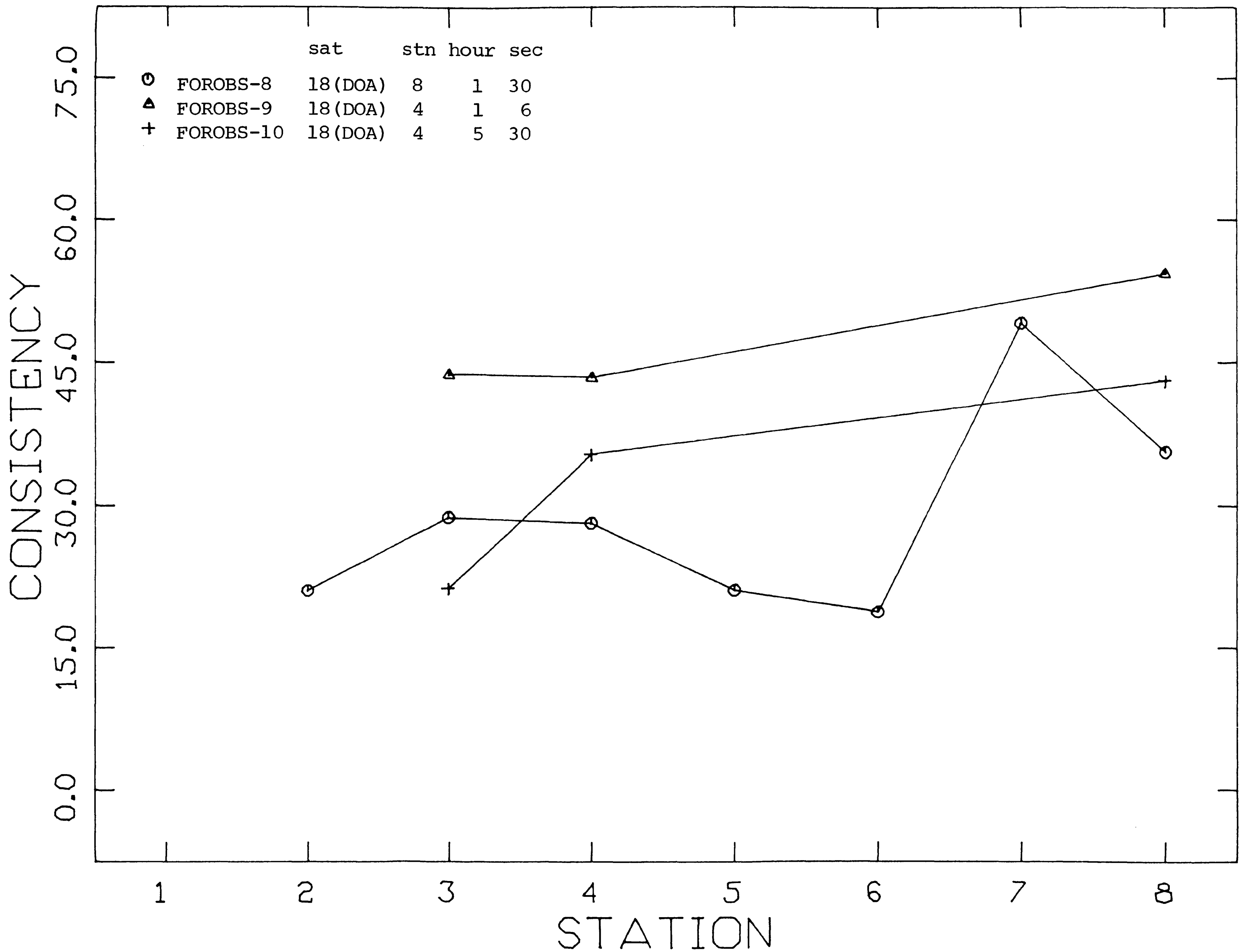


FIGURE 12.15(b)
Discrepancy Vector Consistency for Differential Doppler Observable.
(DIGAP Runs 48-50; Degraded Ephemeris.)

Examination of Figures 12.6 to 12.15 reveals the following:

a) For all observation types (except possibly differential Doppler), results from the 4-station network had smaller discrepancies than from the 8-station network.

b) For all observation types results from the five hour time span runs generally had smaller discrepancies and better consistencies than from the one hour time span.

c) For all observation types the discrepancies resulting from the 4-satellite runs are generally larger than for the 18-satellite runs. However, there was no marked difference between the 4-satellite and 18-satellite consistencies, except for C/A-code differential pseudoranging and differential Doppler, for which the 4-satellite consistency was better.

d) The removal of simulated bias errors reduced the discrepancies and improved the consistencies for the interferometric delay and differential carrier phase observation types, but left the results for the other observation types unchanged.

e) Discrepancies using the interferometric delay and differential carrier phase observation types are typically below 8 cm.

f) Discrepancies using the P-code differential pseudorange observation type are typically below 50 cm.

g) Discrepancies using the C/A-code differential pseudorange observation type and using the differential Doppler observation type are typically below 5 m.

h) Consistencies using the interferometric delay and differential carrier phase results are typically below 10; using the P-code differential pseudorange technique they are typically below 3; using the C/A -code differential pseudorange technique they are typically below 8; and using the differential Doppler technique they are typically below 60. This indicates severely overoptimistic estimates of the Doppler standard deviations.

i) With the exception of differential Doppler, the Denial of Accuracy results revealed an approximately linear degradation with baseline length in both discrepancy and consistency. This is expected, since the orbit biases introduced to simulate Denial of Accuracy were left unmodelled in the adjustment.

j) The Denial of Accuracy degradation worsened the discrepancies typically by the following factors:

- 25 times worse for interferometric delay and differential carrier phase techniques.
- 5 times worse for the two pseudoranging techniques.
- No significant change for the differential Doppler technique.

k) The Denial of Accuracy degradation worsened the consistencies by roughly a factor of 10 for all observation techniques, except for differential Doppler, for which there was no significant change.

l) The Denial of Accuracy results were not significantly affected by the observation time span (the 1-hour and 5-hour results were similar).

Chapter 13
CONCLUSIONS AND RECOMMENDATIONS

13.1 Conclusions

We have developed mathematical models and computer software to generate and process simulated differential GPS observations, and (with some additional development) actual differential GPS observations, when they become available in the near future.

We have identified applications for differential GPS positioning, including crustal movement monitoring (with an accuracy specification of 1 cm to 2 cm), mining subsidence (5 cm to 10 cm), rural cadastral surveying (25 cm to 50 cm), and mapping control (5 m).

Our simulations indicate that

(a) interferometric delay and differential carrier phase observations are capable of satisfying all of the above specifications (given appropriate satellite constellations and observing time spans);

(b) P-code differential pseudorange observations can satisfy all but the first of the above specifications;

(c) C/A-code differential pseudorange observations and differential Doppler observations probably are capable of satisfying the last of the above specifications.

13.2 Denial of Accuracy Considerations

In this study a first attempt was made at determining the possible effects of the proposed intentional degradation of the GPS signals (called "Denial of Accuracy" or "Selective Availability") upon differential GPS positioning performance.

These effects depend critically on the relationship between the correlation time of the degradation and the time span of the differential observations. For example, if the degradation correlation time is much longer than the observing time span, the degradation can be treated as a set of biases. By estimating these biases simultaneously with station and clock parameters, we can essentially eliminate their effect.

If the degradation correlation time is much shorter than the observing time span, the degradation can be treated as noise, in which case it is not necessary to use bias parameter estimation to reduce the effect. The effect will be reduced through averaging.

The simulations we report here were deliberately pessimistic. We chose to model the degradation as if it had a very long correlation time, so that biases were introduced into the observations (through biased ephemeris information). We also chose not to include bias parameter estimation to reduce the effect of the degradation.

The consequence is that our results, using the most precise observation types, worsened (in discrepancy vector length) from the 10 cm level to the 5 m level (using a one hour observing time span) and from the 1 cm to the 10 cm level (using a five hour observing time span). The one hour results are consistent with the simple geometrical analysis of Chapter 4.4, from which we would expect differential position errors to be reduced as compared with the satellite position errors by a factor which is the ratio of the baseline length to the orbit height (roughly 1 to 100 in our case). The five hour results are better than this simple geometrical model since the effect of the biases, which were uncorrelated between satellites, was averaged over eleven different satellites rather than only five as for the one hour results. These then are the worst case results.

Future investigations, aimed at further reducing the effect of DOA, depend on the assumptions made concerning the correlation time of the DOA degradation. Recent results of Kalafus [1982] indicate that this correlation time may be much shorter than the typical one or two hour observing time span envisioned for differential GPS positioning.

However, it would be prudent to be capable of accommodating both possibilities. For that reason we plan and recommend the modification of DIGAP to accommodate satellite bias parameter estimation, as well as accommodating correlated noise modelling.

13.3 Recommendations

In developing the mathematical models and software described in this report, many questions were raised which could not be fully explored within the time constraints imposed on this work. They are important, perhaps critical, issues however, and should be investigated in detail. Some of these questions are

(1) What is the best geometry for differential GPS positioning? For example, in our simulations we have used all visible satellites. What is the effect of choosing only, say, the "best" four? How would the best four be determined? One suggestion is to use a criterion established for real time navigation. But is this criterion also applicable for fixed-point positioning? For differential GPS positioning? Are there ground station configurations that are better, geometrically, than others? Does optimization of the geometry for highest accuracy; least atmospheric effects; or least influence of orbital uncertainties, result in different criteria?

(2) How inaccurate can the a priori coordinates of the ground stations be, before the adjustment fails to converge?

(3) Which kind of sequential or recursive processing of the observations would be most efficient and convenient?

(4) What happens when more than one kind of differential GPS observation is used? How do the various clock and atmospheric effects interact? How should the combined models be constructed? This is of practical concern, since the Texas Instruments' GEOSTAR GPS receiver, soon to be available, will be capable of providing several kinds of observations simultaneously.

(5) How well can the differential carrier phase cycle ambiguity be resolved, and by what technique?

(6) In our simulations we have assumed our errors either to be statistically independent or else completely dependent (biases). What effect on the results would (more realistic) correlated error models have?

(7) What is the effect of different DOA degradation scenarios on differential GPS positioning?

(8) For monitoring applications, is it practical to have one receiver and an array of antennas?

There are a number of improvements to our software that should be made to make it more convenient, useful, and the results easier to interpret and understand. These include addition of an interactive front-end input program, provision of intermediate solutions during a run, addition of the capability of combining different observation types, addition of the capability of estimating bias parameters in addition to the present clock parameters, and addition of output plotting routines.

REFERENCES

Beser, J. and B.W. Parkinson (1981). "The application of NAVSTAR differential GPS in the civilian communiity." Proceedings of the Thirty-Seventh Annual Meeting of The Institute of Navigation (U.S.), Annapolis, MD, June, pp. 60-74.

Bomford, G. (1971). Geodesy. 3rd ed., Oxford University Press, Oxford.

Bossler, J.D., C.C. Goad and P.L. Bender (1981). "Using the GPS for geodetic positioning." Bulletin Geodesique, Vol. 54, No. 4, pp. 553-563.

Brown, D.C. (1976). "Doppler positioning by the short arc method." Proceedings of the First International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, NM, October, pp. 97-140.

Cannon, W.H. (1978). "The classical analysis of the response of a long baseline radio interferometer." Geophysical Journal of the Royal Astronomical Society, Vol. 53, pp. 503-530.

Chrzanowski, A. and W. Faig (1981). "Monitoring of mining subsidence." 74th Annual Convention of the Canadian Institute of Surveying, St. John's, Newfoundland, May.

Cnossen, R., J.D. Cardall and D. Devito (1981). "Civil applications of differential GPS using a single channel sequential receiver." NASA Report CR 166168, Ames Research Center, Moffet Field, CA, NTIS N81-28073.

Coco, D.S. and J.R. Clynch (1982). "The variability of the tropospheric range correction due to water vapor fluctuations." Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, NM, February, in press.

Counselman, C.C., R.J. Cappallo, S.A. Gourevitch, R.L. Greenspan, T.A. Herring, R.W. King, A.E.E. Rogers, I.I. Shapiro, R.E. Snyder, D.H. Steinbrecher and A.R. Whitney (1982). "Accuracy of relative positioning by interferometry with GPS: Double-blind test results." Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, NM, February, in press.

Davidson, D.D. (1980). "A least squares adjustment for long baseline interferometry." Department of Surveying Engineering Technical Report 71, University of New Brunswick, Fredericton.

Geckle, W.J. and M.M. Feen (1980). "Ionospheric refraction correction model for single-frequency Doppler navigation." Proceedings of the IEEE 1980 Position Location and Navigation Symposium, (PLANS 80), Atlantic City, NJ, December, pp. 22-26.

Herring, T.A., R.W. King, R.B. Langley, P.J. Morgan, I.I. Shapiro, C.C. Counselman III (1981). "Analysis of lunar laser ranging data and performance and analysis of VLBI observations for geodetic purposes." Air Force Geophysical Laboratory Report TR-81-0358, Cambridge, MA.

Hoar, G.J. (1982). Satellite Surveying. Magnavox Advanced Products and Systems Company Report MX-TM-3346-81, Torrance, CA.

Hopfield, H.S. (1969). "Two quartic tropospheric refractivity profile for correcting satellite data." Journal of Geophysical Research, Vol. 74, No. 1, pp. 4487-4499.

Hopfield, H.S. (1971). "Tropospheric effect on electromagnetically measured range: Prediction from surface weather data." Radio Science, Vol. 6, No. 3, pp. 357-367.

Hui, P.J. (1982). "Impact of different GPS signal processing techniques on geodetic equipment design." Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, NM, February, in press.

Kalafus, R.M. (1982). "NAVSTAR GPS accuracy studies." Proceedings of Surface Transportation Navigation Users Conference, Washington, D.C. USDOT, November.

Kouba, J. (1982). "A review of geodetic and geodynamic satellite Doppler positioning." Submitted to Reviews of Geophysics and Space Physics.

Krakiwsky, E.J., D.E. Wells and P. Kirkham (1972). "Geodetic control from Doppler satellite observations." The Canadian Surveyor, Vol. 26, No. 2, pp. 146-162.

Lachapelle, G. and R.L. Wade (1982). "NAVSTAR/GPS single point positioning." Proceedings of the American Congress of Surveying and Mapping/American Society of Photogrammetry Annual Convention, Denver, March.

Lambert, A., W.H. Cannon, R.B. Langley, J.D. Boal and H. Dragert (1981). "Proposal for Canadian participation in NASA crustal dynamics project 1983-1986." Unpublished manuscript.

Langley, R.B. (1979). "Precision geodesy and astrometry with a three station long baseline interferometer." Ph.D. Dissertation, York University, Toronto.

Lorrain, P. and D.R. Corson (1970). Electromagnetic Fields and Waves. 2nd ed., W.H. Freeman and Company, San Francisco.

MacDoran, P.F., D.J. Spitzmesser and L.A. Buennagel (1982). "SERIES: Satellite Emission Range Inferred Earth Surveying." Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, NM, February, in press.

Martin, E.H. (1980). "GPS user equipment error models." In: Global Positioning System, monograph of the Institute of Navigation, pp. 109-118.

McLaughlin, A.W. (1982). Personal communication.

Meeks, M.L. (ed.) (1976). Radio telescopes. Part B of Vol. 12, Astrophysics, of the series "Methods of Experimental Physics", Academic Press, New York.

Mertikas, S.P. and D.E. Wells (1982). "Geometrical analysis of differential GPS navigation." Proceedings of the National Marine Meeting of The Institute of Navigation (U.S.), Cambridge, MA, October, in press.

NASA (1981). "NASA geodynamics program: Annual report for 1980." Technical Memorandum 84010, Geodynamics Program Office, NASA, Washington, D.C.

Ontario Ministry of Natural Resources (1975). "Report to the task force on geographical referencing: Technical aspects of implementing the Ontario Ministry of Natural Resources proposal for mapping Ontario." Technical Production Team, Chairperson: Ms J. Zend, Division of Lands.

Payne, C.R. (1982). "NAVSTAR Global Positioning System: 1982." Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, NM, February, in press.

Rino, C.L., M.D. Cousins and J.A. Klobuchar (1981). "Amplitude and phase scintillation measurements using the Global Positioning System." Proceedings of the Symposium on the Effect of the Ionosphere on Radiowave Systems, Washington, April, Paper 3A-12.

Spilker, J.J. (1980). "GPS signal structure and performance characteristics." In: Global Positioning System, monograph of the Institute of Navigation, pp. 29-54.

van Dierendonck, A.J., S.S. Russell, E.R. Kopitzke and M. Birnbaum (1980). "The GPS navigation message." In: Global Positioning System, monograph of the Institute of Navigation, pp. 55-73.

Vaníček, P. (1976). "Pattern of recent vertical crustal movements in Maritime Canada." Canadian Journal of Earth Sciences, Vol. 13, No. 5, pp. 661-667.

Walker, J.G. (1977). "Continuous whole-earth coverage by circular-orbit satellite patterns." Royal Aircraft Establishment Technical Report 770044, Farnborough, U.K.

Ward, P. (1981). "An inside view of pseudorange and delta pseudorange measurements in a digital NAVSTAR GPS receiver." Paper presented at ITC, San Diego.

Ward, P. (1982). "An advanced NAVSTAR GPS geodetic receiver." Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, NM, February, in press.

Wells, D.E. (1974). "Doppler satellite control." Department of Surveying Engineering Technical Report 29, University of New Brunswick, Fredericton.

Wells, D.E., P. Vaníček and D. Delikaraoglou (1981). "Application of NAVSTAR/GPS to geodesy in Canada. Pilot study." Department of Surveying Engineering Technical Report 76, University of New Brunswick, Fredericton.

Wells, D.E., D. Delikaraoglou and P. Vaníček (1982). "Marine navigation with NAVSTAR/Global Positioning System (GPS) today and in the future." The Canadian Surveyor, Vol. 36, No. 1, pp. 9-28.

Appendix A

GPS BIBLIOGRAPHY

This appendix lists approximately 250 documents related to GPS, held within the Department of Surveying Engineering. These documents are in the process of being catalogued on the University of New Brunswick online catalogue system--PHOENIX. The PHOENIX document numbers and storage locations are shown on this list, for those documents catalogued so far.

GPS MASTER REFERENCE LIST

1 October 1982

Adams, J.R. (1980). "Global Positioning System." Sheltech Canada Surveying Division, Calgary, Alberta, March. (Phoenix:GPS-Sheltech; 179312)

Altshuler, E.E. and P.M. Kalaghan (1974). "Tropospheric range error corrections for the NAVSTAR system." Air Force Cambridge Research Labs. AFCRL-TR-74-0198, NTIS microfiche #AD-786 928. (Phoenix:GPS-DOD; 179184)

Anderle, R.J. (1978). "Geodetic applications of the NAVSTAR Global Positioning System." Proceedings of the Second International Symposium on Problems Related to the Redefinition of North American Geodetic Networks, Arlington, April, pp. 463-480. (Phoenix:GPS-NSWC; 179315)

Anderle, R.J. (1979). "Accuracy of geodetic solutions based on Doppler measurements of the NAVSTAR Global Positioning System satellites." Bulletin Geodesique, Vol. 53, pp. 109-116. (Phoenix:GPS-NSWC; 179244)

Anderle, R.J. (1979). "Advanced satellite systems and their applications." Paper presented at the XVII General Assembly of the International Union of Geodesy and Geophysics, Canberra, Australia, December.

Anderle, R.J. (1980). "Application of NAVSTAR GPS geodetic receiver to geodesy and geodynamics." Naval Surface Weapons Center TR 80-282, Dahlgren, VA.

Anderle, R.J. (1982?). "Doppler test results of experimental GPS receiver." Naval Surface Weapons Center technical report, Dahlgren, VA.

Anderle, R.J. and A.G. Evans (1982). "Relative positioning test using the Global Positioning System and Doppler techniques." Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, NM, February, pp. (Phoenix:GPS-NSWC; 179305)

Angus-Leppan, P.V. (1982). "NAVSTAR Global Positioning System. Prospects for geodesy." Notes written while author on sabbatical leave, from the University of New South Wales, at the Geodetic Survey of Canada, Ottawa. (Phoenix:GPS-GSC; 179190)

Angus-Leppan,P.V. (1982). "Current status of GPS geodetic equipment." Report written while author on sabbatical leave, from the University of New South Wales, at the Geodetic Survey of Canada, Ottawa. (Phoenix: GPS-GSC; 179191)

Anon. (1974). "New space navigation satellite planned." Aviation Week and Space Technology, July, pp. 69-70. (Phoenix:GPS-MISC; 179226)

Anon. (1980). "Performance specification for GPS user equipment (CANFOR-2)." Appendix 'B', GPS-CAN-02, June.

APL (1981). "The design of a GPS geodetic receiver." Vol. 1 of Space Department Report SDO-5962, The Johns Hopkins University Applied Physics Laboratory, Silver Springs, MD.

Bartholomew, C.A. (1979). "Clocks: Evolution of frequency standards." In: Principles and Operational Aspects of Precision Position Determination Systems, Ed. C.T. Leondes. NATO AGARDograph No. 245, pp. 7-1 to 7-11.

Bender, E. (1979). "NAVSTAR passes sea trials." Sea Technology, March, pp. 29-30. (Phoenix:GPS-MISC; 179225)

Bender, P.L. (1980). "Establishment of terrestrial reference frames by new observational techniques." Paper presented IAU Colloquium No. 56, Warsaw, September. (Phoenix:GPS-JILA; 179193)

Bender, P.L. (1980). "Improved methods for measuring present crustal movements." To appear in Dynamics of Plate Interiors, AGU Geodynamics Series. (Phoenix:GPS-JILA; 179194)

Bender, P.L. and D.R. Larden (1982). "TOPEX orbit determination using GPS signals plus a sidetone ranging system." Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, NM, February, pp. (Phoenix:GPS-JILA; 179284)

Beser, J. and B.W. Parkinson (1981). "The application of NAVSTAR differential GPS in the civilian community." Proceedings of the thirty-seventh annual meeting of the U.S. Institute of Navigation, Annapolis, MD, June, pp. 60-74. (Phoenix:GPS-MISC; 179285)

Blitzkow, D. (1980). "Global Positioning System: General aspects." Handwritten notes. (Phoenix:GPS-MISC; 179206)

Bogen, A.H. (1974). "Geometric performance of the Global Positioning System." Aerospace Corporation, Systems Engineering Operations, TR-0074(4461-02)-2; SAMSO-TR-74-169; NTIS microfiche #AD-783 210. (Phoenix:GPS-AEROSPACE; 179172)

Book, S.A., W.F. Brady and P.K. Mazaika (1980). "The nonuniform GPS constellation." Proceedings of the IEEE 1980 Position Location and Navigation Symposium (PLANS 80), Atlantic City, NJ, December, pp. 1-8.

Borel, M.J., J.N. Damoulakis, D.R. Delzer, T.D. Fuchser, J.H. Hinderer, C.R. Johnson and D.J. Pinkos (1979). "Texas Instruments Phase I GPS user equipment." In: Principles and Operational Aspects of Precision Position Determination Systems, Ed. C.T. Leondes. NATO AGARDograph No. 245, pp. 15-1 to 15-15.

Bossler, J.D. (1981). "A note on Global Positioning System activities." American Congress of Surveying and Mapping Bulletin, No. 74, August, pp. 39-40. (Phoenix:GPS-NGS; 179240)

Bossler, J.D. (1982). "Status of the development of geodetic global positioning receivers." To be presented at the ASCE convention, New Orleans, LA, 25-29 October.

Bossler, J.D. and W.E. Strange (1982). "Summary of GPS geodetic hardware concepts." Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, NM, February, pp. (Phoenix:GPS-NGS; 179241)

Bossler, J.D., C.C. Goad and P.L. Bender (1981). "Using the GPS for geodetic positioning." Bulletin Geodesique, Vol. 54, No. 4, pp. 553-563.

Bower, T.P. (1980). "Navigation processing design for a low-cost GPS navigation system." Proceedings of the IEEE Position Location and Navigation Symposium (PLANS 80), Atlantic City, NJ, December, pp. 17-21.

Brady, W.F. and P.S. Jorgensen (1981). "Worldwide coverage of the Phase II NAVSTAR satellite constellation." Proceedings of the National Aerospace Meeting of the Institute of Navigation, Philadelphia, April, pp. 33-40. (Phoenix:GPS-AEROSPACE; 179171)

Brown, A.K., W.M. Bowles and T.P. Thorvaldsen (1982). "Interferometric attitude determination using the Global Positioning System: A new gyrotheodolite." Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, NM, February, pp. (Phoenix:GPS-MISC; 179288)

Butterfield, F.E. and R.E. Sung (1979). "Phase II GPS receiver design philosophy." In: Principles and Operational Aspects of Precision Position Determination Systems, Ed. C.T. Leondes. NATO AGARDograph No. 245, pp. 17-1 to 17-9.

Canadian Marconi Company (1981). "Statement of work, for GPS Task Group and CMC, to develop GPS user equipment specifications." Canadian Marconi Company, Montreal. (Phoenix: GPS-MARCONI; 179216)

Canadian Marconi Company (1981). "NAVSTAR Global Positioning System, briefing to industry and government." Canadian Marconi Company, Montreal, March. (Phoenix:GPS-MARCONI; 179217)

Canadian Marconi Company (1981). "Final report on the study of satellite signal processing techniques applicable to GPS equipment." CMA Document No. 0680-1001, DO17/DO17A-81045, Montreal, June.

Canadian Marconi Company (1982). "CMA 782: GPS satellite positioning system." Canadian Marconi Company, Montreal. (Phoenix:GPS-MARCONI; 179210)

Chapman, J.C. Jr. (1976). "Comparison of low-cost computer algorithms for Global Positioning System users." MS thesis, Air Force Institute of Technology (AU), Ohio, GA/MC/76M-1; NTIS microfiche #AD-A022 989.

Chappell, P. and H. Wesson (1982). "High-accuracy navigation for long-range offshore geophysical exploration." Texas Instruments Inc., Lewisville, TX. (Phoenix:GPS-TI; 179306)

Cnossen, R. (1980). "Low cost GPS navigation receiver for general aviation." Magnavox Report MX-TM-3309-80. Paper presented at 32nd annual Helicopter Association of American Meeting and Industry Showcase, Las Vegas, Nevada, February. (Phoenix:GPS-MAGNAVOX; 179205)

Cnossen, R. and J.D. Cardall (1980). "Civil helicopter applications of the NAVSTAR Global Positioning System." Presented at the Advanced Rotorcraft Technology Workshop, NASA Ames Research Center, Moffet Field, CA. (Phoenix:GPS-NASA;)

Cnossen, R., J.D. Cardall and D. Devito (1981). "Civil applications of differential GPS using a single channel sequential receiver." NASA Report CR 166168, Ames Research Center, Moffet Field, CA, NTIS N81-28073. (Phoenix:GPS-NASA;)

Coco, D.S. and J.R. Clynch (1982). "The variability of the tropospheric range correction due to water vapour fluctuations." Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, NM, February.

Counselman, C.C. (1980). "Texas Instruments GPS receiver." Letter to J.D. Bossler, 8 May. (Phoenix:GPS-MIT; 179238)

Counselman, C.C. (1980). "Collins (TI) GPS receiver." Letter to J.D. Bossler, 15 August. (Phoenix:GPS-MIT; 179237)

Counselman, C.C. (1980). "Proposal from MIT to NASA, Office of Space and Terrestrial Applications, Resource Observation Divison, Geodynamics Program on very long baseline interferometric geodesy with GPS satellites." Department of Earth and Planetary Sciences, MIT, July. (Phoenix:GPS-MIT; 179232)

Counselman, C.C. (1981). "Relative positions determined with centimetre accuracy through interferometry with GPS." Proceedings of the thirty-seventh annual meeting of the U.S. Institute of Navigation, Annapolis, MD, June, pp.

