GPS SUBSIDENCE STUDY OF THE COSTA BOLIVAR OIL FIELDS, VENEZUELA

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PREFACE

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GPS SUBSIDENCE STUDY OF THE COSTA BOLIVAR OIL FIELDS, VENEZUELA

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PREFACE

This technical report is a reproduction of a thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering in the Department of Geodesy and Geomatics Engineering, May 1995. The research was supervised by Dr. Adam Chrzanowski, and funding was provided partially by the Natural Sciences and Engineering Research Council of Canada, Maraven S.A. of Venezuela, and the University of New Brunswick.

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Abstract

The Costa Bolivar Oil Fields, located along the east coast of Lake Maracaibo, contain some of the richest oil deposits in South America. Exploitation of these reserves, located some 300m to 1000m below the lake surface, has led to some considerable subsidence along the east coast shore. The accumulated subsidence since 1932 has resulted in the land mass being some 4m below the lake surface. Consequently, a 46km dyke was constructed and maintained to protect the low lying inhabited area and production utilities.

Up until 1986, monitoring of the dyke and surrounding area utilised conventional geodetic measurements. At this time, UNB proposed that the Global Positioning System (GPS) could provide some significant savings by replacing some of the lengthy and costly levelling surveys. Since 1987 both GPS and geodetic levelling data have been collected periodically to assess the performance of the GPS in this project. Prior to 1993, problems with the GPS data and its processing have limited the analysis. An incomplete satellite constellation, noisy single frequency data, and systematic biases in both the data and the processing software, have all contributed to a problematic study.

This thesis has evaluated the GPS data to date and assessed its usefulness for subsidence studies in this area. It has revealed that the present methodology employed has produced very promising results in the last two years, but some additional strategies are still required to gain full confidence in the GPS results.

Table of Contents

List of Figures

List of Tables

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Funding was provided in part by the University of New Brunswick and the Natural Sciences and Engineering Research Council (NSERC) in Canada, and Maraven S.A. in Venezuela.

This thesis is dedicated to my family in England; Will, Janet, Dominic and Katrina Walford.

Chapter 1

Introduction

1.1 Lago De Maracaibo

The Costa Bolivar Oil Fields extend some 120km along the east coast of Lake Maracaibo, spanning the areas of Cabimas, Tia Juana, Lagunillas, Bachaquero and Mene Grande (figure 1.1). The topography in this region is characterised by marshy lowland flats extending some hundreds of kilometres, which are, on average, only a few metres above the lake surface level.

Long term oil exploitation, dating back to 1914, has resulted in extensive ground subsidence, reaching 5m in places. Present rates of vertical movement have been up to 20cm/year. Consequently, a portion of the subsidence zone now lies 4m below the lake surface. A 46km protective dyke was constructed and maintained to protect the low lying inhabited area and production facilities. Ground subsidence has also increased the amount of water in the lowland marshes, thus an irrigation system was implemented to pump the water back into the lake [Murria, 1988].

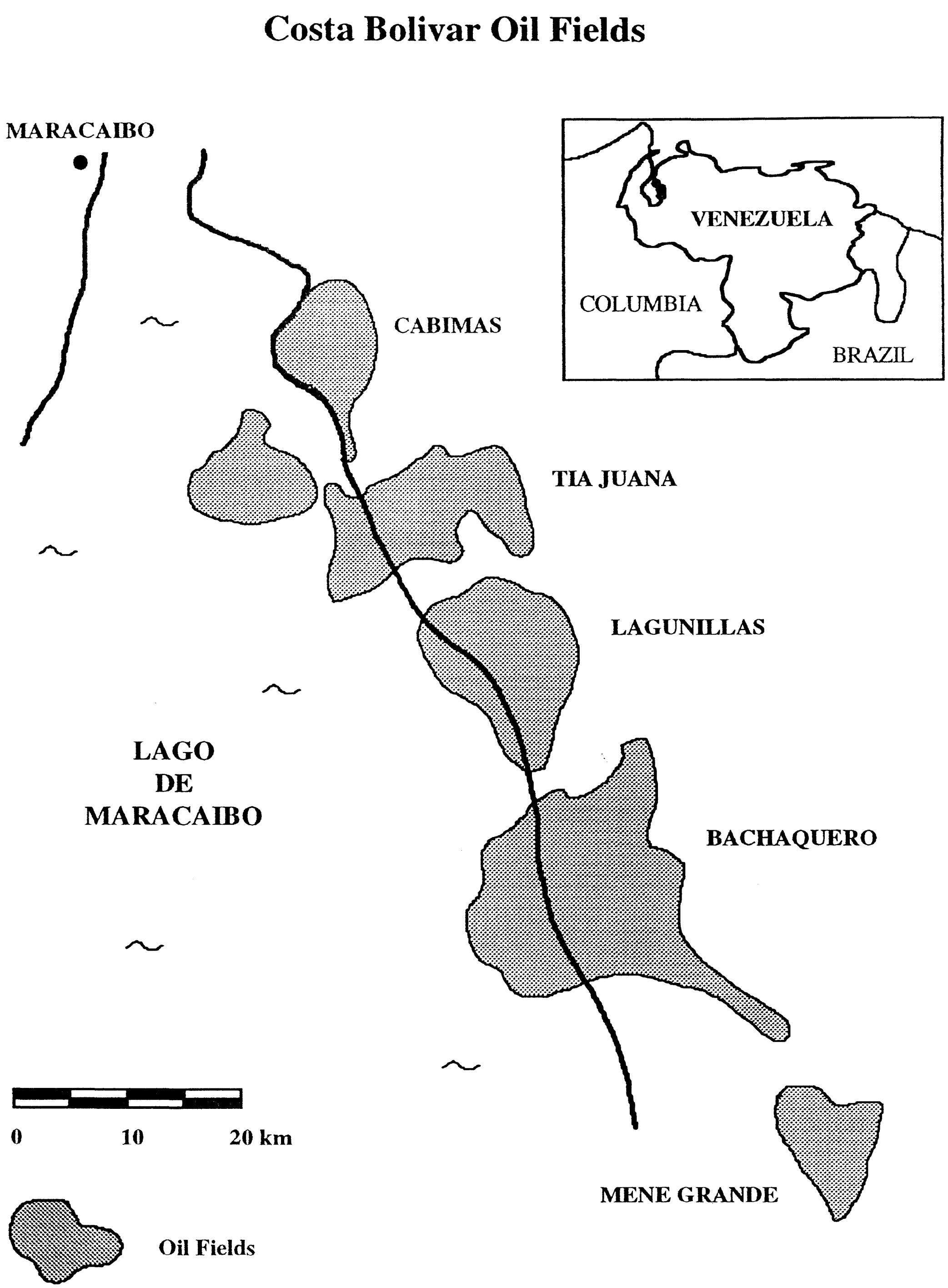

Figure 1.1. Relative location of the Costa Bolivar Oil Fields [after Puig, 1984].

1.2 Monitoring Scheme

In 1929, when the first signs of deformation were noticed, a monitoring scheme was established, which up until 1987, has predominantly utilised precise geodetic levelling. The need for a monitoring scheme is three fold.

- To update the irrigation system, which consists of a number of downhill channels, ferrying the water to the pumping stations along the dyke. The location and grade of the channels is dictated by the subsidence.
- To monitor and upgrade the height of the dyke.
- To study the effects of the oil extraction and correlate the subsidence with the volume of extracted oil.

A main levelling network of some 1436 benchmarks covers the area between Tia Juana and Bachaquero (figure 1.2). It consists of three primary lines of first order class two (U.S. specifications) covering 618.9km, intertwined with 553.7km of second order class two densification lines. Two additional sub-networks are located in Cabimas and Mene Grande creating 188 stations, and a further 160.1km and 67.3km of first and second order lines, respectively. Full re-observation of the levelling network is carried out on a bi-annual basis. In the present day this method has become costly and lengthy. A complete overview of the levelling network and surveys, up to 1988, can be found in Leal [1989].

To date, precise geodetic levelling has provided consistently good results, achieving an accuracy of 20-30mm (@95% confidence) for the subsidence determination [Leal, 1989].

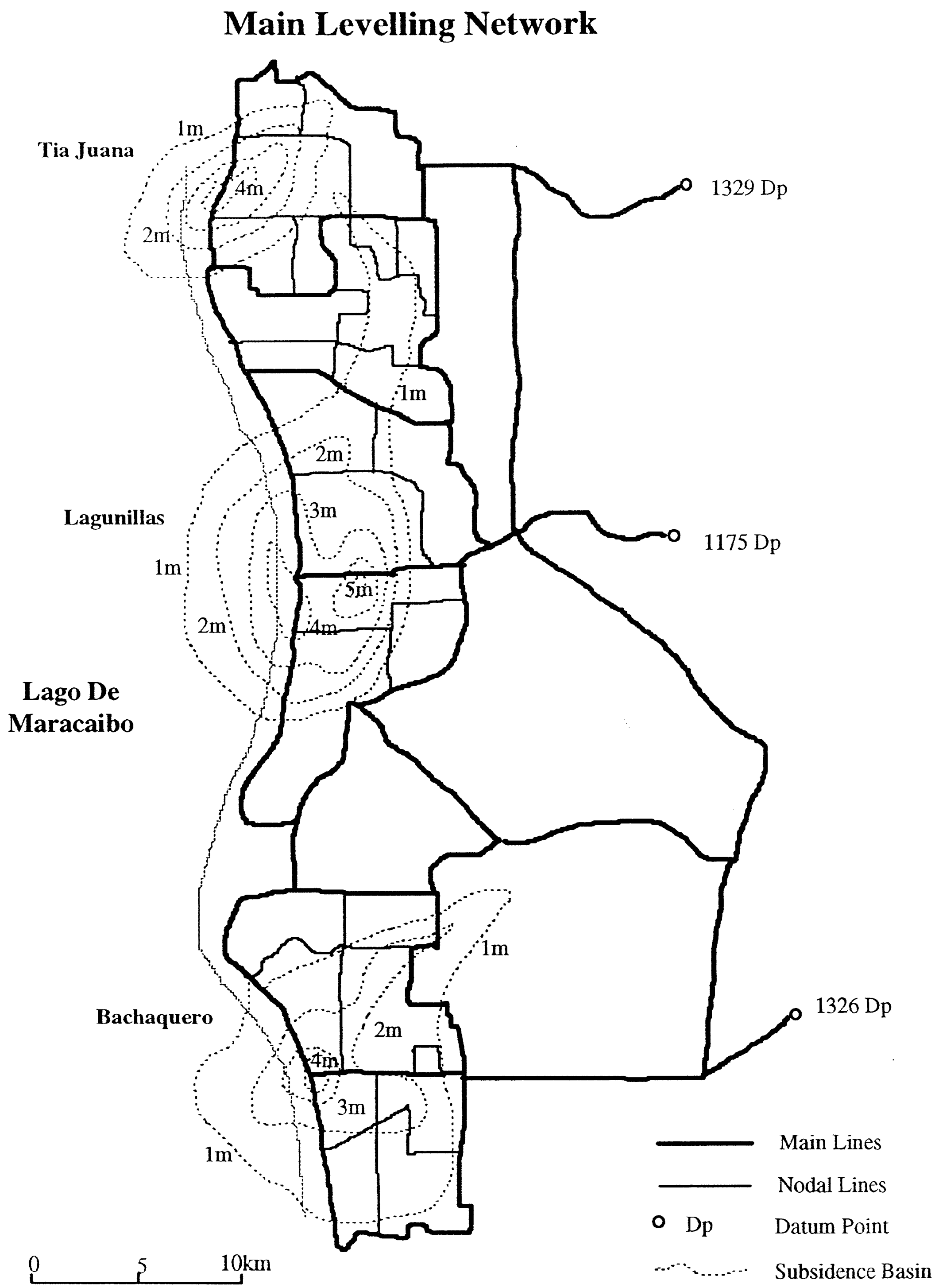

Figure 1.2. Main Levelling network [after Leal, 1989], showing accumulated subsidence since 1929.

The expanding size of the exploitation area has led to a very large network covering some 1300km^2, encompassing 1624 benchmarks. The re-survey of this network takes six levelling crews approximately two months to complete.

In 1984, Maraven S.A., one of the state owned oil companies working in the area, and responsible for the monitoring of ground subsidence and stability of the dyke, undertook the task of maximising productivity and cutting back costs. In 1986, the Department of Surveying Engineering at the University of New Brunswick (UNB) proposed that the Global Positioning System (GPS), if accurate enough, could provide considerable savings in both time and manpower, over the conventional levelling surveys, in the ground subsidence studies.

It was proposed in 1986, [Chrzanowski et al, 1989] that the use of the GPS could:

- Replace the long lines of first order levelling, connecting the subsidence area to the three datum benchmarks, established in a presumably stable area (figure 1.2).
- Provide a frame work of points to be densified with the second order levelling, thus disbanding the first order levelling surveys, and providing savings up to 30% [Leal, 1989].
- Provide additional information on the horizontal movements.

In 1987, two test surveys were performed using single frequency GPS, in the Tia Juana/Lagunillas area, covering one third of the primary levelling network. The analysis of the GPS survey revealed that the accuracy attained in Venezuela was considerably lower than a similar style survey conducted in Canada. The less precise results were attributed to the hot and humid climate experienced in Venezuela, which increased the tropospheric effects. Despite the results being slightly worse than desired, a full implementation of the GPS in the subsidence area was introduced in April 1988, for further more detailed analysis. Yearly GPS campaigns after this date created expansions to the network, which by 1994, involved 26 stations, spanning the five main oil fields, from Cabimas down to Mene Grande (figure 1.3). A more detailed description of the GPS network is given in chapter two.

1.3 Studies To Date

The application of the GPS in this area has been studied recently by the following people and organisations.

Chrzanowski et al [1989] published results of the 1987 test surveys and of the first full GPS campaign of 1988, deriving mathematical models for the combination of GPS and levelling in ground subsidence studies.

Leal [1989] studied the integration of Levelling and GPS data for subsidence monitoring. He concluded at the time, that some inconsistencies between the two methods existed, possibly a systematic effect, that would be better estimated under a future stronger GPS system.

Pedroza [1989] examined the effects of the troposphere and satellite geometry in the GPS applied to ground subsidence in the Lake Maracaibo area. He concluded that at the time, the tropospheric effect was significant on low elevation satellites, and different geometry of satellites also significantly affected the baseline results. Local atmospheric measurements found no evidence of local variations.

Chen and Chrzanowski [1990] studied the integration of the GPS and levelling in ground subsidence studies, developing mathematical algorithms for the estimation of the GPS systematic biases and observation weights. Using the subsidence data up until 1988, they successfully filtered out the GPS biases and derived estimates for the GPS heights, for moderate to hot and humid climates.

Usher Canada Ltd. and Coler and Colantonio Inc. [1990] assisted UNB and Maraven S.A. with the two GPS campaigns of 1988 and 1990, respectively, but had trouble finding meaningful results, concluding that the 1988 data was of poor quality. The use of single frequency receivers, a lack of baseline redundancy and a minimal number of satellites in each campaign, dictated the low accuracy of the results

Chrzanowski et al [1991] studied the results from the 1990 and 1991 data sets, and found significant rotations between the two campaigns, about all three axes through the fixed point. The largest was a 1" rotation about an east/west axis. They concluded that unmodelled ionospheric refraction and the systematic effects of the troposphere, as well as biases in the fixed co-ordinates had most likely contributed to the rotation.

Westrop [1991] investigated the 1990 and 1991 campaigns using more sophisticated GPS software (UNB's DIPOP) and modelling techniques to evaluate the various errors and systematic effects, causing such noisy data. She concluded that most of the noise was caused by the troposphere. Different tropospheric models were implemented in the processing, but none could reduce the noisiness of the data. Systematic errors in the GPS were also detected, causing rotations between surveys. Their source however, was unidentified.

Chrzanowski and Chen [1992] published a paper on the systematic errors of GPS baselines and their effect on ground subsidence studies. They used the 1990 and 1991 data sets as a case study, to model the biases, and develop a strategy for minimising the effects in deformation studies, concluding that the fiducial point approach should be utilised ideally.

The author has been involved in the reprocessing and evaluation of the five most recent GPS campaigns, since July 1992, hoping that the study would reveal in more detail some of the sources causing such noisy data and some of the systematic effects in the GPS results, particularly from the more recent campaigns of 1992 to 1994. These campaigns performed by Maraven S.A. were observed with dual frequency receivers, and utilised all the experience gained in the previous years.

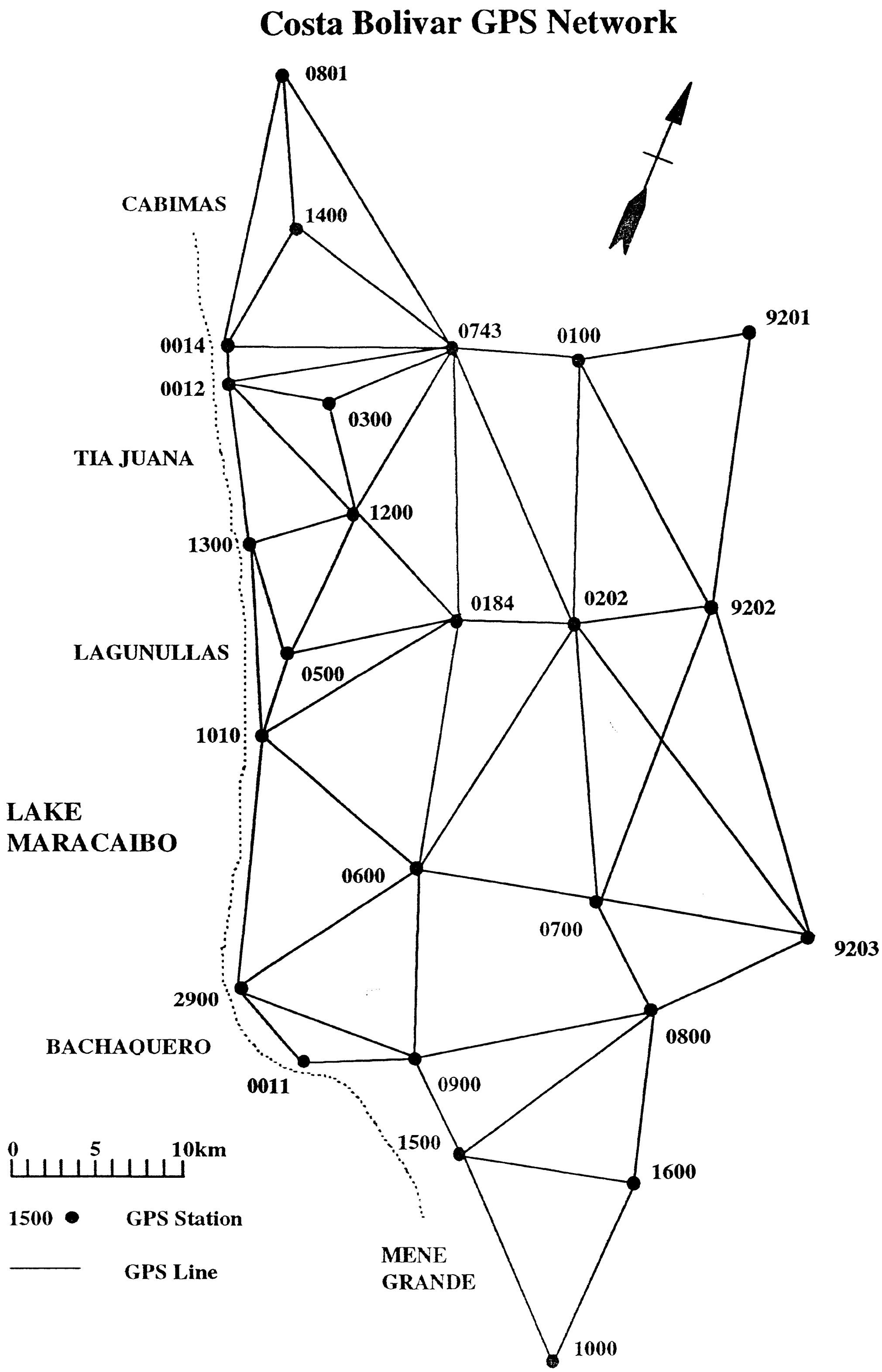

Figure 1.3. Costa Bolivar GPS network.

1.4 Thesis Objective

The objective of this author's research was to study some of the GPS campaigns to date, namely the latter surveys of 1990 to 1994. More emphasis has been placed on the years 1992 to 1994, where the author had much more involvement in the data processing stage. Previous studies of the 1990 and 1991 data have shown certain systematic biases to exist [Chrzanowski et al, 1991; Chrzanowski and Chen, 1992]. This report examines whether these biases still exist, under a more fully implemented satellite constellation, and searches for the cause of such effects. Are they due to the GPS errors, propagation effects or software processors? Finally, an assessment of the results and accuracy achievable in this equatorial region, with the present network and observing/processing strategies currently being used, has been made. Recommendations on future campaigns are presented.

As mentioned in section 1.2, precise levelling has provided subsidence results with an accuracy of 20-30mm (@95%), or 15-20mm (@95%) for the absolute heights of each campaign. Thus the approximate accuracy for one campaign is 7-10mm (@68%).

It is expected, that if the GPS can give an absolute station error ellipse of ≤15mm (@68%) for a single campaign, then its use in establishing a framenet for the levelling surveys could be justified [Leal, 1989].

1.5 Author's Contribution

Leading on from the previous studies, the author has carried out the following:

- Analysed the data for systematic effects, specifically the ionospheric delay and multipath.
- Analysed the baseline results of the three most recent campaigns, and assessed the baseline errors using the MINQE technique.
- Investigated the effects of using two different *commercial style* GPS processors, and various different solution types, both single and dual frequency, finding systematic biases and differences to still exist in all the solution types.
- Analysed the GPS results from 1990 to 1994 for subsidence, after removing some of the above biases, achieving consistent results in the horizontal component, regardless of the processing strategy, and promising results for the vertical component, from the last two campaigns.
- Derived an update for the overall optimum accuracy achievable with the present scenario.

1.6 Thesis Outline

This thesis is purely concerned with the application of the GPS in the Lago de Maracaibo area. Although the campaigns from 1990 to 1994 will be used in the analysis of subsidence, only the data from years 1992 to 1994 will undergo scrutiny. A discussion of the GPS data to date is given in chapter two.

Many problems were encountered with the GPS data and results, in most of the campaigns. Some of these problems can be attributed to the systematic biases and errors in the GPS data. Chapter three gives some background into this area.

All the campaigns 1990 to 1994 were observed using Trimble ST or SST receivers. However, data processing was carried using two different software processors; Trimble's *Trimvec Plus* and Ashtech's *Geodetic Post Processing Software*, using a variety of processing solution types. These are discussed in chapter four.

An assessment of the satellite data quality of four campaigns was made using the program *Quality Check* available from UNAVCO [UNAVCO, 1993]. The results of the analysis are presented briefly in chapter five.

The results of the processing in which the author was involved are presented and discussed in chapter six. The campaigns of 1992 to 1994 are shown, as well as the test baseline results for 1992. The results for the prior campaigns are documented, but not discussed in detail. A comparison of the final adjusted co-ordinates between campaigns produced some interesting biases, especially between different solution types. These systematic biases are discussed. It is common knowledge that the results from commercial GPS processors often contain highly over optimistic standard errors for the baseline components. The results of an investigation into an alternative weighting scheme, using Minimum Norm Quadratic Estimation (MINQE), is also presented.

Analysis of the displacements is carried out for the campaigns 1990 to 1994, and the results are presented in chapter seven. Subsidence displacements were broken down into their respective horizontal and vertical components, and examined after the removal of systematic biases.

Finally, conclusions and recommendations are drawn on the last five campaigns of GPS data, and presented in the last chapter.

Chapter 2

GPS Surveys to Date

2.1 GPS Campaigns

Since its proposal in 1986, GPS data has been collected on and off for eight years, culminating in a network of 26 stations covering an area of 2100km^2 , encompassing the five main oil reserves from Cabimas to Mene Grande (figure 1.3).

The first so called *test surveys* were carried in the Tia Juana area, by UNB and Maraven, S.A., in April and October of 1987. Simultaneous precise levelling was carried out for a comparison. Optimistic results were obtained under a limited constellation, during short windows with relatively poor receivers by today's standards. Considering that all the problems would be ironed out in the future campaigns, 1988 saw the go ahead of a much fuller network to replace parts of the primary levelling network. This was considered the first of the yearly campaigns to be undertaken using the GPS. All data was collected using Wild-Magnavox WM101 single frequency receivers, with the help of Usher Canada Ltd, who also did the processing using the PoPS 2.01 software [Frei et al, 1986]. Overall, the above problems during both of the test surveys reduced the observation's significance.

The second survey contained very noisy data, giving ambiguity fixing problems. Ionospheric disturbance was considered the most likely cause.

Leal [1989] concluded that the expected accuracy in the height component was 29mm (@68%) for a single campaign with the GPS, which is considerably worse than the desired 10-15mm (cf. section 1.4).

The next campaign was in 1990, to coincide with the bi-annual levelling data, and was conducted using more sophisticated Trimble 4000ST and Trimble 4000SL receivers, again single frequency. This campaign was expanded to 20 stations covering much of the oil exploitation area. Observation periods were for two hours on average, and conducted at various times in the day.

The campaign of 1991 was broken down into three periods, the first in February, then March and finally August. The first two periods covered most of the 1990 GPS network, but with a very small amount of redundancy. During August newly upgraded dual frequency receivers, Trimble *Geodetic Surveyor II* 4000SST were employed, but only sixteen baselines (out of 60) were re-observed. This last section has not been dealt with in this report. The first two periods were combined together, into one epoch adjustment. The campaigns of 1990 and 1991 were conducted and processed with the help of Coler and Colantonio Inc. [1991]. They reported that although observation procedures and the constellation had improved in 1991, the "*data had been tough to work with*", and eight baselines had to be re-observed. The report quoted possible causes to be: *"varying atmospheric conditions (effecting the tropospheric delay); Earth's magnetic field; interference from radio waves and debris from sunbursts in the atmosphere."* Again the noisiness of the data caused ambiguity fixing problems. Wrongly fixed ambiguities in a single frequency solution will drastically alter baseline results by up to 10cm or more. This would be more pronounced in a limited constellation. Sky plots of the six campaigns 1988 to 1994 can be seen in figure 2.1.

The campaign of 1992 saw the first full use of dual frequency receivers. Observations were conducted by Maraven S.A. Shortly after this time the author became involved in the project, visiting the location and becoming involved in the post processing. Three new stations (9201, 9202 and 9203, figure 1.3) known as the *benchmark* stations were established in an expected stable zone. Unfortunately, in 1992, although three dual frequency receivers were employed, only two of the three receivers in each session were observing the L2 band. This meant that only one of the possible three baselines can be processed in dual frequency mode, which is insufficient for a strong network. Combining one dual and one single frequency line for each session meant that 33 out of 60 independent lines were dual frequency. However, as discussed in chapter five, this proved to be problematic. Single frequency data for 1990, 1991, and 1992 is very noisy.

The 1993 and 1994 campaigns successfully observed the whole network with dual frequency data. These data sets proved far superior to prior campaigns. This in whole was not due to dual frequency observations, but a significant decrease in the noise level of the data, due to a much less disturbed ionosphere/troposphere. A more detailed analysis of the data quality for 1992 to 1994 is given in chapters five and six. The 1993 and 1994 campaigns were conducted by Maraven and processed by Maraven and UNB.

Station	1990	1991	1992	1993	1994
0011	■	■	■	■	■
0012	■	■	■	■	■
0014	■	■	■	■	■
0100	■	■	■	■	■
0184	■	■	■	■	Destroyed
0184B					■
0202	■	■	■	■	■
0300	■	■	■	■	■
0500	■		■	■	Destroyed
0600	■	■	■	■	■
0700	■	■	■	■	■
0743	■	■	■	■	■
0800	■	■	■	■	■
0801	■	■	■		■
0900	■	■	■	■	■
1000	Destroyed		■	■	■
1010	■	■	■	■	■
1200	■	■	■	■	■
1300	■	■	■	■	■
1400	■		■		
1500	■		■		
1600	■		■		
212A					■
2900	■	■	■	■	■
9201			■	■	■
9202			■	■	■
9203			■	■	■
BMA8				■	
TOTAL	22	17	25	22	22
# Of Ind. Baselines	50	26	60	53	46

Key : ■ : Observed Stations

Table 2.1. GPS network 1990 - 1994.

TYPICAL SKY DISTRIBUTION OF GPS SATELLITES IN VENEZUELA

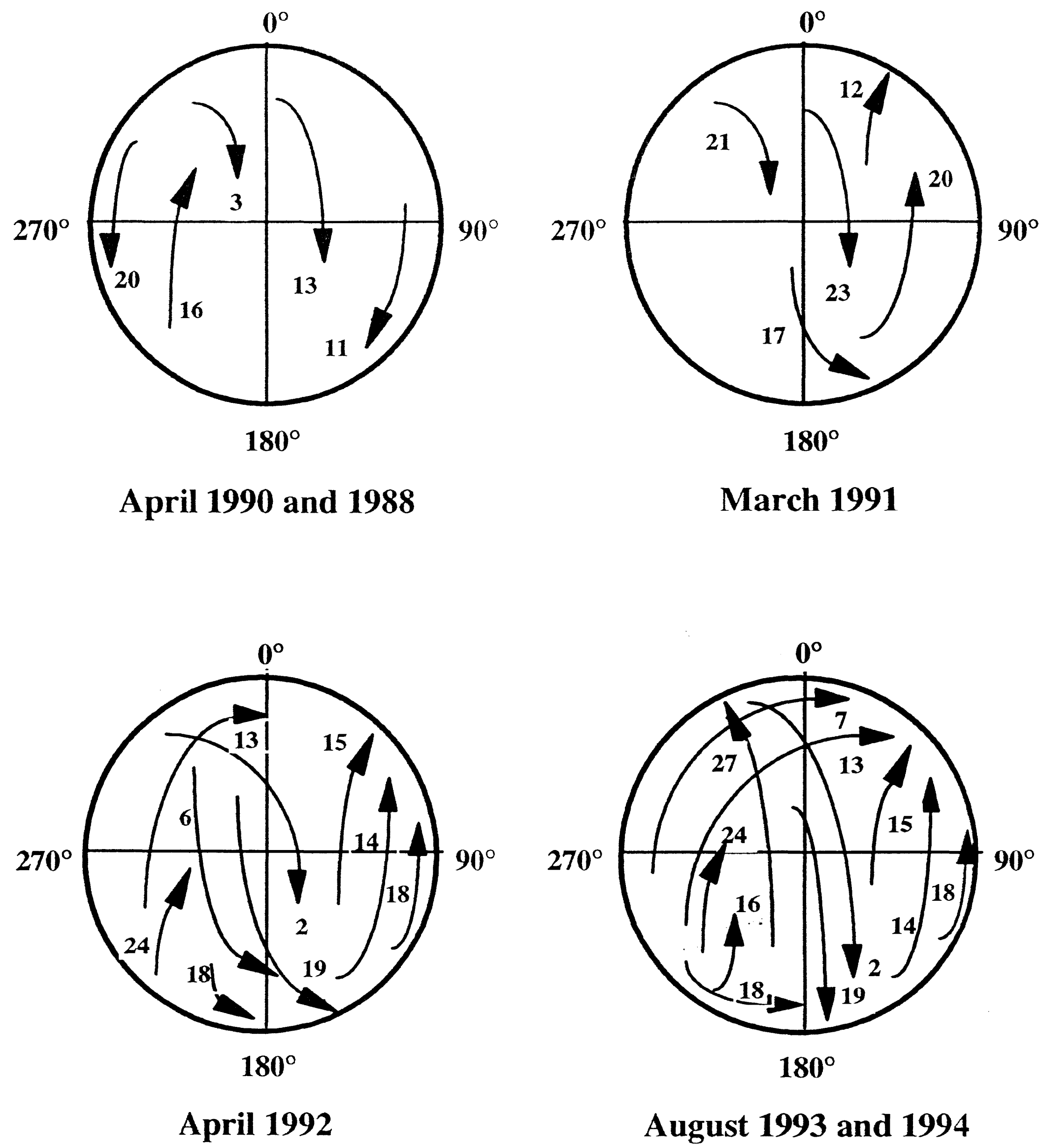

Figure 2.1. GPS skyplots 1988 - 1994.

Since 1988, the six campaigns have not fully covered the entire GPS network, due to yearly expansions and the odd station destruction (see table 2.1). A central core from Tia Juana down to Bachaquero (involving 17 of the 26 stations) has been continually observed throughout this period. Thus this report has focused primarily on these stations only, and the campaigns 1990 to 1994, as the 1988 campaign was of the poorest quality compared to the later surveys.

By 1994 the GPS network covered some 70km*30km*100m, with 26 stations, and involved some 90 baselines (60 independent). The lengths of which vary from 2.5-31km, with elevation differences generally no greater than 60m.

2.2 Test Baselines

In late 1991 and 1992, after the purchase of the newly upgraded receivers, an experiment was carried out by UNB and Maraven to frequently re-observe some baselines, in addition to the yearly campaigns, to analyse the systematic effects over time with a changing constellation. These data sets have been collectively termed the *test baselines*. GPS data was collected on a monthly to quarterly basis, in a portion of the network between Lagunillas and Bachaquero. Six baselines in the region of Bachaquero were observed for periods of four hours on two consecutive days. These are tabulated in table 2.2. The author processed and analysed the test baseline data from 1992, the results of which are discussed in chapter six.

Baseline	Length (m)	Azimuth (deg)
0600 - 0700	10189.0	64.9
0600 - 0184	14054.4	333.9
0184 - 0700	17498.5	118.3
0600 - 2900	13404.1	209.7
0600 - 1010	13820.8	286.7
1010 - 2900	16945.4	157.1

Table 2.2. Test baselines.