Counselman, C.C. (1981). "Miniature Interferometric Terminals for Earth Surveying (MITES)." CSTG Bulletin No. 3, May. International Coordination of Space Techniques for Geodesy and Geodynamics, Commission VIII, International Association of Geodesy, pp. (Phoenix:GPS-MIT; 179233)

Counselman, C.C. (1982). "The Macrometer™ interferometric surveyor." Proceedings of the Internatioinal Symposium on Land Information at the Local Level, University of Maine at Orono, August, pp. 233-241. (Phoenix:GPS-MIT;)

Counselman, C.C. and S.A. Gourevitch (1981). "Miniature interferometer terminals for earth surveying: ambiguity and multipath with Global Positioning System." IEEE Transactions on Geoscience and Remote Sensing, Vol. GE-19, No. 4, pp. 244-252. (Phoenix:GPS-MIT; 179235 - 2 copies)

Counselman, C.C. and I.I. Shapiro (1979). "Miniature interferometer terminals for earth surveying." Bulletin Geodesique, Vol. 53, pp. 139-163. (Phoenix:GPS-MIT; 179234)

Counselman, C.C. and D.H. Steinbrecher (1982). "The Macrometer™: A compact radio interferometry terminal for geodesy with GPS." Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, NM, February, pp. (Phoenix:GPS-MIT; 179301)

Counselman, C.C., I.I. Shapiro, R.L. Greenspan and D.B. Cox (1980). "Backpack VLBI terminal with subcentimeter capability." Radio Interferometry, NASA CP-2115, pp. 409-414. (Phoenix:GPS-MIT; 179231)

Counselman, C.C., R.J. Cappallo, S.A. Gourevitch, R.L. Greenspan, T.A. Herring, R.W. King, A.E.E. Rogers, I.I. Shapiro, R.E. Snyder, D.H. Steinbrecher and A.R. Whitney (1982). "Accuracy of relative positioning by interferometry with GPS: Double-blind test results." Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, NM, February, pp. (Phoenix:GPS-MIT; 179300)

Counselman, C.C., S.A. Gourevitch, R.W. King, T.A. Herring, I.I. Shapiro, R.L. Greenspan, A.E.E. Rogers, A.R. Whitney and R.J. Cappallo (1981). "Accuracy of baseline determinations by MITES assessed by comparison with tape, theodolite and geodimeter measurements." EOS, Transactions of the American Geophysical Union, Vol. 62, p. 260 (abstract only).

Cox, D.B. Jr. (1979). "Integration of GPS with inertial navigation systems." In: Principles and Operational Aspects of Precision Position Determination Systems, Ed. C.T. Leondes. NATO AGARDograph No. 245, pp. 19-1 to 19-10.

Dean, W.N. and D.A. Feldman (1980). "Coast Guard/Marad tests of the GPS navigation set type Z. Phase I static tests." Magnavox Report MX-TM-3323-80. Originally presented at the Marine Meeting of The Institute of Navigation, Yorktown, VA. (Phoenix:GPS-USCG; 179249)

Delikaraoglou, D. (1979). "From Transit to NAVSTAR: One step closer to precise offshore positioning." Presented at the sixth annual meeting of the Canadian Geophysical Union, Fredericton, June.

Delikaraoglou, D. (1981). "Application of NAVSTAR/GPS to precise positioning." Paper presented at annual meeting of the Canadian Geophysical Union, Calgary, Alberta, May.

Delikaraoglou, D. (1982). "The continuing evolution of NAVSTAR/GPS survey navigation capabilities. Recent test results." EOS, Transactions American Geophysical Union, Vol. 63, No. 18, p. 300 (abstract only).

Delikaraoglou, D. and D.E. Wells (1982). "The continuing evolution of NAVSTAR/GPS survey navigation capabilities. Recent test results." Presented at the spring meeting of the American Geophysical Union, Philadelphia, June.

Deutsche Gesellschaft fur Ortung und Navigation Ev. (1981). Report of the West German Working Group "Positioning and Navigation in Near-earth Areas with the Help of Satellite Systems". (Phoenix:GPS-ESA; 179189)

Dicke, R.H., R. Beringer, R.L. Kyhl and A.B. Vane (1946). "Atmospheric absorption measurements with a microwave radiometer." Physical Review. Vol. 70, Nos. 5 and 6, pp. 340-348. (Phoenix:GPS-WATER VAPOUR; 179257)

Dunn, P.D. and J.W. Rees (1980). "Applications of the Global Positioning System (GPS) satellite receivers for hydrographic surveying." Proceedings of the American Congress of Surveying and Mapping Fall technical meeting, Niagara Falls, N.Y., October, pp.

Dyment, M.J. (1980). "Proposal to analyse NAVSTAR attitude and heading reference system." Report prepared by Canadian Marconi Company, CMC Document No. P-1720, for Department of National Defence, Ottawa, August. (Phoenix:GPS-MARCONI; 179215)

Dyment, M.J. (1981). "NAVSTAR potential for the Canadian marine community." Presented at CASI meeting, Halifax, November. (Phoenix:GPS-MARCONI; 179290)

Dyment, M.J. and D.F. Liang (19). "Dynamic performance analysis of NAVSTAR/GPS navigation filters." AGARD Conference Proceedings No. 298, "Precision Positioning and Inertial Guidance Sensors Technology and Operational Aspects", pp. 15-1 to 15-19.

Elrod, B.D., H.A. Bustamante and F.D. Natali (1980). "A GPS receiver design for general aviation navigation." Proceedings of the IEEE Position Location and Navigation Symposium (PLANS 80), Atlantic City, NJ, December, pp. 33-41.

Emara-Shabaik, H.E. (1979). "Alternate constellations for the Global Positioning System." In: Principles and Operational Aspects of Precision Position Determination Systems, Ed. C.T. Leondes. NATO AGARDograph No. 245, pp. 23-1 to 23-37.

Encyclopedia Britannica ( ). "Radiation." pp. 247-256. (Phoenix: GPS-WATER VAPOUR; 179255)

Encyclopedia Britannica ( ). "Radio astronomy." pp. 1076-1077. (Phoenix:GPS-WATER VAPOUR; 179256)

Euler, W.C. (1980). "A perspective on civil use of GPS." Paper presented at The Institute of Navigation, 36th Annual Meeting, Monterey, CA, June. (Phoenix:GPS-MAGNAVOX; 179204)

European Space Agency (1980). "Feasibility study of a simple Global Positioning System (GPS) for civil application." ESA Committee to Review the Application of Satellites and other Techniques to Civil Aviation. (Phoenix:GPS-ESA; 179186)

European Space Agency (1981). "Agenda and minutes of West German working group, positioning and navigation in near-earth areas with the help of satellite systems." September. (Phoenix:GPS-ESA; 179188)

Evans, A.G., R.J. Anderle and B.R. Hermann (1982). "Colocation test results from experimental Global Positioning System geodetic receivers." Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, NM, February, pp. (Phoenix:GPS-NSWC; 179304)

Evans, A.G., B.R. Hermann and P.J. Fell (1981). "Global Positioning System sensitivity experiment." Navigation, Journal of The Institute of Navigation, Vol. 28, No. 2, pp. 77-92. (Phoenix:GPS-NSWC; 179314)

Fell, P.J. (1974). "Multiple satellite data processing for the NAVSTAR Global Positioning System." Naval Surface Weapons Center, DL Technical Report TR-3210, Dahlgren, VA, October. (Phoenix:GPS-NSWC; 179243)

Fell, P.J. (1980). "Geodetic positioning using a Global Positioning System of satellites." Department of Geodetic Science Report 299, The Ohio State University, Columbus, Ohio, June.

Fell, P.J. (1980). "Geodetic positioning using a Global Positioning System of satellites." Proceedings of the IEEE Position Location and Navigation Symposium (PLANS 80), Atlantic City, NJ, December, pp. 42-47.

Fell, P.J. (1980). "An analytic technique for statistically modelling random atomic clock errors in estimation." Proceedings of the twelfth annual Precise Time and Time Interval Applications and Planning Meeting, PTTI Conference, Goddard Space Flight Center, December.

Gardner, C.S., J.R. Rowlett and B.E. Hendrickson (1978). "Ray tracing evaluation of a technique for correcting the refraction errors in satellite tracking data." Applied Optics, Vol. 17, No. 19, pp. 3143-3145. (Phoenix:GPS-WATER VAPOUR; 179259)

Gilbert, G.A., E.H. Martin, D. Symes and C. Mathews (1979). "Civil applications of NAVSTAR GPS." In: Principles and Operational Aspects of Precision Position Determination Systems, Ed. C.T. Leondes, NATO AGARDograph No. 245, pp. 21-1 to 21-26.

Glazer, B.G. (1979). "GPS receiver operation." In: Principles and Operational Aspects of Precision Position Determination Systems, Ed. C.T. Leondes. NATO AGARDograph Noo. 245, pp. 16-1 to 16-5.

Gold, R. (1967). "Optimal binary sequences for spread spectrum multiplexing." IEEE Transactions on Information Theory, IT-13, pp. 619-621. (Phoenix:GPS-MAGNAVOX; 179199, 179200)

Grant, S.T. (1973). "Rho-rho Loran-C combined with satellite navigation for offshore surveys." International Hydrographic Review, Vol. 50, pp. 35-54.

Grant, S.T. (1976). "Integration of passive ranging Loran-C satellite navigation, ship's log and ship's gyrocompass." Master of Science in Engineering thesis, Department of Surveying Engineering, University of New Brunswick, Fredericton, N.B.

Grant, S.T. and D.E. Wells (1982). "Interactions among integrated system components." Presented at the International Association of Geodesy Symposium on Marine Geodesy, Tokyo, May.

Greenspan, R.L., A.Y. Ng, J.M. Przyjemski and J.D. Veale (1982). "Accuracy of relative positioning by interferometry with reconstructed carrier GPS: Experimental results." Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, NM, February, pp. (Phoenix:GPS-MISC; 179286)

Guiraud, F.O., J. Howard and D.C. Hogg (1979). "A dual-channel microwave radiometer for measurement of precipitable water vapor and liquid." IEEE Transactions on Geoscience Electronics, Vol. GE-17, No. 4, pp. 129-136. (Phoenix:GPS-WATER VAPOUR; 179261)

Harbour, W.H. and M. Rochette (1979). "The GPS upload station." In: Principles and Operational Aspects of Precision Position Determination Systems, Ed. C.T. Leondes. NATO AGARDograph No. 245, pp. 12-1 to 12-5

Harrington, R.L., W.A. Fabrizio and E. Salinas (1979). "Monitor stations." In: Principles and Operational Aspects of Precision Position Determination Systems, Ed. C.T. Leondes. NATO AGARDograph No. 245, pp. 11-1 to 11-9.

Hatch, R. (1982). "The synergism of GPS code and carrier measurements." Magnavox Advanced Products and Systems Company Report MX-TM-3353-82. Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, NM, February, pp. (Phoenix: GPS-MAGNAVOX; 179292)

Healy, M.S. (1981). "NAVSTAR/GPS navigation satellite systems status." Federal Register, 'Notices', Vol. 46, No. 66, pp. 20724-5. (Phoenix: GPS-DOD; 179176)

Henderson, D.W. and H. Coriat (1980). "Status report--Global Positioning System." Navigation, Journal of The Institute of Navigation, Vol. 27, No. 1, pp. 54-64. (Phoenix:GPS-DOD; 179181)

Henderson, D.W. and J.A. Strada (1979). "NAVSTAR: Field test results." Magnavox Report MX-TM-3316-80A, July 1980. Paper presented at The Institute of Navigation, National Aerospace Symposium, Springfield, VA, March. (Phoenix:GPS-MAGNAVOX; 179208)

Hermann, B.R. (1981). "Formulation for the NAVSTAR Geodetic Receiver System (NGRS)." Naval Surface Weapons Center Report NSWC TR-81-348, Dahlgren, VA. (Phoenix:GPS-NSWC; 179316)

Heuerman, H.R. (1982). "Global Positioning System geodetic tracking program." Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, NM, February, pp. (Phoenix:GPS-DOD; 179280)

Hogg, D.C., F.O. Guiraud, J. Howard, A.C. Newell, D.P. Kremer and A.G. Repjar (1979). "An antenna for dual-wavelength radiometry at 21 and 32 GHz." IEEE Transactions on Antennas and Propagation, Vol. AP-27, No. 6, pp. 764-770. (Phoenix:GPS-WATER VAPOUR; 179260)

Hopfield, H.S. (1969). "Two-quartic tropospheric refractivity profile for correcting satellite data." Journal of Geophysical Research, Vol. 74, pp. 4487-4499.

Howell, W.E., W.T. Bundick and W.F. Hodge (1980). "Civil aviation applications of NAVSTAR/GPS through differential techniques." Paper presented at National Telecommunications Conference, Houston, TX, December. (Phoenix:GPS-NASA; 179239)

Hui, P.J. (1981). "Progress report for EMR: Satellite signal processing techniques study--Jan 2-30, 1981." Report prepared by Canadian Marconi Company for the Department of Energy, Mines and Resources, Ottawa. (Phoenix:GPS-MARCONI; 179214)

Hui, P.J. (1981). "Final report summary on the study of satellite signal processing techniques applicable to GPS geodetic equipment." Report prepared by Canadian Marconi Company (CMC Document No. 0680-1004) for the Department of Energy, Mines and Resources, Ottawa, September. (Phoenix:GPS-MARCONI; 179221)

Hui, P.J. (1982). "Requirement definition study." Report prepared by Canadian Marconi Company for the Department of Energy, Mines and Resources, Ottawa, January. (Phoenix:GPS-MARCONI; 179220)

Hui, P.J. (1982). "Impact of different GPS signal processing techniques on geodetic equipment design." Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, NM, February, pp. (Phoenix:GPS-MARCONI; 179291)

Hui, P.J. (1982). "Impact of continuous integrated Doppler counting on GPS geodetic equipment system design." Canadian Marconi Company, Montreal, February. (Phoenix:GPS-MARCONI; 179219)

Hui, P.J. (1982). "System definition study." Report prepared by Canadian Marconi Company (CMC Document No. 0680-1007) for the Department of Energy, Mines and Resources, Ottawa, March. (Phoenix:GPS-MARCONI; 179212)

Hui, P.J. (1982). "On satellite signal processing techniques applicable to GPS geodetic equipment." The Canadian Surveyor, Vol. 36, No. 1, March, pp. 43-55. (Phoenix:GPS-MARCONI; 179211, draft only)

Hui, P.J. (1982). "Comments on MacDoran's SLIC and SERIES carrier regenerator." Personnal communication, Canadian Marconi Company, Montreal, May. (Phoenix:GPS-MARCONI; 179289)

Hurley, M.J., J.L. Kramer and D.D. Thornburg (1979). "Master control station." In: Principles and Operational Aspects of Precision Position Determination Systems, Ed. C.T. Leondes. NATO AGARDograph No. 245, pp. 9-1 to 9-8.

Icenbice, P.J. (1978). "Transit position 'accuracy' extrapolated to GPS." Presented at The Institute of Navigation thirty-fourth annual meeting, Arlington, VA, June. (Phoenix:GPS-JMR; 179195)

Institute of Navigation (1980). "Global Positioning System." Collected reprints of papers published in Navigation, The Institute of Navigation, Washington. (Phoenix:GEODESY; 176188)

International Association of Geodesy (1979). "Special issue on NAVSTAR/GPS." Bulletin Geodesique, Vol. 53, No. 2.

International Frequency Registration Board (1982). "Advance publication of information on a planned USSR satellite network (GLONASS)." (Phoenix: GPS-MISC; 179230)

Interstate Electronics Corporation (1981). "GPS tracking technology study." Anaheim, CA, March. (Phoenix:GPS-INTERSTATE; 179192)

Jacobson, L. (1976). "User equipment for the NAVSTAR Global Positioning System." Magnavox Report MX-TM-3212-76. Paper presented at National Telecommunications Conference, Dallas, TX, December. (Phoenix: GPS-MAGNAVOX; 179209)

Jacobson, L.J. (1979). "GPS is on the ground: The Global Positioning System manpack." Signal, Journal of the U.S. Armed Forces Communications and Electronics Assn., March, pp. 47-48. (Phoenix: GPS-MAGNAVOX; 179201 - 2 copies)

Jacobson, L. and L. Huffman (1979). "Satellite navigation with GPS." Magnavox Report MX-TM-3322-80. Reprinted from Satellite Communications, July. (Phoenix:GPS-MAGNAVOX; 179198)

Jespersen, J.L., M. Weiss, D.D. Davis and D.W. Allan (1980). "Global Positioning System for accurate time and frequency transfer and for cost-effective civilian navigation." Proceedings of the IEEE Position Location and Navigation Symposium (PLANS 80), Atlantic City, NJ, December, p. 468 (abstract only).

Johnson, H.C. (1979). "GPS master control station operations." In: Principles and Operational Aspects of Precision Position Determination Systems, Ed. C.T. Leondes. NATO AGARDograph No. 245, pp. 10-1 to 10-3.

Jorgensen, P.S. (1978). "Ionospheric measurements from NAVSTAR satellites." Report prepared by the Satellite Systems Division of the Aerospace Corporation, El Segundo, CA, for Space and Missile Systems Organization, Air Force Systems Command, Los Angeles Air Force Station, Los Angeles, CA. Report SAMSO-TR-79-29, December.

Jorgensen, P.S. (1980). "Combined pseudo range and Doppler positioning for the stationary NAVSTAR user." Proceedings of the IEEE Position Location and Navigation Symposium (PLANS 80), Atlantic City, NJ, December, pp. 450-458.

Jorgensen, P.S. (1980). "NAVSTAR/Global Positioning System--18 satellite constellation." Navigation, Journal of The Institute of Navigation (U.S.), Vol. 27, No. 2, pp. 89-100.

Joseph, K.M., R. Thorensen, J.J. Winterhalter and J.R. Champion (1980). "NAVSTAR GPS receiver for satellite applications." Paper presented at AGARD 31st Guidance and Control Panel Symposium, London, October. (Phoenix:GPS-MAGNAVOX; 179207)

Klass, P.J. (1973). "Compromise reached on NAVSAT." Aviation Week and Space Technology, Nov., pp. 46-51. (Phoenix:GPS-MISC; 179228)

Kouba, J. (1982). "GPS related research and development at the Earth Physics Branch, EMR." Report to the NACCSM subcommittee on satellite positioning, June. (Phoenix:GPS-EPB; 179327)

Kruczynski, L.R. (1978). "Aircraft navigation with the limited operational phase of the NAVSTAR Global Positioning System." Navigation, Journal of The Institute of Navigation (U.S.), Vol. 25, No. 2, pp. 246-257

Kumar, M., P.J. Fell and A.J. Pilkington (1982). "A geometric approach with the NAVSTAR Global Positioning System." Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, NM, February, pp. (Phoenix:GPS-DOD; 179279)

Lachapelle, G. (1982). "Geodetic applications of the NAVSTAR/Global Positioning System on land and offshore." Invited paper, Congreso VII Panamericano Nacional Fotogrametria, Fotointerpretation y Geodesia, Mexico, September.

Lachapelle, G. and N. Beck (1982). "NAVSTAR/GPS single point positioning at Sheltech Canada--Preliminary results." The Canadian Surveyor, Vol. 36, No. 1, pp. 29-42. (Phoenix:GPS-SHELTECH; 179270, 179271)

Lachapelle, G. and J. Kouba (1980). "Relationship between terrestrial and satellite Doppler systems." Proceedings of IAU Colloquium No. 56 on Reference Coordinate Systems for Earth Dynamics, Reidel, Dordrecht, pp. 195-203.

Lachapelle, G. and R.L. Wade (1982). "NAVSTAR/GPS single point positioning." Proceedings of the American Congress of Surveying and Mapping, American Society of Photogrammetry annual convention, Denver, March, pp. (Phoenix:GPS-SHELTECH; 179272--3 copies)

Lachapelle, G., N. Beck and P. Heroux (1982). "NAVSTAR/GPS single point positioning using pseudo-range and Doppler observations." Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, NM, February, pp. (Phoenix:GPS-SHELTECH; 179274--2 copies)

Langley, R.B., J.D. McLaughlin and D.E. Wells (1982). "The potential engineering and land surveying market for GPS." Presented at the Speciality Conference on Engineering Applications of Space Age Surveying Technology, American Society of Civil Engineers, Division of Surveying, Nashville, Tennessee, June.

Larden, D.R. and P.L. Bender (1982). "Preliminary study of GPS orbit determination accuracy achievable from worldwide tracking data." Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, NM, February, pp. (Phoenix:GPS-JILA; 179283)

Liang, D.F., D.B. Reid, R.H. Johnson and B.G. Fletcher (19). "Development of aiding GPS/strapdown inertial navigation system." NATO AGARD Conference Proceedings No. 272, "Advances in Guidance and Control Systems using Digital Techniques", pp. 15-1 to 15-15.

Logsdon, T. (19). "Satellites bring new precision to navigation." High Technology, July/August, pp. 61-66. (Phoenix:GPS-MISC; 179299)

MacDoran, P.F. (1979). "Satellite Emission Radio Interferometric Earth Surveying: SERIES--GPS geodetic system." Bulletin Geodesique, Vol. 53, pp. 117-138. (Phoenix:GPS-JPL; 179197 - 2 copies)

MacDoran, P.F. (1982). "NAVSTAR-GPS as a universal geodetic resource." Paper presented at Space Geodesy #7 Symposium, European Geophysical Society, Leeds, England, August.

MacDoran, P.F., D.J. Spitzmesser and L.A. Buennagel (1982). "SERIES: Satellite Emission Range Inferred Earth Surveying." Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, NM, February, pp. (Phoenix:GPS-JPL; 179293)

Magnavox (1981). "GPS presentation." 1981 briefing, February. (Phoenix: GPS-MAGNAVOX;)

Martin, E.H. (1980). "GPS user equipment error models." Navigation, Journal of The Institute of Navigation (U.S.), Vol. 25, No. 2, pp. 201-210.

McCaskill, T.B. and J.A. Buisson (1975). "NTS-1 (Timation IIII) Quartz- and rubidium-oscillator frequency stability results." Naval Research Lab., NRL Report 7932; NTIS microfiche #AD-A019 156.

Melton, W.C. (1981). "Time-of-arrival measurements possible with use of Global Positioning System." Defense Electronics, Vol. 13, No. 12, pp. 90-98. (Phoenix:GPS-STI; 179310)

Mertikas, S.P. and D.E. Wells (1982). "Geometrical analysis of differential GPS navigation." Proceedings of the National Marine Meeting of The Institute of Navigation (U.S.), Cambridge, MA, October.

Miller, B. (1974). "Satellite navigation network defined." Aviation Week and Space Technology, April, pp. 22-23. (Phoenix:GPS-MISC; 179227)

Milliken, R.J. and C.J. Zoller (1978). "Principle of operation of NAVSTAR and system characteristics." Navigation, Journal of The Institute of Navigation (U.S.), Vol. 25, No. 2, pp. 95-106.

Milliken, R.J. and C.J. Zoller (1979). "Principle of operation of NAVSTAR and system characteristics." In: Principles and Operational Aspects of Precision Position Determination Systems, Ed. C.T. Leondes. NATO AGARDography No. 245, pp. 4-1 to 4-12.

Mueller, I.I. and B. Archinal (1981). "Geodesy and the Global Positioning System." Presented at IAG Symposium on Geodetic Networks and Computations, Munich, August. (Phoenix:GPS-OSU; 179247)

Nash, J.M. (1975). "Covariance analysis of the DD 963 navigation system." Naval Electronics Laboratory Center Technical Report 1967, San Diego, CA. Prepared for Naval Ship Engineering Center, Hyattsville, MD, and Naval Sea Systems Command, Washington, D.C.

National Aeronautics and Space Administration (1981). "ARIES: Space technology applied to earthquake research." Jet Propulsion Laboratory #400-108 4/81, Pasadena, CA.

National Ocean Industries Association (1982). "Minutes of the satellite radionavigation subcommittee of the telecommunications policy committee." Washington, D.C., March. (Phoenix:GPS-NOIA; 179242)

Newell, V.E. and D.D. Winter (1981). "Application of the Global Positioning System to nearshore hydrographic surveys." U.S. Naval Postgraduate School thesis, Monterey, September.

Nissim, W. and C.J. Zoller (1979). "Launch vehicles." In: Principles and Operational Aspects of Precision Position Determination Systems, Ed. C.T. Leondes. NATO AGARDograph No. 245, pp. 22-1 to 22-15.

Noe, P.S., V.T. Rhyne and J.H. Painter (1980). "The C/A code GPS receiver at sea." Proceedings of the IEEE Position Location and Navigation Symposium (PLANS 80), Atlantic City, NJ, December, pp. 48-50.

Norton, J.H. (1982). "NAVSTAR Global Positioning System." International Hydrographic Review, Vol. 59, pp. 23-30. (Phoenix:GPS-MISC; 179317)

Ohnishi, K. (1979). "On the optimal selection of satellites in GPS." In: Principles and Operational Aspects of Precision Position Determination Systems, Ed. C.T. Leondes. NATO AGARDograph No. 245, pp. 24-1 to 24-5.

Parkinson, D.W. (1979). "The Global Positioning System (NAVSTAR)." Bulletin Geodesique, Vol. 53, pp. 89-108. (Phoenix:GPS-DOD; 179180)

Payne, C.R. Jr. (1982). "NAVSTAR Global Positioning System: 1982." Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, NM, February, pp. (Phoenix:GPS-DOD; 179177)

Perreault, P. (19). "Civilian receivers navigate by satellite." Microwave Systems News, . (Phoenix:GPS-STI; 179331)

Piscane, V.L., M.M. Feen and M. Sturmanis (1972). "Prediction techniques for the effect of the ionosphere on pseudo-ranging from synchronous altitude satellites." Report prepared by The Johns Hopkins University, Applied Physics Laboratory for the Space and Missile Systems Organization, Los Angeles, CA, Report SAMSO-TR-72-22, APL/JHU TG 1197.

Preston, R.A., R. Ergas, H.F. Hinteregger, C.A. Knight, D.S. Robertson, I.I. Shapiro, A.R. Whitney, A.E.E. Rogers and T.A. Clark (1972). "Interferometric observations of an artificial satellite." Science, Vol. 178, pp. 407-409. (Phoenix:GPS-MIT; 179302)

Putkovich, K. (1980). "USNO GPS program." Proceedings of the twelfth annual Precise Time and Time Interval Applications and Planning Meeting, PTTI Conference, Goddard Space Flight Center, December.

Putkovich, K. (1980). "USNO GPS and Transit programs." Proceedings of the IEEE Position Location and Navigation Symposium (PLANS 80), Atlantic City, NJ, December, pp. 152-153.

Radio Technical Commission for Marine Services (1981). "Federal radionavigation plan review." RTCM paper 342-81/DO-9, Washington. (Phoenix:GPS-RTCM; 179248)

Rauch, S. (1980). "Unsolicited proposal to study satellite signal processing techniques applicable to GPS geodetic equipment." Prepared by Canadian Marconi Company (CMC Proposal No. P-2040) for the Department of Energy, Mines and Resources, Ottawa, March. (Phoenix:GPS-MARCONI; 179213)

Resch, G.M. and E.S. Claflin (19). "Microwave radiometry as a tool to calibrate tropospheric water-vapor delay." Radio Interferometry, pp. 377-384. (Phoenix:GPS-WATER VAPOUR; 179268)

Rino, C.L., M.D. Cousins and J.A. Klobuchar (1981). "Amplitude and phase scintillation measurements using the Global Positioning System." Proceedings of the Symposium on the Effect of the Ionosphere on Radiowae Systems, Washington, April, Paper 3A-12.

Rockwell International (1975). "GPS interface control document." Collins Government Avionics Division. (Phoenix:GPS-DOD; 179183)

Rockwell International (1981). "Feasibility concept for a translocation survey GPS receiver design." Final report #523-0771152-00111R by Collins Government Avionics Division for the Department of Commerce, National Geodetic Survey. (Phoenix:GPS-COLLINS; 179174 - 2 copies)

Rogers, A.E.E. et al. (1974). "Astrometric and geodetic parameters." pp. 271-272. (Phoenix:GPS-MIT; 179303)

Rosetti, C. (1981). "Prospects for NAVSAT--a future worldwide civil navigation-satellite system." European Space Agency, Paris. (Phoenix: GPS-ESA; 179282)

Rosetti, C. (19). "Prospects for a future civil worldwide navigation satellite system--NAVSAT." European Space Agency, Paris. (Phoenix: GPS-ESA; 179187--2 copies)

Russell, S.S. and J.H. Schaibly (1978). "Control segment and user performance." Navigation, Journal of The Institute of Navigation (U.S.), Vol. 25, No. 2, pp. 74-80.

Sansom, R.E. (1980). "Space applications of the Global Positioning System (GPS)." Magnavox Report MX-TM-3325-80. Invited paper for the 1980 IEEE Telecommunications Conference, December. (Phoenix:GPS-MAGNAVOX; 179202)

Schaibly, J.H. (1976). "Simulated and projected performance of the NAVSTAR/GPS control segment." Presented at the AIAA Guidance and Control Conference, San Diego.

Schaibly, J.H. and M.D. Harkins (1979). "The NAVSTAR Global Positioning System control segment performance during 1978." Proceedings of the Second International Geodetic Symposium on Satellite Doppler Positioning, Austin, TX, pp.

Schaibly, J.H. and E.L. Lasley (1979). "Ephemeris and clock determination in GPS." In: Principles and Operational Aspects of Precision Position Determination Systems, Ed. C.T. Leondes. NATO AGARDograph No. 245, pp. 14-1 to 14-7.

Schmidt, J.R. (1975). "Computer error analysis of tropospheric effects for the NAVSTAR Global Positioning System." MS thesis, Air Force Institute of Technology, GE/EE/75-7; NTIS microfiche #AD-A017 183.

Schmitt, A.F. and J.J. Bowden (1979). "Application of GPS to low cost tactical weapons." In: Principles and Operational Aspects of Precision Position Determination Systems, Ed. C.T. Leondes. NATO AGARDograph No. 245, pp. 20-1 to 20-10.