Chapter 3

GPS Errors and Biases

Information on the GPS is now widely available, in many thorough literature. Some recommended texts are Wells et al [1986], Hofmann-Wellenhof et al [1992], Seeber [1993] and Leick [1994]. This chapter will only discuss the errors and biases in the GPS, which are pertinent to this thesis.

3.1 Satellite/Receiver

3.1.1 Clock Biases

A synchronised time scale, namely **GPS time**, is the basis for precise positioning using GPS. The satellite clocks consist of caesium or rubidium oscillators, and are of the highest stability ($1*10^{-11}$ to $1*10^{-12}$sec.). However, regular monitoring is still carried out to ensure that each clock stays within ±1ms of GPS time [Wells et al, 1986]. Polynomials are produced to describe the drift of each satellite clock, which are then transmitted to the user in the **broadcast message**. Receiver clocks, which typically utilise quartz oscillators ($1*10^{-10}$sec.), can have much larger biases that can be estimated in the post processing. Stability of the receiver clock throughout its observation period is more important than the accuracy. Strict adherence to GPS time is more important in single point positioning. In relative positioning, differencing of the observations will eliminate most of the errors in both the satellite and receiver clocks. Problems will only arise if different receiver types are utilised, which observe at different epochs.

3.1.2 Broadcast Orbits

In the case of this study, broadcast orbits have been utilised in the post processing of the GPS data. The **broadcast ephemeris**, provided by the GPS Operational Control Segment, is computed from a series of five global tracking and monitor sites. Orbits are computed from the previous seven days, and then extrapolated for the following day(s). Sequential improvements are made to the orbits using the most recently available tracking data. The complexity of modelling all the forces acting on the satellite leads to errors in the computed orbits, which rapidly increase after the given time period of use. Orbital errors are broken down into three components; **along track**, **cross track** and **radial**. Remondi and Hofmann-Wellenhof [1990] compared the broadcast and **precise ephemerides** produced by the National Geodetic Survey and found *"the maximum along track differences to be 5.3, 13.3 and 21m for caesium, rubidium, and quartz clock satellites, respectively."* In the case of single point positioning this error will translate directly into the point position error. But in relative positioning some of the error will cancel out. A **rule of thumb** guideline is given as [Beutler et al, 1984]:

$$\frac{\delta b}{b}=\frac{\delta r}{\rho} \tag{3.1}$$

where δb is the baseline error

b is the baseline length

δr is the orbit error

ρ is the satellite-receiver range

Assuming an ephemeris error of 20m (say), the baseline error becomes 3cm for a 30km baseline (the longest line in the Costa Bolivar GPS network). Chen and Langley [1990a] consider this to be too pessimistic and quote an alternative formula. Wells et al [1986], Beutler et al [1989a], and Spofford [1992] predicted the accuracy of the broadcast ephemeris to be 0.5ppm, under a full constellation.

3.1.3 Multipath

Multipath is defined as one or more reflected signals reaching the antenna, in addition to the direct signal. Two situations are possible; reflection at the satellite and reflection around the antenna. For short baselines, satellite multipath is considered to be the same for both receivers, so will cancel in the observation differencing [Georgiadou and Kleusberg, 1988]. Receiver multipath affects both the carrier phase and code measurements, but by far the greatest effect is on the code. Multipath is site and antenna dependent. A recent test of the new TurboRogue receiver found effects on the C/A and P-code measurements to be 72cm and 22cm respectively [Meehan et al, 1992a]. Carrier phase measurement can experience phase shifts up to 90° of the wavelength, which on L_1 could result in a 5cm bias [Georgiadou and Kleusberg, 1988]. New style micro-strip antennas are reported to be almost free of phase multipath effects [Doucet, 1989].

3.1.4 Fixed Co-ordinate Bias

In relative GPS, one requires the absolute co-ordinates of one so called *fixed point*, in the network, from which **co-ordinate seeding** can take place. In a first campaign situation, these are usually not known, and are obtained from a best pseudorange position from the GPS data or from past Transit/Doppler satellite data if available. Both methods have limitations on the accuracy obtainable. In either case, any bias of the estimated co-ordinates from the true WGS84 co-ordinates will cause systematic rotations and scale changes of the baseline components. Santerre [1989] demonstrated that a horizontal offset of 10m would primarily cause a 0"-0.12" vertical rotation of the network, about a horizontal axis perpendicular to the offset. A secondary scale bias of 0-0.5ppm per 10m offset could also be expected. For an offset in the height component, the primary effect would be a 0.2ppm horizontal scale change per 10m offset.

In the case of deformation studies, it is usual to use the same estimated co-ordinates for the same fixed point(s) in each campaign, depending on the type of **datum constraint** used. It is then expected that the effect of the bias would be the same from year to year and thus cancel out. The above effect however, was still investigated using the 1992 data set. Results and rotations are shown in section 6.8.3.

3.1.5 Selective Availability

Selective availability is the intentional degrading of the GPS accuracy, to non authorised users. It involves two processes, **dithering** of the satellite clock and **degeneration** of the orbital parameters in the broadcast message. Both effects will further bias the pseudorange. In relative positioning, dithering effects can be elliminated through receiver differencing, providing observations are made at identical epochs. However, the errors in the orbital parameters, will only be reduced [Georgiadou and Doucet, 1990].

3.2 Atmospheric Effects

3.2.1 Ionospheric Effect

The **ionosphere** is that region of the atmosphere extending approximately 50km to 1000km, made up of electrically charged atoms and molecules. High energy photons, in the sun's extreme ultraviolet and x-ray radiation, colliding with the atoms, cause the release of their electrons, resulting in **free electrons**, and positively charged atoms and molecules, termed ions. Thus this process is known as **ionisation.** It is the number of free electrons, or more correctly the density, that affect the propagation of radiowaves through this medium. Solar flares, storms and geomagnetic activity enhance the effect.

The electron density is measured as the number of free electrons in a vertical column with a cross sectional area of $1m^2$. This number is denoted as the **Total Electron Content** (TEC). Typical zenith values are $5*10^{16}$ to $5*10^{17}$ free electrons per m^2 [Davidson et al, 1983]. To simplify the number, a base unit has been defined, called the Total Electron Content Unit (TECU) where 1 TECU = 10^{16} electrons. TEC along the signal path can be substantially higher, depending on the zenith angle to the satellite.

At night, the free electrons and ions tend to recombine, reducing TEC, thus a strong diurnal variation occurs. The diurnal variation in most areas follows a general trend, whereby the value of TEC peaks around 1400hr, local time, until approximately 2000hr, before decreasing overnight. Much shorter and longer term periods of TEC variation also occur. Short term variations of approximately 10 minutes can be caused by wave like disruptions in the upper neutral atmosphere, from severe weather fronts and volcanic activity. These are denoted as **Travelling Ionospheric Disturbances** (TID). Longer term periods of 27 days, coinciding with rotation of the sun, are caused by high speed solar wind streams containing high energy particles spuen from the coronal holes. Seasonal periods, coinciding with the spring and vernal equinoxes also occur, and are linked to the changing elevation angle of the sun. A much stronger variation occurs on an 11 year period, and is linked to the **solar sunspot cycle**. The most recent peak (cycle #22) occurred between 1989 and 1992 (figure 5.1). It can be seen that the time period from minimum to maximum, is shorter than from maximum to minimum, and thus some additional disturbances can be expected a few years after the maximum.

Spatial variations of TEC also occur, which pose more of a problem to relative GPS positioning. Generally TEC values are highest in the equatorial regions and decrease towards the poles. Spatial variations of TEC cause horizontal gradients in both the N/S and E/W directions. N/S gradients tend to be worse than E/W. Low elevation satellites on opposite sides of the horizon can have sub-ionospheric points separated by some 3000km [Klobuchar, 1990]. It is unlikely that the satellite paths would undergo similar ionospheric effects, thus observation differencing would not eliminate the problem. Dual frequency processing can use certain linear combinations to reduce the effect, but single frequency users could expect scale biases of up to 30ppm, in the baseline length [Wanninger, 1993].

Ionospheric studies in the equatorial and polar regions have revealed further short term effects, known as **scintilations**. These scintilations or small scale irregularities cause both refraction and diffraction of the GPS signal [Wanninger, 1993]. Three distinct bands are defined (figure 3.1). Scintilations mainly occur in the **equatorial anomaly**, which is a band stretching ± 15° either side of the geomagnetic equator. Studies by Wanninger and Campos [1991,1992], have shown there to be a distinctive diurnal variation, with maximum scintilations effects occurring between sunset and midnight, and sometimes lasting well into the morning. These effects are often higher than the first such maximum, experienced after noon, local time. Seasonal variations with respect to longitude also occur. The region between the Americas and India suffer worst effects between September and March, with little chance of effects between April and August. The situation is reversed for the Pacific region. A strong correlation with the 11 year solar sunspot cycle is also evident. The polar regions also experience scintilation effects, but generally only at night and at certain times of the year, and are not as pronounced as equatorial regions. Mid latitudes are generally free of such effects, however in times of high scintilation activity, the auroral and equatorial regions have been known to extend into the usual mid latitudes.

Refraction causes curvature of the ray path and propagation of the signal velocity. Diffraction causes both signal fading and enhancements, commonly known as amplitude scintilations. Severe amplitude scintilations can result in loss of lock of the signal, depending on key factors such as receiver bandwidth and type of tracking channel. Squaring receivers have a S/N ratio 30db lower than direct code-correlation [Leick,1994], and are more likely to suffer from data loss and cycle slips. Amplitude scintilations can be examined by plotting receiver S/N ratios for each satellite at each epoch. Signal to noise ratios vary with satellite elevation, and scintilations would appear as spikes in this arc.

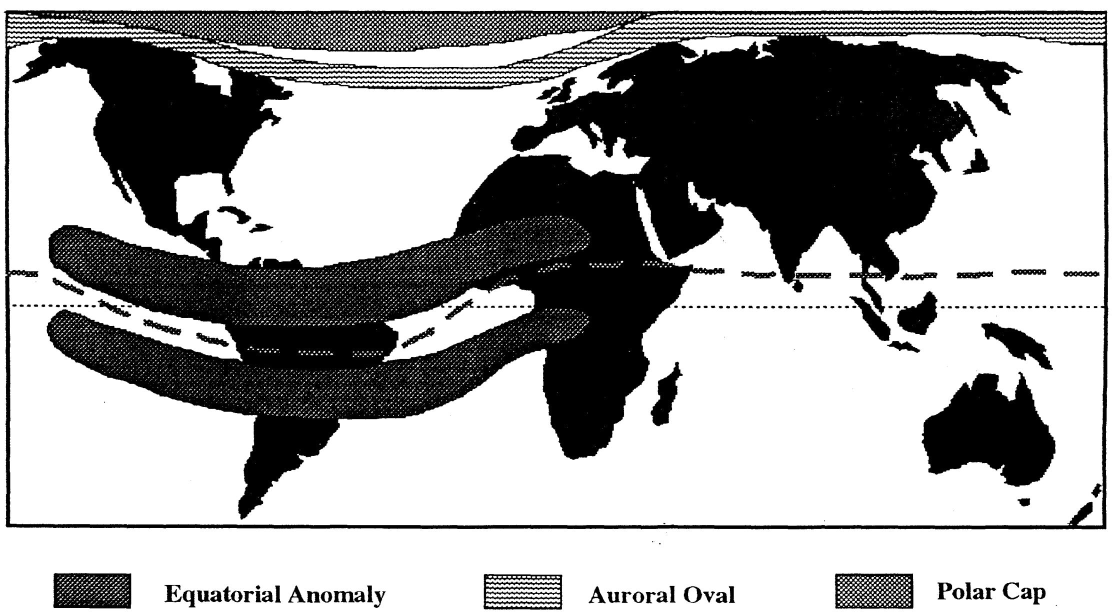

Figure 3.1. Major geographic areas of the Ionosphere [after Bishop et al, 1991].

Phase scintilations result from both refraction and diffraction, causing shifts in the phase by up to several cycles between two epochs. This complicates data processing as such a phase shift may appear as a cycle slip. Rapid phase scintilations can cause phase changes beyond the bandwidth of the receiver, again resulting in loss of lock. Phase scintilations can be examined from single station dual frequency data. Relative ionospheric delay and rate of change (ROC) of the delay can be calculated from a combination of the code and carrier observables. Effects would show up as spikes in the ROC plots (cf. chapter five).

3.2.1.1 Ionospheric Effects on GPS Code and Carrier.

Refraction of the GPS signal in its travel through this medium is proportional to the density of free electrons along the signal path. The GPS signal consisting of the carrier phase, a pure sinusoid and the modulated carrier (code), an amalgamation of many pure sinusoids, is affected in different ways [Klobuchar, 1990].

According to Seeber [1993] the refraction coefficient for carrier signals is defined as:

$$n_p = 1 + \frac{C_2}{f^2} + \frac{C_3}{f^2} + \frac{C_4}{f^2} + \ldots.. \tag{3.2}$$

Where C_2 is defined as $-40.3n_e$, f the frequency, and n_e is the local electron density (el/m^3). Neglecting higher order terms, the refraction index of the carrier phase becomes:

$$n_p = 1 - \frac{40.3}{f^2} n_e \tag{3.3}$$

Similarly, for the code, a refraction coefficient is defined as:

$$n_g = 1 - \frac{C_2}{f^2} - \frac{2C_3}{f^2} - \frac{3C_4}{f^2} - \ldots.. \tag{3.4}$$

Which, after neglecting the higher order terms, becomes:

$$n_g = 1 + \frac{40.3}{f^2} n_e \qquad (3.5)$$

Integration of the refractive index along the signal path will provide the effect of the ionosphere, after accounting for the geometric distance, giving [Davidson et al, 1983]:

$$\delta\rho_{ion} = \int_{SAT}^{REC} (n_g - 1)\ ds \qquad (3.6)$$

$$\delta\rho_{ion} = \frac{40.3\,TEC}{f^2} \quad \text{(metres)} \qquad (3.7)$$

Typical values can vary from 50m in the zenith to 150m on the horizon [Wells et al,1986]. The effect on the phase is of roughly the same magnitude, with opposite sign, in cycles.

3.2.2 Tropospheric Effect.

The **troposphere** is one part of the so called **neutral atmosphere**, where no ionisation occurs, which extends up to about 40km. The troposphere itself is the first layer extending from the ground to 9-16km, depending on the latitude. Unlike the ionosphere, the troposphere is not dispersive for microwave frequencies, thus the propagation effect on the carrier phase and modulation is the same, and is not frequency dependent. Thus an elimination of the effect through linear combinations of the two signal frequencies is not possible.

The propagation of signals through this medium depends on the temperature, pressure and water vapour content. Temperature and pressure gradients tend to vary gradually over space and time, but water vapour content can be widely varied. Measurements of the temperature and pressure can be easily made at the receiver site, but these figures do not really correlate to the conditions along the signal path. Observations of water vapour content require expensive and bulky equipment. Thus modelling of the refractive index of the troposphere can be awkward. Integration of the refractive index along the signal path will yield the effect on the range. The refractivity can be broken into two unequal parts; a dry component, making up about 90%, and a wet component, the remainder. Integration of the refractivity along the signal path is complicated. One such formula, derived by Hopfield [1971] and modified by Seeber [1993] is as follows:

$$\delta\rho_{trop} = \frac{K_d}{\sin(E^2 + 6.25)^{0.5}} + \frac{K_w}{\sin(E^2 + 2.25)^{0.5}} \qquad (3.8)$$

$$K_d = 155.2 * 10^{-7} \frac{P}{T} H_d$$

$$K_w = 155.2 * 10^{-7} \frac{4810e}{T^2} H_w$$

where	K_d, K_w	describe the dry and wet components
	E	satellite elevation in degrees
	P	air pressure, in Hectopascal (HPa)
	T	temperature, in degrees Kelvin
	e	partial pressure of the water vapour, in Hectopascal
	H_d, H_w	are the effective altitudes of the dry and wet terms

The zenith tropospheric delay is very susceptible to small changes in the meteorological values, which cause changes in the baseline height component. These effects are greatly magnified for lower elevation satellites. Beutler et al [1989b] quote that a one degree error in the relative temperatures of the baseline ends, can cause a bias of 10-80mm, in the height component. The climate in this region is such that high temperatures and relative humidity are experienced all year, which are fairly stable.