Senus, W.J. (1982). "The Global Positioning System (GPS)--geodetic receivers." Proceedings of the International Symposium on Land Information at the Local Level, University of Maine at Orono, August, pp. 220-232. (Phoenix:GPS-DOD;)

Sheltech Canada (1980). "Announcement of receipt of GPS receiver." Sheltech Canada, Calgary, Alberta. (Phoenix:GPS-SHELTECH; 179275)

Sheltech Canada (1981). "Next generation receiver preliminary requirements (GPS)." Calgary, Alberta, March. (Phoenix:GPS-SHELTECH; 179276)

Sheltech Canada (1981). "Preliminary results--Sheltech Calgary warehouse." Notes. (Phoenix:GPS-SHELTECH; 179332)

Sims, M.L. (1980). "GPS prototype progress report." Letter to J.D. Bossler, 17 December. (Phoenix:GPS-NSWC; 179246)

Sims, M.L. (1981). "Progress report on GPS prototype." Letter to J.D. Bossler, 12 February. (Phoenix:GPS-NSWC; 179245)

Sims, M.L. (1982). "GPS geodetic receiver system." Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, NM, February, pp. (Phoenix:GPS-NSWC; 179313)

Sklar, J.R. and L.L. Horowitz (1979). "Performance enhancement of the GPS receiver by data-free operation." In: Principles and Operational Aspects of Precision Position Determination Systems, Ed. C.T. Leondes. NATO AGARDograph No. 245,, pp. 18-1 to 18-6.

Snider, J.B., H.M. Burdick and D.C. Hogg (1980). "Cloud liquid measurement with a ground-based microwave instrument." Radio Science, Vol. 15, No. 3, pp. 683-693. (Phoenix:GPS-WATER VAPOUR; 179262)

Spilker, J.J. (1978). "GPS signal structure and performance characteristics." Navigation, Journal of The Institute of Navigation (U.S.), Vol. 25, No. 2, pp. 121-146.

Spilker, J.J. (1979). "Global Positioning System: Signal structure and performance characteristics." In: Principles and Operational Aspects of Precision Position Determination Systems, Ed. C.T. Leondes. NATO AGARDograph No. 245, pp. 5-1 to 5-35.

Spiess, F.N. (1981). "Report on meeting of panel on ocean bottom positioning of the NAS/NRC committee on geodesy." National Research Council, Office of Earth Sciences, Committee on Geodesy, Washington, April. (Phoenix:GPS-MISC; 179224)

Stansell, T.A., Jr. (1978). "Civil marine applications of the Global Positioning System." Magnavox Report MX-TM-3272-78 for Navigation, the Journal of The Institute of Navigation (U.S.), Vol. 25, No. 2, pp. 224-235. (Phoenix:GPS-MAGNAVOX; 179203)

Stansell, T.A. (1981). "The continuing evolution of satellite-based geodetic positioning and survey navigation capabilities." Presented at thirteenth annual Offshore Technology Conference, Houston, TX, May. (Phoenix:GPS-MAGNAVOX; 179325)

Straiton, A.W. (1975). "The absorption and reradiation of radio waves by oxygen and water vapor in the atmosphere." IEEE Transactions on Antennas and Propagation, July, pp. 595-597. (Phoenix:GPS-WATER VAPOUR; 179258)

Sudworth, J.P. (1979). "A simple NAVSTAR receiver." From: Case Studies in Advanced Signal Processing (ed. P.M. Grant), Peebles, Scotland. IEEE Conference Publication 180, pp. 85-89. (Phoenix:GPS-MISC; 179222)

Teasley, S.P., W.M. Hoover and C.R. Johnson (1980). "Differential GPS navigation." Proceedings of the IEEE Position Location and Navigation Symposium (PLANS 80), Atlantic City, NJ, December, pp. 9-16.

Tennant, D.M. (1980). "NAVSTAR Global Positioning System (GPS) clock program: present and future." Proceedings of the twelfth annual Precise Time and Time Interval Application and Planning meeting. NASA conference publication 2175, pp. 703-718.

Texas Instruments Inc. (19). "GPS satellite coverage." Lewisville, TX. (Phoenix:GPS-TI; 179277)

Thompson, M.C. (1971). "A radio-optical dispersometer for studies of atmospheric water vapor." Remote Sensing of Environment, Vol. 2, pp. 37-40. (Phoenix:GPS-WATER VAPOUR; 179263)

Thompson, T. (1980). "Performance of the SATRACK/Global Positioning system Trident I missile tracking system." Proceedings of the IEEE Position Location and Navigation Symposium (PLANS 80), Atlantic City, NJ, December, pp. 445-449.

Underwood, D. (1982). "GPS." Submitted to Rotor and Wing. (Phoenix: GPS-MISC; 179223)

United States Department of Defense (1974). "NAVSTAR Global Positioning System: An evolutionary research and development program." 1974 briefing (A). (Phoenix:GPS-DOD; 179179)

United States Department of Defense (1974). "NAVSTAR Global Positioning system: A joint service program." 1974 briefing (B). (Phoenix: GPS-DOD; 179178)

United States Department of Defense (1974). "System specification for the Global Positioning System. Appendix II, Navigation signal structure." SS-GPS-101B, Code Identification 07868. (Phoenix:GPS-DOD;179182)

United States Department of Defense (1981). "GPS presentation and information briefing." 1981 briefing. (Phoenix:GPS-DOD;)

United States Department of Defense (1981). "Department of Defense authorization act 1982." House of Representatives Report No. 97-311, Conference Report, pp. 89-90. Aviation Week, p. 61, December 21. (Phoenix:GPS-DOD; 179185)

United States Department of Defense (1982). "NAVSTAR Global Positioning System user charges." RTCM paper 74-82/SC 78-82, preliminary report to the Senate and House Committees on Armed Services, March. (Phoenix: GPS-DOD; 179175)

United States Department of Defense/Department of Transportation (1980). "Radionavigation plans and policy." Vol. I of Federal Radionavigation Plan, U.S. Department of Defense document # DOD-NO.4650.4-P,I, and U.S. Department of Transportation document # DOT-TSC-RSPA-80-16,I, July. (Phoenix:GPS-FRP; 179251)

United States Department of Defense/Department of Transportation (1980). "Requirements." Vol. II of Federal Radionavigation Plan, U.S. Department of Defense document # DOD-No.4650.4-P,II, and U.S. Department of Transportation document # DOT-TSC-RSPA-80-16,II, July. (Phoenix: GPS-FRP; 179252)

United States Department of Defense/Department of Transportation (1980). "Radionavigation system characteristics." Vol. III of Federal Radionavigation Plan, U.S. Department of Defense document # DOD-No. 4650.4-P,III, and U.S. Department of Transportation document # DOT-TSC-RSPA-80-16,III, July. (Phoenix:GPS-FRP; 179253)

United States Department of Defense/Department of Transportation (1980). "Radionavigation research, engineering and development." Vol. IV of Federal Radionavigation Plan, U.S. Department of Defense document # DOD-No.4650.4-P,IV, and U.S. Department of Transportation document # DOT-TSC-RSPA-80-16,IV, July. (Phoenix:GPS-FRP; 179254)

United States Department of Defense/Department of Transportation (1982). "Radionavigation plans and policy." Vol. I of Federal Radionavigation Plan, U.S. Department of Defense document # DOD-4650.4-P-I, and U.S. Department of Transportation document # DOT-TSC-RSPA-81-12-I, March.

United States Department of Defense/Department of Transportation (1982). "Requirements." Vol. II of Federal Radionavigation Plan, U.S. Department of Defense document # DOD-4650.4-P-II, and U.S. Department of Transportation document # DOT-TSC-RSPA-81-12-II, March.

United States Department of Defense/Department of Transportation (1982). "Radionavigation system characteristics." Vol. III of Federal Radionavigation Plan, U.S. Department of Defense document # DOD-4650.4-P-III, and U.S. Department of Transportation document # DOT-TSC-RSPA-81-12-III, March.

United States Department of Defense/Department of Transportation (1982). "Radionavigation research, engineering and development." Vol. IV of Federal Radionavigation Plan, U.S. Department of Defense document # DOD-4650.4-P-IV, and U.S. Department of Transportation document # DOT-TSC-RSPA-81-12-IV, March.

United States Department of Transportation (1982). "Navigation safety regulations; Radar requirement for certain tankers of 10 000 gross tons or more." U.S. Coast Guard, Federal Register, Vol. 47, No. 153, August 9, Rules and Regulations, pp. 34388-9.

United States Department of Transportation (1982). "Electronic position fixing devices." U.S. Coast Guard, Federal Register, Vol. 47, No. 158, August 16, Proposed Rules, pp. 35531-2.

United States Department of Transportation (1982). "NAVSTAR GPS." 1982 briefing. (Phoenix:GPS-DOT; 179334)

United States General Accounting Office (1981). "DOT should terminate further LORAN-C development and modernization and exploit the potential of the NAVSTAR/Global Positioning system." Report MASAD-81-42, Washington, D.C. (Phoenix:GPS-USCG; 179250)

University of Texas (1981). "Invitation to bid on procurement of a field portable GPS receiving system." University of Texas at Austin, Applied Research Lab, Austin, TX. (Phoenix:GPS-TI; 179278)

Upadhyay, T.N. and J.N. Damoulakis (1980). "Sequential piecewise recursive filter for GPS low-dynamics navigation." IEEE Transactions on Aerospace and Electronic Systems, Vol. AES-16, No. 4, pp. 481-491.

van Dierendonck, A.J. (1979). "GPS time." In: Principles and Operational Aspects of Precision Position Determination Systems, Ed. C.T. Leondes. NATO AGARDograph No. 245, pp. 8-1 to 8-10.

van Dierendonck, A.J., S.S. Russell and E.R. Kopitake (1979). "The GPS navigation message." In: Principles and Operational Aspects of Precision Position Determination Systems, Ed. C.T. Leondes. NATO AGARDograph No. 245, pp. 6-1 to 6-21.

van Dierendonck, A.J., Q.D. Hua, J.R. McLean and A.R. Denz (1981). "Time transfer using NAVSTAR GPS." Standard Telecommunciations Inc. report STI-TM-9828, Sunnyvale, CA. (Phoenix:GPS-STI; 179309)

van Dierendonck, A.J., S.S. Russell, E.R. Kopitzke and M. Birnbaum (1980). "The GPS navigation message." Navigation, Journal of The Institute of Navigation (U.S.), Vol. 25, No. 2, pp. 147-165.

Varnum, F. and J. Chaffee (1982). "Data processing at the Global Positioning System master control station." Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, NM, February, pp. (Phoenix:GPS-DOD; 179281)

von Braun (1974). "24 satellites to give global pinpoint navigation." Popular Science, Sept., pp. 60-62, 112. (Phoenix:GPS-MISC; 179229)

Walker, J.G. (1977). "Continuous whole-earth coverage by circular-orbit satellite patterns." Royal Aircraft Establishment Technical Report 770044, Farnborough, U.K.

Ward, P. (1980). "An advanced NAVSTAR GPS multiplex receiver." Proceedings of the IEEE Position Location and Navigation Symposium (PLANS 80), Atlantic City, NJ, December, pp. 51-58.

Ward, P. (1981). "An inside view of pseudorange and delta pseudorange measurements in a digital NAVSTAR/GPS receiver." Presented at the ITC/USA/'81 International Telemetering Conference, San Diego, October, 16 pages. (Phoenix:GPS-TI; 179307)

Ward, P. (1982). "An advanced NAVSTAR GPS geodetic receiver." Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, NM, February, pp. (Phoenix:GPS-TI; 179308)

Waters, J.W. (1976). "Absorption and emission by atmospheric gases." Ch. 2.3 in Methods of Experimental Physics, Vol. 12, Part B (Radio Telescopes) of Astrophysics, ed. M.L. Meeks. Academic Press, New York (ISBN 0-12-475952-1, v.12, pt.B). (Phoenix:GPS-WATER VAPOUR; 179269)

Wells, D.E. (1969). "Experience with satellite navigation during the summer of 1968." The Canadian Surveyor, Vol. 23, pp. 334-348.

Wells, D.E. (1981). "Comments on Canadian Marconi final report on the 'Study of Satellite Signal Processing Techniques Applicable to GPS Geodetic Equipment'." Department of Surveying Engineering, University of New Brunswick, Fredericton, September. (Phoenix:GPS-MARCONI; 179218)

Wells, D.E. and D. Delikaraoglou (1980). "NAVSTAR performance analysis." Department of Surveying Engineering Technical Report 75, University of New Brunswick, Fredericton.

Wells, D.E. and D. Delikaraoglou (1982). "Models for combining single channel NAVSTAR/GPS with dead reckoning for marine positioning." Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, NM, February, pp.

Wells, D.E. and D. Delikaraoglou (1982). "NAVSTAR data analysis." Department of Surveying Engineering Report, University of New Brunswick, Fredericton.

Wells, D.E. and S.T. Grant (1981). "An adaptable integrated navigation system: BIONAV." Proceedings of the Canadian Petroleum Association Colloquium III on Petroleum Mapping and Surveys in the '80s, Banff, October, pp. 195-208.

Wells, D.E. and G. Lachapelle (1981). "Impact of NAVSTAR/GPS on land and offshore positioning in the '80s." Proceedings of the Canadian Petroleum Association Colloquium III on Petroleum Mapping and Surveys in the '80s, Banff, October, pp. 305-322.

Wells, D.E., D. Delikaraoglou and P. Vaníček (1981). "Navigating with the Global Positioning system." Presented at 74th annual meeting of CIS, St. John's, Newfoundland, May 22.

Wells, D.E., D. Delikaraoglou and P. Vaníček (1982). "Marine navigation with the NAVSTAR/Global Positioning System (GPS) today and in the future." The Canadian Surveyor, Vol. 36, No. 1, pp. 9-28.

Wells, D.E., G. Lachapelle and S.T. Grant (1982). "Enhanced offshore positioning using current Global Positioning System capabilities." Presented at the International Association of Geodesy Symposium on Marine Geodesy, Tokyo, May.

Wells, D.E., P. Vaníček and D. Delikaraoglou (1981). "The application of NAVSTAR/GPS to geodesy in Canada. Pilot study." Department of Surveying Engineering Technical Report 76, University of New Brunswick, Fredericton.

West, S. (1982?) "A SERIES look at the earth." Science News, Vol. 115, pp. 58-59.

Westwater, E.R. (1978). "The accuracy of water vapor and cloud liquid determination by dual-frequency ground-based microwave radiometry." Radio Science, Vol. 13, No. 4, pp. 677-685. (Phoenix:GPS-WATER VAPOUR; 179264)

Westwater, E.R. and F.O. Guiraud (1980). "Ground-based microwave radiometric retrieval of precipitable water vapor in the presence of clouds with high liquid content." Radio Science, Vol. 15, No. 5, pp. 947-957. (Phoenix:GPS-WATER VAPOUR; 179265)

Wilheit, T.T. and A.T.C. Chang (1980). "An algorithm for retrieval of ocean surface and atmospheric parameters from the observations of the scanning multichannel microwave radiometer." Radio Science, Vol. 15, No. 3, pp. 525-544. (Phoenix: GPS-WATER VAPOUR; 179266)

Witherspoon, J.T. and L. Schuchman (1979). "A time transfer unit for GPS." In: Principles and Operational Aspects of Precision Position Determination Systems, Ed. C.T. Leondes. NATO AGARDograph No. 245, pp. 13-1 to 13-6.

Wong, R.V.C. and K.-P. Schwarz (1982). "Offshore positioning with an integrated GPS/inertial navigation system." Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning, Las Cruces, NM, February, pp. (Phoenix:GPS-MISC; 179287)

Wu, S-C (1979). "Optimum frequencies of a passive microwave radiometer for tropospheric path-length correction." IEEE Transactions on Antennas and Propagation, Vol. AP-27, No. 2, pp. 233-239. (Phoenix:GPS-WATER VAPOUR; 179267)

APPENDIX B

THE POTENTIAL ENGINEERING AND LAND SURVEYING MARKET FOR GPS*

R.B. Langley, J.D. McLaughlin, D.E. Wells

Dept. of Surveying Engineering
University of New Brunswick
P.O. Box 4400
Fredericton, N.B. Canada
E3B 5A3

The following notes are a speculative assessment of the potential GPS market in the engineering and land surveying fields. They are based in part on a review of the evolving positional information requirements in surveying, on the potential application of production economic models developed by Robert Noyce et al.*, and on the history of implementation of other surveying technologies such as EDM and TRANSIT.*

1. Introduction

Originally conceived as a tool for military navigation, the Global Positioning System (GPS) is currently being proposed for a number of civilian uses. One of these civilian uses is surveying. In this paper we shall consider the potential surveying market for GPS. We will indicate some of its uses and we will attempt to outline a scenario for the growth of GPS utilization in surveying. In so doing, we will rely heavily on the histories of two other advanced technologies in surveying: electromagnetic distance measurement (EDM) and TRANSIT satellite Doppler positioning and also on the production economic models of high technology proposed by Robert Noyce *(1977)*.

We will look at GPS solely as a positioning tool. It should be emphasized at the outset that GPS is not a panacea for all problems in surveying. Indeed it likely will be of little assistance in the setting-out problem with which surveyors must deal and for which, for example, the total station is a very powerful tool.

GPS has the capability to provide accurate point position and relative position information. However, it is possible, and indeed probable, that the United States military auuthorities will restrict civilian access to GPS. This restriction may result in a degradation of point position accuracy to about 500 m. Due to this possibility we will here concentrate on the techniques for obtaining relative positions through differential methods.

---

* Corrected version of a paper presented at the American Society of Civil Engineers Specialty Conference on Engineering Applications of Space Age Surveying Technology, Nashville, TN; 16-19 June 1982.

Differential methods of using the signals of the GPS have potential advantages over other geodetic positioning techniques with respect to convenience, accuracy and cost. In a differential mode, two or more GPS receivers simultaneously receive signals from the same set of satellites. The resulting observations are subsequently processed to obtain the interstation baseline vectors. There are four types of measurement which could be used differentially: pseudo-range, integrated Doppler frequency, carrier phase and interferometric time delay.

Accuracy projections for interstation baseline vector determinations using the GPS interferometric or differential phase techniques range between a few millimetres for baselines of a few kilometres *(Counselman and Steinbrecher, 1982)* to a few decimetres for baseline lengths up to 5,000 km. These projections assume observing periods of about one hour. The GPS differential Doppler technique should give decimetre accuracy on a 500 km baseline after the accumulation of about eight hours of observations *(Fell, 1980)*. Similar accuracies are achievable only with very precise terrestrial techniques and with other extraterrestrial techniques such as TRANSIT differential integrated Doppler, satellite laser ranging, and very long baseline interferometry (VLBI) using quasars.

GPS provides cost advantages over terrestrial techniques since intervisibility between stations is not required. Very precise control surveys done with terrestrial techniques often require the erection of towers and favourable observing weather. Both requirements extend the time and expense of surveys. Even with the erection of towers, intervisibility requirements limit terrestrial station separations usually to less than 50 km. Without the constraint of intervisibility, control points can be selected to better optimize network geometry. Similarly rural surveys, while not as demanding in terms of accuracy, often involve cutting intervisibility lines through brush or forest, again resulting in extra time and expense.

Mobile laser ranging and mobile VLBI using quasars both use much bulkier and costlier equipment than GPS and require road access, site preparation, and much longer setup times. Laser ranging additionally requires favourable observing weather.

TRANSIT integrated Doppler baseline determinations are at present accurate to a few decimetres and in principle should be determinable to within a few centimetres, with improvements in hardware and software *(Kouba, 1982)*. Although TRANSIT receivers are competitive in cost and size with GPS receivers, differential GPS provides a cost advantage over TRANSIT due to the speed of positioning, requiring only one hour rather than one or two days of observations for each baseline determination.

The estimated one sigma uncertainties in baselines that could be achieved using a variety of positioning techniques are represented approximately in Figure 1. In general, the uncertainties represent the ranges of precision or repeatability that have been or could be obtained with the techniques. Only quasar VLBI and laser ranging can provide precisions comparable to those of GPS over a wide range of station separations. But this can only be achieved with far greater expense.

The scenarios of GPS utilization in surveying to be discussed subsequently are predicated on several assumptions. We assume that GPS will be operational from 1988 *(United States Department of Defense/Department of Transportation, 1980)*, and that possible budget and technical difficulties will be overcome and will not further delay this schedule. We also assume that denial of access to full GPS accuracy for civilian realtime navigation will have no effect on GPS performance for differential fixed-site surveying. We further assume that GPS surveying equipment will be developed to meet the markets identified later in this paper, and that the cost of this equipment will fall as these markets are penetrated, in accordance with rules and precedents we later cite. Finally we assume that possible fees for GPS usage *(United States Department of Defense, 1982)* will be small and will not affect market development. The first steps in these developments have resulted in proposed or actual equipment such as the Macrometer *(Counselman and Steinbrecher, 1982)*, the Texas Instruments 4100 receiver *(Ward, 1982)* and the SERIES and TRANSIT add-on concepts *(MacDoran et al., 1982)*.

2. Economic Considerations in Surveying Technology

The interaction of technology and economics is perhaps best illustrated by the evolution of microelectronics:

> "The small size of microelectronic devices has been important in many applications, but the major impact of this new technology has been to make electronic functions more reproducible, more reliable and much less expensive. With each technical development costs have decreased, and the ever lower costs have promoted a widening range of applications; the quest for technical advances has been required by economic competition and compensated by economic reward." *(Noyce, 1977)*

The economics of high technology industries are influenced in part by technological advancement, and in part by economies of scale and advancement along a production learning curve. Figures 2 and 3 show the history of an example from the computer memory field. The figures reflect the fact that most high technology industries are able to reduce costs (in constant dollars) by 20 to 30 per cent each time cumulative output is doubled *(Forester, 1981)*.

To get an indication of how the growth of GPS utilization in surveying might progress, let us examine the recent history of two significant surveying technologies: EDM and TRANSIT satellite Doppler positioning.

The earliest terrestrial EDM instruments were developed as a by-product of research initiatives by *Bergstrand (1951) and Wadley*

(1957). The first commercial instruments (eg., the Model 2 Geodimeter) were awkward, heavy (approximately 40 lbs) and complex to operate. They served a very small, specialist market. Subsequently, developments in the early 1960s resulted in lighter, easier-to-use equipment. The EDM market grew slowly as it was still primarily specialist oriented (precise engineering and control surveys). Although there was no decrease in systems cost, there was a gradual improvement in performance-to-cost ratios.

The market until the late 1960s was characterized by: a) a virtual monopoly by two manufacturers; and b) small volume production. The demand was influenced by the size and complexity of the instrumentation, conservativeness of the surveying profession and probably also by poor marketing. Indeed it is often argued that the original manufacturers misread the market for short range equipment and concentrated on the long range, specialized end of the market.

Major developments in the late 1960s included the entry of new manufacturers, significant technological innovations (eg., the introduction of infrared) and the development of new marketing strategies. The first infrared instruments (eg., DI 10) introduced circa 1968 were heavy (25-30 lbs), had a short range (1 km) and were relatively expensive ($20,000 in 1982 dollars). Today superior equipment is available for $5,000 (1982 dollars).

In examining the evolution of the EDM market from a national perspective, we estimate that probably less than 10% of private survey firms in Canada had EDM equipment in the 1960s. This increased to 50% by 1975 and is currently in excess of 90% (see Figure 4). The surveying market has grown from a few hundred instruments in the 1960s to a current estimated Canadian population of about 5,000, with a replacement market of 500-600 units per year.

The TRANSIT system, although developed for military use starting in 1958, was first made available to civilians in 1967. It was designed to be a marine navigation aid, and today that remains its primary role for an overwhelming majority of its users. However, beginning in the late 1960s the use of TRANSIT for positioning points in surveying was developed. The accuracies available from TRANSIT relative positioning have improved from several metres to a few decimetres over the past 12 years.

While the number of receiver manufacturers has increased from two in 1967 to over two dozen today, only three or four manufacturers have developed products specifically designed for the surveying market. The total number of TRANSIT receivers in use has expanded exponentially, as shown in Figure 5(a), however most of this growth has been due to inexpensive single channel navigation receivers designed for small boats. Nonetheless, the geodetic user community also has increased significantly over the years as shown in Figure 5(b).

3. Forecasts for GPS Utilization in the Surveying Field

Technological forecasting is a dangerous business. However, armed with the histories of the high technology developments in the surveying field outlined above, we will attempt to suggest in broad terms a possible scenario concerning the potential growth of GPS use in the surveying community.

The growth of GPS use in surveying will be related to the overall use of GPS. Figure 6 illustrates the projected growth of non-terrestrial GPS receivers as envisioned by the Department of Defense in a recent report to the Senate and House Committees on Armed Services *(United States Department of Defense, 1982)*. Note once again the slow initial growth followed by a period of rapid growth and the turn over as market saturation is reached. The potential market for engineering and land surveying applications of GPS is a small fraction of the total GPS market but one that is probably not that much different from say the commercial aviation or merchant marine markets. To help envision how it will evolve we have broken the market down into three broad divisions: entry, transition and mature.

3.1. The Entry Market

The entry market will be the first to be penetrated. It is essentially the TRANSIT replacement market and is made up of national survey organizations and large surveying firms involved in major network projects and perhaps very large engineering projects. Because of the initial high cost of the technology only organizations conducting geodynamics surveys and precise control surveys will be able to afford to purchase units.

The approximate cost of a basic GPS receiving and processing system consisting of two receivers and a processor will be initially about $250,000 and this will probably drop to the $125,000 range at the entry commercial (transition) stage *(Bossler, 1981)*. At this price level, several hundred units could likely be sold through 1983. Although we indicate the cost of a two receiver system, we do not mean to imply that this is the mode in which all surveys will be done. For improved network accuracy and shorter overall field time, surveys will likely involve a number of receivers operating simultaneously.

3.2. Geodynamics and Control Survey Applications

Let us look at two possible early uses of GPS in surveying. In surveys conducted to yield information on geodynamical processes the highest accuracy possible is required. The cost and time to survey are generally of lesser importance. An example of such surveys is illustrated in Figure 7. The map shows a network of sites in Alaska and northwestern Canada which will be visited in 1984 and in following years by mobile quasar-observing VLBI systems as part of the National Aeronautics and Space Administration's Crustal Dynamics Project *(NASA, 1979)*.

The baselines interconnecting the sites will be determined with average uncertainties of about 2-3 cm. The interpretation of the VLBI baseline determinations in terms of the average strain across elements of the network requires that possible local movements of the observing sites be adequately modelled. This will necessitate the establishment of local stability networks to detect vertical and horizontal movements of the VLBI sites with respect to the surrounding terrain. The local strains should be determined with an accuracy at least as great as that of the VLBI baseline determinations, something which differential GPS techniques could adequately supply.

The second type of survey for which early use of GPS could be justified is that conducted for precise geodetic control. In such surveys there is an accuracy floor at about the decimeter level. Below this level the benefits of increased accuracy decrease sharply. The accuracy floor is balanced by a cost ceiling in the neighbourhood of several hundreds of dollars per point. A specific example of a precise control survey is one proposed for the 1:50,000 mapping of Ellesmere Island. Ellesmere Island is situated in the Canadian Arctic. Possibly of high economic importance, it is isolated and has rugged, difficult terrain. It has been proposed to establish eighteen control points around the perimeter of the island to support the photogrammetry survey of the interior. Figure 8 is an outline map of the island showing the proposed control points. In order to reduce expenses, as short a field time as possible is desired for the establishment of control. Because of the potential of its short observing periods, GPS readily fulfills this requirement.

3.3. The Transition and Mature Markets

We believe that the successful application of GPS technology to the entry market will lead to the adoption of the technology by the engineering and land surveying market in general. This will likely proceed in two steps resulting in the second and third marketing units alluded to earlier.

The first step will involve private surveyors working in collaboration with a high technology service company, cooperative or state or national government agency. Perhaps a private surveyor would purchase one receiver at a cost of about $50,000. He would then operate the receiver at various sites as a remote station while the service company simultaneously operates a base station. The service company might process the collected data and provide the resulting baseline determinations to the surveyor. This is what we call the transition market. As the costs of the technology fall still lower, it should become feasible for private surveying firms to purchase complete systems and to operate them independently. A purchase price of $50,000 for a basic *system* is probably the threshold where the technology would be attractive to these smaller firms. The gradual purchase of complete systems by private firms is what we have termed the mature market.

It is important to recognize in this discussion that significant penetration of the engineering and land surveying market will only be achieved if, in addition to low cost, the systems can provide realizable accuracies in the three to five centimetre range from an observing time of the order of fifteen minutes. Only then will GPS be competitive with existing technology.

3.4. Engineering and Land Surveying Applications

What then are some of the applications of GPS in the engineering and land surveying fields? Engineering surveys embrace a wide variety of accuracies and scales. Some engineering surveys, such as those involved in road, rail and power line construction, demand accuracies which can be met by the TRANSIT system, for example. We will not consider this type of survey. In other engineering surveys the accuracy requirements are often as high as those for geodynamics surveys, but the spatial separations are generally shorter and of course the costs must be competitive with alternative techniques. An example would be the monitoring of ground subsidence as a consequence of mining and mineral exploitation (see Figure 9). Although this monitoring can be carried out by conventional surveys and also by some newly developed instrumentation *(Chrzanowski and Faig, 1981)*, these methods have not been entirely adequate due to difficulties experienced with the terrain in many mining areas and the necessity for continuous monitoring of the movements.

In land surveying there are two broad areas of concern. On the one hand there is a microlevel concern with delimiting individual parcels (the traditional land surveying function). On the other there is the macrolevel concern with construction of parcel-based land information systems (the multipurpose cadastre concept).

The delimitation of individual parcels is concerned with area, linear measurements and especially with the location and relocation of boundaries. Typical accuracy requirements are given in the following table:

Class	Area	Tolerance
A	urban core	5 cm
B	urban-suburban	10 cm
C	rural	50 cm

There is no doubt that differential GPS could meet these tolerances. From an economic perspective, there are two extreme situations: a) large urban subdivision surveys (characterized by low travel costs, easy access to control, distribution of fixed costs over a large number of parcels, client with money, high land values); and b) individual rural lot surveys (burdened with high travel costs, difficult access to control, all costs being absorbed by a single lot, client without money, low land values). Given these accuracy and economic considerations, we believe that the applications of GPS to traditional land surveying can be ranked in the following order of diminishing potential:

a) control densification for land surveys;
b) large rural surveys;
c) perimeter control for large land development projects;
d) land surveys in urban core areas (where there are significant intervisibility problems);
e) other land surveys.

It is initially envisaged that GPS will be used by public agencies administering large tracts of land (eg. Bureau of Land Management), and that this will be followed by the gradual acquisition by large regional/national companies and service bureaus and ultimately by private surveyors.

Turning to the macrolevel perspective, it is increasingly being accepted that a geodetic framework forms the spatial foundation for the creation of any integrated land records and information system. It not only provides accurate and efficient means for referencing data, it also provides a uniform, effective language for interpreting and disseminating land information. In this regard, GPS potentially represents a major breakthrough in providing efficient control densification - a major concern to the land information management community *(National Research Council, 1980)*. At the same time, of course, it also raises the question of whether densification is even necessary. As Duane Brown has noted:

> "Such a system would require profound reconsideration of the very need for a geographic data base based on closely spaced monumentation. This is especially so if the system could successfully operate amid the obstacles of an urban environment, for then it would suffice to have a single base station at a convenient point in each county operating in conjunction with any number of mobile units operated by private surveyors performing routine surveys. Alternatively, in difficult areas one could envision a MITES-like system used in conjunction with a compact (second or third generation) inertial system, the former providing nearby temporary control for the latter. Such a hybrid system could establish a geographic cadastre without recourse to a dense geographic data base. ... The foregoing considerations make it clear that emerging technology will be of increasing, and ultimately dominant, importance in the establishment of the geographic cadastre. We must accord due weight to such developments." *(Brown, 1979)*.

4. Conclusion

The Global Positioning System has the potential to provide distinct benefits in engineering and land surveying applications with which no other technology at the present time can economically compete. The surveying community has the need of its convenience, accuracy and cost effectiveness. We estimate that the eventual surveying market is about 5,000 to 10,000 units in North America and perhaps triple this number worldwide (for the correlation between North American and global markets see, for example, Norman *(1980)*). If this market is to be realized, surveyors must appreciate the concepts, advantages and constraints of GPS and the manufacturers must develop an understanding of the special nature of the surveying market. This meeting of the American Society of Civil Engineers is an important step in this educational process.

REFERENCES

BABBAGE, G. (1981), "Inertial surveying - a study in accuracy and versatility", *Proceedings of the Second International Symposium on Inertial Technology for Surveying and Geodesy,* pp. 351-357, Banff, Alberta, June.

BERGSTRAND, E. (1951), "Measurement of distances with the Geodimeter", *Rikets Allmanna Kartverk Middelande,* Vol. 26.

BROWN, D. (1979), "Photogrammetric densification of geodetic nets, a technology whose time has passed?", paper presented to the International Symposium on Current Trends in the Development, Execution and Use of Aerial Triangulation, Brisbane, Queensland, October.

BOSSLER, J.D. (1981), "A note on Global Positioning System activities", *American Congress on Surveying and Mapping Bulletin,* August, pp. 39-40.

CHRZANOWSKI, A. and W. FAIG (1981), "Monitoring of mining subsidence", a paper presented at the 74th Annual Convention of the Canadian Institute of Surveying, St. John's, Newfoundland.

CARTER, W.E. and D.S. ROBERTSON (1982), "Geodynamic measurements from the HRAS-Westford POLARIS Radio Interferometer", a paper presented at the International Association of Geodesy General Meeting, Tokyo, May.

COUNSELMAN, C.C. and D.H. STEINBRECHER (1982), "The Macrometer: A compact radio interferometry terminal for geodesy with GPS", *Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning*, Las Cruces, NM, February, in press.

FELL, P.J. (1980), "Geodetic positioning using a Global Positioning System of satellites", *Department of Geodetic Science Report 299*, The Ohio State University, Columbus, OH.

FORESTER, T. (ed.) (1981), *The Microelectronics Revolution*, The M.I.T. Press, Cambridge, MA.

HOAR, G.J. (1982), *Satellite Surveying*, TM-3346-81, Magnavox Advanced Products and Systems Company, Torrance, CA.

HOTHEM, L.D. and G.J. EDLER (1982), "Analysis of point and semishort arc solutions using Fort Davis Doppler test survey data", *Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning*, Las Cruces, NM, February, in press.

KOUBA, J. (1982), "A review of geodetic and geodynamic satellite Doppler positioning", prepublication manuscript.

MACDORAN, P.F., D.J. SPITZMESSER and L.A. BUENNAGEL (1982), "SERIES: Satellite Emission Range Inferred Earth Surveying", *Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning*, Las Cruces, NM, February, in press.

NATIONAL RESEARCH COUNCIL (1980), *Need for a Multipurpose Cadastre*, National Academy Press, Washington, D.C.

NASA (1979), *Application of Space Technology to Crustal Dynamics and Earthquake Research,* NASA Technical Paper 1464, NASA Scientific and Technical Information Branch, Washington, D.C.

NORMAN, C. (1980), *"Microelectronics at Work: Productivity and Jobs in the World Economy"*, Worldwatch Institute, Washington, D.C.

NOYCE, R. (1977), "Microelectronics", *Scientific American*, Vol. 237, No. 3, pp. 62-69; reprinted in Forester (1981) *op. cit.*

UNITED STATES DEPARTMENT OF DEFENSE, (1982) "NAVSTAR Global Positioning System User Charges", RTCM Paper 74-82/SC 78-82.

UNITED STATES DEPARTMENT OF DEFENSE/DEPARTMENT OF TRANSPORTATION (1980), "Radionavigation plans and policy", Vol. I of *Federal Radionavigation Plan*, U.S. Department of Defense and U.S. Department of Transportation, July.

VANICEK, P. and E.J. KRAKIWSKY (1982), *Geodesy: The Concepts*, North-Holland Publishing Company, Amsterdam.

WADLEY, T.L. (1957), "The Tellurometer system of distance measuring", *Empire Survey Review*, Vol. XIV, No. 105 and 106.

WARD, P. (1982), "An advanced NAVSTAR GPS geodetic receiver", *Proceedings of the Third International Geodetic Symposium on Satellite Doppler Positioning*, Las Cruces, NM, February, in press.

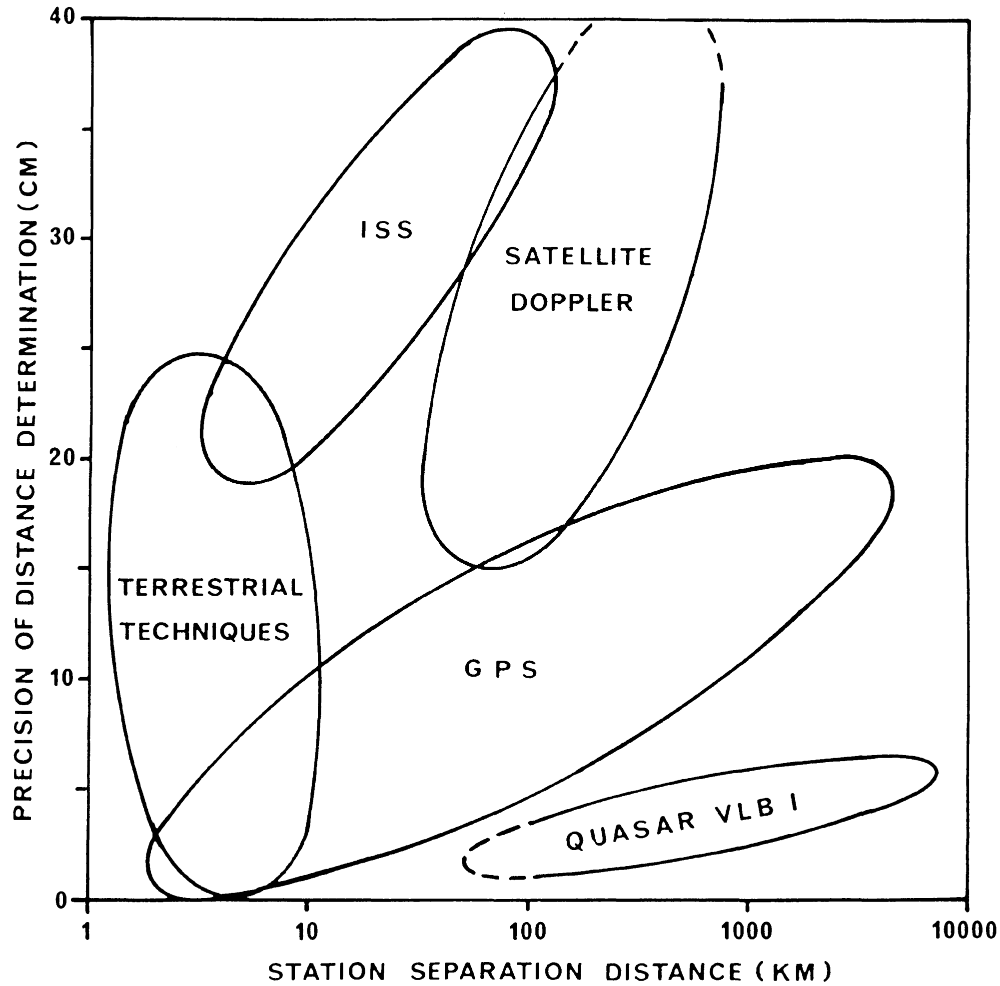


Figure 1 - Precision of distance determinations achieved or achievable using different techniques. Ellipses have been used to delineate the ranges of feasible station separations and ranges of precision. The delineations of separation and precision are at best fuzzy and should be interpretted accordingly. Sources: ISS (Inertial Surveying Systems) (*Babbage, 1981*), Terrestrial (*Vanicek and Krakiwsky, 1982*), Satellite Doppler (*Hothem and Edler, 1982*), GPS (*Counselman and Steinbrecher, 1982*). The precisions of satellite laser ranging have not been indicated; they lie approximately between those of GPS and quasar VLBI.

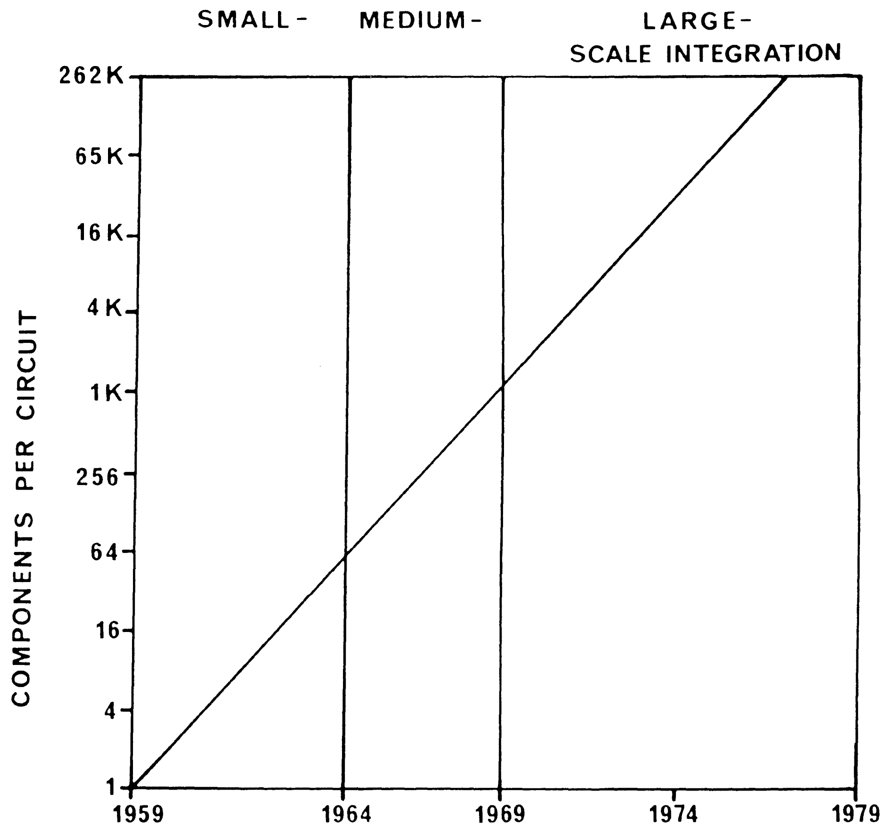


Figure 2 - Number of components per circuit in computer memories. After Noyce (1977).

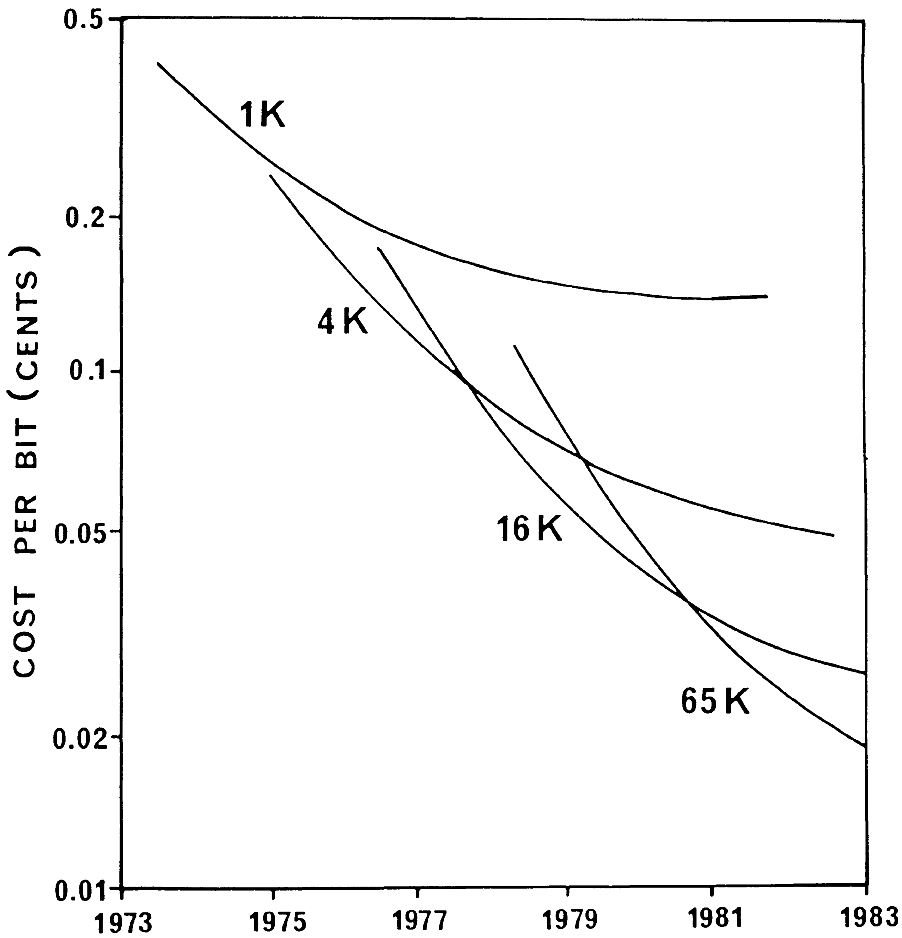


Figure 3 - Cost per bit of computer memory. After Noyce (1977).

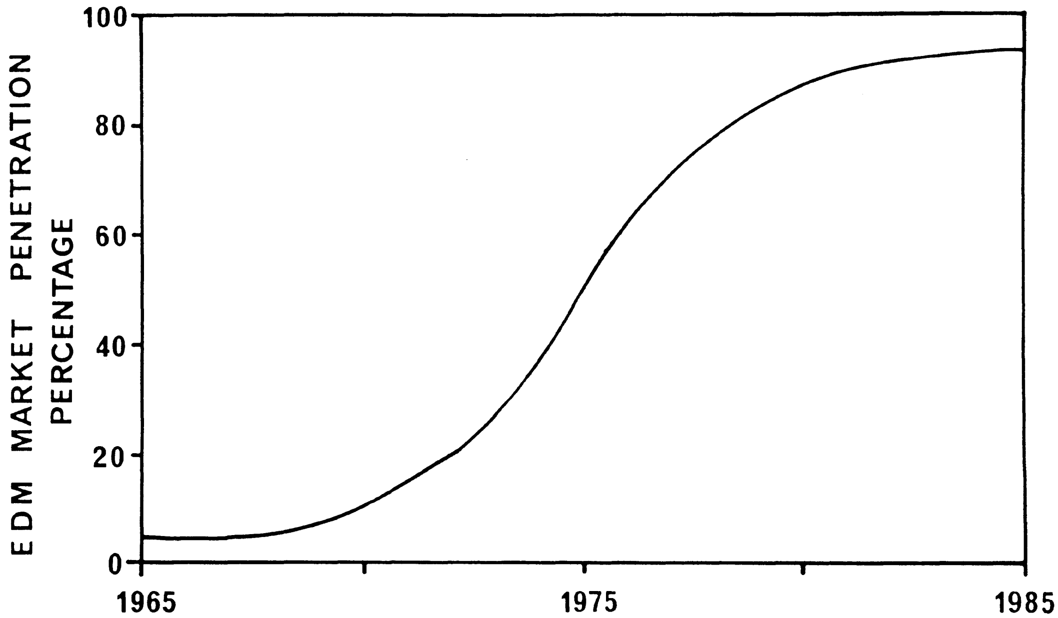


Figure 4 - Growth in number of private Canadian survey firms using EDM equipment.

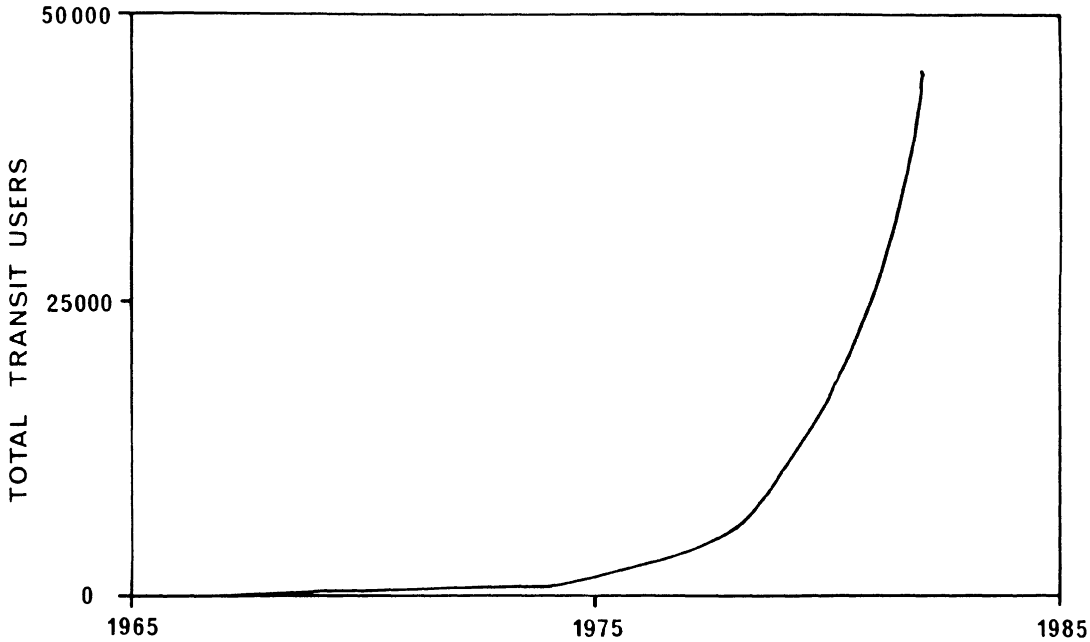


Figure 5 (*a*) - Growth in the number of nagivation and geodetic satellite Doppler receivers. After Hoar (1982).

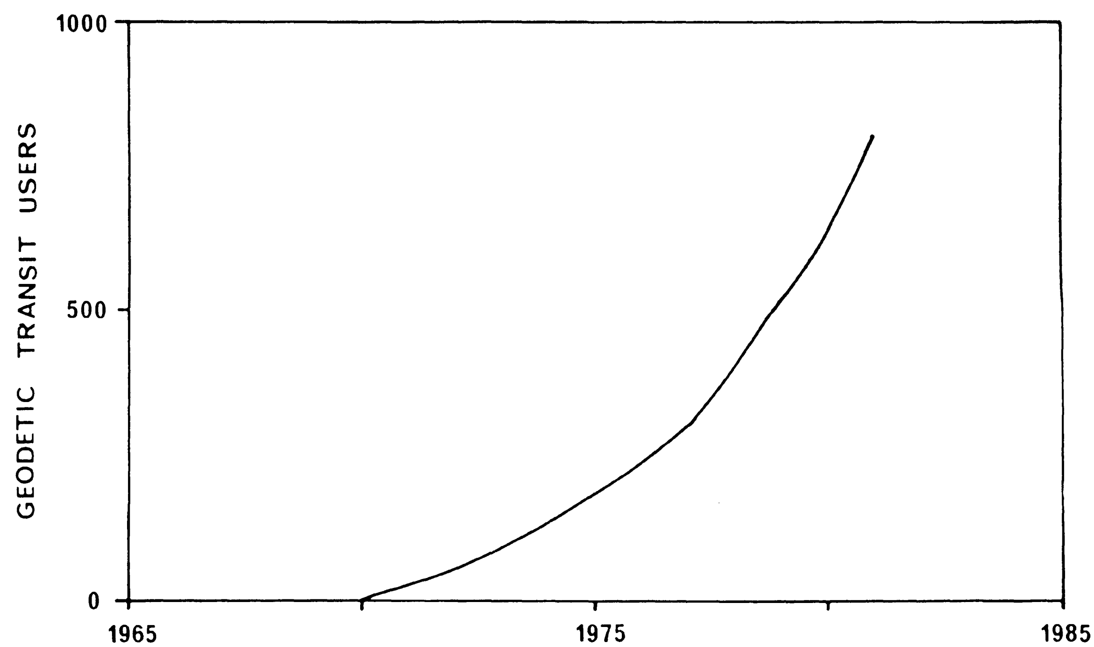


Figure 5 (*b*) - Growth in the number of geodetic satellite Doppler receivers alone. After Hoar (1982).

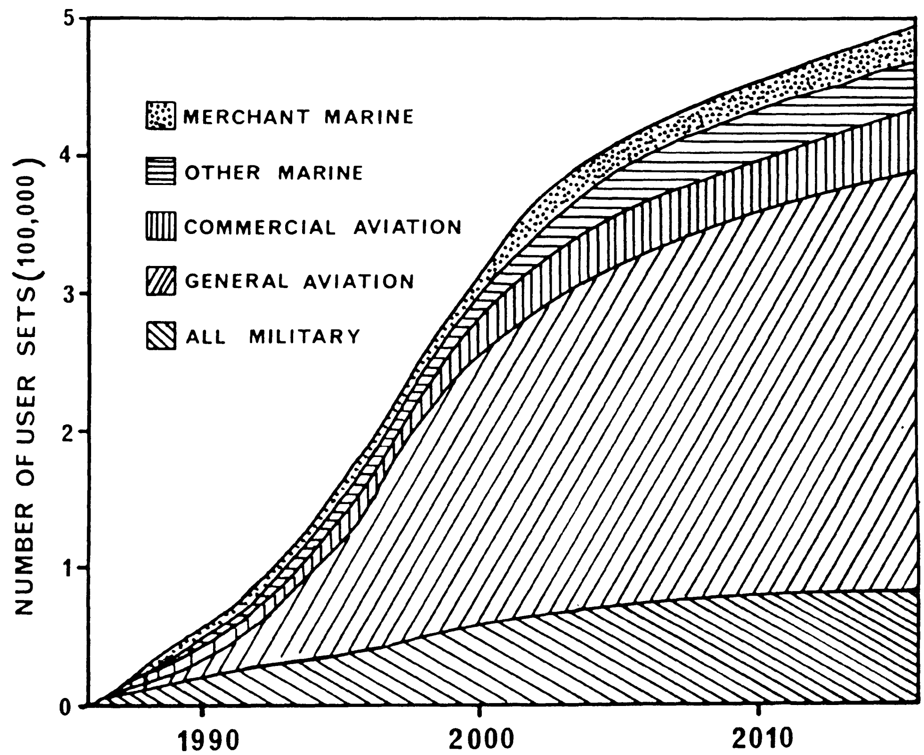


Figure 6 - Projected growth in the number of non-terrestrial GPS receiver sets. Source: United States Department of Defense (*1982*).

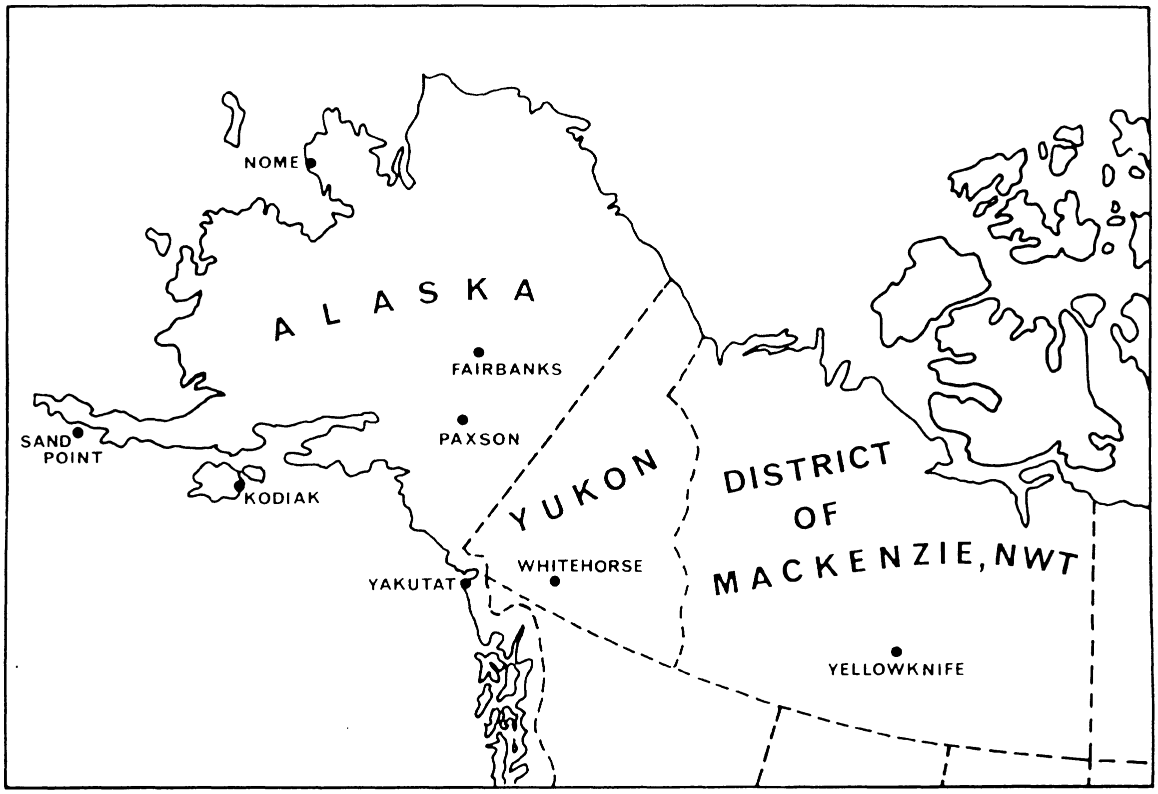
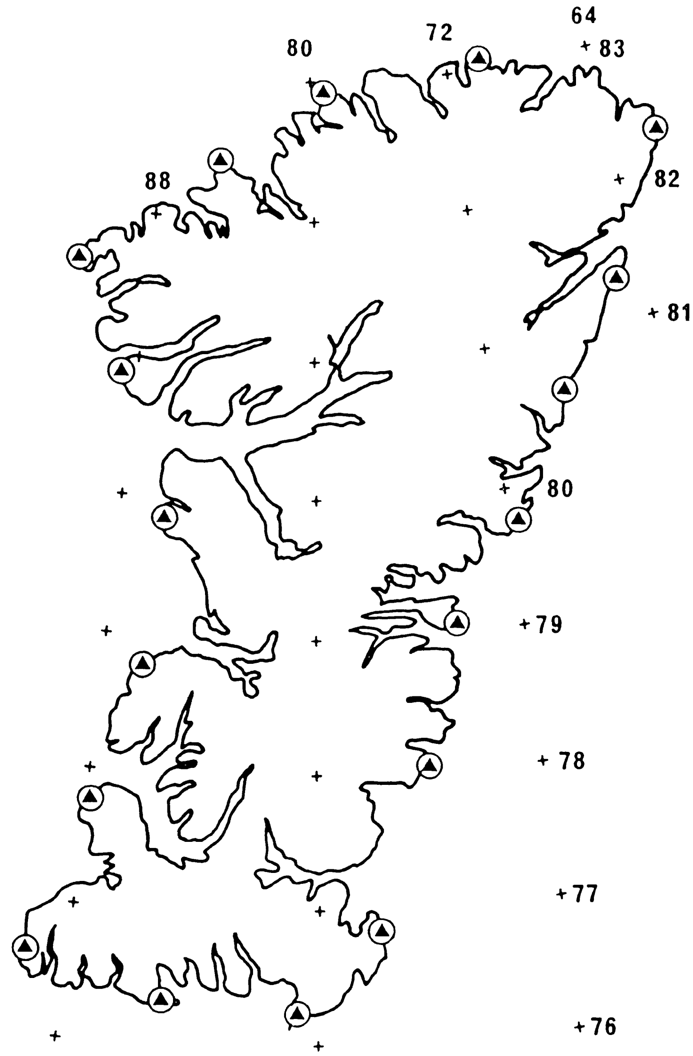


Figure 7 - Sites in Alaska and northwestern Canada to be visited by mobile VLBI equipment beginning in 1984.