3.3 Carrier Beat Phase Ambiguity and Cycle Slips

Until such time, as the code observable becomes accurate enough to well within half a cycle of the carrier phase, the question of **carrier phase ambiguity** will remain. The search for the true ambiguity and fixing it to its integer value is key to precise baseline determination, especially in small to medium networks [Wubbena, 1988]. This process is made easier when a variety of data types are available. Hofmann-Wellenhof et al [1992] quote three strategies, and give an in-depth derivation. Single frequency ambiguity resolution is the hardest, as the ambiguity value is biased by the effects of the atmosphere and orbit errors. Observation differencing alleviates the problem to some extent. The use of dual frequency data eases the problem more, by allowing different linear combinations of the L1 and L2 observables to be made, resulting in a larger (or smaller) wavelength, which can be more easily resolved. The so called **wide** and **narrow lane** techniques are well discussed [Blewitt, 1989]. However, there is often a trade off between better ambiguity resolution, observation noise, error suppression, and whether or not the ambiguity is integer in nature. Bruyninx [1994] summarises the advantages of different combinations. A combination of dual frequency code and carrier data can be made to eliminate the effects of biases (including the ionosphere), providing an observable with an integer ambiguity and a long wavelength (cf. section 4.3).

Cycle slips or loss of lock on the signal, further complicate the problem. If lock is maintained on other satellites, or enough data has been acquired prior to the slip, they often can be easily repaired. Failing repair, a new ambiguity has to be computed, weakening the baseline quality. Further complications arise when jumps in the phase occur, due to the rapid effects of ionospheric activity that exceed the phase wavelength. Such jumps may become confused as cycle slips and be corrected as such.

3.4 Residual Effects

A few smaller biases and errors are also present in the system, which contribute to the overall noise level of the results. These include **hardware** biases in both the satellite and receiver, **observation noise** and **antenna phase centre variations**. Current technology dictates the level of hardware biases, or electrical delays in the satellite or receivers circuitry. Seeber [1993] quotes receiver biases to be about 2.5mm. Observation noise is dependent on the signal to noise ratio of the satellite signal, type of receiver tracking channel and the receiver bandwidth. The general rule of thumb guideline is that observation resolution is 1% of the wavelength [Wells et al, 1986]. However, current digital receiver technology has advanced this to about 1.5cm for the P-code, and 1.3mm for the L1 carrier phase [Meehan et al, 1992b]. Antenna phase centre variations are less common in modern antennas. Using the same antenna type, variations are less than 5mm, but variations up to a few centimetres can be expected if different antenna types are mixed in one campaign [Geiger, 1990].

3.5 Anti-Spoofing

Anti-spoofing (AS), although not a bias, is a current problem and concern for geodetic surveyors. AS or encryption of the P-code, basically denies unauthorised users access to the **Precise Positioning Service** (PPS). Up until now, current GPS work in geodetic surveying has made maximum use of the P-code, enabling many ambiguity resolution techniques and optimal ionospheric removal. Different receiver types handle AS in various different ways, recovering some aspects of the P-code.

Chapter 4

GPS Processing

This chapter outlines the GPS software used in the processing of the data; some reasons for choosing the software; the processing procedures and the different solution types employed.

4.1 Software Selection

The selection of "which software to use" was made for a number of reasons. Firstly, most of the campaigns have been observed with Trimble receivers, and two have already been processed (namely 1990 and 1991) by Usher Canada Ltd. and Coler and Colantonio Inc. [1990] and Coler and Colantonio Inc. [1991], using the Trimble *Trimvec Plus* software [Trimble, 1992]. Secondly, the *Trimvec Plus* software is also currently being used by Maraven for processing. Such commercial processors are fairly automated in their approach to GPS baseline processing, and thus lend themselves to cost cutting of the survey. At present, it seems only fitting that this processor be a part of the analysis. Unfortunately, *Trimvec Plus* lacks the ability to allow the user to view the least squares residuals of the Double Difference processing. This is an important part of any GPS survey, as they can reveal the solution quality, show systematic trends and ensure complete cycle slip fixing. Thus a second processor was chosen to process the 1992 and 1993 campaigns, which had this feature. Due to familiarity and ease of use, the Ashtech *Geodetic Post Processing Software* (GPPS) was chosen [Ashtech, 1993]. This would also provide an interesting comparison between two so called *Black Box* commercial processors. In the case of the *Trimvec Plus* software, a number of different processors are available. The author chose to use the *Trimvec Multi Baseline Processor* (TRIMMBP) of the *Trimvec Plus* software (version E). The Ashtech software was GPPS (version 4.50).

It is realised that for a complete study, the use of a more sophisticated software such as UNB's *Differential Post Processor* (DIPOP) [Chen and Langley, 1990b] would be very beneficial in revealing any problems or systematic trends or biases that may be inherent in the commercial software. Unfortunately, this was considered beyond the scope of the thesis, to process a whole campaign with a third processor. However a brief comparison of the two commercial processors and DIPOP was made on a separate smaller data set, from a network observed for the Superconducting Super Collider project in Texas, and is discussed later in section 4.5.

4.2 Software Comparison

Both commercial software packages operate on a similar format, aiming for optimum user friendliness by providing a fully automated system, in which the elimination of noisy/bad data, detection and treatment of cycle slips, and ambiguity resolution, are all handled within the software. A user more familiar with such questions, can select manual processing mode, to *tweak* the results, but still has little influence on the end results. Little is published about the algorithms and criteria used to answer these questions. Thus, an assessment of performance and compatibility mainly relies on a comparison of output files. This would involve comparing baseline components for both float and fixed Double Difference solutions, rms of the residuals, ambiguity ratio factors, percentage of rejected data, loop misclosures and residual plots (if available) of the single baseline solutions. In a network of independent baselines, final adjusted co-ordinates, magnitude and distribution of residuals can be compared. A posterior variance factors will assess the quality of the GPS processor weights, which in general are over optimistic.

Generally, the two software work on a similar basis. The main difference lies within the interface. GPPS uses a step by step *interactive screen* approach, whereas TRIMMBP utilises a *command line* approach. The only significant limitations between the software are that GPPS does not allow the user to delete portions of one satellite data, but only the whole satellite, or the whole portion of all the satellites, which can be quite drastic. TRIMMBP lacks the capability to view the Double Difference residuals, and does not allow the user to select the reference satellite. GPPS will only carry out single baseline processing, whereas TRIMMBP can handle both single baseline and session processing.

4.3 Solution Types

In addition to L1 and L2 single frequency processing, both software offer combined frequency processing to eliminate the ionospheric effect and provide stronger ambiguity resolution. The first combination, denoted L3, is the so called *Ionospheric Free Combination* [Ashtech, 1993].

$$L3 = L1 - (f_{L2} / f_{L1})\, L2 \qquad (4.1)$$

where $L1, L2$ are the phase measurements

f_{L1} , f_{L2} are the L1 and L2 frequencies

By nature, the L3 solution removes almost all of the ionospheric effect, but is limited to float ambiguities and can be up to three times noisier than L1 only. A fixed ambiguity combination can be made via the *Wide-Lane* technique discussed by Blewitt [1989]. The combination is seen in the following equations [Talbot, 1992]:

$$L_{WL} = [(L_1 / \lambda_{L1}) - (L_2 / \lambda_{L2})]\, \lambda_{WL} \qquad (4.2)$$

where L_{WL} is the wide-lane phase measurement

λ_{L1} ,λ_{L2} ,λ_{WL} are the corresponding wavelengths

According to Trimble [1992], this combination will eliminate most of the ionospheric effect. This analysis found this not to be the case. According to Wubbena [1989], the wide-lane combination contains an ionospheric bias similar to that on L1 or L2 only. This combination has been denoted by L0 in the rest of the thesis.

GPPS offers a slight variation on the above two techniques, in order to achieve an integer ambiguity combination with a reduced ionospheric effect. Termed the *Wide-Lane Ionospheric Free* solution, it is seen in the following equations [Ashtech, 1993]:

$$N_{WL} = N_1 + N_2 \qquad \text{or} \qquad N_2 = N_1 - N_{WL} \tag{4.3}$$

$$N_3 = N_1 + AN_2$$

where A is a frequency ratio for ionospheric removal

N_1, N_2, N_{WL} are the corresponding ambiguities

$$N_3 = N_1 + A(N_1 - N_{WL}) \tag{4.4}$$

Once the wide lane bias (N_{WL}) is fixed, then the L1 bias can be fixed through the ionospheric-free combination. This combination is also denoted by L0 in the thesis. The author wishes to point out that any future reference to a TRIMMBP L0 solution will imply the *Wide-Lane* combination, whereas a GPPS L0 solution will imply the *Wide-Lane Ionospheric Free* combination.

The newest release of the TRIMMBP software (called *GPS Survey*), now offers another combination to tackle this problem. The combination is a *Wide/Narrow Lane* solution, whereby the wide-lane phase measurement is combined with the narrow-lane code measurement, to obtain a strong estimate of the wide-lane ambiguity. This ambiguity is free of atmospheric, ephemeris, satellite clock and receiver clock errors. It is shown in the following equations [Talbot, 1992]:

$$L_{WL} = [\,(L1 / \lambda_{L1}) - (L2 / \lambda_{L2})\,]\,\lambda_{WL} \tag{4.5}$$

$$P_{NL} = [\,(P1 / \lambda_{L1}) + (P2 / \lambda_{L2})\,]\,\lambda_{NL} \tag{4.6}$$

where P_{NL} is the narrow-lane code measurement

P1, P2 are the L1 and L2, P-code measurements

By equating the wide-lane phase measurement and the narrow-lane code measurement, a direct estimate of the wide-lane phase ambiguity can be found, as follows [Talbot, 1992]:

$$N_{WL} = (P_{NL} + L_{WL}) / \lambda_{WL} \tag{4.7}$$

The tropospheric effect is estimated using the *Modified Hopfield* model in TRIMMBP and the *Hopfield* model in GPPS.

4.4 Data Processing

As mentioned earlier, the GPS campaigns 1990; 1991; 1993 and 1994 were also processed by a third party. Results and conclusions for these campaigns are contained in Usher Canada Ltd. and Coler and Colantonio Inc. [1990], Coler and Colantonio Inc. [1991], and Congecca [1993,1994]. Final adjusted co-ordinates for these years are tabulated in Appendix B. The author processed data from 1992, 1993 and 1994 in both TRIMMBP and GPPS using a variety of solution types. These are tabulated in table 4.1. The two TRIMMBP L0 solutions were provided by Maraven S.A.

Year	Software	Technique
1992	Trimble TRIMMBP	L1
1992	Ashtech GPPS	L1
1992	Trimble TRIMMBP	L0 (all available)
1993	Ashtech GPPS	L1
1993	Ashtech GPPS	L3
1993	Trimble TRIMMBP	L0
1994	Trimble TRIMMBP	L0
1994	Ashtech GPPS	L3

Table 4.1. Software employed between 1992 and 1994.

In table 4.1, the column containing *technique* relates to the processing technique employed. Where L1 is the *"single frequency L1"* solution, L3 is the *"Ionospheric Free Combination"* and L0 is the *"Wide-Lane Combination"*.

Processing procedures were similar for both software. Baselines were processed in a single baseline solution fashion, as opposed to a session solution. Run time parameters were as follows:

TRIMMBP :

: Station 0202 fixed
  Latitude : N 10° 12' 31.80970"
  Longitude : W 71° 9' 11.65150"
  Height : 53.773 m
: Broadcast Ephemeris (Hourly)
: Elevation Mask = 15°
: Default Meteorological Values;
  Temperature : 20 °C
  Pressure : 1013 mb
  Humidity : 50 %
: Modified Hopfield Tropospheric model
: No Ionospheric modelling

GPPS :

: Station 0202 fixed
  Latitude : N 10° 12' 31.80970"
  Longitude : W 71° 9' 11.65150"
  Height : 53.773 m
: Broadcast Ephemeris
: Elevation Mask = 15°
: Default Meteorological Values;
  Temperature : 20 °C
  Pressure : 1010 mb
  Humidity : 50 %
: Hopfield Tropospheric model
: No Ionospheric modelling

Co-ordinates for the fixed point (station 0202) were computed from the pseudorange data observed in 1988. Their worth was questionable. New co-ordinates were made available during December 1993. For consistency, the old co-ordinates have been used in the processing of all the campaigns. The new co-ordinates were obtained from a nearby Transit Doppler Station, observed in 1985 by the University of Zulia in conjunction with the University of Hannover. Station 0202 was tied to the Doppler station with the GPS in 1993. The Doppler station is located some kilometres south of Bachaquero, and is beyond the subsidence zone. The new values disagree with old co-ordinates by 15m in latitude, 3m in longitude and 2m in the height.

Considering the flatness of the network terrain and the stability of the climate, the default surface meteorological values have been used in each software. Trimble [1992] highly recommend using this method, for short baselines with a small height difference (<300m).

For some unknown reason, the two software use slightly different standard meteorological values. Temperature and humidity are equivalent, but pressure is different by 3mb. This is worrying considering the susceptibility of the tropospheric models to the slightest change in atmospheric conditions (cf. section 3.2.2).

In the processing of the 1992 data, it was found that much improved results were obtained when using a cut off angle of 20° as opposed to the normal 15° used in the later campaigns. This was true for both software. Better integer search ratios; rms of the residuals and day to day repeatability were achieved under this setting. This was also true of the 1991 campaign [Coler and Colantonio Inc., 1991]. The 1993 and 1994 campaigns used a 15° elevation mask.

4.5 Test Comparison to DIPOP

In order to gain some insight into the commercial software, a comparison was made with DIPOP, using a small data set from the aforementioned Texas network, utilising DIPOP as a benchmark. The data set obtained with Ashtech LXII receivers consists of three baselines, ranging from 18-28km in length. Full wavelength dual frequency P-code data was observed in two sessions of four hours. All data was processed in both software in three modes L1, L3 and L0. One L3 solution for each baseline was obtained from the DIPOP processor [Komjathy, 1993].

In total, seven solutions were obtained for each baseline (table E1, appendix E). Average rms of the residuals was 16mm for GPPS and 17mm for TRIMMBP. GPPS was consistently around 16mm for all solution types. However TRIMMBP varied a great deal from 5mm to 45mm. The results between GPPS and DIPOP generally agree very well. TRIMMBP did not agree so well, as six of the eighteen solutions appear as outliers; three in L3, two in L1 and one in L0. In the L1 and L0 solutions, the software had problems fixing the ambiguities and rms of the residuals were high. Most of the outliers seem to be weakest in the dx baseline component, compared to DIPOP and GPPS, which in Texas corresponds to the longitudinal component. Four of the six outliers are the longer, 28km, baselines.

Internal and external 3D loop misclosures were calculated for each session and solution. These are tabulated in tables E2 to E8, in appendix E. The DIPOP 3D loop misclosures were good both internally and externally, varying between 14mm and 49mm. This translates to better than 1ppm of the sum of the three distances (approx. 70km). The GPPS loop closures were generally equally good, varying between 7mm and 75mm, still within 1ppm. With six outliers, the TRIMMBP closures are not so consistent, ranging from 9mm to 856mm, i.e. 1-12ppm. Three of the six L0 and L1 external loop misclosures were around 1ppm. All six L3 closures were poor. Such high misclosures could be expected in areas of high ionospheric activity, using L1 solutions, where biases of 5-10ppm can occur. However, three of the six outliers were L3 *ionospheric free* solutions, and QC (cf. section 5.1) analysis of the data showed ionospheric activity to be low.

DIPOP performed well from day to day, giving a repeatability of 1ppm of the baseline length (figure 4.1). All three GPPS solutions also had good repeatability. The largest difference was one L3 solution at 2ppm. Trimvec, because of the outliers, had much worse repeatability. Four of the nine solutions were within 2ppm, three varied between 4-7ppm, and two were blunders.

Using DIPOP as a benchmark, all solutions were differenced with the DIPOP L3 solution (figures 4.2 and 4.3). All eighteen GPPS solutions were within 2ppm. Interestingly enough, all the middle length baselines (23km) agreed within 0.5ppm of DIPOP, in all six solutions. Twelve of the eighteen Trimvec solutions were within 2ppm of DIPOP. Four differed by up to 6ppm, and the remaining two were obvious blunders. No correlation between baseline length or solution type, could be made with the weak solutions.

In general, the Ashtech software handled it's own data very well, and no processing problems were encountered. Trimble software had a few problems in six of the eighteen solutions, but otherwise agreed reasonably well with DIPOP.

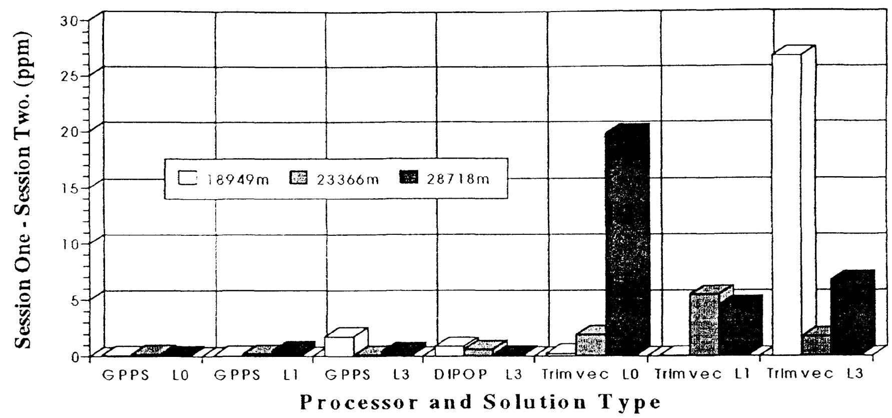

Figure 4.1. Texas data set. Software repeatability in baseline length.