ELLESMERE ISLAND, CANADA

Figure 8 - Mapping control on Ellesmere Island.

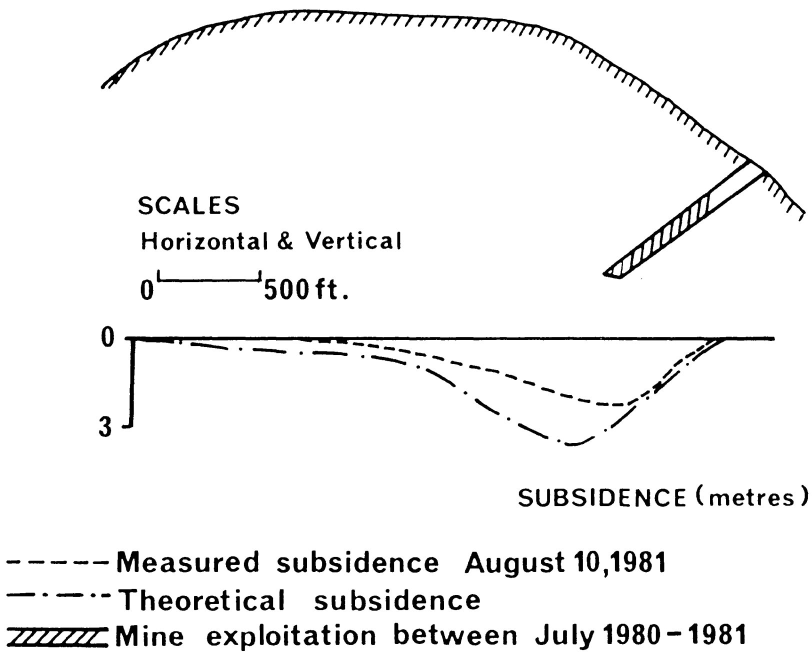


Figure 9 - Mining Subsidence. After Chrzanowski and Faig (1981).

Appendix C

NOTES ON THE RESOLUTION OF CARRIER PHASE MEASUREMENT AMBIGUITY

In the ideal (no refraction, no clock error, perfect synchronization, etc.) case of a fixed station (immobile), we get

$$\rho = (n + \phi) \frac{c}{f} = (N + \Phi) \frac{c}{F} \tag{C.1}$$

where subscripts and superscripts (referring to points to be positioned and satellite positions) are left out for the time being. The same point and the same satellite are assumed unless stated otherwise. The situation refers to satellite time instant t; n, ϕ, f refer to the first carrier L_1 (of f = 10.23 × 154 = 1575.42 MHz), N, Φ, F refer to the second carrier L_2 (of F = 10.23 × 120 = 1227.60 MHz).

We shall denote the pseudorange as

$$\rho^* = cD \quad , \tag{C.2}$$

where D is the observable time of arrival. The real range is then

$$\rho = \rho^* + c(t - T) - cE + D\delta c \quad , \tag{C.3}$$

where t − T is the time synchronization error, E is the time delay in the receiver, and δc is the departure of the actual average speed of light due to passage through the ionosphere and the troposphere. δc is thus generally frequency dependent.

In reality, frequencies f and F, in (C.1), are affected by Doppler shifts δf and δF due to the satellite motion component along the range. Thus (C.1) should be rewritten as

$$\rho = (n + \phi)\ c/(f + \delta f) = (N + \Phi)\ c/(F + \delta F) \quad ,$$

or better still

$$\rho \doteq \frac{c}{f}\, n(1 - \frac{\delta f}{f}) + \frac{c}{f}\, \phi \doteq \frac{c}{F}\, N(1 - \frac{\delta F}{F}) + \frac{c}{F}\, \Phi \quad . \tag{C.4}$$

On the other hand, (C.3) can be rewritten as

$$\rho = c(D + a + D\, \frac{\delta c}{c}) \quad , \tag{C.5}$$

where

$$a = (t - T) - E \tag{C.6}$$

is the total timing error. Equation (C.4), describing an ideal case, would not be of much use to us. A similar equation for the actually observable range, the pseudorange, must be used instead. We have

$$cD \doteq \frac{c}{f} n^*(1 - \frac{\delta f}{f}) + \frac{c}{f} \phi^* \doteq \frac{c}{F} N^*(1 - \frac{\delta F}{F}) + \frac{c}{F} \Phi^* \quad , \tag{C.7}$$

where ϕ^*, Φ^* can be observed and n^*, N^* make up the pseudorange but cannot be observed. Putting (C.5) and (C.7) together, we obtain

$$\left.\begin{aligned} \rho &\doteq \frac{c}{f} n^*(1 - \frac{\delta f}{f}) + \frac{c}{f} \phi^* - ca + D\, \delta c^{(L_1)} \\ \rho &\doteq \frac{c}{F} N^*(1 - \frac{\delta F}{F}) + \frac{c}{F} \Phi^* - ca + D\, \delta c^{(L_2)} \end{aligned}\right\} \tag{C.8}$$

for the two carriers L_1 and L_2.

Clearly, two such equations can be written for any t^i, at which ϕ^{*i}, Φ^{*i} were observed. We thus have

$$\left.\begin{aligned} \rho^i &\doteq \frac{c}{f}[n^{*i}(1 - \frac{\delta f^i}{f}) + \phi^{*i}] - ca^i + D^i\, \delta c^{(L_1)i} \\ \rho^i &\doteq \frac{c}{F}[N^{*i}(1 - \frac{\delta F^i}{F}) + \Phi^{*i}] - ca^i + D^i\, \delta c^{(L_2)i} \end{aligned}\right\} i=0,1,2,\ldots,s \tag{C.9}$$

Denoting

$$\left.\begin{aligned} a^i &= a + da^i \\ \delta c^i &= \delta c + dc^i \\ \rho^i &= \rho^o + \Delta\rho^i + d\rho^i \quad , \end{aligned}\right\} \tag{C.10}$$

where a is the <u>average total timing error</u> during the measurement period, $\delta c^{(L_1)}$, $\delta c^{(L_2)}$ are the <u>average departures of the speed of light</u> from c along the signal path, ρ^o is the <u>initial range</u> (at time t^o) and $\Delta\rho^i$ is the <u>change in range</u> during the time interval $t^i - t^o$ (as evaluated from the ephemeris). The remaining quantities, da^i, dc^i, $d\rho^i$ are departures at times t^i; their combined effect on the actual range can be written as

$$v^{(L)i} = d\rho^i + cda^i - D^i\, dc^{(L)i}, \quad i=0,1,2,\ldots,s \quad . \tag{C.11}$$

This effect, in the absence of a better model for it, will be considered small and random. We can finally write, for all values of i:

$$\left.\begin{aligned} \rho^o + \Delta\rho^i + v^{(L_1)i} &\doteq \frac{c}{f}[n*^i(1 - \frac{\delta f^i}{f}) + \phi*^i] - ca + D^i\, \delta c^{(L_1)} \\ \rho^o + \Delta\rho^i + v^{(L_2)i} &\doteq \frac{c}{F}[N*^i(1 - \frac{\delta F^i}{F}) + \Phi*^i] - ca + D^i\, \delta c^{(L_2)} \end{aligned}\right\} \tag{C.12}$$

where, naturally, $\Delta\rho^o = 0$.

Let us now assume that we can get some initial estimate $\rho^o_{(o)}$ of ρ^o such that

$$\rho^o_{(o)} = n^o_{(o)}\frac{c}{f} = N^o_{(o)}\frac{c}{F} \quad , \tag{C.13}$$

from which we can determine (integer) values $n^o_{(o)}$, $N^o_{(o)}$, <u>initial estimates of unknown</u> n^o, N^o. Denoting

$$\rho^o = \rho^o_{(o)} + \delta\rho^o \quad , \tag{C.14}$$

where $\delta\rho^o$ is the unknown error in the assumed initial range, we get

$$\rho^o_{(o)} + \delta\rho^o + \Delta\rho^i + v^{(L)i} \doteq \frac{c}{f^{(L)}}[n*^{(L)i}(1 - \Delta f^{(L)i}) + \phi*^{(L)i}] - ca + D^i\, \delta c^{(L)} \quad , \tag{C.15}$$

where $\Delta f^{(L)i} = \begin{cases} \delta f^i/f & L=L_1 \\ \delta F^i/F & L=L_2 \end{cases} \quad .$

Using (C.13), (C.15) can be rewritten as

$$\delta\rho^o + \Delta\rho^i + v^{(L)i} \doteq \frac{c}{f^{(L)}}[n*^{(L)i}(1-\Delta f^{(L)i}) - n^{o(L)}_{(o)} + \phi*^{(L)i}] - ca + D^i\delta c^{(L)} . \tag{C.16}$$

In (C.15) the unknowns are: $\delta\rho^o$, $n*^{(L)i}$, a, $\delta c^{(L)}$.

$$\phi*^{(L)i} = \begin{cases} \phi*^i & L = L_1 \\ \phi*^i & L = L_2 \end{cases}$$ is the observable, $\Delta\rho^i$ and $\Delta f^{(L)i}$ are determinable

from the satellite ephemeris for time t^i. Clearly, there is no way of differentiating between $\delta\rho^o$ and ca; they must be lumped together as the <u>bias in the (initial) pseudorange</u>. Hence we have

$$\delta\rho^{o*} = \delta\rho^o + ca \quad . \tag{C.17}$$

It will be convenient to express the refraction effect as

$$D^i \, \delta c^{(L)} = \frac{\rho^i}{c} \, \delta c^{(L)} \quad . \tag{C.18}$$

Similarly, let us express the change in range (due to satellite motion) as

$$\Delta\rho^i = \frac{c}{f^{(L)}}[\Delta n*^{(L)i}(1 - \Delta f^{(L)i}) + \Delta\phi*^{(L)i}] \quad . \tag{C.19}$$

Substituting (C.17), (C.18), and (C.19) back into (C.16) we get

$$\begin{aligned} \delta\rho^{o*} + v^{(L)i} \doteq \frac{c}{f^{(L)}}[(n*^{(L)j} - \Delta n*^{(L)j})(1 - \Delta f^{(L)i}) - \\ - n^{o(L)}_{(o)} + \phi*^{(L)i} - \Delta\phi*^{(L)i}] + \frac{\rho^i}{c} \, \delta c^{(L)} \quad . \end{aligned} \tag{C.20}$$

Realizing now that

$$n*^{(L)j} - \Delta n*^{(L)j} = n*^{(L)o} \quad , \tag{C.21}$$

(where $n*^{(L)o}$ is an integer), is nothing but the <u>ambiguity in the initial pseudorange</u> on the L frequency, denoting the <u>corrected observed phase</u> by

$$\tilde{\phi}^{(L)i} = \phi*^{(L)i} - \Delta\phi*^{(L)i} \quad , \tag{C.22}$$

(where $\tilde{\phi}^{(L)i}$ is a real number), and the <u>correction to the initial estimate</u> $n^{o(L)}_{(o)}$ of $n*^{o(L)}$ (an integer) as

$$\delta n*^{(L)} = n*^{o(L)} - n^{o(L)}_{(o)} \quad , \tag{C.23}$$

we obtain

$$\boxed{\delta\rho^{o*} + v^{(L)i} \doteq \frac{c}{f^{(L)}}[\delta n*^{(L)} - n*^{(L)o}\, \Delta f^{(L)i} + \tilde{\phi}^{(L)i}] + \frac{\rho^i}{c}\,\delta c^{(L)}} \; . \tag{C.24}$$

Let us now have a closer look at (C.24). If the initial estimate of ρ^o was as close as 1 km, then $\delta n*^{(L)}$ would be of the order of 5×10^3. $\Delta f^{(L)i}$ for the velocity of GPS satellites should be smaller than 3×10^{-6}. Thus, in (C.24), $n*^{(L)o}$ can be replaced by $n^{(L)o}$ with an effect on the result being less than 3 mm. We can finally rewrite (C.24) as follows, for all values of i:

$$\left.\begin{aligned} \delta n* - \frac{f}{c}\,\delta\rho^{o*} + \frac{f\rho^i}{c^2}\,\delta c^{(L_1)} &\doteq n^o\, \Delta f^i - \tilde{\phi}^i + v^{(L_1)i} \\ \delta N* - \frac{F}{c}\,\delta\rho^{o*} + \frac{F\rho^i}{c^2}\,\delta c^{(L_2)} &\doteq N^o\, \Delta F^i - \tilde{\Phi}^i + v^{(L_2)i} \end{aligned}\right\} \; . \tag{C.25}$$

In this equation:

(a) $\delta n*$, $\delta N*$ (integers) are the main unknowns, the corrections to the initial estimates $n^o_{(o)}$, $N^o_{(o)}$ (obtained using (C.13) from the estimate of initial range $\rho^o_{(o)}$ assumed good to 1 km). The resulting

$$\left.\begin{aligned} n*^o &= n^o_{(o)} + \delta n* \\ N*^o &= N^o_{(o)} + \delta N* \end{aligned}\right\} \tag{C.26}$$

are the sought ambiguities in the initial pseudoranges observed on the two frequencies.

(b) $\delta\rho^{o*}$ is the unknown bias in (or correction to) the estimate $\rho^o_{(o)}$ of the initial pseudorange ρ^{o*}. The resulting

$$\rho^{o*} = \rho^o_{(o)} + \delta\rho^{o*} \tag{C.27}$$

is the initial pseudorange (at time t^o) burdened by the total timing error (composed of time offset and receiver delay) but rid of the total refraction effect. Obviously, the first effect cannot be resolved within the context of one satellite pass and the solution must be sought using several satellites. This question is not treated here.

(c) $\delta c^{(L_1)}$, $\delta c^{(L_2)}$ are the unknown departures of the actual speed of light for the two carriers L_1 and L_2 from that in a vacuum, i.e., from c. It should be possible to use estimates obtained from one satellite pass for correcting pseudoranges but one suspects that from one pass they would be rather weakly determined. Again the question of determining these "refraction departures" will not be further treated here.

(d) Δf^i, ΔF^i are the relative Doppler frequency shifts due to the satellite motion. They are smaller than 3×10^{-6} and should be modellable from satellite ephemerides for the appropriate time instant t^i. Since $n^o\ \Delta f^i$ (and similarly $N^o\ \Delta F^i$) may reach as much as 375, then to ensure the desired accuracy (taken here as 5 mm) of the overall result, $n^o\ \Delta f^i$ should be accurate to 2.5×10^{-2}, which implies necessary relative accuracy in Δf^i better than 10^{-4}.

(e) $\Delta\rho^i$ is the range change in the period $\langle t^o, t^i \rangle$ (needed to evaluate n^o, N^o, $\tilde{\phi}^i$, $\tilde{\Phi}^i$). It should be obtainable from satellite ephemerides to an accuracy better than a few centimetres.

(f) $\tilde{\phi}^i$, $\tilde{\Phi}^i$ are the observed phases of carrier waves L_1, L_2 corrected for the fraction of wavelength due to $\Delta\rho^i$. Thus

$$\left.\begin{aligned} \tilde{\phi}^i &= \phi^{*i} - \frac{f}{c}\,\Delta\rho^i + \Delta n^{*i}(1 - \Delta f^i) \\ \tilde{\Phi}^i &= \Phi^{*i} - \frac{F}{c}\,\Delta\rho^i + \Delta N^{*i}(1 - \Delta F^i) \end{aligned}\right\} \qquad (C.28)$$

where Δn^{*i}, ΔN^{*i} are the integer number of wavelength in $\Delta\rho^i$ for frequencies f and F. $\tilde{\phi}^i$, $\tilde{\Phi}^i$ are unitless (in fraction of wavelengths), real numbers from <0, 1>.

Equations (C.25) do not have a unique solution δn^*, δN^*, $\delta \rho^{o*}$, $\delta c^{(L_1)}$, $\delta c^{(L_2)}$ because the first three unknowns are linearly dependent. The best cure for this linear dependency is to take the differences of equations for L_2 and L_1 and get (for all values of i):

$$\frac{c}{f}\,\delta n^* - \frac{c}{F}\,\delta N^* + \frac{\rho^i}{c}(\delta c^{(L_1)} - \delta c^{(L_2)}) \doteq n^o\,\Delta f^i - N^o\,\Delta F^i - \tilde{\phi}^i + \tilde{\Phi}^i + v^i. \quad (C.29)$$

A system of m such equations (relating to m satellite positions on the same pass) can be solved to obtain estimates for

$$\boxed{\frac{c}{f}\,\delta n^* - \frac{c}{F}\,\delta N^* = cq = x} \qquad (C.30)$$

and

$$\delta c^{(L_1)} - \delta c^{(L_2)} = y \quad . \qquad (C.31)$$

There is, clearly, nothing further we can do with the difference of the two refraction effects. There is however something we can do with the two main unknowns δn^*, δN^*. Let us have a closer look at this possibility.

Each solution x from (C.30) (and we can get m-1 such solutions from m measurements along one pass) gives us one setup of the kind described below: Equation (C.30) can be regarded as a straight line in two-dimensional real space, coordinated by δn^* and δN^* (see Figure C.1). Here, the slope $F/f = \lambda/\Lambda$ is known exactly ($F/f = 120/154 = 60/77$), while the intercept x/Λ is affected by errors. Because of these errors, the problem has generally no exact solution (δn^*, δN^*), where δn^* and δN^* are both integers.

The best approximate solution can nevertheless be found. Let us consider one way of doing this.

The possible solutions to (C.30) form an integer grid as shown in Figure C.2. We can define as the best solution the point on this grid that lies closest to the real straight line defined by (C.30). Specifically,

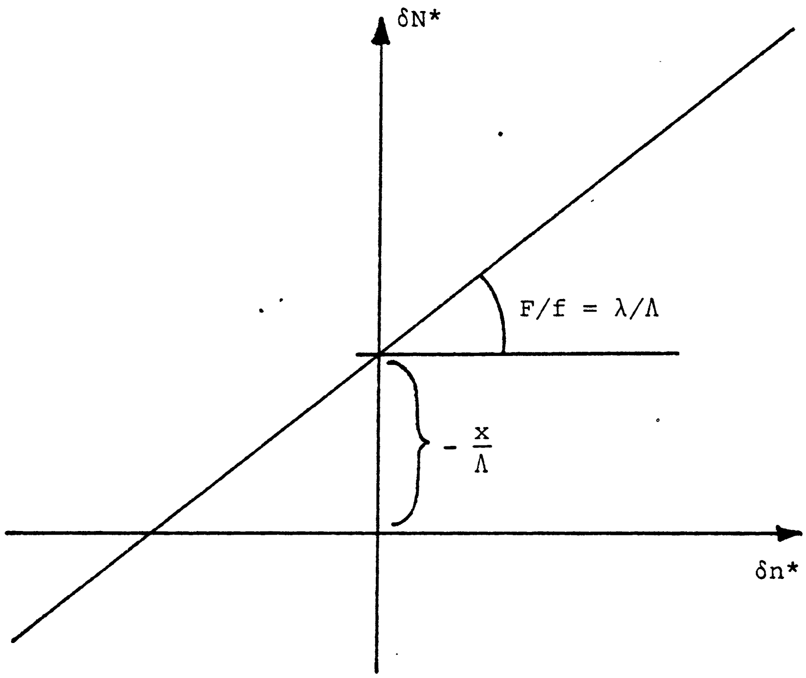


FIGURE C.1

Geometrical Interpretation of Equation (C.30).

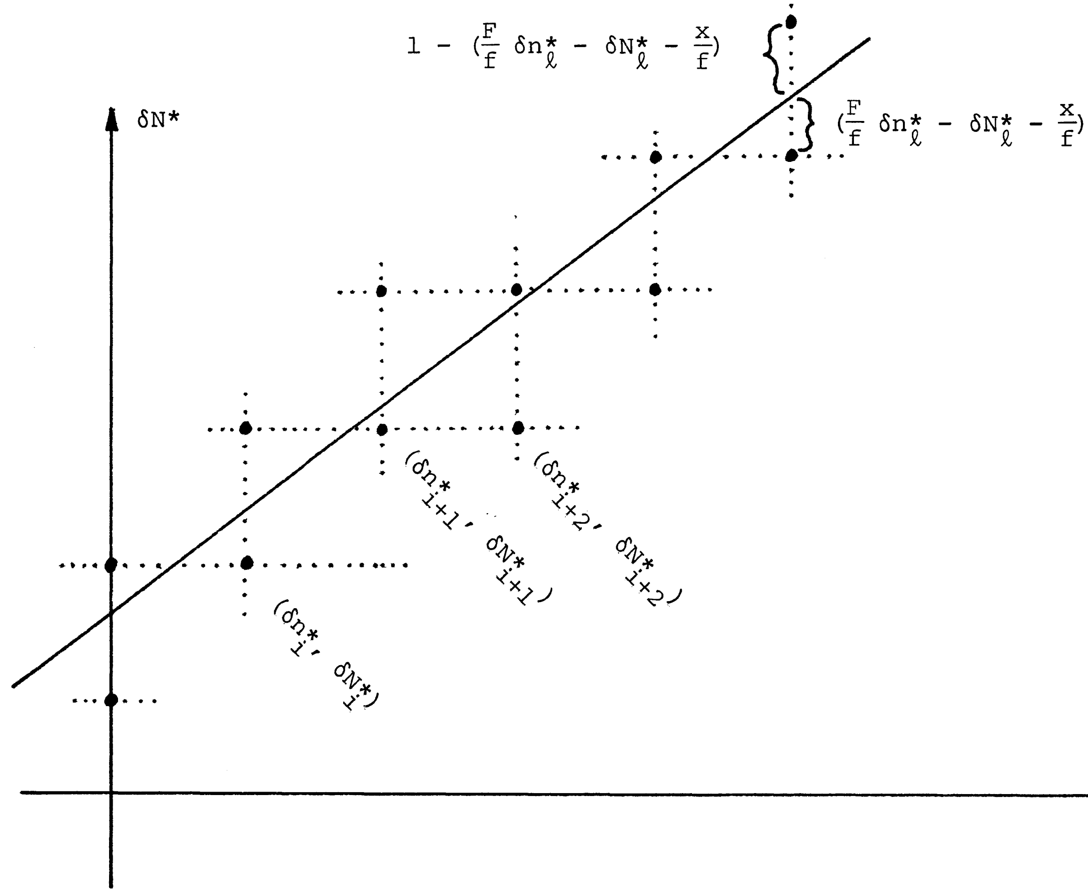


FIGURE C.2

Geometry of Best Integer Solution to Real Line.

the procedure is:

(1) For each integer value of $\delta n_i^* \in \{-39, -38, \ldots, 0, 1, \ldots, 37, 38\}$ find the corresponding integer value for δN_i^* from (C.30):

$$\delta N_i^* = [\frac{F}{f} \delta n_i^* - \frac{x}{f}] \tag{C.32}$$

where [ ] denotes "the integer part of".

(2) The integer grid points defined by the pairs $(\delta n_i^*, \delta N_i^*)$ resulting from this process will all lie below the real line defined by (C.30), due to the truncation in (C.32) (see Figure C.2). However the closest point in the integer grid to the real line may lie above or below the line. Hence we must consider both the set of points $(\delta n_i^*, \delta N_i^*)$ resulting from step (1) above, and the set of points $(\delta n_i^*, \delta N_i^* + 1)$.

(3) The best solution to (C.30) is then the point on the integer grid, selected from these two sets of points, which lies closest to the real line; that is, the best solution $(\delta n_j^*, \delta N_j^*)$ is the one which satisfies the following condition:

$$\min_{\delta n_i^*} \ \min(1 + \delta N_i^* - \frac{F}{f} \delta n_i^* + \frac{x}{f} \ , \ \frac{F}{f} \delta n_i^* - \frac{x}{f} - \delta N_i^*) \tag{C.33}$$

(for the example in Figure C.2 this best solution is the point $(\delta n_{i+2}^*, \delta n_{i+2}^* + 1)$).

It must be noted that if $(\delta n_j^*, \delta N_j^*)$ is a solution to our problem then $(\delta n_j^* + k77, \delta N_j^* + k60)$ for all integer values of k are also solutions; the solution is periodic with periods 77 along δn^*-axis and 60 along δN^*-axis. These translate into the period 14.67 m ($77\ \lambda = 60\ \Lambda = 14.67$ m) along the line $\delta N^* = c_1\ \delta n^* + c_o$. Thus to resolve the ambiguity completely (from 1 pass) an accuracy in the initial range of $\pm$ 7.33 m is needed. If that is not available, then an iterative approach that uses several passes must be used. But that should be a matter for further investigation.

APPENDIX D

Detailed Simulation Output Data

This Appendix contains a one page summary for each of the 50 DIGAP runs listed in Table 12.1(c).

Program Run	Input Data	No. Sats	No. Stn	Time Span (hr)	Sample Interval (sec)	Observation Type
DIGAP-1	FOROBS-1	4	8	1	30	Interferometric
DIGAP-2	FOROBS-2	4	4	1	6	Delay
DIGAP-3	FOROBS-3	4	4	5	30	
DIGAP-4	FOROBS-4	18	8	1	30	
DIGAP-5	FOROBS-5	18	4	1	6	
DIGAP-6	FOROBS-6	18	4	5	30	
DIGAP-7	FOROBS-7	18	4	5	30	
DIGAP-8	FOROBS-8	18(DOA)	8	1	30	
DIGAP-9	FOROBS-9	18(DOA)	4	1	6	
DIGAP-10	FOROBS-10	18(DOA)	4	5	30	
DIGAP-11	FOROBS-1	4	8	1	30	Differential
DIGAP-12	FOROBS-2	4	4	1	6	Carrier
DIGAP-13	FOROBS-3	4	4	5	30	Phase
DIGAP-14	FOROBS-4	18	8	1	30	
DIGAP-15	FOROBS-5	18	4	1	6	
DIGAP-16	FOROBS-6	18	4	5	30	
DIGAP-17	FOROBS-7	18	4	5	30	
DIGAP-18	FOROBS-8	18(DOA)	8	1	30	
DIGAP-19	FOROBS-9	18(DOA)	4	1	6	
DIGAP-20	FOROBS-10	18(DOA)	4	5	30	
DIGAP-21	FOROBS-1	4	8	1	30	P-Code
DIGAP-22	FOROBS-2	4	4	1	6	Differential
DIGAP-23	FOROBS-3	4	4	5	30	Pseudorange
DIGAP-24	FOROBS-4	18	8	1	30	
DIGAP-25	FOROBS-5	18	4	1	6	
DIGAP-26	FOROBS-6	18	4	5	30	
DIGAP-27	FOROBS-7	18	4	5	30	
DIGAP-28	FOROBS-8	18(DOA)	8	1	30	
DIGAP-29	FOROBS-9	18(DOA)	4	1	6	
DIGAP-30	FOROBS-10	18(DOA)	4	5	30	
DIGAP-31	FOROBS-1	4	8	1	30	CA-Code
DIGAP-32	FOROBS-2	4	4	1	6	Differential
DIGAP-33	FOROBS-3	4	4	5	30	Pseudorange
DIGAP-34	FOROBS-4	18	8	1	30	
DIGAP-35	FOROBS-5	18	4	1	6	
DIGAP-36	FOROBS-6	18	4	5	30	
DIGAP-37	FOROBS-7	18	4	5	30	

DIGAP-38	FOROBS-8	18(DOA)	8	1	30	
DIGAP-39	FOROBS-9	18(DOA)	4	1	6	
DIGAP-40	FOROBS-10	18(DOA)	4	5	30	
DIGAP-41	FOROBS-1	4	8	1	30	Differential
DIGAP-42	FOROBS-2	4	4	1	6	Doppler
DIGAP-43	FOROBS-3	4	4	5	30	
DIGAP-44	FOROBS-4	18	8	1	30	
DIGAP-45	FOROBS-5	18	4	1	6	
DIGAP-46	FOROBS-6	18	4	5	30	
DIGAP-47	FOROBS-7	18	4	5	30	
DIGAP-48	FOROBS-8	18(DOA)	8	1	30	
DIGAP-49	FOROBS-9	18(DOA)	4	1	6	
DIGAP-50	FOROBS-10	18(DOA)	4	5	30	

TABLE 12.1(c)

DIGAP Runs.