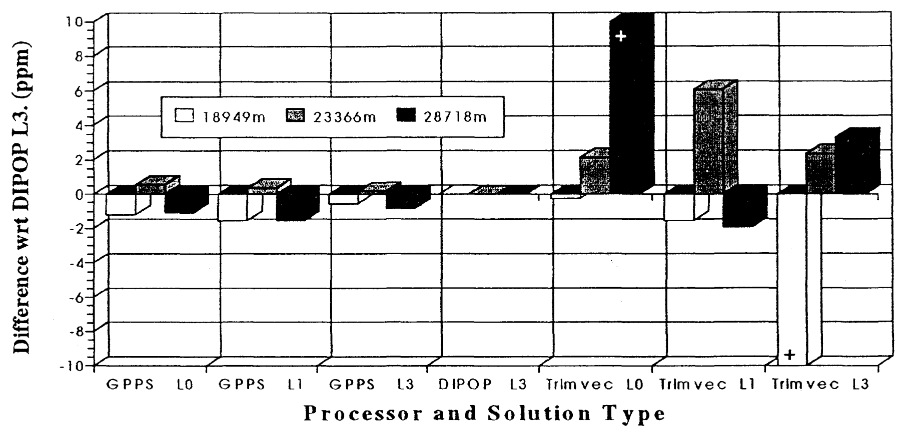

Figure 4.2. Comparison of baseline lengths, wrt DIPOP. (Session One).

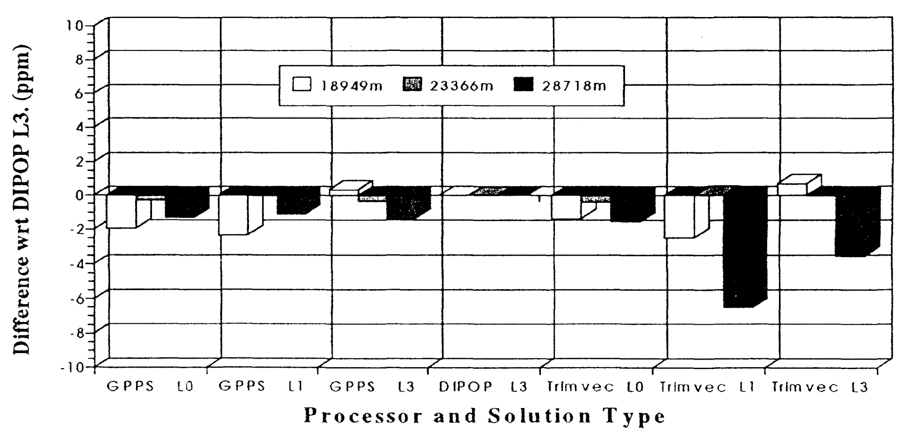

Figure 4.3. Comparison of baseline lengths, wrt DIPOP. (Session Two).

Chapter 5

GPS Data Assessment

A brief assessment of the data quality for the campaigns 1991 to 1994 has been made using the program *Quality Check* available from UNAVCO, Colorado [UNAVCO, 1993].

5.1 Quality Check (QC)

According to the QC documentation [UNAVCO, 1993], *"The QC program forms linear combinations of the GPS range and carrier phase data to compute (1) L1 pseudorange multipath for the C/A or P-code observations, (2) L2 pseudorange multipath for P-code observations, (3) ionospheric phase effects on the L1 carrier frequency and (4) the rate of change of the ionospheric delay"*. The author's main interest in using the program was to evaluate the ionospheric effects (3) and (4), at each station, for each of the last four campaigns. The ionospheric delay is derived from the difference of the L1 and L2 carrier phase equations. Unfortunately, it is not possible to estimate the absolute delay for each signal at lock onto the satellite. Thus, the delay itself is expressed relative to the first observation epoch, where the delay is assumed to be zero. The program requires dual frequency C/A or P-code data from a single station. Thus a full assessment of the 1990 and 1991 campaigns could not be made. However a limited amount of L2 data was available from the August 1991 data set.

5.2 Ionospheric Assessment

Although the August 1991 data set was not incorporated in the deformation study, it did provide the author with dual frequency P-code data with which to analyse using QC. For the sixteen available baselines, QC revealed that the relative ionospheric delay consistently reached 20m after 2 hours, with some peaks up to 30m. The rate of change (ROC) of the delay was also high, on average 80cm/min with peaks up to 120cm/min. The noise level of the 1992 data varied greatly throughout the campaign. The relative ionospheric delay on the L1 signal ranged from 8m to 20m, over 2 hours, with peaks up to 30m, on some days. The ROC was again high, on average 100cm/min, with peaks of 150cm/min. However, disturbances in the 1993 data were much less, and the data much smoother. Relative ionospheric delay was on average 2m over 2hrs, with peaks of 4m. The ROC was on average 20cm/min. On the whole, the effect was an order of magnitude less. This was also true of the 1994 data which was affected much the same as the 1993 data. In the 1991 and 1992 data sets, although the values were fairly high on many days, the delay and ROC were both fairly smooth, i.e. no scintilation type effects were seen.

5.3 Causes of Noisy Data

The high levels of ionospheric delay during 1991 and 1992 data can be attributed to solar sunspot activity. Solar storms and flares directly affect the total electron content in the atmosphere, which in turn delays the travelling signals in a frequency dependent way. According to Blewitt [1989] maximum ionospheric delays occur at the peak of the 11 year solar sunspot cycle, 1989 being the last peak (figure 5.1). The annual maximum is during the spring and vernal equinox, and the diurnal maximum at 1400hr local time. Tropical regions such as Lake Maracaibo are worst affected. Observation times for each campaign are tabulated in the following table 5.1.

Year	Days	Time of Day (local time)	Average Session Length (hours)
1990	115 - 124	2100 - 0800	3
1991	36 - 50	1100 - 2300	2
	77 - 80	0800 - 1200	2
1992	119 - 141	1700 - 2200	2
1993	214 - 230	0800 - 1400	2
1994	110 - 119	0200 - 0700	2

Table 5.1. Observation dates and times.

Three of the campaigns 1990, 1992, and 1994, were conducted at a similar time during the year (around April/May), i.e. one month after the spring equinox. Daily observation times for each campaign were all between early evening and early next morning. Campaign 1991 was conducted one month prior to and around the spring equinox, with daily observation times throughout noon to midnight. However, the 1991 data examined under QC was taken during August, with observation times from 10-16hr (local time). The 1993 campaign was also conducted in August with observation times from late morning to early afternoon.

Unfortunately, no direct correlation of noisy data and observation time could be made, on a diurnal or seasonal basis, in any of the campaigns. The only apparent trend is the greater noise level of the earlier campaigns 1990 to 1992. This would signify the possible tailing off of the 11 year solar cycle, which was the case in cycle 22 (figure 5.1).

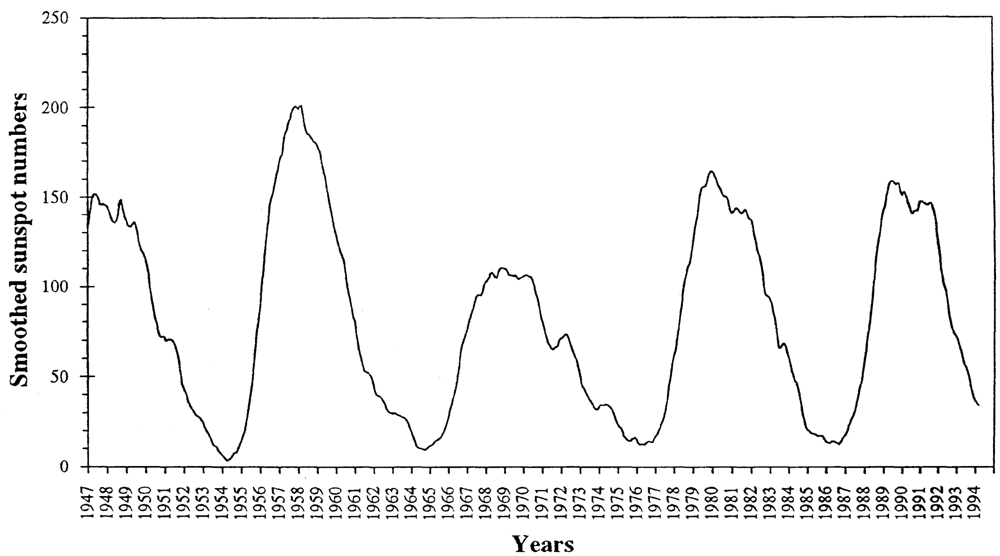

Figure 5.1. Smoothed monthly sunspot numbers [Komjathy, 1995].

During 1991 and 1992, an international joint project under the heading BRASION (BRASil IONosfera) studied the ionospheric effect on the GPS in Brazil. Wanninger and Campos [1991] reported that in the July 1991 campaign, no scintilations were seen but strong ionospheric effects were observed on even short 10km lines, concluding that the effects could be expected for some years before and after sunspot maximum. The second campaign [Wanninger and Campos, 1992] conducted in March 1992, suffered both scintilations and strong ionospheric effects. Long hours of data, more sophisticated post processing software, and access to the S/N ratios from the receiver, allowed for a detailed study of the ionospheric effect. Overall, in 1992, they reported that co-ordinate shifts of 5-30ppm were experienced, with different data sets. The author suspects that the Venezuela 1991 and 1992 campaigns which were carried out at similar times, and also lying within the equatorial anomaly, may have suffered similar effects.

Unfortunately, at this point in time it is unsure to what extent the ionosphere is causing problems. Other sources of error such as the troposphere and multipath could also be contributing. Westrop [1991] attempted to better model the tropospheric delay but could not find a model or technique that performed satisfactory. As mentioned in section 4.4, a higher elevation mask of 20° produced better results in 1991 and 1992. This may signify that the tropospheric delay is fairly pronounced, or being handled incorrectly. Tropospheric models based on the Hopfield model tend to over estimate the delay at lower elevation angles, from 20° and down [Janes et al, 1990].

The accuracy of the orbits will also play a role. As mentioned in section 3.1.2, the accuracy of the broadcast orbits used in this study are expected to be about 0.5ppm. Noisy data in 1992 created inconsistencies up to ten times this value in the baseline results. Thus the use of the broadcast ephemeris was not considered a limiting factor at this stage. Westrop [1991] demonstrated using a few of the 1990 baselines, that differences in the baseline components were between 0.1-1.3ppm, when using the precise ephemeris.

Chapter 6

GPS Results (1992 - 1994)

This chapter looks at the baseline solutions from the campaigns 1992 to 1994, and the 1992 test baselines, processed in TRIMMBP and GPPS, examining the repeatability, double difference residual plots, and the height misclosures. This is followed by the post adjustment analysis, an evaluation through MINQE, and a look at the systematic biases that resulted.

6.1 Baseline Processing Using TRIMMBP and GPPS

The author processed data from the campaigns 1992 to 1994. Results from these years using different solution types can be found in appendix A. Tables for all campaigns contain the baseline components ($\Delta\varphi$, $\Delta\lambda$ and Δh) for each session, together with the rms of the residuals, type of solution (1=L1, 3=L3, 0=L0) and the integer search ratio (ISR). Note that the rms of the residual and integer search ratio have different units in each software. TRIMMBP states that an rms between 0.02-0.09 cycles, for a baseline up to 20km, denotes a good solution [Trimble, 1992]. GPPS rms is given in metres. ISR for TRIMMBP greater than 3.0 denotes a strong solution. GPPS ISR between 95 and 100 indicate all ambiguities were fixed well [Ashtech, 1993].

Of all the campaigns processed by the author, **1992** proved the most problematic. Data was generally very noisy. This was seen through weak L1 solutions and poor day to day repeatability in both the TRIMMBP and GPPS software. Noisy data made ambiguity fixing hard, even on very short (7km) baselines. Solutions between processors differed greatly depending on whether one or both solutions appeared strong. If the rms of the residual was low and the ISR strong, then there was good agreement between the two software at sub-centimetre level. However, if one solution appeared weak, then some very large differences would occur at the deci-metre level, reaching 500mm in one case. This was true for both baseline length and elevation difference. Average differences in the latitude (phi), longitude (lambda) and height baseline components, between the software, are given in table 6.1. Average differences were calculated using all available solutions. Oddly enough, in all solution types, the longitude component is weaker than the height component. A noticeable improvement in all differences is seen from 1992 to 1994.

Generally the rms for the 1992 TRIMMBP L1 solutions was 0.04-0.08 cycles (8-16mm) denoting a good solution. Often only one baseline from each session had a poor rms (up to 0.2 cycles, or 40mm), and these did not agree well with GPPS. The average rms of the GPPS L1 solutions was slightly higher (10-25mm), with occasional baselines reaching 50mm. Weak solutions were not generally confined to the longer baselines. This would suggest a distance independent effect causing the noisy data, such as the troposphere.

Overall the noisiness of the data meant for weak float ambiguity solutions in both software, resulting in some wrongly fixed ambiguity solutions, creating some large differences in the baseline components. Generally fixed ambiguity solutions between the two software agreed slightly better than the float solutions (figures 6.1 and 6.2). Differences were not baseline length dependent.

In **1993**, cross-correlated P-code data was observed. Three solution types were produced; L1, L3 and L0. This data set proved fairly clean and smooth, and all solutions agreed much better between processor and solution type. Baseline lengths between TRIMMBP L0 and GPPS L3 generally varied by 0-50mm, with the odd difference up to 163mm. The mean difference was 37mm (figures 6.3 and 6.4). There was a distinct bias between these two solutions, and a non zero mean can be seen in figure 6.3, denoting generally longer baselines from L0. This bias was not seen in 1992, with the L1 solutions, and is not so prevalent in the 1994 solutions (figure 6.4). Elevation differences generally agreed much better, with an average difference of 24mm.

Year	Solution Types	Phi (mm)	Lambda (mm)	Height (mm)
1992	TRIMMBP L1 - GPPS L1	23	82	56
1993	GPPS L3 - GPPS L1	18	31	18
1993	TRIMMBP L0 - GPPS L1	38	35	27
1993	TRIMMBP L0 - GPPS L3	22	39	24
1994	TRIMMBP L0 - GPPS L3	11	29	15

Table 6.1. Mean baseline differences between software.

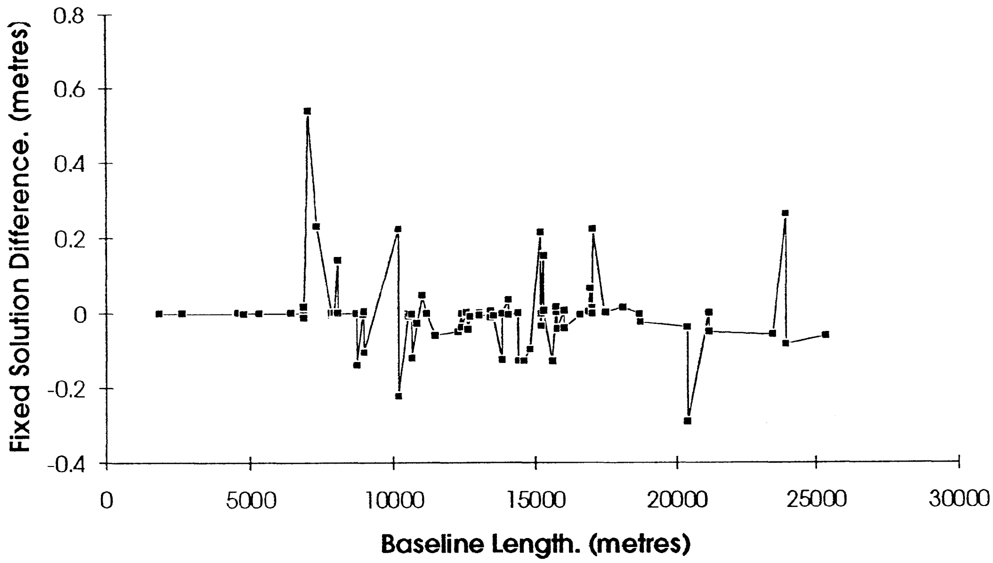

Figure 6.1. 1992 L1 fixed solutions. Baseline length differences. GPPS L1 - TRIMMBP L1