SUMMARY OF DIFFERENTIAL GPS RESULTS   WED. OCT. 20. 1982 14:09:46

DIFGPS HEADER = OCT. 11.1982:DIFTAP:S002256:F10:DD:ALL RANDOM ERRORS NONZERO (4 SAT. ABER. IN)
FOROBS HEADER = FILE: LANGLEY.GPS.OBSERV11.DATA:8 STATIONS;OBS CREATED:WED. OCT. 20. 1982 004257
DIGAP HEADER = INTERFEROMETRIC   EIGHT STATIONS

TOTAL OBSERVATIONS = 12574 ON DAY 316 . 1981 FROM 18: 0: 6 TO 18:59:36. SPAN= 0 HR(S). 59 MIN.
SATELLITES USED =   6   8   9   5

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	2PTSAPIN	2(6)	-1(13)	-27(16)	28(16)
3	3PTSAPIN	0(6)	-25(13)	30(16)	40(20)
4	4PTSAPIN	-6(6)	-7(13)	7(16)	13(17)
5	5PTSAPIN	-12(6)	-2(13)	2(16)	13(8)
6	6PTSAPIN	-8(5)	34(13)	-52(16)	64(19)
7	7PTSAPIN	-7(6)	39(13)	-70(16)	82(19)
8	8PTSAPIN	-14(6)	38(13)	-63(16)	76(19)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	2PTSAPIN	-20(8)	1(7)	-18(19)	28(16)
3	3PTSAPIN	3(8)	-11(7)	38(19)	40(20)
4	4PTSAPIN	2(8)	-9(7)	8(19)	13(17)
5	5PTSAPIN	3(8)	-12(7)	0(19)	13(8)
6	6PTSAPIN	-10(8)	6(7)	-61(19)	64(19)
7	7PTSAPIN	-19(8)	8(7)	-78(19)	82(19)
8	8PTSAPIN	-13(8)	1(7)	-74(19)	76(19)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	2PTSAPIN	21(8)	-1(7)	-18(19)	46848
3	3PTSAPIN	-3(8)	11(7)	38(19)	92429
4	4PTSAPIN	-2(9)	9(7)	8(19)	142000
5	5PTSAPIN	-3(8)	13(7)	0(19)	185998
6	6PTSAPIN	7(7)	-9(8)	-61(19)	100581
7	7PTSAPIN	9(6)	-18(9)	-78(19)	123360
8	8PTSAPIN	7(5)	-11(9)	-74(19)	154584

DIGAP-1

SUMMARY OF DIFFERENTIAL GPS RESULTS   TUE. OCT. 19. 1982 19:31:11

DIFGPS HEADER = OCT. 11,1982:DIFTAP:S002256:F10:DD:ALL RANDOM ERRORS NONZERO (4 SAT. ABER. IN)
FOROBS HEADER = FILE: LANGLEY.GPS.OBSERV12.DATA:4 STATIONS;OBS CREATED:TUE. OCT. 19. 1982 023229
DIGAP HEADER = INTERFEROMETRIC   FOUR STATIONS

TOTAL OBSERVATIONS = 13369 ON DAY 316 , 1981 FROM 18: 0: 6 TO 18:59:36. SPAN= 0 HR(S). 59 MIN.
SATELLITES USED =   6   8   9   5

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I	O N	
2	3PTSAPIN	0(4)	-13(8)	12(10)	18(12)
3	4PTSAPIN	1(4)	-26(8)	10(10)	28(11)
4	8PTSAPIN	-17(4)	71(9)	-94(10)	120(12)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I	O N	
2	3PTSAPIN	0(5)	-6(5)	17(12)	18(12)
3	4PTSAPIN	-10(5)	-10(5)	24(12)	28(11)
4	8PTSAPIN	-11(5)	12(4)	-118(12)	120(12)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T I	O N	
2	3PTSAPIN	1(5)	7(4)	17(12)	92429
3	4PTSAPIN	10(5)	12(4)	24(12)	142000
4	8PTSAPIN	-2(3)	-16(6)	-118(12)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   WED. NOV. 24, 1982   13:23:37

DIFGPS HEADER = OCT. 11,1982:DIFTAP:S002256:F10:DD:ALL RANDOM ERRORS NONZERO (4 SAT. ABER. IN)
FOROBS HEADER = FILE: LANGLEY.GPS.OBSERV13.DATA:4 STATIONS;OBS CREATED:TUE. OCT. 19. 1982 184347
DIGAP HEADER = INTERFEROMETRIC   FOUR STATIONS. FOUR SATELLITES. FIVE HOURS

TOTAL OBSERVATIONS = 10112 ON DAY 316 , 1981 FROM 17: 0: 6 TO 21:59:36. SPAN= 4 HR(S). 59 MIN.
SATELLITES USED =   6   8   9   5

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	6(5)	-28(7)	4(7)	30(8)
3	4PTSAPIN	4(5)	-20(7)	0(7)	21(8)
4	8PTSAPIN	-22(5)	-1(7)	-10(7)	26(5)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	-17(6)	-6(3)	23(9)	30(8)
3	4PTSAPIN	-14(6)	-4(3)	14(9)	21(8)
4	8PTSAPIN	-1(6)	-21(3)	-12(9)	26(5)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	18(6)	8(3)	23(9)	92429
3	4PTSAPIN	15(6)	7(3)	14(9)	142000
4	8PTSAPIN	19(4)	12(5)	-12(9)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   FRI, APR. 08, 1983 19:13:32

DIFGPS HEADER = MARCH 29,1983:DIFGPS:SL3722:F01:DD:ALL BIASES NONZERO (18 SAT, ABER. IN)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV43.DATA:8 STNS;30 S   CREATED:WED, MAR. 30, 1983 171752
DIGAP HEADER = EIGHT STATIONS   INTERFEROMETRY   18 SATS , WITH NOISE

TOTAL OBSERVATIONS = 18666 ON DAY 316 , 1981 FROM 18: 0: 6 TO 19: 0: 6. SPAN= 1 HR(S), 0 MIN.
SATELLITES USED = 2 5 7 10 15 12

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	2PTSAPIN	-4(4)	-13(6)	-23(9)	28(6)
3	3PTSAPIN	0(4)	0(6)	-9(9)	10(9)
4	4PTSAPIN	0(4)	14(6)	-50(9)	53(9)
5	5PTSAPIN	7(4)	-6(6)	-47(9)	49(8)
6	6PTSAPIN	4(4)	-13(6)	-40(9)	44(7)
7	7PTSAPIN	3(4)	-29(6)	-51(9)	60(6)
8	8PTSAPIN	-3(4)	-22(6)	-61(9)	66(7)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	2PTSAPIN	-23(5)	-10(3)	-10(10)	28(6)
3	3PTSAPIN	-6(5)	0(3)	-6(10)	10(9)
4	4PTSAPIN	-25(5)	6(3)	-45(10)	53(9)
5	5PTSAPIN	-39(5)	3(3)	-27(9)	49(8)
6	6PTSAPIN	-37(5)	-1(3)	-19(10)	44(7)
7	7PTSAPIN	-55(5)	-8(3)	-17(10)	60(6)
8	8PTSAPIN	-56(5)	-12(3)	-31(9)	66(7)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	2PTSAPIN	25(5)	9(3)	-10(10)	46848
3	3PTSAPIN	6(5)	1(4)	-6(10)	92429
4	4PTSAPIN	26(5)	-2(4)	-45(10)	142000
5	5PTSAPIN	40(5)	0(4)	-28(10)	185998
6	6PTSAPIN	36(5)	-12(4)	-20(10)	100581
7	7PTSAPIN	49(4)	-28(4)	-18(10)	123360
8	8PTSAPIN	44(4)	-36(4)	-32(10)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   SUN, APR. 10, 1983 15:48:37

DIFGPS HEADER = MARCH 29,1983:DIFGPS:SL3722:F01:DD:ALL BIASES NONZERO (18 SAT, ABER. IN)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV44.DATA:4 STNS;18 SAT CREATED:THU, MAR. 31, 1983 014818
DIGAP HEADER = FOUR STATIONS INTERFEROMETRY   OBS 6 SEC   18 SATS,WITH NOISE

TOTAL OBSERVATIONS = 20010 ON DAY 316 , 1981 FROM 18: 0: 0 TO 19: 0: 0. SPAN= 1 HR(S), 0 MIN.
SATELLITES USED =   2   5   7 10 15 12

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	3(2)	-17(4)	10(6)	21(5)
3	4PTSAPIN	7(2)	-9(4)	-11(6)	17(3)
4	8PTSAPIN	0(2)	-25(4)	-31(6)	41(3)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	-5(3)	-4(2)	20(6)	21(5)
3	4PTSAPIN	-16(3)	2(2)	0(6)	17(3)
4	8PTSAPIN	-38(3)	-9(2)	-6(6)	41(3)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	6(3)	5(2)	20(6)	92429
3	4PTSAPIN	17(3)	0(2)	0(6)	142000
4	8PTSAPIN	32(3)	-24(3)	-7(6)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   SUN, APR. 10, 1983 13:11:15

DIFGPS HEADER = MARCH 29,1983:DIFGPS:SL3722:F01:DD:ALL BIASES NONZERO (18 SAT, ABER. IN)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV45.DATA:4 STNS;6 S   CREATED:THU, APR. 07, 1983 010216
DIGAP HEADER = FOUR STATIONS INTERFEROMETRY   OBS 30 SEC   18 SATS,WITH NOISE

TOTAL OBSERVATIONS = 19527 ON DAY 316 , 1981 FROM 17: 0: 6 TO 21:59:36. SPAN= 4 HR(S), 59 MIN.
SATELLITES USED =   3   5   7   8 10 15   2 12   4 17 14

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	7(3)	-10(4)	-12(4)	18(3)
3	4PTSAPIN	16(3)	-20(4)	-11(4)	29(3)
4	8PTSAPIN	-2(3)	-28(4)	-13(4)	32(3)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	-17(3)	2(2)	0(5)	18(3)
3	4PTSAPIN	-26(3)	5(2)	9(5)	29(3)
4	8PTSAPIN	-27(3)	-13(2)	7(5)	32(3)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	18(3)	0(2)	0(5)	92429
3	4PTSAPIN	27(3)	-1(2)	9(5)	142000
4	8PTSAPIN	29(3)	-12(3)	7(5)	154584

```
SUMMARY OF DIFFERENTIAL GPS RESULTS          WED, APR. 13, 1983  21:20:04
-----------------------------------

DIFGPS HEADER = MARCH 10,1983:DIFGPS:SL3722:F03:DD:ONLY RANDOM NOISE (18 SAT  )
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV46.DATA:4 STNS;30 S   CREATED:WED, APR. 13, 1983 184329
DIGAP  HEADER = FOUR STATIONS INTERFEROMETRY   OBS 30 SEC     18 SATS,WITH NOISE

TOTAL OBSERVATIONS =  19527 ON DAY 316 , 1981 FROM 17: 0: 6  TO 21:59:36. SPAN=  4 HR(S), 59 MIN.
SATELLITES USED =   3   5   7   8  10  15   2  12   4  17  14
```

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	0(3)	4(4)	-1(4)	5(5)
3	4PTSAPIN	4(3)	1(4)	4(4)	5(4)
4	8PTSAPIN	-4(3)	4(4)	-6(4)	9(5)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	1(3)	1(2)	-3(5)	5(5)
3	4PTSAPIN	2(3)	3(2)	4(5)	5(4)
4	8PTSAPIN	0(3)	-2(2)	-8(5)	9(5)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	0(3)	0(2)	-3(5)	92429
3	4PTSAPIN	-1(3)	-3(2)	4(5)	142000
4	8PTSAPIN	2(3)	1(3)	-8(5)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   SUN, APR. 10, 1983 14:10:45

DIFGPS HEADER = APRIL 6,1983:DIFGPS:SL3722:F02:DD:ALL BIASES NONZERO (18 SAT, DGR'D EPH)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV47.DATA:8 STNS;30 S   CREATED:SAT, APR. 09, 1983 221510
DIGAP HEADER = EIGHT STATIONS   INTERFEROMETRY   18 SATS , WITH NOISE

TOTAL OBSERVATIONS = 18666 ON DAY 316 , 1981 FROM 18: 0: 6 TO 19: 0: 6. SPAN= 1 HR(S), 0 MIN.
SATELLITES USED =   2   5   7 10 15 12

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)		DY (SD-DY)		DZ (SD-DZ)		DR (SD-DR)	
1	1PTSAPIN	F I X E D		S T A T I O N					
2	2PTSAPIN	284(	16)	62(	26)	-187(	38)	346(	23)
3	3PTSAPIN	407(	16)	339(	26)	-358(	38)	640(	29)
4	4PTSAPIN	532(	16)	633(	26)	-598(	38)	1021(	32)
5	5PTSAPIN	815(	16)	666(	26)	-748(	38)	1292(	29)
6	6PTSAPIN	999(	16)	-367(	26)	-295(	38)	1105(	17)
7	7PTSAPIN	1518(	16)	-982(	26)	-230(	38)	1823(	20)
8	8PTSAPIN	2067(	16)	-1642(	26)	-147(	38)	2645(	23)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)		DLON (SD-DLON)		DHGT (SD-DHGT)		DR (SD-DR)	
1	1PTSAPIN	F I X E D		S T A T I O N					
2	2PTSAPIN	-174(	21)	284(	15)	-94(	42)	346(	23)
3	3PTSAPIN	-146(	21)	513(	15)	-352(	41)	640(	29)
4	4PTSAPIN	-161(	21)	751(	15)	-671(	41)	1021(	32)
5	5PTSAPIN	-335(	21)	1021(	15)	-716(	41)	1292(	29)
6	6PTSAPIN	-749(	21)	755(	15)	296(	41)	1105(	17)
7	7PTSAPIN	-1265(	21)	985(	15)	867(	41)	1823(	20)
8	8PTSAPIN	-1803(	21)	1242(	15)	1483(	41)	2645(	23)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)		DAZ (SD-DAZ)		DELEV (SD-DELEV)		BASELINE (IN M)
1	1PTSAPIN	F I X E D		S T A T I O N				
2	2PTSAPIN	151(	21)	-296(	15)	-94(	42)	46848
3	3PTSAPIN	174(	21)	-503(	15)	-353(	42)	92429
4	4PTSAPIN	233(	21)	-729(	15)	-674(	41)	142000
5	5PTSAPIN	386(	21)	-998(	15)	-721(	41)	185998
6	6PTSAPIN	394(	20)	-989(	16)	293(	41)	100581
7	7PTSAPIN	355(	19)	-1565(	17)	863(	41)	123360
8	8PTSAPIN	161(	18)	-2184(	19)	1481(	41)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   SUN, APR. 10, 1983 20:34:01

DIFGPS HEADER = APRIL 6,1983:DIFGPS:SL3722:F02:DD:ALL BIASES NONZERO (18 SAT, DGR'D EPH)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV48.DATA:4 STNS;6 S   CREATED:SUN, APR. 10, 1983 163548
DIGAP HEADER = FOUR STATIONS INTERFEROMETRY   OBS 30 SEC   18 SATS,WITH NOISE

TOTAL OBSERVATIONS = 20010 ON DAY 316 , 1981 FROM 18: 0: 0 TO 19: 0: 0. SPAN= 1 HR(S), 0 MIN.
SATELLITES USED =   2   5   7 10 15 12

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	410(13)	322(20)	-342(29)	625(22)
3	4PTSAPIN	537(13)	612(20)	-565(29)	991(24)
4	8PTSAPIN	2070(13)	-1640(20)	-128(29)	2645(17)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	-147(16)	509(12)	-330(32)	625(22)
3	4PTSAPIN	-153(16)	747(12)	-633(32)	991(24)
4	8PTSAPIN	-1790(16)	1245(11)	1496(32)	2645(17)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	175(16)	-498(12)	-331(32)	92429
3	4PTSAPIN	225(16)	-725(12)	-635(32)	142000
4	8PTSAPIN	151(14)	-2176(14)	1494(32)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   TUE, APR. 12, 1983 05:53:04

DIFGPS HEADER = APRIL 6,1983:DIFGPS:SL3722:F02:DD:ALL BIASES NONZERO (18 SAT, DGR'D EPH)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV49.DATA:4 STNS;30 S   CREATED:SUN, APR. 10, 1983 222945
DIGAP HEADER = FOUR STATIONS INTERFEROMETRY   OBS 30 SEC   18 SATS,WITH NOISE

TOTAL OBSERVATIONS = 19527 ON DAY 316 , 1981 FROM 17: 0: 6 TO 21:59:36. SPAN= 4 HR(S), 59 MIN.
SATELLITES USED =   3   5   7   8 10 15   2 12   4 17 14

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	252(17)	-594(25)	294(27)	710(32)
3	4PTSAPIN	306(17)	-842(25)	428(27)	993(32)
4	8PTSAPIN	1728(17)	-2041(25)	839(28)	2804(30)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	-271(18)	-24(14)	655(34)	710(32)
3	4PTSAPIN	-352(18)	-83(14)	925(34)	993(32)
4	8PTSAPIN	-1298(18)	772(14)	2362(34)	2804(30)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	274(18)	40(15)	653(34)	92429
3	4PTSAPIN	353(18)	120(15)	921(34)	142000
4	8PTSAPIN	228(16)	-1497(16)	2359(34)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   MON, OCT. 18, 1982 13:51:49

DIFGPS HEADER = OCT. 11,1982:DIFTAP:S002256:F10:DD:ALL RANDOM ERRORS NONZERO (4 SAT. ABER. IN)
FOROBS HEADER = FILE: LANGLEY.GPS.OBSERV11.DATA:8 STATIONS;OBS CREATED:SAT, OCT. 16, 1982 103727
DIGAP HEADER = CARRIER PHASE   EIGHT STATIONS

TOTAL OBSERVATIONS = 12574 ON DAY 316 , 1981 FROM 18: 0: 6 TO 18:59:36. SPAN= 0 HR(S), 59 MIN.
SATELLITES USED = 6 8 9 5

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I	O N	
2	2PTSAPIN	15(6)	18(13)	-61(16)	66(18)
3	3PTSAPIN	7(6)	12(13)	-63(16)	65(18)
4	4PTSAPIN	1(6)	-11(13)	-22(16)	26(11)
5	5PTSAPIN	10(6)	0(13)	-51(16)	53(16)
6	6PTSAPIN	-4(6)	28(13)	-74(16)	80(19)
7	7PTSAPIN	14(6)	17(13)	-82(16)	86(18)
8	8PTSAPIN	15(6)	38(13)	-104(16)	113(19)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I	O N	
2	2PTSAPIN	-34(8)	21(7)	-51(19)	66(18)
3	3PTSAPIN	-37(8)	11(7)	-51(19)	65(18)
4	4PTSAPIN	-23(8)	-3(7)	-8(19)	26(11)
5	5PTSAPIN	-39(8)	8(7)	-33(19)	53(16)
6	6PTSAPIN	-30(8)	8(7)	-73(19)	80(19)
7	7PTSAPIN	-49(8)	20(7)	-66(19)	86(18)
8	8PTSAPIN	-49(8)	29(7)	-96(19)	113(19)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T I	O N	
2	2PTSAPIN	33(8)	-23(7)	-51(19)	46848
3	3PTSAPIN	38(8)	-8(7)	-51(19)	92429
4	4PTSAPIN	23(9)	7(7)	-9(19)	142000
5	5PTSAPIN	40(8)	-5(7)	-33(19)	185998
6	6PTSAPIN	25(7)	-18(9)	-73(19)	100581
7	7PTSAPIN	25(6)	-46(9)	-67(19)	123360
8	8PTSAPIN	7(5)	-56(9)	-96(19)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   TUE. OCT. 19. 1982   19:10:48

DIFGPS HEADER = OCT. 11,1982:DIFTAP:S002256:F10:DD:ALL RANDOM ERRORS NONZERO (4 SAT, ABER. IN)
FOROBS HEADER = FILE: LANGLEY.GPS.OBSERV12.DATA:4 STATIONS;OBS CREATED:TUE. OCT. 19. 1982 023229
DIGAP HEADER = CARRIER PHASE   FOUR STATIONS

TOTAL OBSERVATIONS = 13369 ON DAY 316 , 1981 FROM 18: 0: 6 TO 18:59:36. SPAN= 0 HR(S), 59 MIN.
SATELLITES USED =   6   8   9   5

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX	(SD-DX)	DY	(SD-DY)	DZ	(SD-DZ)	DR	(SD-DR)
1	1PTSAPIN	F I X E D		S T A T I O N					
2	3PTSAPIN	11(	4)	-18(	9)	-5(	11)	23(	6)
3	4PTSAPIN	20(	4)	-36(	9)	-4(	11)	43(	7)
4	8PTSAPIN	1(	4)	45(	9)	-94(	11)	105(	13)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT	(SD-DLAT)	DLON	(SD-DLON)	DHGT	(SD-DHGT)	DR	(SD-DR)
1	1PTSAPIN	F I X E D		S T A T I O N					
2	3PTSAPIN	-19(	5)	2(	5)	11(	12)	23(	6)
3	4PTSAPIN	-33(	5)	2(	5)	26(	12)	43(	7)
4	8PTSAPIN	-34(	5)	19(	5)	-96(	12)	105(	13)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN	(SD-DLEN)	DAZ	(SD-DAZ)	DELEV	(SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D		S T A T I O N				
2	3PTSAPIN	20(	5)	0(	5)	11(	12)	92429
3	4PTSAPIN	35(	6)	1(	4)	25(	12)	142000
4	8PTSAPIN	5(	4)	-38(	6)	-97(	12)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   WED. NOV. 24. 1982   17:45:27

DIFGPS HEADER = OCT. 11,1982:DIFTAP:S002256:F10:DD:ALL RANDOM ERRORS NONZERO (4 SAT. ABER. IN)
FOROBS HEADER = FILE: LANGLEY.GPS.OBSERV13.DATA:4 STATIONS;OBS CREATED:TUE. OCT. 19. 1982 184347
DIGAP HEADER = CARRIER PHASE   FOUR STATIONS. FOUR SATELLITES. FIVE HOURS

TOTAL OBSERVATIONS = 10112 ON DAY 316 , 1981 FROM 17: 0: 6 TO 21:59:36. SPAN= 4 HR(S). 59 MIN.
SATELLITES USED =   6   8   9   5

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	0(5)	-11(7)	-21(7)	25(6)
3	4PTSAPIN	2(5)	-19(7)	-8(7)	22(6)
4	8PTSAPIN	-25(5)	3(7)	-20(7)	33(7)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	-22(6)	-4(3)	-8(9)	25(6)
3	4PTSAPIN	-19(6)	-6(3)	7(9)	22(6)
4	8PTSAPIN	-4(6)	-21(4)	-23(9)	33(7)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	23(6)	6(3)	-8(9)	92429
3	4PTSAPIN	19(6)	9(3)	6(9)	142000
4	8PTSAPIN	20(4)	10(5)	-24(9)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS FRI, APR. 08, 1983 02:21:01

DIFGPS HEADER = MARCH 29,1983:DIFGPS:SL3722:F01:DD:ALL BIASES NONZERO (18 SAT, ABER. IN)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV43.DATA:8 STNS;30 S CREATED:WED, MAR. 30, 1983 171752
DIGAP HEADER = EIGHT STATIONS CARRIER PHASE 18 SATS , WITH NOISE

TOTAL OBSERVATIONS = 18666 ON DAY 316 , 1981 FROM 18: 0: 6 TO 19: 0: 6. SPAN= 1 HR(S), 0 MIN.
SATELLITES USED = 2 5 7 10 15 12

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	2PTSAPIN	-2(4)	-9(6)	-2(9)	11(4)
3	3PTSAPIN	5(4)	-3(6)	-6(9)	9(5)
4	4PTSAPIN	3(4)	-5(6)	-25(9)	27(7)
5	5PTSAPIN	-1(4)	-3(6)	-40(9)	42(8)
6	6PTSAPIN	4(4)	-2(6)	-31(9)	33(8)
7	7PTSAPIN	4(4)	-43(6)	-2(9)	45(6)
8	8PTSAPIN	7(4)	-29(6)	-52(9)	61(6)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	2PTSAPIN	-7(5)	-6(3)	3(9)	11(4)
3	3PTSAPIN	-8(5)	3(3)	0(9)	9(5)
4	4PTSAPIN	-22(5)	0(3)	-13(9)	27(7)
5	5PTSAPIN	-29(5)	-2(3)	-27(9)	42(8)
6	6PTSAPIN	-25(5)	2(3)	-19(9)	33(8)
7	7PTSAPIN	-32(5)	-13(3)	26(9)	45(6)
8	8PTSAPIN	-57(5)	-4(3)	-17(9)	61(6)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	2PTSAPIN	9(5)	7(3)	3(9)	46848
3	3PTSAPIN	9(5)	-2(3)	0(9)	92429
4	4PTSAPIN	23(5)	2(3)	-13(9)	142000
5	5PTSAPIN	30(5)	5(3)	-28(9)	185998
6	6PTSAPIN	22(5)	-11(4)	-20(9)	100581
7	7PTSAPIN	35(4)	-9(4)	26(9)	123360
8	8PTSAPIN	40(4)	-42(4)	-17(9)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   SUN, APR. 10, 1983 15:11:57

DIFGPS HEADER = MARCH 29,1983:DIFGPS:SL3722:F01:DD:ALL BIASES NONZERO (18 SAT, ABER. IN)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV44.DATA:4 STNS;18 SAT CREATED:THU, MAR. 31, 1983 014818
DIGAP HEADER = FOUR STATIONS CARRIER PHASE   OBS 6 SEC   18 SATS,WITH NOISE

TOTAL OBSERVATIONS = 20010 ON DAY 316 , 1981 FROM 18: 0: 0 TO 19: 0: 0. SPAN= 1 HR(S), 0 MIN.
SATELLITES USED = 2 5 7 10 15 12

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	8(2)	-16(4)	10(6)	22(5)
3	4PTSAPIN	13(2)	-15(4)	-2(6)	20(3)
4	8PTSAPIN	0(2)	-26(4)	-28(6)	40(3)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	-7(3)	0(2)	20(6)	22(5)
3	4PTSAPIN	-15(3)	5(2)	11(6)	20(3)
4	8PTSAPIN	-37(3)	-10(2)	-3(6)	40(3)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	8(3)	0(2)	20(6)	92429
3	4PTSAPIN	17(3)	-2(2)	11(6)	142000
4	8PTSAPIN	32(3)	-21(3)	-4(6)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   FRI, APR. 08, 1983 21:55:44

DIFGPS HEADER = MARCH 29,1983:DIFGPS:SL3722:F01:DD:ALL BIASES NONZERO (18 SAT, ABER. IN)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV45.DATA:4 STNS;30S   CREATED:THU, APR. 07, 1983 010216
DIGAP HEADER = FOUR STATIONS CARRIER PHASE   OBS 30 SEC   18 SATS,WITH NOISE

TOTAL OBSERVATIONS = 19527 ON DAY 316 , 1981 FROM 17: 0: 6 TO 21:59:36. SPAN= 4 HR(S), 59 MIN.
SATELLITES USED =   3   5   7   8 10 15   2 12   4 17 14

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	11(3)	-11(4)	-11(4)	20(3)
3	4PTSAPIN	20(3)	-22(4)	-7(4)	31(3)
4	8PTSAPIN	8(3)	-38(4)	-7(4)	40(4)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	-19(3)	5(2)	2(5)	20(3)
3	4PTSAPIN	-26(3)	8(2)	14(5)	31(3)
4	8PTSAPIN	-32(3)	-7(2)	21(5)	40(4)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	20(3)	-3(2)	2(5)	92429
3	4PTSAPIN	28(3)	-4(2)	14(5)	142000
4	8PTSAPIN	27(3)	-20(3)	20(5)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   WED, APR. 13, 1983 20:56:06