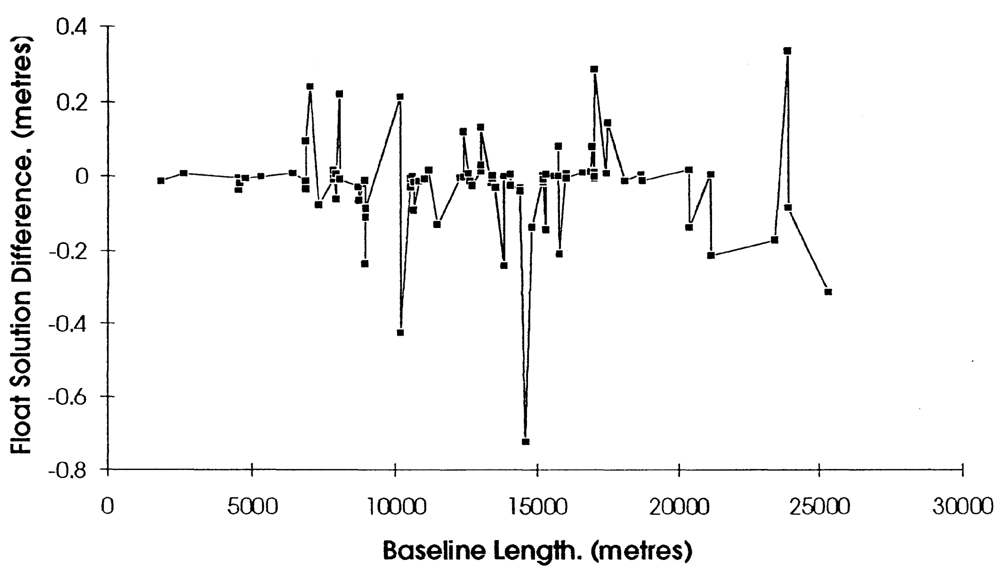

Figure 6.2. 1992 L1 float solutions. Baseline length differences. GPPS L1 - TRIMMBP L1

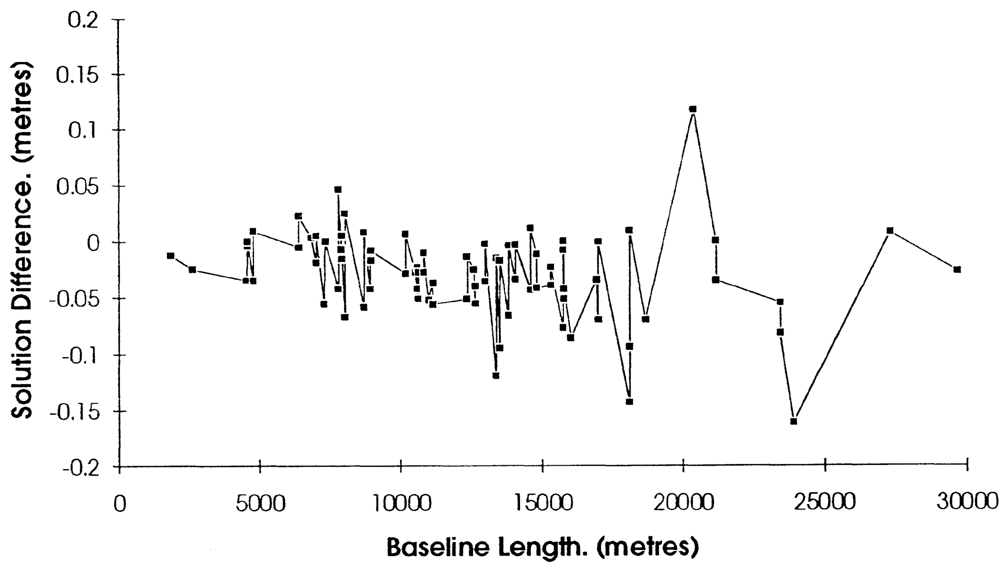

**Figure 6.3. 1993 data set. Baseline length differences.
GPPS L3 - TRIMMBP L0**

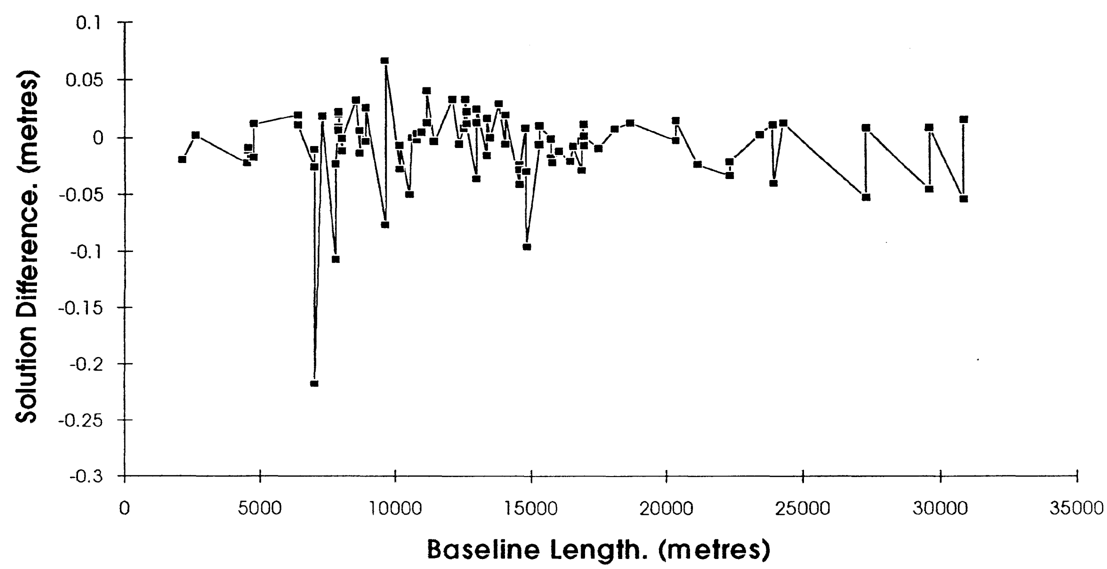

**Figure 6.4. 1994 data set. Baseline length differences.
GPPS L3 - TRIMMBP L0**

During January **1994**, the US Department of Defence permanently activated Anti-Spoofing (AS), thus denying the true P-code to civilian users. Under such conditions the Trimble 4000SST receiver switches to L2 squaring mode. This tracking process is inherently noisier than the cross-correlation technique (Leick, 1994), used in the previous years. However this was not seen in the results. Average rms of the residuals and differences between the solutions in 1994, were noticeably smaller than the previous year (table 6.1). This was not expected.

6.2 Baseline Repeatability (Campaigns 1992 - 1994)

Twenty five baselines were observed more than once during the 1992 campaign. Repeatability was poor in both software, due to one solution being weak in half of the cases. Thus average repeatability (mean values) in the baseline lengths and elevations differences were artificially high for 1992. Other statistics were calculated, such as the variance and median, but all gave similar values as the mean for 1992. Table 6.2 shows average repeatability in the latitude (phi), longitude (lambda) and height components for all solutions types and years.

Of the 90 observed baselines, 33 could be processed in dual frequency mode. Processing of the baselines in the TRIMMBP software using the L0 combination, proved fairly straight forward. Repeatability, although a small sample (9 repeated baselines), appeared better (table 6.2).

Year	Solution Type	RMS (mm)	Epochs Rejected	Repeatability Phi (mm)	Repeatability Lambda (mm)	Repeatability Height (mm)
1992	TRIMMBP L1	18	12/210	49	150	96
1992	GPPS L1	24	30/2400	27	70	75
1992	TRIMMBP L0	28	140/2400	29	25	54
1993	TRIMMBP L0	23	40/2900	19	16	39
1993	GPPS L3	17	20/2900	11	43	38
1993	GPPS L1	23	20/2900	17	20	33
1994	TRIMMBP L0	23	30/3000	16	16	36
1994	GPPS L3	11	20/3000	11	32	26

Table 6.2. Mean repeatability, in the baseline components.

Day to day repeatability improved drastically in 1993, with all solutions giving similar values. The phi components were strongest, and height the weakest, as expected. The L3 solutions showed a significant weakness in the lambda component. In 1994, average repeatability in the GPPS L3 solutions was slightly better than in 1993, whilst the TRIMMBP L0 solutions gave very similar values to the previous year.

6.3 Test Baselines

Results for the six baselines frequently observed during late 1991 and 1992 are discussed. All baselines were processed using the GPPS software, mainly to examine the residual plots. Three solution types were employed, L1 *single frequency*; L3 *ionospheric free combination* and L0 *wide-lane ionospheric free combination*, as discussed in section 4.3. One baseline was processed in TRIMMBP using the L0 *wide lane combination*.

Analysis of the baseline solutions showed some interesting results in the GPPS solutions. Firstly, it was revealed that the L1 baseline length solutions provide very noisy, almost random, results compared to L3 and L0. This is to be expected, due to the non treatment of the ionospheric effect. It is hoped that for short baselines up to 20km, the effect would be similar at both receivers, and thus cancel out. However for the Lago de Maracaibo area, this is not so, and the use of dual frequency receivers is paramount to a meaningful study of subsidence. Single frequency solutions were weakest between days 50 and 200, of the year. Before and after these dates, a reasonable agreement was seen. The dual frequency solutions gave much better results, with L0 slightly more consistent than the L3 solutions, although a couple of solutions still contained spikes (0600-0700 and 0600-0184, on day 365). Baseline lengths in all L1 solutions varied by 10-30cm. L3 solutions varied 2-10cm in baseline length throughout the year, whilst L0 varied only 2-3cm, after accounting for any linear trend. Some definite linear changes in baseline length can be seen in three of the solutions, all showing changes of approximately 5cm/year. No correlation between the noisy L1 data and the baseline length or azimuth could be seen.

Changes in elevation difference were not so clear even in the L0 and L3 solutions. All solutions showed great variation in the four baselines, from 2-10cm, masking any subsidence trend. A distinct correlation between the L0 and L3 results can be seen, and both show the same fluctuations. Thus it would appear that both L3 and L0 are free of biases in the horizontal, but both suffer a similar bias in the height.

The one baseline processed in the TRIMMBP software (0600-1010) showed fairly good agreement with GPPS. L1 results generally differed by a few centimetres, at each epoch, but some obvious differences occurred on a few days. L3 results agreed very well (up to 1cm) in both baseline length and elevation difference, except on day 63, where the difference reached 10cm, in the length. L0 results showed a bias in the length, with the TRIMMBP L0 (wide lane) giving 2ppm longer baselines than the GPPS L0 (wide lane ionospheric free) solutions.

6.4 GPPS Double Difference Residual Plots

Analysis of the 1992 double difference residual plots from GPPS L1 showed a variety of trends, between 4-8cm, on nearly all the baselines, with a few baselines reaching 16cm. These extreme cases show distinct correlation with rising or setting of the satellite. Some examples of residual plots for the years 1992 and 1993 are given in appendix D.

1993 GPPS L1 double difference residual plots contained trends equal to those of 1992 (2-8cm), without the extreme cases, although rms of the residuals and ISR were on the whole better. L3 plots were generally very good, slightly noisier than L1, but showing no short term trends. A few baselines showed some longer term trends up to 4cm.

Residual plots for the 1994 GPPS L3 solutions were generally good, and very similar to those of 1993, again with some baselines showing some longer term trends, up to 4cm. Frequent gaps in the data were prevalent in some plots, which is expected with squared data. A test for multipath could be carried out on fifteen of the 1992 and 1993 baselines, by examining the same baselines, observed at similar times on consecutive days, and repeated trends up to about 2cm were seen on three lines.

6.5 GPS Height Misclosures

Independent height misclosures were calculated from twenty five triangles in the network, for all solution types. The average misclosures are summarised in table 6.3. As a rough guideline, an acceptable misclosure of 1ppm per baseline was assumed, which translates to 1.7ppm over three baselines, assuming the random propagation of errors. Both the 1992 L1 solutions exceed this tolerance, with the TRIMMBP processor giving slightly worse closures than GPPS. All solution types in 1993 and 1994, including L1, gave similar average misclosures, within each year. A noticeable improvement is seen from 1993 to 1994. Similar misclosures between single and dual frequency solution types in 1993, suggests that the errors are not frequency dependent.

Year	Solution Types	Average Misc. (ppm)	Ferrero Mean. (ppm)
1992	TRIMMBP L1	3.10	2.30
1992	GPPS L1	1.90	1.35
1993	GPPS L1	0.74	0.56
1993	GPPS L3	0.71	0.55
1993	TRIMMBP L0	0.75	0.54
1994	TRIMMBP L0	0.38	0.33
1994	GPPS L3	0.46	0.45

Table 6.3. Average GPS height misclosures. (Approx. 30km triangles).

6.6 Post Adjustment Analysis

All campaigns were put through a 3D Cartesian adjustment, using a minimum constraint, fixing station 0202. In 1992, the L1 fixed ambiguity solutions were used. Residuals of the XYZ baseline components were poor in 1992, often up to 5cm and higher. GPPS L1 contained noticeably larger residuals than the TRIMMBP L1. Some baselines had to be rejected. The author tried to mix float and fixed solutions into one adjustment, but the few float solutions chosen over their fixed counterpart, came up with very large residuals.

An attempt was also made with the 1992 data, to adjust a combination of single and dual frequency solutions, but to no avail. Adjustment residuals of the baseline components were between 5-20cm, some higher, for nearly all the baselines, indicating a large difference between the two solution types.

In 1993, residuals were much lower, generally up to 2cm, with only a few reaching 5cm, in all solutions types, L1 included. No baselines had to be rejected. Residuals in 1994 were of the same magnitude as 1993, which again was not expected, with the squared data.

A posteriori variance factors varied widely, between solutions types and processors, indicating incorrect baseline weights (table 6.4). Campaigns 1990 and 1991 were processed using an earlier version of the Trimvec software, which may account for the significant difference from 1992. All latter TRIMMBP L1 and L0 weights were over optimistic. GPPS L3 solutions gave reasonable results.

Year	Software and Solution Type	A Posteriori Variance Factor
1990	TRIMMBP L1	0.3
1991	TRIMMBP L1	0.3
1992	TRIMMBP L1	48.5
1992	GPPS L1	6.6
1993	TRIMMBP L0	333.8
1993	GPPS L3	0.6
1993	GPPS L1	5.1
1994	TRIMMBP L0	256.6
1994	GPPS L3	0.8

Table 6.4. Adjustment a posteriori variance factors.

Average relative station error ellipses also varied, mainly between year and solution type (table 6.5). Relative error ellipses were multiplied by the a posteriori variance factor. The 1992 GPPS L1 gave the largest ellipses. 1993 GPPS L1 and TRIMMBP L0 gave the smallest. Again, the GPPS L3 solutions showed a bias in the lambda component, most likely due to the prominent N/S direction of the satellites.

Year	Solution Type	Phi (mm)	Lambda (mm)	Height (mm)
1990	TRIMMBP L1	15	18	36
1991	TRIMMBP L1	14	28	35
1992	TRIMMBP L1	18	20	45
1992	GPPS L1	27	30	76
1993	TRIMMBP L0	18	20	39
1993	GPPS L3	14	45	28
1993	GPPS L1	16	18	35
1994	TRIMMBP L0	15	19	38
1994	GPPS L3	11	45	19

Table 6.5. Average relative station error ellipses (@95%, for a 10km baseline).

Final adjusted co-ordinates for all years are tabulated in tables B1 to B9, in appendix B. Average differences in final adjusted co-ordinates are tabulated in table 6.6. Horizontal displacements between all years are plotted in figures B1 to B7, appendix B. Vertical displacements for years 1992 to 1994 are tabulated in table 7.1. In most cases, horizontal displacement fields show systematic scale changes and rotations. Comparisons of different solution types, during the same years, also show systematic biases. Table 6.6 shows average differences between the adjusted co-ordinates for different solution types. It can be seen that the single frequency solutions of 1992 agree well in the horizontal components, but not in the height, whilst the opposite is true for the dual frequency solutions of 1993 and 1994. L1 and L0 solutions of 1993 were very weak in the horizontal, but good in the height.

Year	Solution Types	Phi (mm)	Lambda (mm)	Height (mm)
1992	TRIMMBP L1 - GPPS L1	8	12	23
1993	GPPS L3 - GPPS L1	24	16	14
1993	TRIMMBP L0 - GPPS L1	47	43	10
1993	TRIMMBP L0 - GPPS L3	25	32	9
1994	TRIMMBP L0 - GPPS L3	14	14	7

Table 6.6. Mean differences between adjusted co-ordinates.

6.7 Evaluation Using MINQE

Overall pooled error ellipses of the relative co-ordinates changes between campaigns, were approximately 5cm in the horizontal and 7cm in the vertical, after the removal of biases. The question arises as to why these are so high. GPS observation weights from the processors are often over optimistic. The use of variance/covariance estimation techniques such as MINQE, may provide some insights into the appropriateness of the weights. The MINQE approach of evaluating the accuracy and error model, is discussed in detail by Chen [1983] and applied by Chen et al [1990a].

The MINQE program [Caissy, 1994] was used to re-estimate the baseline component errors, for the years 1992 and 1993, using the same baselines employed in the adjustments of section 6.6, i.e. the independent lines only. The results of the MINQE assessment are tabulated in table 6.7. MINQE revealed the accuracy to be similar for all solution types and years, estimating the phi and lambda components to be around 14mm and the height about 30mm, which is consistent with the values attained in 1990 and 1991 [Chrzanowski et al, 1991]. The 1993 GPPS L3 solution was noticeably higher in the lambda component.

Year	Solution Type	Phi (mm)	Lambda (mm)	Height (mm)
1992	TRIMMBP L1	11	10	23
1992	GPPS L1	14	21	28
1993	GPPS L1	12	13	29
1993	GPPS L3	11	30	33
1993	TRIMMBP L0	14	13	33

Table 6.7. MINQE assessment of the baseline components. (10km baseline).

Baseline solutions were re-adjusted using the MINQE weights, and displacements and their pooled error ellipses recomputed. No significant changes were seen in the displacements and the error ellipse size, and only some small rotations of the error ellipses were seen. Thus it would seem that the relative weights of the processors are appropriate, and that scaling by the a posteriori variance factor from the adjustment, is all that is required. The question remains as to why the error ellipses are so high.

In hind sight, considering the size of the network, minimal observation times and the processing procedures used, pooled error ellipses of this size should be expected, i.e. 7cm over a 70km network. Which, of course, translates to 1ppm in the horizontal component. Breaking the so called **1ppm barrier**, which has been demonstrated in many case studies over the last few years, will require some changes in the present scenario.

6.8 Systematic Biases

6.8.1 Biases Between Different Software

This comparison was hindered by a lack of results from common solution types in each processor. Only L1 data from 1992, and some L3 data from the *test baselines*, was available. From the L1 data, no noticeable difference in the horizontal components could be seen. Average differences in the final adjusted co-ordinates were 8mm and 12mm for phi and lambda, respectively. Displacement differences are shown in figure C1, appendix C. However, adjusted station heights differed on average by 24mm, reaching 89mm in one case. These are shown in table C1, appendix C. A rotation of 1.5±0.4ppm about a north/south axis, was found to exist between the two solutions. A disagreement in the heights would suggest a problem with modelling of the tropospheric delay. The delay itself is frequency independent, thus different combinations of the L1 and L2 signals would be affected the same. The use of different models could cause such a difference, which is the case between TRIMMBP and GPPS. The use of slightly different default pressure values may also contribute to the problem. These might explain the 1992 differences, but does not explain the good agreement that was seen in 1993 and 1994, with the dual frequency data (cf. section 6.6). Differences in the L3 solutions of the *test baselines* were already discussed in section 6.3, and none were seen. On the whole it is believed that the two software give compatible results, between similar solution types.

6.8.2 Biases Between Different Solution Types

As expected, biases were found between different solution types, for the same year. A comparison between the two dual frequency solutions TRIMMBP L0 and GPPS L3, for 1993, revealed a good agreement in the height component and some significant differences in the horizontal component, mainly in longitude. This resulted in a significant scale bias between the two solutions types. This was unexpected, and it is thought that the TRIMMBP L0 solution does not remove the ionospheric effect as much as claimed. 1994 shows a smaller scale bias, but with an additional rotation. Differences between final adjusted co-ordinates are tabulated in tables C2 and C3, in appendix C, and plotted in figures C3 and C4. A comparison between GPPS L1 and GPPS L3, is shown also, and a scale bias is evident (figure C2, appendix C).

It was expected that the 1994 results (L2 squared data) would give worse agreement than the 1993 (cross-correlated P-code). However this was not the case and differences were smaller in 1994 between L3 and L0, in the horizontal components (table 6.6).

Overall it was found that the single frequency solutions agreed well in phi and lambda but differed slightly in the height. This is most likely due to the use of different tropospheric models, or met. values. The dual frequency solutions showed the opposite trends, indicating that the ionospheric effect is only seen in the horizontal component.

6.8.3 Fixed Co-ordinate Bias

The effect of shifting the co-ordinates of the fixed point was seen in the TRIMMBP L1 solutions for 1992. A shift of 0.5" (≈15m) was applied to the phi component of station 0202, and reprocessing of the network carried out. Horizontal components changed little, but heights changed significantly, as expected. A rotation of 0.8ppm (0.16") about an east/west axis was seen, which corresponds well with Santerre's [1989] value of 0.1"/10m.

6.9 Discussion

Overall, the quality of the data has seen a marked improvement since 1992, which was of very poor quality. This was seen through very poor day to day repeatability of the baseline solutions, noisy residual plots and large vertical loop misclosures. Results from 1992 were weak in all three components. Thus it is expected that the problems are a combination of the ionospheric and tropospheric effects. Multipath effects of a few centimetres were seen on a few baselines, which would contribute to the errors, but it is not considered a dominant one.

A comparison of the 1992 GPPS and TRIMMBP L1 results in table 6.1, revealed that large differences were seen between all the components of the baseline solutions (23-82mm). However, differences between final adjusted co-ordinates were significantly lower in all components (8-23mm), indicating the differences to be of a random nature. In 1993 and 1994 this was not quite the case, as differences in the horizontal components barely changed, but an improvement in the height was seen, indicating a systematic difference in the horizontal and again a more random difference in the height.

Chapter 7

Deformation Analysis

This chapter examines the displacements given by the GPS, after removing the systematic biases.

7.1 Horizontal Analysis

Knowing that systematic biases exist between solutions types, our picture of deformation displacements between two epochs is also likely to be distorted. Figures B1 to B7, in appendix B, derived from the adjusted co-ordinates holding station 0202 fixed, show horizontal displacements between the years 1990 and 1994. Scale biases and some rotations can be seen.

Biases were removed between all years and solution types, to see if better agreement of the displacement field would be seen. This was carried out following the UNB Generalised Method of Deformation Surveys, to obtain a displacement field free of datum distortions [Chen et al, 1990b]. An Iterative Weighted Similarity Transformation (IWST) software provided by Grodecki [1994], was used to remove any systematic translations, rotations and scale. Figures B8 to B14, in appendix B, show horizontal displacements after the removal of the systematic biases.

Displacements between 1990, 1991, and 1992 became random and insignificant, with only station 0600 showing significant movement (figures B8 and B9). Unfortunately only one solution type was available in each epoch, so no additional comparisons can be made.

The resulting displacements for the years 1992 to 1993, in all cases were very similar, (see figures B10 to B12). This is a good sign, indicating that even single frequency solutions can provide equivalent displacements to dual frequency solutions, if the biases are removed. Unfortunately pooled error ellipses (approx. 50mm, @95 %) are too high to show the remaining displacements to be significant. As expected, these are worse for the single frequency solutions. Again, station 0600 showed significant displacement.

Between 1993 and 1994, similar solution types could be compared. However, the two cases did not give similar displacement fields after the IWST, (figures B13 and B14). The displacements are much smaller than previous years, and none are considered significant. Close inspection revealed the GPPS L3 displacements not to change, indicating no bias between the solutions, which is promising. The TRIMMBP L0 displacement field did change, as a definite scale bias was evident. Displacements after IWST were very small, and only station 0600 showed sign of significant movement. Again pooled error ellipses are high.

7.2 Vertical Analysis

For the vertical analysis, displacements from precise levelling are available for comparison. It was hoped that the height differences from the GPS would correlate somewhat with the levelling differences. Table 7.1 shows a comparison of some cases. Very little correlation can be seen, between the early campaigns 1990 to 1993, but a much improved agreement was seen between 1993 and 1994.

Stn	GPS Subsidence (m)				Levelling Subsidence (m)			
	T 90 L1 to T 91 L1	T 91 L1 to T 92 L1	T 92 L1 to T 93 L0	T 93 L0 to T 94 L0	1990 to 1991	1991 to 1992	1992 to 1993	1993 to 1994
0202	0.000	0.000	0.000	0.000	-0.001	0.000	0.000	0.000
0011	0.127	-0.234	0.075	-0.010	-0.047	-0.015	-0.022	-0.056
0012	-0.019	-0.060	0.071	-0.031	-0.035			
0014	-0.031	-0.033	0.097	-0.017	-0.011	0.007	-0.016	0.001
0100	-0.105	0.136	-0.026	-0.016	0.001	0.000	0.000	-0.002
0184	-0.013	-0.015	0.042				-0.004	
0300	-0.025	-0.025	0.055	-0.036	-0.013	-0.016	-0.020	-0.040
0500	-0.062	-0.100	0.074		-0.042	-0.018	-0.067	
0600	0.034	-0.216	0.019	-0.058			-0.067	-0.059
0700	0.073	-0.021	-0.017	-0.002			0.006	-0.008
0743	-0.016	-0.002	0.051	0.000	0.004	-0.002	-0.012	0.007
0800	0.071	-0.030	-0.006	-0.020				
0900	0.158	-0.220	0.104	-0.014				
1010	0.022	-0.163	0.058	-0.053	-0.028	-0.068	-0.042	-0.041
1200	-0.039	-0.070	0.018	-0.035	-0.046	-0.041	-0.060	-0.029
1300	0.019	-0.076	0.100	-0.016	-0.055			
2900	0.063	-0.230	0.137	-0.064	-0.056	-0.036	-0.003	-0.042
9201		0.068	-0.107	-0.060				
9202		0.103	-0.076	-0.003				
9203		-0.019	-0.059	-0.005				
Key :	T 92 L1 : indicates a TRIMMBP 1992 L1 solution							

Table 7.1. Comparison of GPS and Levelling subsidence.

In all epochs, except 1993 to 1994, the GPS subsidence show uplifts of many of the points, due to tilts in the results. Pooled error ellipses of the subsidence determination, after the least squares adjustments, are on average 70mm (@95%).

A test was carried out to remove the subsidence (taken from the levelling results) to see if a common bias would remain. Results are tabulated in table 7.2. Between all years and all solution types vertical rotations about one or both horizontal axis were seen. Rotations vary between 2-7ppm (0.4-1.4") and are seen in all solution types. However, a significant decrease is seen between 1993 and 1994, with the dual frequency solutions. The most probable causes of vertical rotations are mis-modelling of the tropospheric delay or ephemeris errors. GPS subsidence before the removal of rotation bias is seen in figure 7.1, for one case.

Epochs	Solution Types	About N/S axis (ppm)	About E/W axis (ppm)
1990-1991	T(L1) - T(L1)	-	4.8±0.7
1991-1992	T(L1) - T(L1)	3.5±0.7	-7.1±0.6
	T(L1) - G(L1)	3.6±0.8	-7.1±0.7
1992-1993	G(L1) - G(L1)	-3.7±0.6	4.5±0.6
	T(L1) - T(L0)	-5.6±0.5	4.8±0.5
	G(L1) - G(L3)	-4.5±0.6	5.4±0.5
1993-1994	T(L0) - T(L0)	-	0.8±0.3
	G(L3) - G(L3)	0.5±0.3	-
1990-1994	T(L1) - T(L0)	-2.7±0.5	2.1±0.5
Key :	T = TRIMMBP G = GPPS		

Table 7.2. GPS vertical rotation between years and solution types.

Taking the differences between the levelling subsidence and the GPS subsidence as true differences, an approximate accuracy for the GPS subsidence, could be estimated. We can also estimate a value for the accuracy of the GPS heights for one campaign, by subtracting the levelling accuracy (10mm, @68%).

$$\sigma^2_{GPS} = \sigma^2_{Diff} - \sigma^2_{Lev} \tag{7.1}$$

where

$$\sigma_{Diff} = \sqrt{\frac{\sum Diff^2}{2n}} \tag{7.2}$$

The results are tabulated in table 7.3, column one. These are pessimistic estimates as they are contaminated by the rotation biases. Rotations were removed from all cases and GPS subsidence re-calculated. A remarkable improvement was seen in all solution types, bar one.

Campaign and Solution Types	GPS Hgt Accuracy Before Removal (mm)	GPS Hgt Accuracy After Removal (mm)
T 90 L1 - T 91 L1	53	21
T 91 L1 - T 92 L1	82	16
T 91 L1 - G 92 L1	82	20
T 92 L1 - T 93 L0	64	12
G 92 L1 - G 93 L1	51	18
G 92 L1 - G 93 L3	63	19
T 93 L0 - T 94 L0	13	15 (5, without 1 outlier)
G 93 L3 - G 94 L3	13	5
T 90 L1 - T 94 L0	26	13

Table 7.3. Estimated GPS height accuracy (@68% confidence), for one campaign, before and after removal of the rotations.

Between TRIMMBP 1993 and 1994, a slight degradation of the accuracy is seen. This is because of one outlier. After its removal, both solution types were at a similar level. GPS subsidence after rotation removal is seen in table 7.4 (all cases) and figure 7.2. GPS height accuracy was re-estimated and is shown in table 7.3, column two.

Stn.	1991-90	1992-91		1993-92			1994-93		1994-90
	TRIM	TRIM	GPPS	TRIM	GPPS	GPPS	TRIM	GPPS	TRIM
	L1-L1	L1-L1	L1-L1	L0-L1	L3-L1	L1-L1	L0-L0	L3-L3	L0-L1
0011	-0.007	-0.033	-0.041	-0.061	-0.033	-0.044	0.013	-0.055	-0.103
0012	0.010			-0.037	-0.011	-0.003	-0.036	-0.035	-0.092
0014	0.009	-0.002	-0.006	-0.009	0.032	0.040	-0.024	-0.004	-0.036
0100	-0.036	0.055	0.054	0.007	0.027	0.027	-0.028	-0.024	0.003
0184	-0.023	0.014	0.025	0.009	0.001	0.004			
0300	0.008	-0.012	-0.049	-0.013	-0.069	-0.074	-0.042	-0.032	-0.065
0500	-0.105	0.007	0.028	-0.037	-0.059	-0.049			
0600				-0.040	-0.078	-0.072	-0.046	-0.073	-0.247
0700				-0.003	0.023	0.030	0.006	-0.008	0.041
0743	0.043	-0.043	-0.022	0.034	0.046	0.033	-0.010	0.001	0.023
0800				0.023	0.043	0.041	-0.008	-0.019	0.031
0900				0.025	0.030	0.035	0.006	-0.040	-0.006
1010	-0.029	-0.048	-0.048	-0.056	-0.057	-0.054	-0.044	-0.051	-0.189
1200	-0.040	-0.024	-0.009	-0.055	-0.044	-0.056	-0.035	-0.027	-0.161
1300	-0.036			-0.008	-0.028	-0.026	-0.013	0.001	-0.024
2900	-0.063	-0.026	-0.027	-0.015	-0.016	-0.007	-0.043	-0.081	-0.163
9201				0.004	0.009	0.026	-0.077	-0.038	
9202				-0.018	-0.023	-0.015	-0.007	0.004	
9203				0.045	0.041	0.043	-0.001	-0.011	
0202	fixed	fixed	fixed	fixed	fixed	fixed	fixed	fixed	fixed

Table 7.4. GPS subsidence, after removal of vertical rotations (m).

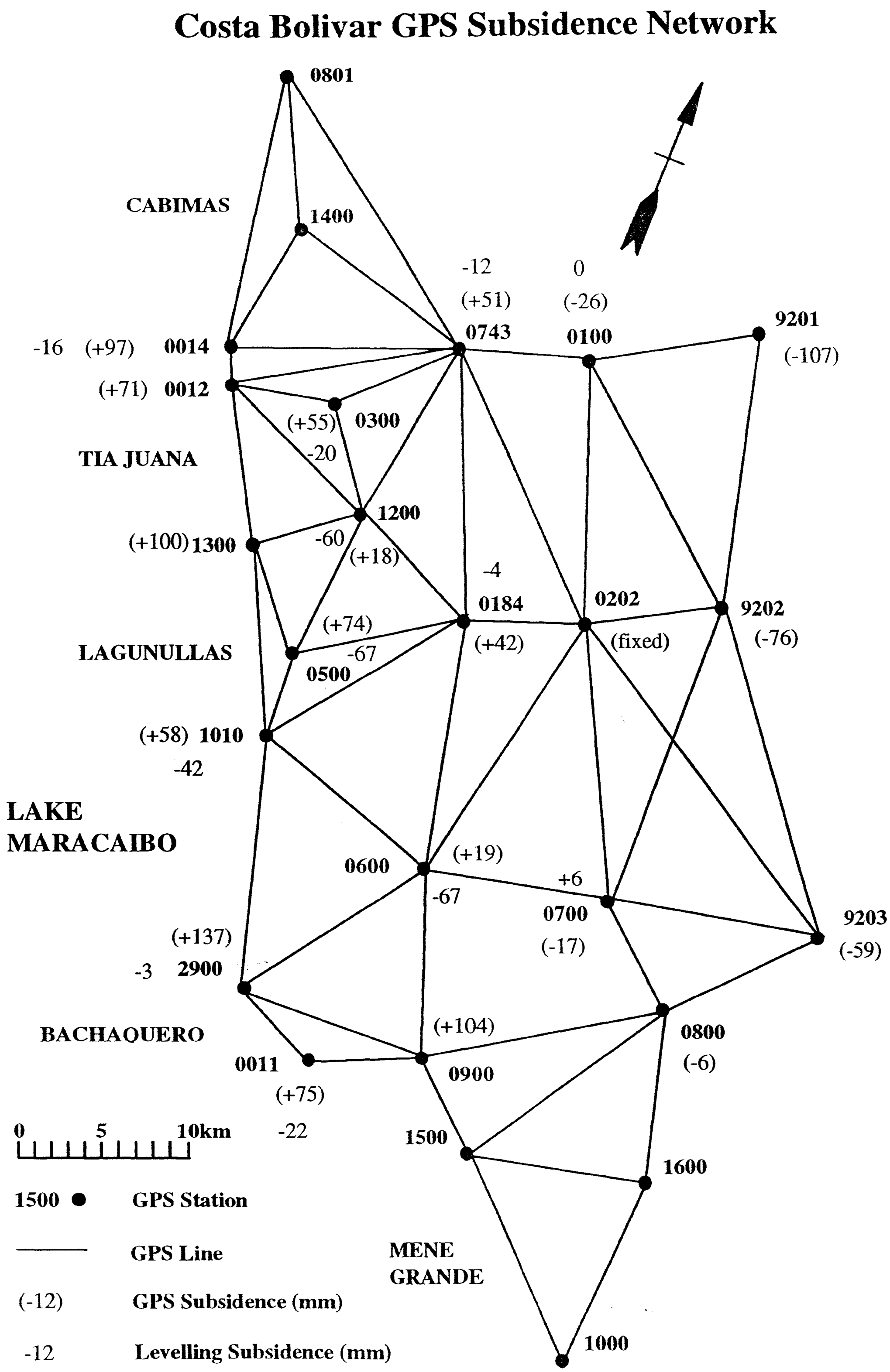

Figure 7.1. GPS and Levelling subsidence. 1992 to 1993, before rotation removal.