DIFGPS HEADER = MARCH 10,1983:DIFGPS:SL3722:F03:DD:ONLY RANDOM NOISE (18 SAT)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV46.DATA:4 STNS:30 S   CREATED:WED, APR. 13, 1983 184329
DIGAP HEADER = FOUR STATIONS CARRIER PHASE   OBS 30 SEC   18 SATS,WITH NOISE

TOTAL OBSERVATIONS = 19527 ON DAY 316 , 1981 FROM 17: 0: 6 TO 21:59:36. SPAN= 4 HR(S), 59 MIN.
SATELLITES USED = 3 5 7 8 10 15 2 12 4 17 14

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	4(3)	2(4)	0(4)	4(3)
3	4PTSAPIN	8(3)	0(4)	8(4)	11(4)
4	8PTSAPIN	6(3)	-5(4)	0(4)	9(4)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	0(3)	4(2)	0(5)	4(3)
3	4PTSAPIN	2(3)	6(2)	9(5)	11(4)
4	8PTSAPIN	-5(3)	3(2)	5(5)	9(4)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	1(3)	-3(2)	0(5)	92429
3	4PTSAPIN	0(3)	-6(2)	9(5)	142000
4	8PTSAPIN	1(3)	-6(3)	5(5)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   SUN, APR. 10, 1983 14:44:11

DIFGPS HEADER = APRIL 6,1983:DIFGPS:SL3722:F02:DD:ALL BIASES NONZERO (18 SAT, DGR'D EPH)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV47.DATA:8 STNS;30 S   CREATED:SAT, APR. 09, 1983 221510
DIGAP HEADER = EIGHT STATIONS CARRIER PHASE   18 SATS , WITH NOISE

TOTAL OBSERVATIONS = 18666 ON DAY 316 , 1981 FROM 18: 0: 6 TO 19: 0: 6. SPAN= 1 HR(S), 0 MIN.
SATELLITES USED = 2 5 7 10 15 12

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	2PTSAPIN	287(16)	66(26)	-166(38)	338(21)
3	3PTSAPIN	414(16)	335(26)	-355(38)	640(29)
4	4PTSAPIN	535(16)	612(26)	-572(38)	995(31)
5	5PTSAPIN	806(16)	669(26)	-741(38)	1284(29)
6	6PTSAPIN	999(16)	-357(26)	-286(38)	1099(17)
7	7PTSAPIN	1519(16)	-997(26)	-181(38)	1827(21)
8	8PTSAPIN	2079(16)	-1649(26)	-137(38)	2657(23)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	2PTSAPIN	-158(21)	287(15)	-80(41)	338(21)
3	3PTSAPIN	-149(21)	517(15)	-346(41)	640(29)
4	4PTSAPIN	-158(21)	745(15)	-639(41)	995(31)
5	5PTSAPIN	-325(21)	1014(15)	-716(41)	1284(29)
6	6PTSAPIN	-736(21)	760(15)	296(41)	1099(17)
7	7PTSAPIN	-1242(21)	980(15)	912(41)	1827(21)
8	8PTSAPIN	-1804(21)	1249(15)	1497(41)	2657(23)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	2PTSAPIN	135(21)	-298(15)	-81(41)	46848
3	3PTSAPIN	176(21)	-506(15)	-347(41)	92429
4	4PTSAPIN	229(21)	-723(15)	-642(41)	142000
5	5PTSAPIN	376(21)	-992(15)	-721(41)	185998
6	6PTSAPIN	380(20)	-988(16)	293(41)	100581
7	7PTSAPIN	341(19)	-1547(17)	908(41)	123360
8	8PTSAPIN	156(18)	-2190(19)	1495(41)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS SUN, APR. 10, 1983 20:03:30

DIFGPS HEADER = APRIL 6,1983:DIFGPS:SL3722:F02:DD:ALL BIASES NONZERO (18 SAT, DGR'D EPH)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV48.DATA:4 STNS;6 S CREATED:SUN, APR. 10, 1983 163548
DIGAP HEADER = FOUR STATIONS CARRIER PHASE OBS 6 SEC 18 SATS,WITH NOISE

TOTAL OBSERVATIONS = 20010 ON DAY 316 , 1981 FROM 18: 0: 0 TO 19: 0: 0. SPAN= 1 HR(S), 0 MIN.
SATELLITES USED = 2 5 7 10 15 12

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX	(SD-DX)	DY	(SD-DY)	DZ	(SD-DZ)	DR	(SD-DR)
1	1PTSAPIN	F I X E D		S T A T I O N					
2	3PTSAPIN	416(	13)	323(	20)	-343(	29)	629(	22)
3	4PTSAPIN	542(	13)	606(	20)	-556(	29)	986(	24)
4	8PTSAPIN	2069(	13)	-1641(	20)	-125(	29)	2645(	17)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT	(SD-DLAT)	DLON	(SD-DLON)	DHGT	(SD-DHGT)	DR	(SD-DR)
1	1PTSAPIN	F I X E D		S T A T I O N					
2	3PTSAPIN	-149(	16)	514(	12)	-329(	32)	629(	22)
3	4PTSAPIN	-153(	16)	749(	12)	-621(	31)	986(	24)
4	8PTSAPIN	-1788(	16)	1244(	11)	1499(	32)	2645(	17)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN	(SD-DLEN)	DAZ	(SD-DAZ)	DELEV	(SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D		S T A T I O N				
2	3PTSAPIN	177(	16)	-504(	12)	-331(	32)	92429
3	4PTSAPIN	225(	16)	-728(	12)	-623(	32)	142000
4	8PTSAPIN	150(	14)	-2174(	14)	1497(	32)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   TUE, APR. 12, 1983 05:53:04

DIFGPS HEADER = APRIL 6,1983:DIFGPS:SL3722:F02:DD:ALL BIASES NONZERO (18 SAT, DGR'D EPH)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV49.DATA:4 STNS;30 S   CREATED:SUN, APR. 10, 1983 222945
DIGAP HEADER = FOUR STATIONS CARRIER PHASE   OBS 30 SEC   18 SATS,WITH NOISE

TOTAL OBSERVATIONS = 19527 ON DAY 316 , 1981 FROM 17: 0: 6 TO 21:59:36. SPAN= 4 HR(S), 59 MIN.
SATELLITES USED =   3   5   7   8 10 15   2 12   4 17 14

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	257(17)	-596(25)	295(27)	713(32)
3	4PTSAPIN	310(17)	-844(25)	432(27)	998(32)
4	8PTSAPIN	1739(17)	-2051(25)	846(28)	2820(30)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	-272(18)	-20(14)	658(34)	713(32)
3	4PTSAPIN	-352(18)	-80(14)	930(34)	998(32)
4	8PTSAPIN	-1303(18)	778(14)	2376(34)	2820(30)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	276(18)	37(14)	656(34)	92429
3	4PTSAPIN	353(18)	117(15)	926(34)	142000
4	8PTSAPIN	226(16)	-1505(16)	2373(34)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   WED. OCT. 20. 1982   08:39:23

DIFGPS HEADER = OCT. 11,1982:DIFTAP:S002256:F10:DD:ALL RANDOM ERRORS NONZERO (4 SAT. ABER. IN)
FOROBS HEADER = FILE: LANGLEY.GPS.OBSERV11.DATA:8 STATIONS;OBS CREATED:WED. OCT. 20. 1982 004257
DIGAP HEADER = PSEUDO RANGE   EIGHT STATIONS

TOTAL OBSERVATIONS = 12574 ON DAY 316 , 1981 FROM 18: 0: 6 TO 18:59:36. SPAN= 0 HR(S). 59 MIN.
SATELLITES USED =   6   8   9   5

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I	O N	
2	2PTSAPIN	-127(79)	245(172)	-114(211)	300(214)
3	3PTSAPIN	-117(79)	18(172)	592(211)	604(207)
4	4PTSAPIN	-14(79)	115(172)	96(212)	151(94)
5	5PTSAPIN	-117(79)	-134(171)	367(212)	408(240)
6	6PTSAPIN	8(79)	-104(171)	133(210)	170(255)
7	7PTSAPIN	-124(78)	-397(171)	434(210)	602(250)
8	8PTSAPIN	-180(78)	199(170)	155(209)	310(104)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I	O N	
2	2PTSAPIN	125(106)	-11(92)	-271(246)	300(214)
3	3PTSAPIN	453(106)	-99(93)	388(246)	604(207)
4	4PTSAPIN	146(107)	36(93)	-6(246)	151(94)
5	5PTSAPIN	202(108)	-164(93)	314(245)	408(240)
6	6PTSAPIN	18(106)	-35(91)	165(245)	170(255)
7	7PTSAPIN	68(105)	-276(90)	530(245)	602(250)
8	8PTSAPIN	292(105)	-86(89)	-60(245)	310(104)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T I	O N	
2	2PTSAPIN	-124(102)	22(96)	-271(246)	46848
3	3PTSAPIN	-454(108)	74(90)	391(246)	92429
4	4PTSAPIN	-141(111)	-50(88)	-4(246)	142000
5	5PTSAPIN	-206(109)	152(90)	317(246)	185998
6	6PTSAPIN	0(86)	41(110)	165(245)	100581
7	7PTSAPIN	129(75)	257(117)	529(245)	123360
8	8PTSAPIN	-112(71)	283(119)	-58(245)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   TUE, OCT. 19, 1982   18:40:56

DIFGPS HEADER = OCT. 11,1982:DIFTAP:S002256:F10:DD:ALL RANDOM ERRORS NONZERO (4 SAT, ABER. IN)
FOROBS HEADER = FILE: LANGLEY.GPS.OBSERV12.DATA:4 STATIONS;OBS CREATED:TUE, OCT. 19, 1982 023229
DIGAP HEADER = PSEUDO RANGE   FOUR STATIONS

TOTAL OBSERVATIONS = 13369 ON DAY 316 , 1981 FROM 18: 0: 6 TO 18:59:36. SPAN= 0 HR(S). 59 MIN.
SATELLITES USED =   6   8   9   5

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	-136(50)	85(109)	124(134)	204(75)
3	4PTSAPIN	-80(50)	132(109)	-69(135)	170(135)
4	8PTSAPIN	-196(50)	248(109)	14(134)	317(92)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	184(68)	-87(59)	-1(156)	204(75)
3	4PTSAPIN	63(68)	-16(59)	-156(156)	170(135)
4	8PTSAPIN	233(67)	-80(57)	-198(156)	317(92)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	-187(69)	77(57)	0(156)	92429
3	4PTSAPIN	-65(70)	10(56)	-155(156)	142000
4	8PTSAPIN	-82(45)	234(76)	-197(156)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   WED, NOV. 24, 1982 14:12:07

```
DIFGPS HEADER = OCT. 11,1982:DIFTAP:S002256:F10:DD:ALL RANDOM ERRORS NONZERO (4 SAT.  ABER. IN)
FOROBS HEADER = FILE: LANGLEY.GPS.OBSERV13.DATA:4 STATIONS;OBS CREATED:TUE, OCT. 19, 1982 184347
DIGAP  HEADER = PSEUDO RANGE          FOUR STATIONS, FOUR SATELLITES, FIVE HOURS

TOTAL OBSERVATIONS =  10112 ON DAY 316 , 1981 FROM 17: 0: 6  TO 21:59:36. SPAN=  4 HR(S), 59 MIN.
SATELLITES USED =   6   8   9   5
```

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	61(60)	-33(95)	159(91)	174(101)
3	4PTSAPIN	56(60)	-27(95)	105(91)	122(102)
4	8PTSAPIN	-5(60)	15(94)	20(91)	25(71)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	67(73)	40(45)	155(116)	174(101)
3	4PTSAPIN	37(73)	39(45)	109(116)	122(102)
4	8PTSAPIN	25(73)	1(45)	3(116)	25(71)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	-63(74)	-43(44)	155(116)	92429
3	4PTSAPIN	-30(74)	-41(44)	110(116)	142000
4	8PTSAPIN	-15(51)	19(69)	4(116)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   FRI, APR. 01, 1983 17:52:19

DIFGPS HEADER = MARCH 29,1983:DIFGPS:SL3722:F01:DD:ALL BIASES NONZERO (18 SAT, ABER. IN)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV43.DATA:8 STNS;30 S   CREATED:WED, MAR. 30, 1983 171752
DIGAP HEADER = EIGHT STATIONS PSEUDORANGE (P-CODE)   18 SATS,WITH NOISE

TOTAL OBSERVATIONS = 18666 ON DAY 316 , 1981 FROM 18: 0: 6 TO 19: 0: 6. SPAN= 1 HR(S), 0 MIN.
SATELLITES USED =   2   5   7 10 15 12

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	2PTSAPIN	7(49)	163(78)	-254(114)	303(124)
3	3PTSAPIN	65(49)	113(78)	-110(113)	171(106)
4	4PTSAPIN	88(49)	167(77)	-48(113)	195(81)
5	5PTSAPIN	-2(49)	269(77)	-218(113)	347(117)
6	6PTSAPIN	76(49)	320(77)	-183(113)	377(104)
7	7PTSAPIN	35(49)	74(77)	32(113)	88(53)
8	8PTSAPIN	62(49)	124(77)	-109(113)	177(105)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	2PTSAPIN	-66(109)	75(79)	-285(57)	303(124)
3	3PTSAPIN	-20(92)	107(80)	-131(80)	171(106)
4	4PTSAPIN	48(68)	151(80)	-113(101)	195(81)
5	5PTSAPIN	25(45)	112(80)	-326(113)	347(117)
6	6PTSAPIN	65(79)	202(68)	-311(102)	377(104)
7	7PTSAPIN	61(73)	62(50)	-12(115)	88(53)
8	8PTSAPIN	-9(73)	106(47)	-140(116)	177(105)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	2PTSAPIN	59(123)	-79(62)	-285(47)	46848
3	3PTSAPIN	26(59)	-104(122)	-131(54)	92429
4	4PTSAPIN	-33(56)	-154(126)	-113(47)	142000
5	5PTSAPIN	-22(58)	-112(111)	-326(74)	185998
6	6PTSAPIN	-141(119)	-159(57)	-309(61)	100581
7	7PTSAPIN	-86(70)	-8(110)	-11(65)	123360
8	8PTSAPIN	-78(67)	-73(107)	-140(72)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   SAT, APR. 02, 1983 00:38:19

DIFGPS HEADER = MARCH 29,1983:DIFGPS:SL3722:F01:DD:ALL BIASES NONZERO (18 SAT, ABER. IN)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV44.DATA:4 STNS;18 SAT CREATED:THU, MAR. 31, 1983 014818
DIGAP HEADER = FOUR STATIONS PSEUDORANGE (P-CODE)   18 SATS,WITH NOISE

TOTAL OBSERVATIONS = 20010 ON DAY 316 , 1981 FROM 18: 0: 0 TO 19: 0: 0. SPAN= 1 HR(S), 0 MIN.
SATELLITES USED =   2   5   7 10 15 12

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	-46(31)	48(49)	17(72)	69(38)
3	4PTSAPIN	-12(31)	-16(49)	95(72)	97(75)
4	8PTSAPIN	35(31)	12(49)	67(72)	76(65)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	58(59)	-21(51)	-30(51)	69(38)
3	4PTSAPIN	59(43)	-18(51)	76(65)	97(75)
4	8PTSAPIN	43(47)	37(30)	51(74)	76(65)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	-58(38)	19(78)	-30(34)	92429
3	4PTSAPIN	-58(36)	12(80)	76(30)	142000
4	8PTSAPIN	-54(43)	11(69)	51(46)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS SAT, APR. 09, 1983 18:35:19

DIFGPS HEADER = MARCH 29,1983:DIFGPS:SL3722:F01:DD:ALL BIASES NONZERO (18 SAT, ABER. IN)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV45.DATA:4 STNS;6 S CREATED:THU, APR. 07, 1983 010216
DIGAP HEADER = FOUR STATIONS PSEUDORANGE (P-CODE) 30 SEC 18 SATS,WITH NOISE

TOTAL OBSERVATIONS = 19527 ON DAY 316 , 1981 FROM 17: 0: 6 TO 21:59:36. SPAN= 4 HR(S), 59 MIN.
SATELLITES USED = 3 5 7 8 10 15 2 12 4 17 14

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	0(34)	16(51)	-26(55)	31(65)
3	4PTSAPIN	53(34)	45(51)	33(55)	76(32)
4	8PTSAPIN	6(34)	-5(51)	-33(55)	35(48)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	-7(45)	6(53)	-28(44)	31(65)
3	4PTSAPIN	35(36)	67(54)	12(51)	76(32)
4	8PTSAPIN	-28(38)	3(32)	-18(66)	35(48)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	8(34)	-5(68)	-29(32)	92429
3	4PTSAPIN	-27(36)	-69(67)	12(30)	142000
4	8PTSAPIN	15(37)	-24(64)	-19(37)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   THU, APR. 14, 1983 01:31:01

DIFGPS HEADER = MARCH 10,1983:DIFGPS:SL3722:F03:DD:ONLY RANDOM NOISE (18 SAT)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV46.DATA:4 STNS;30 S   CREATED:WED, APR. 13, 1983 184329
DIGAP HEADER = FOUR STATIONS PSEUDORANGE (P-CODE)   OBS 30 SEC   18 SATS,WITH NOISE

TOTAL OBSERVATIONS = 19527 ON DAY 316 , 1981 FROM 17: 0: 6 TO 21:59:36. SPAN= 4 HR(S), 59 MIN.
SATELLITES USED =   3   5   7   8 10 15   2 12   4 17 14

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	-7(34)	30(51)	-16(55)	35(65)
3	4PTSAPIN	41(34)	66(51)	49(55)	92(34)
4	8PTSAPIN	5(34)	27(51)	-26(55)	38(64)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	11(45)	6(53)	-32(44)	35(65)
3	4PTSAPIN	64(36)	65(54)	6(51)	92(34)
4	8PTSAPIN	-1(38)	15(32)	-34(66)	38(64)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	-10(34)	-5(68)	-32(32)	92429
3	4PTSAPIN	-56(36)	-71(67)	7(30)	142000
4	8PTSAPIN	-10(37)	-10(64)	-34(37)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   SUN, APR. 10, 1983 16:35:01

DIFGPS HEADER = APRIL 6,1983:DIFGPS:SL3722:F02:DD:ALL BIASES NONZERO (18 SAT, DGR'D EPH)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV47.DATA:8 STNS;30 S   CREATED:SAT, APR. 09, 1983 221510
DIGAP HEADER = EIGHT STATIONS PSEUDORANGE (P - CODE)   OBS 30 SEC   18 SATS, WITH NOISE

TOTAL OBSERVATIONS = 18666 ON DAY 316 , 1981 FROM 18: 0: 6 TO 19: 0: 6. SPAN= 1 HR(S), 0 MIN.
SATELLITES USED =   2   5   7 10 15 12

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	2PTSAPIN	297(51)	239(81)	-419(119)	567(105)
3	3PTSAPIN	473(51)	451(81)	-459(119)	800(95)
4	4PTSAPIN	619(51)	786(81)	-596(119)	1165(96)
5	5PTSAPIN	805(51)	942(81)	-919(119)	1543(101)
6	6PTSAPIN	1071(51)	-33(81)	-438(119)	1157(53)
7	7PTSAPIN	1550(51)	-878(81)	-146(119)	1788(65)
8	8PTSAPIN	2133(52)	-1495(81)	-195(118)	2613(68)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	2PTSAPIN	-217(114)	370(83)	-369(60)	567(105)
3	3PTSAPIN	-161(97)	620(84)	-477(84)	800(95)
4	4PTSAPIN	-86(71)	896(84)	-739(106)	1165(96)
5	5PTSAPIN	-270(48)	1130(84)	-1015(118)	1543(101)
6	6PTSAPIN	-646(83)	959(71)	5(107)	1157(53)
7	7PTSAPIN	-1148(77)	1057(52)	872(121)	1788(65)
8	8PTSAPIN	-1757(77)	1361(49)	1374(122)	2613(68)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	2PTSAPIN	186(130)	-385(65)	-370(50)	46848
3	3PTSAPIN	194(62)	-609(128)	-478(56)	92429
4	4PTSAPIN	173(59)	-880(132)	-741(50)	142000
5	5PTSAPIN	324(61)	-1110(116)	-1020(78)	185998
6	6PTSAPIN	216(125)	-1136(60)	3(64)	100581
7	7PTSAPIN	219(74)	-1546(115)	870(68)	123360
8	8PTSAPIN	37(70)	-2222(113)	1373(75)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   SUN, APR. 10, 1983 22:05:34

DIFGPS HEADER = APRIL 6,1983:DIFGPS:SL3722:F02:DD:ALL BIASES NONZERO (18 SAT, DGR'D EPH)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV48.DATA:4 STNS;6 S   CREATED:SUN, APR. 10, 1983 163548
DIGAP HEADER = FOUR STATIONS PSEUDORANGE (P-CODE)   OBS #6 SEC   18 SATS,WITH NOISE

TOTAL OBSERVATIONS = 20010 ON DAY 316 , 1981 FROM 18: 0: 0 TO 19: 0: 0. SPAN= 1 HR(S), 0 MIN.
SATELLITES USED = 2 5 7 10 15 12

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	360(33)	389(53)	-336(77)	628(61)
3	4PTSAPIN	517(33)	605(53)	-458(77)	919(61)
4	8PTSAPIN	2105(33)	-1602(53)	-30(77)	2646(48)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	-84(63)	491(54)	-381(55)	628(61)
3	4PTSAPIN	-78(46)	726(55)	-556(69)	919(61)
4	8PTSAPIN	-1707(50)	1292(32)	1554(79)	2646(48)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	110(41)	-485(83)	-382(37)	92429
3	4PTSAPIN	149(38)	-713(86)	-558(32)	142000
4	8PTSAPIN	63(46)	-2141(73)	1553(49)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   WED, APR. 13, 1983 04:36:51

DIFGPS HEADER = APRIL 6,1983:DIFGPS:SL3722:F02:DD:ALL BIASES NONZERO (18 SAT, DGR'D EPH)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV49.DATA:4 STNS;30 S   CREATED:SUN, APR. 10, 1983 222945
DIGAP HEADER = FOUR STATIONS PSEUDORANGE (P-CODE)   OBS 30 SEC   18 SATS,WITH NOISE

TOTAL OBSERVATIONS = 19527 ON DAY 316 , 1981 FROM 17: 0: 6 TO 21:59:36. SPAN= 4 HR(S), 59 MIN.
SATELLITES USED =   3   5   7   8 10 15   2 12   4 17 14

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	245(37)	-567(56)	279(61)	679(71)
3	4PTSAPIN	343(37)	-776(56)	473(61)	972(73)
4	8PTSAPIN	1738(37)	-2018(57)	819(62)	2787(66)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	-261(50)	-19(59)	626(49)	679(71)
3	4PTSAPIN	-290(40)	-21(59)	927(57)	972(73)
4	8PTSAPIN	-1299(42)	789(35)	2335(73)	2787(66)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	265(38)	35(75)	624(36)	92429
3	4PTSAPIN	297(40)	52(75)	924(34)	142000
4	8PTSAPIN	214(41)	-1509(71)	2333(41)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   SAT. NOV. 27. 1982 13:27:51

DIFGPS HEADER = OCT. 11,1982:DIFTAP:S002256:F10:DD:ALL RANDOM ERRORS NONZERO (4 SAT. ABER. IN)
FOROBS HEADER = FILE: LANGLEY.GPS.OBSERV11.DATA:8 STATIONS;OBS CREATED:WED. OCT. 20. 1982 004257
DIGAP HEADER = C/A PSEUDO RANGE.8 STATIONS.4 SATELLITES.1 HOUR.RATE=30S

TOTAL OBSERVATIONS = 12574 ON DAY 316 , 1981 FROM 18: 0: 6 TO 18:59:36. SPAN= 0 HR(S). 59 MIN.
SATELLITES USED = 6 8 9 5

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	2PTSAPIN	-1295(783)	2469(1712)	-900(2102)	2931(2038)
3	3PTSAPIN	-1179(784)	414(1711)	5653(2105)	5789(2001)
4	4PTSAPIN	-89(785)	1223(1709)	895(2108)	1518(919)
5	5PTSAPIN	-1067(785)	-1322(1707)	3647(2111)	4024(2406)
6	6PTSAPIN	164(783)	-1356(1705)	1809(2097)	2267(2542)
7	7PTSAPIN	-1179(782)	-4332(1699)	4980(2090)	6706(2507)
8	8PTSAPIN	-1671(781)	1650(1696)	2123(2087)	3166(1161)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	2PTSAPIN	1440(1051)	-128(920)	-2548(2452)	2931(2038)
3	3PTSAPIN	4498(1058)	-891(923)	3534(2450)	5789(2001)
4	4PTSAPIN	1446(1067)	442(926)	-137(2447)	1518(919)
5	5PTSAPIN	1994(1073)	-1529(925)	3143(2445)	4024(2406)
6	6PTSAPIN	282(1053)	-414(911)	2211(2445)	2267(2542)
7	7PTSAPIN	860(1049)	-2843(901)	6012(2441)	6706(2507)
8	8PTSAPIN	3042(1045)	-875(890)	64(2441)	3166(1161)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	2PTSAPIN	-1433(1015)	244(958)	-2543(2452)	46848
3	3PTSAPIN	-4514(1077)	635(895)	3567(2452)	92429
4	4PTSAPIN	-1392(1102)	-591(872)	-122(2451)	142000
5	5PTSAPIN	-2035(1088)	1407(894)	3173(2450)	185998
6	6PTSAPIN	-77(860)	493(1095)	2212(2445)	100581
7	7PTSAPIN	1209(744)	2739(1169)	6000(2439)	123360
8	8PTSAPIN	-1195(705)	2931(1186)	78(2437)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   TUE. OCT. 19, 1982   18:27:45

DIFGPS HEADER = OCT. 11,1982:DIFTAP:S002256:F10:DD:ALL RANDOM ERRORS NONZERO (4 SAT. ABER. IN)
FOROBS HEADER = FILE: LANGLEY.GPS.OBSERV12.DATA:4 STATIONS;OBS CREATED:TUE. OCT. 19, 1982 023229
DIGAP HEADER = C/A PSEUDO RANGE   FOUR STATIONS

TOTAL OBSERVATIONS = 13369 ON DAY 316 , 1981 FROM 18: 0: 6 TO 18:59:36. SPAN= 0 HR(S), 59 MIN.
SATELLITES USED =   6   8   9   5

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	-1365(499)	980(1088)	1129(1338)	2025(705)
3	4PTSAPIN	-812(499)	1559(1087)	-788(1340)	1927(1372)
4	8PTSAPIN	-1803(497)	1849(1081)	992(1332)	2767(681)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	1844(673)	-818(587)	-175(1557)	2025(705)
3	4PTSAPIN	732(678)	-68(589)	-1780(1556)	1927(1372)
4	8PTSAPIN	2441(665)	-917(567)	-923(1558)	2767(681)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	-1888(685)	713(569)	-161(1558)	92429
3	4PTSAPIN	-754(701)	-7(555)	-1772(1558)	142000
4	8PTSAPIN	-802(448)	2486(755)	-913(1556)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   WED. NOV. 24. 1982   17:27:40

DIFGPS HEADER = OCT. 11,1982:DIFTAP:S002256:F10:DD:ALL RANDOM ERRORS NONZERO (4 SAT. ABER. IN)
FOROBS HEADER = FILE: LANGLEY.GPS.OBSERV13.DATA:4 STATIONS;OBS CREATED:TUE. OCT. 19. 1982 184347
DIGAP HEADER = C/A PSEUDO RANGE   FOUR STATIONS, FOUR SATELLITES, FIVE HOURS

TOTAL OBSERVATIONS = 10112 ON DAY 316 , 1981 FROM 17: 0: 6 TO 21:59:36. SPAN= 4 HR(S). 59 MIN.
SATELLITES USED = 6 8 9 5

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	554(597)	-75(944)	1554(904)	1651(934)
3	4PTSAPIN	524(599)	-89(948)	1049(906)	1176(942)
4	8PTSAPIN	155(596)	172(941)	295(906)	375(634)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	838(732)	469(445)	1343(1154)	1651(934)
3	4PTSAPIN	500(732)	435(445)	971(1159)	1176(942)
4	8PTSAPIN	272(728)	210(448)	151(1154)	375(634)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	-799(738)	-515(438)	1349(1153)	92429
3	4PTSAPIN	-440(740)	-484(435)	976(1158)	142000
4	8PTSAPIN	-330(510)	83(688)	155(1153)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS THU, APR. 07, 1983 01:42:51

DIFGPS HEADER = MARCH 29,1983:DIFGPS:SL3722:F01:DD:ALL BIASES NONZERO (18 SAT, ABER. IN)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV43.DATA:8 STNS;30 S CREATED:WED, MAR. 30, 1983 171752
DIGAP HEADER = EIGHT STATIONS PSEUDORANGE (C/A-CODE) OBS 30 SEC 18 SATS , WITH NOISE

TOTAL OBSERVATIONS = 18666 ON DAY 316 , 1981 FROM 18: 0: 6 TO 19: 0: 6. SPAN= 1 HR(S), 0 MIN.
SATELLITES USED = 2 5 7 10 15 12

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	2PTSAPIN	23(49)	104(78)	-314(114)	332(122)
3	3PTSAPIN	119(49)	4(78)	-219(113)	250(95)
4	4PTSAPIN	182(49)	4(77)	-211(113)	280(82)
5	5PTSAPIN	106(49)	50(77)	-437(113)	454(111)
6	6PTSAPIN	53(49)	187(77)	-318(113)	374(121)
7	7PTSAPIN	-52(49)	-82(77)	-127(113)	161(79)
8	8PTSAPIN	-98(49)	-55(77)	-294(113)	316(104)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	2PTSAPIN	-150(109)	65(79)	-288(57)	332(122)
3	3PTSAPIN	-184(92)	109(80)	-128(80)	250(95)
4	4PTSAPIN	-199(68)	166(80)	-102(101)	280(82)
5	5PTSAPIN	-303(45)	117(80)	-315(113)	454(111)
6	6PTSAPIN	-109(79)	126(68)	-333(102)	374(121)
7	7PTSAPIN	-126(73)	-81(50)	-56(115)	161(79)
8	8PTSAPIN	-209(73)	-113(47)	-206(116)	316(104)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	2PTSAPIN	144(123)	-76(62)	-288(47)	46848
3	3PTSAPIN	189(59)	-98(122)	-129(54)	92429
4	4PTSAPIN	215(56)	-143(126)	-105(47)	142000
5	5PTSAPIN	306(58)	-98(111)	-320(74)	185998
6	6PTSAPIN	48(119)	-158(57)	-334(61)	100581
7	7PTSAPIN	150(70)	-17(110)	-57(65)	123360
8	8PTSAPIN	217(67)	-93(107)	-209(72)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS SUN, APR. 10, 1983 22:59:47

DIFGPS HEADER = MARCH 29,1983:DIFGPS:SL3722:F01:DD:ALL BIASES NONZERO (18 SAT, ABER. IN)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV44.DATA:4 STNS:18 SAT CREATED:THU, MAR. 31, 1983 014818
DIGAP HEADER = FOUR STATIONS PSEUDORANGE (C/A-CODE) OBS 30 SEC 18 SATS,WITH NOISE

TOTAL OBSERVATIONS = 20010 ON DAY 316 , 1981 FROM 18: 0: 0 TO 19: 0: 0. SPAN= 1 HR(S), 0 MIN.
SATELLITES USED = 2 5 7 10 15 12

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	7(31)	-60(49)	-91(72)	111(49)
3	4PTSAPIN	82(31)	-179(49)	-66(72)	208(39)
4	8PTSAPIN	-125(31)	-167(49)	-117(72)	241(36)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	-104(59)	-19(51)	-27(51)	111(49)
3	4PTSAPIN	-188(43)	-2(51)	87(65)	208(39)
4	8PTSAPIN	-156(47)	-182(30)	-14(74)	241(36)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	104(38)	26(78)	-27(34)	92429
3	4PTSAPIN	189(36)	23(80)	85(30)	142000
4	8PTSAPIN	241(43)	-9(69)	-17(46)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   SUN, APR. 10, 1983 13:28:56

DIFGPS HEADER = MARCH 29,1983:DIFGPS:SL3722:F01:DD:ALL BIASES NONZERO (18 SAT, ABER. IN)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV45.DATA:4 STNS;6 S   CREATED:THU, APR. 07, 1983 010216
DIGAP HEADER = FOUR STATIONS PSEUDORANGE (C/A-CODE)   OBS 30 SEC   18 SATS,WITH NOISE

TOTAL OBSERVATIONS = 19527 ON DAY 316 , 1981 FROM 17: 0: 6 TO 21:59:36. SPAN= 4 HR(S), 59 MIN.
SATELLITES USED =   3   5   7   8 10 15   2 12   4 17 14

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	61(34)	-92(51)	-144(55)	183(37)
3	4PTSAPIN	159(34)	-116(51)	-146(55)	246(35)
4	8PTSAPIN	-138(34)	-202(51)	-160(55)	294(34)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	-178(45)	16(53)	-29(44)	183(37)
3	4PTSAPIN	-226(36)	94(54)	13(51)	246(35)
4	8PTSAPIN	-204(38)	-207(32)	-28(66)	294(34)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	180(34)	-5(68)	-31(32)	92429
3	4PTSAPIN	236(36)	-68(67)	10(30)	142000
4	8PTSAPIN	290(37)	-31(64)	-31(37)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   THU, APR. 14, 1983 00:35:46

DIFGPS HEADER = MARCH 10,1983:DIFGPS:SL3722:F03:DD:ONLY RANDOM NOISE (18 SAT)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV46.DATA:4 STNS:30 S   CREATED:WED, APR. 13, 1983 184329
DIGAP HEADER = FOUR STATIONS PSEUDORANGE (C/A-CODE)   OBS 30 SEC   18 SATS,WITH NOISE

TOTAL OBSERVATIONS = 19527 ON DAY 316 , 1981 FROM 17: 0: 6 TO 21:59:36. SPAN= 4 HR(S), 59 MIN.
SATELLITES USED =   3   5   7   8 10 15   2 12   4 17 14

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I	O N	
2	3PTSAPIN	54(34)	-77(51)	-133(55)	164(38)
3	4PTSAPIN	147(34)	-94(51)	-129(55)	218(35)
4	8PTSAPIN	-140(34)	-169(51)	-152(55)	268(35)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I	O N	
2	3PTSAPIN	-159(45)	15(53)	-33(44)	164(38)
3	4PTSAPIN	-196(36)	92(54)	8(51)	218(35)
4	8PTSAPIN	-176(38)	-195(32)	-43(66)	268(35)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M
1	1PTSAPIN	F I X E D	S T A T I	O N	
2	3PTSAPIN	160(34)	-5(68)	-34(32)	92429
3	4PTSAPIN	206(36)	-70(67)	6(30)	142000
4	8PTSAPIN	264(37)	-17(64)	-46(37)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   SUN, APR. 10, 1983 13:55:06

DIFGPS HEADER = APRIL 6,1983:DIFGPS:SL3722:F02:DD:ALL BIASES NONZERO (18 SAT, DGR'D EPH)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV47.DATA:8 STNS;30 S   CREATED:SAT, APR. 09, 1983 221510
DIGAP HEADER = EIGHT STATIONS PSEUDORANGE (C/A - CODE)   OBS 30 SEC   18 SATS, WITH NOISE

TOTAL OBSERVATIONS = 18666 ON DAY 316 , 1981 FROM 18: 0: 6 TO 19: 0: 6. SPAN= 1 HR(S), 0 MIN.
SATELLITES USED =   2   5   7 10 15 12

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	2PTSAPIN	313(52)	180(81)	-478(119)	600(104)
3	3PTSAPIN	527(51)	343(81)	-568(119)	848(95)
4	4PTSAPIN	713(51)	623(81)	-759(119)	1214(97)
5	5PTSAPIN	914(51)	723(81)	-1138(119)	1630(101)
6	6PTSAPIN	1048(51)	-166(81)	-573(119)	1206(57)
7	7PTSAPIN	1461(52)	-1035(81)	-306(119)	1818(63)
8	8PTSAPIN	1972(52)	-1675(81)	-379(118)	2615(66)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	2PTSAPIN	-300(114)	360(83)	-372(60)	600(104)
3	3PTSAPIN	-324(97)	623(84)	-474(84)	848(95)
4	4PTSAPIN	-334(71)	911(84)	-728(106)	1214(97)
5	5PTSAPIN	-598(48)	1135(84)	-1004(119)	1630(101)
6	6PTSAPIN	-820(83)	883(71)	-17(107)	1206(57)
7	7PTSAPIN	-1335(77)	912(52)	828(121)	1818(63)
8	8PTSAPIN	-1956(77)	1141(49)	1308(122)	2615(66)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	2PTSAPIN	270(130)	-382(65)	-373(50)	46848
3	3PTSAPIN	357(62)	-602(128)	-477(56)	92429
4	4PTSAPIN	421(59)	-870(132)	-733(50)	142000
5	5PTSAPIN	652(61)	-1096(116)	-1013(78)	185998
6	6PTSAPIN	406(125)	-1135(60)	-20(64)	100581
7	7PTSAPIN	456(74)	-1554(115)	824(68)	123360
8	8PTSAPIN	333(70)	-2242(113)	1304(75)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   SUN, APR. 10, 1983 21:30:54

DIFGPS HEADER = APRIL 6,1983:DIFGPS:SL3722:F02:DD:ALL BIASES NONZERO (18 SAT, DGR'D EPH)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV48.DATA:4 STNS:6 S   CREATED:SUN, APR. 10, 1983 163548
DIGAP HEADER = FOUR STATIONS PSEUDORANGE (C/A-CODE)   OBS 86 SEC   18 SATS,WITH NOISE

TOTAL OBSERVATIONS = 20010 ON DAY 316 , 1981 FROM 18: 0: 0 TO 19: 0: 0. SPAN= 1 HR(S), 0 MIN.
SATELLITES USED =   2   5   7 10 15 12

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I	O N	
2	3PTSAPIN	414(33)	280(53)	-445(77)	670(62)
3	4PTSAPIN	611(33)	442(53)	-621(77)	977(61)
4	8PTSAPIN	1944(34)	-1783(53)	-214(77)	2647(46)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I	O N	
2	3PTSAPIN	-247(63)	494(55)	-377(55)	670(62)
3	4PTSAPIN	-326(46)	742(55)	-545(69)	977(61)
4	8PTSAPIN	-1907(50)	1072(32)	1488(80)	2647(46)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T I	O N	
2	3PTSAPIN	273(41)	-478(83)	-379(37)	92429
3	4PTSAPIN	398(38)	-702(86)	-550(32)	142000
4	8PTSAPIN	359(46)	-2161(73)	1484(49)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   WED, APR. 13, 1983 03:50:43

DIFGPS HEADER = APRIL 6,1983:DIFGPS:SL3722:F02:DD:ALL BIASES NONZERO (18 SAT, DGR'D EPH)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV49.DATA:4 STNS:30 S   CREATED:SUN, APR. 10, 1983 222945
DIGAP HEADER = FOUR STATIONS PSEUDORANGE (C/A-CODE)   OBS 30 SEC   18 SATS,WITH NOISE

TOTAL OBSERVATIONS = 19527 ON DAY 316 , 1981 FROM 17: 0: 6 TO 21:59:36. SPAN= 4 HR(S), 59 MIN.
SATELLITES USED = 3 5 7 8 10 15 2 12 4 17 14

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	307(37)	-676(56)	162(61)	761(66)
3	4PTSAPIN	449(37)	-938(56)	294(61)	1081(68)
4	8PTSAPIN	1592(37)	-2215(57)	693(62)	2815(66)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	-432(50)	-9(59)	626(49)	761(66)
3	4PTSAPIN	-552(40)	5(59)	929(57)	1081(68)
4	8PTSAPIN	-1475(42)	577(35)	2326(73)	2815(66)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	436(38)	35(75)	623(36)	92429
3	4PTSAPIN	561(41)	53(75)	923(34)	142000
4	8PTSAPIN	489(41)	-1516(71)	2321(41)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS SAT, FEB. 12, 1983 19:53:07

DIFGPS HEADER = FILE: DEMITRIS.GPS.OBSERV30.DATA:8 STNS;30 S CREATED:THU, FEB. 10, 1983 180231
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV30.DATA:8 STNS;30 S CREATED:THU, FEB. 10, 1983 180231
DIGAP HEADER = EIGHT STATIONS CONTINUOUSLY INTEGRATED DOPPLER 4 SATS,WITH NOISE

TOTAL OBSERVATIONS = 12574 ON DAY 316 , 1981 FROM 18: 0: 6 TO 18:59:36. SPAN= 0 HR(S), 59 MIN.
SATELLITES USED = 6 8 9 5

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	2PTSAPIN	-2021(43)	-2864(94)	5486(116)	6511(134)
3	3PTSAPIN	-1557(43)	-566(94)	4952(116)	5222(121)
4	4PTSAPIN	1719(43)	1098(94)	1192(116)	2363(35)
5	5PTSAPIN	1497(43)	-2086(94)	2454(116)	3553(129)
6	6PTSAPIN	-1286(43)	-3783(94)	7248(116)	8277(138)
7	7PTSAPIN	119(43)	-630(94)	2026(115)	2125(132)
8	8PTSAPIN	892(43)	443(94)	-872(115)	1324(108)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	2PTSAPIN	2435(117)	-3044(95)	5215(40)	6511(134)
3	3PTSAPIN	3488(110)	-1651(94)	3518(57)	5222(121)
4	4PTSAPIN	1007(90)	2023(92)	688(87)	2363(35)
5	5PTSAPIN	-120(55)	464(93)	3520(113)	3553(129)
6	6PTSAPIN	2821(89)	-2743(86)	7281(94)	8277(138)
7	7PTSAPIN	926(73)	-148(62)	1907(122)	2125(132)
8	8PTSAPIN	-558(62)	995(42)	-671(135)	1324(108)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	2PTSAPIN	-2163(141)	3230(49)	5223(45)	46848
3	3PTSAPIN	-3549(38)	1451(136)	3544(66)	92429
4	4PTSAPIN	-780(59)	-2118(136)	696(49)	142000
5	5PTSAPIN	200(32)	-454(128)	3518(83)	185998
6	6PTSAPIN	-1449(138)	3635(51)	7293(48)	100581
7	7PTSAPIN	-599(43)	705(126)	1913(79)	123360
8	8PTSAPIN	-442(38)	-1054(124)	-666(84)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   TUE, FEB. 15, 1983 10:28:32

DIFGPS HEADER = FEB. 09,1983:DIFTAP:S003757:F06:DD:ALL BIASES NONZERO (4 SAT, ABER. IN)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV31.DATA:4 STNS;6 S   CREATED:SAT, FEB. 12, 1983 140351
DIGAP HEADER = FOUR STATIONS CONTINUOUSLY INTEGRATED DOPPLER   4 SATS,WITH NOISE

TOTAL OBSERVATIONS = 13460 ON DAY 316 , 1981 FROM 18: 0: 0 TO 19: 0: 0. SPAN= 1 HR(S), 0 MIN.
SATELLITES USED =   6   8   9   5

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	-1547(32)	-572(71)	4967(87)	5234(91)
3	4PTSAPIN	1737(32)	1087(71)	1180(87)	2365(26)
4	8PTSAPIN	905(32)	385(70)	-782(87)	1257(77)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	3492(82)	-1644(71)	3535(43)	5234(91)
3	4PTSAPIN	987(68)	2035(69)	691(65)	2365(26)
4	8PTSAPIN	-539(47)	984(32)	-566(101)	1257(77)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	-3552(28)	1444(102)	3562(49)	92429
3	4PTSAPIN	-758(44)	-2127(102)	699(37)	142000
4	8PTSAPIN	-443(29)	-1032(93)	-560(63)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   TUE, FEB. 15, 1983 11:52:13

DIFGPS HEADER = FEB. 09,1983:DIFTAP:S003757:F06:DD:ALL BIASES NONZERO (4 SAT, ABER. IN)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV32.DATA:4 STNS;30 S   CREATED:MON, FEB. 14, 1983 120511
DIGAP HEADER = FOUR STATIONS CONTINUOUSLY INTEGRATED DOPPLER   4 SATS,WITH NOISE

TOTAL OBSERVATIONS = 10112 ON DAY 316 , 1981 FROM 17: 0: 6 TO 21:59:36. SPAN= 4 HR(S), 59 MIN.
SATELLITES USED =   6   8   9   5

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	-1914(78)	2638(124)	-3243(119)	4599(150)
3	4PTSAPIN	1438(79)	2286(125)	-3023(119)	4054(128)
4	8PTSAPIN	177(78)	1860(124)	-2532(119)	3147(144)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	126(103)	-610(132)	-4555(88)	4599(150)
3	4PTSAPIN	-1026(82)	2277(135)	-3192(105)	4054(128)
4	8PTSAPIN	-533(90)	904(72)	-2966(150)	3147(144)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	-193(71)	603(153)	-4554(86)	92429
3	4PTSAPIN	1225(102)	-2155(148)	-3206(59)	142000
4	8PTSAPIN	-413(69)	-978(149)	-2961(93)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS FRI, APR. 01, 1983 16:25:12

DIFGPS HEADER = MARCH 29,1983:DIFGPS:SL3722:F01:DD:ALL BIASES NONZERO (18 SAT, ABER. IN)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV43.DATA:8 STNS:30 S CREATED:WED, MAR. 30, 1983 171752
DIGAP HEADER = EIGHT STATIONS CONTINUOUSLY INTEGRATED DOPPLER 18 SATS,WITH NOISE

TOTAL OBSERVATIONS = 18666 ON DAY 316 , 1981 FROM 18: 0: 6 TO 19: 0: 6. SPAN= 1 HR(S), 0 MIN.
SATELLITES USED = 2 5 7 10 15 12

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	2PTSAPIN	671(34)	-739(54)	2031(78)	2263(86)
3	3PTSAPIN	-28(34)	804(53)	1460(78)	1667(57)
4	4PTSAPIN	649(34)	-970(53)	2881(78)	3109(86)
5	5PTSAPIN	-316(34)	1055(53)	-1047(78)	1521(84)
6	6PTSAPIN	984(34)	-1423(53)	1010(78)	2004(77)
7	7PTSAPIN	-146(34)	1702(53)	1966(78)	2605(47)
8	8PTSAPIN	2129(34)	-2020(53)	1516(78)	3304(72)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	2PTSAPIN	673(75)	295(54)	2140(39)	2263(86)
3	3PTSAPIN	1538(64)	316(55)	562(55)	1667(57)
4	4PTSAPIN	1144(47)	172(55)	2886(70)	3109(86)
5	5PTSAPIN	59(31)	163(55)	-1510(78)	1521(84)
6	6PTSAPIN	-555(55)	302(47)	1901(70)	2004(77)
7	7PTSAPIN	2522(50)	559(34)	335(80)	2605(47)
8	8PTSAPIN	-939(51)	1148(32)	2952(80)	3304(72)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN
1	1PTSAPIN	F I X E D	S T A T I O N		
2	2PTSAPIN	-685(85)	-239(43)	2143(33)	46848
3	3PTSAPIN	-1512(41)	-402(84)	574(37)	92429
4	4PTSAPIN	-1086(39)	-291(87)	2898(33)	142000
5	5PTSAPIN	-70(40)	-166(76)	-1509(51)	185998
6	6PTSAPIN	407(82)	-496(40)	1898(42)	100581
7	7PTSAPIN	-2295(48)	1177(76)	357(45)	123360
8	8PTSAPIN	-282(46)	-1448(74)	2956(49)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   FRI, APR. 01, 1983 18:41:45

DIFGPS HEADER = MARCH 29,1983:DIFGPS:SL3722:F01:DD:ALL BIASES NONZERO (18 SAT, ABER. IN)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV44.DATA:4 STNS;18 SAT CREATED:THU, MAR. 31, 1983 014818
DIGAP HEADER = FOUR STATIONS CONTINUOUSLY INTEGRATED DOPPLER   18 SATS,WITH NOISE

TOTAL OBSERVATIONS = 20010 ON DAY 316 , 1981 FROM 18: 0: 0 TO 19: 0: 0. SPAN= 1 HR(S), 0 MIN.
SATELLITES USED =   2   5   7 10 15 12

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	-24(24)	791(38)	1477(56)	1676(41)
3	4PTSAPIN	656(24)	-975(38)	2893(56)	3123(62)
4	8PTSAPIN	2126(24)	-2015(38)	1549(56)	3314(52)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	1539(45)	313(39)	584(39)	1676(41)
3	4PTSAPIN	1146(33)	176(39)	2899(50)	3123(62)
4	8PTSAPIN	-912(36)	1147(23)	2972(57)	3314(52)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	-1513(29)	-399(60)	595(26)	92429
3	4PTSAPIN	-1088(28)	-295(62)	2912(23)	142000
4	8PTSAPIN	-298(33)	-1426(53)	2976(35)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   SAT, APR. 09, 1983 18:55:26

DIFGPS HEADER = MARCH 29,1983:DIFGPS:SL3722:F01:DD:ALL BIASES NONZERO (18 SAT, ABER. IN)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV45.DATA:4 STNS;6 S   CREATED:THU, APR. 07, 1983 010216
DIGAP HEADER = FOUR STATIONS CONTINUOUSLY INTEGRATED DOPPLER   OBS 30 SEC   18 SATS,WITH NOISE

TOTAL OBSERVATIONS = 19527 ON DAY 316 , 1981 FROM 17: 0: 6 TO 21:59:36. SPAN= 4 HR(S), 59 MIN.
SATELLITES USED =   3   5   7   8 10 15   2 12   4 17 14

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	948(42)	316(64)	1339(70)	1671(62)
3	4PTSAPIN	1548(43)	-456(64)	0(70)	1614(51)
4	8PTSAPIN	2008(42)	72(64)	492(70)	2069(49)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	828(57)	993(67)	1059(56)	1671(62)
3	4PTSAPIN	-780(45)	1205(68)	739(65)	1614(51)
4	8PTSAPIN	-199(48)	1871(40)	861(83)	2069(49)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	-761(43)	-1037(85)	1064(40)	92429
3	4PTSAPIN	912(46)	-1114(85)	729(39)	142000
4	8PTSAPIN	-1333(47)	-1315(81)	877(46)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   THU, APR. 14, 1983 01:52:42

DIFGPS HEADER = MARCH 10,1983:DIFGPS:SL3722:F03:DD:ONLY RANDOM NOISE (18 SAT)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV46.DATA:4 STNS;30 S   CREATED:WED, APR. 13, 1983 184329
DIGAP HEADER = FOUR STATIONS CONTINUOUSLY INTEGRATED DOPPLER   OBS 30 SEC   18 SATS

TOTAL OBSERVATIONS = 19527 ON DAY 316 , 1981 FROM 17: 0: 6 TO 21:59:36. SPAN= 4 HR(S), 59 MIN.
SATELLITES USED =   3   5   7   8 10 15   2 12   4 17 14

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	953(42)	357(64)	1341(70)	1683(61)
3	4PTSAPIN	1554(43)	-392(64)	1(70)	1603(50)
4	8PTSAPIN	2016(42)	77(64)	519(70)	2083(49)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	855(57)	1014(67)	1036(56)	1683(61)
3	4PTSAPIN	-738(45)	1237(68)	702(65)	1603(50)
4	8PTSAPIN	-180(48)	1879(40)	880(83)	2083(49)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	3PTSAPIN	-787(43)	-1060(85)	1042(40)	92429
3	4PTSAPIN	873(46)	-1151(85)	692(38)	142000
4	8PTSAPIN	-1352(47)	-1305(81)	896(46)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   SUN, APR. 10, 1983 17:12:56

DIFGPS HEADER = APRIL 6,1983:DIFGPS:SL3722:F02:DD:ALL BIASES NONZERO (18 SAT, DGR'D EPH)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV47.DATA:8 STNS;30 S   CREATED:SAT, APR. 09, 1983 221510
DIGAP HEADER = EIGHT STATIONS CONTINUOUSLY INTEGRATED DOPPLER 18 SATS , WITH NOISE

TOTAL OBSERVATIONS = 18666 ON DAY 316 , 1981 FROM 18: 0: 6 TO 19: 0: 6. SPAN= 1 HR(S), 0 MIN.
SATELLITES USED = 2 5 7 10 15 12

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	2PTSAPIN	524(39)	-656(61)	1911(90)	2087(99)
3	3PTSAPIN	-274(39)	960(61)	1270(90)	1615(56)
4	4PTSAPIN	335(39)	-771(61)	2636(90)	2767(98)
5	5PTSAPIN	-719(39)	1267(61)	-1413(90)	2031(96)
6	6PTSAPIN	630(39)	-1323(61)	607(90)	1587(84)
7	7PTSAPIN	-594(39)	1748(61)	1393(89)	2313(47)
8	8PTSAPIN	1595(39)	-2048(61)	778(89)	2711(76)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	2PTSAPIN	692(86)	196(62)	1960(45)	2087(99)
3	3PTSAPIN	1587(73)	160(63)	256(63)	1615(56)
4	4PTSAPIN	1203(53)	-26(63)	2491(80)	2767(98)
5	5PTSAPIN	68(36)	-110(63)	-2025(89)	2031(96)
6	6PTSAPIN	-657(63)	22(54)	1445(80)	1587(84)
7	7PTSAPIN	2295(58)	169(40)	-236(91)	2313(47)
8	8PTSAPIN	-1306(58)	646(37)	2285(92)	2711(76)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T	I O N	
2	2PTSAPIN	-697(98)	-139(49)	1962(37)	46848
3	3PTSAPIN	-1573(47)	-248(96)	267(43)	92429
4	4PTSAPIN	-1171(44)	-99(100)	2505(38)	142000
5	5PTSAPIN	-103(46)	107(88)	-2024(59)	185998
6	6PTSAPIN	607(94)	-279(45)	1440(49)	100581
7	7PTSAPIN	-1877(55)	1334(87)	-218(51)	123360
8	8PTSAPIN	330(53)	-1425(85)	2282(57)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   SUN, APR. 10, 1983 22:29:42

DIFGPS HEADER = APRIL 6,1983:DIFGPS:SL3722:F02:DD:ALL BIASES NONZERO (18 SAT, DGR'D EPH)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV48.DATA:4 STNS;6 S   CREATED:SUN, APR. 10, 1983 163548
DIGAP HEADER = FOUR STATIONS CONTINUOUSLY INTEGRATED DOPPLER)   OBS @6 SEC   18 SATS

TOTAL OBSERVATIONS = 20010 ON DAY 316 , 1981 FROM 18: 0: 0 TO 19: 0: 0. SPAN= 1 HR(S), 0 MIN.
SATELLITES USED = 2 5 7 10 15 12

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	-269(25)	944(40)	1289(58)	1620(37)
3	4PTSAPIN	342(25)	-778(40)	2651(58)	2784(64)
4	8PTSAPIN	1591(25)	-2047(40)	812(58)	2717(50)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	1588(47)	157(41)	280(41)	1620(37)
3	4PTSAPIN	1206(35)	-22(41)	2509(52)	2784(64)
4	8PTSAPIN	-1280(38)	644(24)	2308(60)	2717(50)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	-1573(31)	-246(63)	292(28)	92429
3	4PTSAPIN	-1173(29)	-103(65)	2522(24)	142000
4	8PTSAPIN	316(34)	-1404(55)	2304(37)	154584

SUMMARY OF DIFFERENTIAL GPS RESULTS   WED, APR. 13, 1983 04:45:35

DIFGPS HEADER = APRIL 6,1983:DIFGPS:SL3722:F02:DD:ALL BIASES NONZERO (18 SAT, DGR'D EPH)
FOROBS HEADER = FILE: DEMITRIS.GPS.OBSERV49.DATA:4 STNS:30 S   CREATED:SUN, APR. 10, 1983 222945
DIGAP HEADER = FOUR STATIONS CONTINUOUSLY INTEGRATED DOPPLER 30 S   18 SATS,WITH NOISE

TOTAL OBSERVATIONS = 19527 ON DAY 316 , 1981 FROM 17: 0: 6 TO 21:59:36. SPAN= 4 HR(S), 59 MIN.
SATELLITES USED =   3   5   7   8 10 15   2 12   4 17 14

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED CARTESIAN COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DX (SD-DX)	DY (SD-DY)	DZ (SD-DZ)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	1078(73)	-2009(111)	2139(121)	3127(147)
3	4PTSAPIN	1720(74)	-4208(111)	1353(121)	4744(134)
4	8PTSAPIN	2661(73)	465(111)	-553(121)	2758(64)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED GEODETIC COORDINATES IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLAT (SD-DLAT)	DLON (SD-DLON)	DHGT (SD-DHGT)	DR (SD-DR)
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	-204(98)	121(115)	3118(96)	3127(147)
3	4PTSAPIN	-2363(78)	-243(117)	4106(112)	4744(134)
4	8PTSAPIN	-840(83)	2626(69)	28(144)	2758(64)

DISCREPANCY BETWEEN A PRIORI AND ADJUSTED BASELINE COMPONENTS IN MM (ADJUSTED MINUS A PRIORI)

STN	NAME	DLEN (SD-DLEN)	DAZ (SD-DAZ)	DELEV (SD-DELEV)	BASELINE (IN M
1	1PTSAPIN	F I X E D	S T A T I O N		
2	3PTSAPIN	234(75)	-108(148)	3116(70)	92429
3	4PTSAPIN	2371(80)	492(147)	4079(67)	142000
4	8PTSAPIN	-1539(80)	-2286(140)	46(80)	154584