Costa Bolivar GPS Subsidence Network

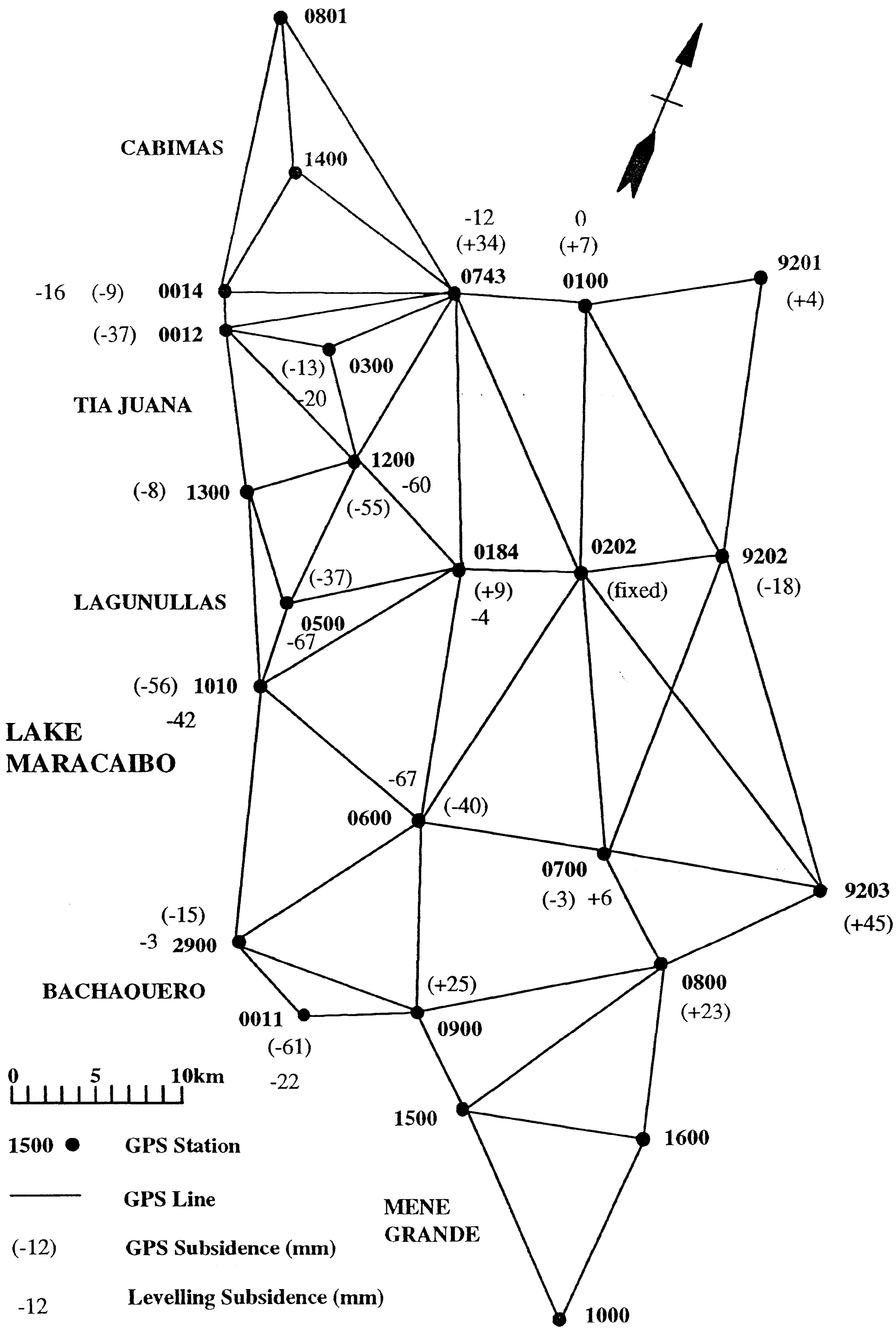

Figure 7.2. GPS and Levelling subsidence. 1992 to 1993, after rotation removal.

It can be seen that the GPS accuracy of the heights for one campaign showed a vast improvement after removal of the rotations. The values attained from the subsidence differences are in stark contrast to the values attained from the least squares adjustments and MINQE analysis of one campaign. It is required that GPS heights for one campaign give an accuracy of <15mm (@68%). According to the estimates obtained through the subsidence differences, this has been achieved during the last two years.

7.3 Discussion

The results have shown that horizontal deformation can be detected regardless of solution type, providing biases are removed from the non ionospheric solutions, i.e. L1 and L0. This was demonstrated in the 1992 test baselines and the campaigns of 1992 to 1994. Vertical subsidence shows very comparable results to levelling, also regardless of solution type, once biases are removed. The last two years saw a drastic reduction in the vertical rotations, decreasing to less than 1ppm, between the two dual frequency campaigns. This would suggest a possible frequency dependent effect such as the ionospheric delay. Although the estimated accuracy of the GPS heights has approached the required level, without any proper treatment of the tropospheric delay in the post processing stage, further investigation is still required to assess the true cause of the rotations.

Conclusions and Recommendations

The following conclusions have been drawn from the evaluation of the past five GPS campaigns between 1990 and 1994.

First and foremost, it would appear that the present GPS methodology, field technique, and post processing employed, is unable to compete with precise levelling at the desired accuracy (subsidence: 20-30mm, @95%). Analysis of the error ellipses after the least squares adjustment, reveal that the GPS will provide 50mm and 70mm (@95%) for the subsidence in the horizontal and vertical components, respectively. However, a comparison of the subsidence differences between the GPS and levelling reveal the accuracy to be much better, in the order of 40mm (@95%) for the subsidence. Estimates of the last two campaigns have shown an improvement due to less noisy, dual frequency data, from a more complete satellite constellation.

As with previous studies of earlier campaigns, systematic biases, mainly horizontal scale changes up to 5ppm and vertical rotations up to 1.4", still exist in the data. Biases are independent of processor type, considering the two commercial software packages used in this study, but are dependent on the type of processing solution employed. Biases vary from year to year, and a considerable decrease is seen in the last two epochs. Although large horizontal biases are still evident during this period, these can be handled adequately using a suitable solution type. Vertical rotations were reduced to less than 1ppm, during these periods of dual frequency data. The cause of this needs further investigation.

Single frequency solutions contain biases in the horizontal and vertical components. The two dual frequency solution types gave very compatible results in the height, and agreed reasonably well with the levelling subsidence, in the last epoch, prior to removal of biases, which is fairly promising. TRIMMBP L0 solutions suffered horizontal scale biases, due to the non treatment of the ionosphere. L3 solutions seemed to be free of horizontal biases, but their larger error ellipses show displacements to be less significant, due to the L3 combination being inherently noisier than other combinations.

The test baselines from 1992 demonstrated that consistent deformation results can be attained in the baseline length, with suitable solution types, but the height component needs modelling to remove rotations. GPPS L0 showed very good agreement with L3, in both baseline length and the height, but both suffered a similar bias in the height, masking the subsidence trend. This is contrary to the reasonable agreement in height attained in later years. Inadequate handling of the tropospheric delay is the suspected cause.

The removal of horizontal biases gave compatible displacements regardless of solution type. This on the whole is also quite promising. However, the poor day to day repeatability and weak solutions, made for large error ellipses in all solution types, reducing the significance of the displacements.

MINQE analysis gave very similar results for the least squares error ellipses, indicating that software weights obtained from the software solutions for the baseline components are suitable providing one scales the covariance matrix by the a posteriori variance factor from the post adjustment.

Relative accuracy (for two successive campaigns) is deemed to be about 1ppm and 1.5ppm in the horizontal and vertical displacements respectively, with the present arrangement. An improved accuracy should be attained with some modifications. Three options are considered.

(1) If commercial software are still to be employed, then longer sessions (possibly 4hrs) or more importantly, extra sessions are needed. At present, each station is only visited once to three times per campaign. All stations should be observed in at least three different sessions. The author feels that a large redundancy of data is important, when using commercial software, in such a situation. In the post processing stage, the use of a *wide-lane ionospheric free* combination is very beneficial. The present Trimble software, being employed, does not allow this. However, the new Trimble *GPS Survey* does allow a similar combination. Although present commercial software provide linear combinations with a long wavelength, fixed ambiguity, and ionospheric reduction, they still lack

adequate handling of the tropospheric delay, which in this case study is quite likely to be a limiting factor.

(2) It is highly recommended by the author that the switch to a more sophisticated, i.e. scientific style, processor be made, if the desired accuracy is to be achieved, in a project of this size and nature. Such software today provide the above linear combinations and allow for stochastic modelling of the tropospheric effect. This should be first tested using the 1993 - 1994 data sets.

(3) The use of the so called fiducial station strategy would be very beneficial in this network to elliminate the effects of systematic biases, from year to year.

The use of Trimble 4000SST receivers will also be a restricting factor, considering the *permanent* activation of Anti Spoofing. Upgrading to the much improved Trimble 4000SSE receivers, which can recover the P-code group delay, would be beneficial, and a necessity if the above linear combinations are to be employed.

The overall conclusion is that the use of the GPS in precision geodetic surveys in the hot and humid climate of the equatorial region, still requires further research. The systematic biases (rotations and scale changes) of the GPS network are much larger than those experienced in more moderate climates, as discussed by other authors.

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Appendix A

Baseline Results 1992 to 1994

This appendix contains tables of the individual baseline components ($\delta\phi$, $\delta\lambda$ and δh) for each solution type, during the years 1992 to 1994. Where applicable differences are also given between different solution types.

Note: tables in this appendix may extend over a page.

Table A1. 1992 GPPS L1 and TRIMMBP L1 solutions.
Baseline components in Phi/Lambda/Height, and software differences.

Day/ Sess		Stn. 1	Stn. 2	GPPS L1 fixed solutions. rms (m)	ISR	Delta Phi (dms)			Delta Lambda (dms)			dh (m)	TRIMMBP L1 fixed solutions. rms (cyc)	ISR	Delta Phi (dms)			Delta Lambda (dms)			dh (m)	Software Diff's. (mm) ϕ	λ	h
119	1	0202	9202	0.022	100.0	0	2	59.74602	0	3	1.37466	29.674	0.073	3.7	0	2	59.74598	0	3	1.37467	29.671	1	0	3
119	1	0202	0100	0.030	100.0	0	7	48.88589	0	3	29.37683	44.060	0.109	2.1	0	7	48.88575	0	3	29.37685	44.053	4	-1	7
119	1	0202	0700	0.024	100.0	0	5	36.82514	0	6	10.76890	3.419	0.120	1.8	0	5	36.82607	0	6	10.76117	3.352	-29	235	67
119	1	0100	9201	0.022	100.0	0	3	38.07018	0	4	27.41300	13.612	0.059	3.4	0	3	38.07011	0	4	27.41305	13.606	2	-2	6
119	1	9202	9201	0.031	98.8	0	8	27.21012	0	2	3.33866	28.003	0.086	2.9	0	8	27.20984	0	2	3.33875	27.996	9	-3	7
119	1	9202	0700	0.029	100.0	0	8	36.57124	0	3	9.39427	33.090	0.112	1.8	0	8	36.57110	0	3	9.39417	33.087	4	3	3
120	1	0202	0100	0.053	99.2	0	7	48.88758	0	3	29.37751	44.110	0.053	1.2	0	7	48.88713	0	3	29.37710	44.094	14	12	16
120	1	0202	9202	0.023	100.0	0	2	59.74624	0	3	1.37412	29.694	0.093	4.6	0	2	59.74635	0	3	1.37419	29.693	-3	-2	1
120	1	0202	9203	0.050	77.2	0	2	48.93986	0	12	30.94301	86.107	0.195	1.2	0	2	48.94162	0	12	30.94455	86.020	-54	-47	87
120	1	0100	9201	0.023	99.9	0	3	38.07007	0	4	27.41297	13.663	0.073	3.6	0	3	38.07014	0	4	27.41316	13.663	-2	-6	0
120	1	9202	9201	0.038	82.5	0	8	27.21098	0	2	3.34342	28.214	0.182	1.6	0	8	27.21120	0	2	3.34817	28.362	-7	-145	-148
120	1	9202	9203	0.054	69.6	0	5	48.68682	0	9	29.56936	56.368	0.206	1.6	0	5	48.68847	0	9	29.56977	56.314	-51	-12	54
121	1	0202	9202	0.030	100.0	0	2	59.74588	0	3	1.37441	29.691	0.083	1.2	0	2	59.74613	0	3	1.37417	29.687	-8	7	4
121	1	0202	0700	0.024	100.0	0	5	36.82543	0	6	10.76915	3.431	0.085	4.9	0	5	36.82528	0	6	10.76892	3.413	5	7	18
121	1	9203	9202	0.058	97.5	0	5	48.68563	0	9	29.56626	56.271	0.235	1.4	0	5	48.68778	0	9	29.57610	56.418	-66	-300	-147
121	1	0700	0800	0.016	100.0	0	2	31.50287	0	3	35.36518	12.932	0.056	1.5	0	2	31.50301	0	3	35.36507	12.921	-4	3	11
121	1	0700	9203	0.037	100.0	0	2	47.88485	0	6	20.17505	89.553	0.078	1.5	0	2	47.88504	0	6	20.17529	89.510	-6	-7	43
121	1	9203	0800	0.031	100.0	0	5	19.38768	0	2	44.80998	76.610	0.206	1.2	0	5	19.38817	0	2	44.80549	76.810	-15	137	-200
125	1	0743	0801	0.029	89.7	0	7	6.05687	0	10	57.69066	53.299	0.110	1.9	0	7	6.05575	0	10	57.69469	53.101	34	-123	198
125	1	0743	1400	0.017	99.9	0	0	31.74286	0	7	52.22734	42.763	0.060	2.3	0	0	31.74289	0	7	52.22731	42.759	-1	1	4
125	1	1400	0801	0.020	96.0	0	6	34.31408	0	3	5.46264	10.568	0.070	1.7	0	6	34.31416	0	3	5.46266	10.571	-2	-1	-2
126	1	0743	0801	0.030	98.6	0	7	6.05413	0	10	57.69667	53.414	0.103	1.2	0	7	6.04999	0	10	57.68915	53.198	127	229	216
126	1	0743	0014	0.025	99.7	0	2	9.00510	0	6	47.19265	51.310	0.092	1.7	0	2	9.00512	0	6	47.19259	51.297	-1	2	13
126	1	0014	0801	0.025	99.7	0	9	15.06060	0	4	10.49621	2.185	0.091	1.1	0	9	15.06067	0	4	10.49619	2.199	-2	1	-14
126	2	0743	0014	0.019	99.9	0	2	9.00539	0	6	47.19341	51.306	0.073	1.5	0	2	9.00562	0	6	47.19354	51.283	-7	-4	23
126	2	0743	1400	0.018	100.0	0	0	31.74224	0	7	52.22802	42.822	0.164	2.6	0	0	31.74020	0	7	52.23237	42.590	63	-132	232

126	2	1400	0014	0.010	100.0	0	2	40.74763	0	1	5.03458	8.485	0.040	5.3	0	2	40.74761	0	1	5.03460	8.468	1	-1	17
127	1	0743	0014	0.019	99.9	0	2	9.00517	0	6	47.19370	51.317	0.069	3.5	0	2	9.00501	0	6	47.19371	51.285	5	0	32
127	1	0743	0012	0.020	99.9	0	3	20.59060	0	5	59.32993	50.412	0.076	2.9	0	3	20.59046	0	5	59.32992	50.399	4	0	13
127	1	0014	0012	0.007	100.0	0	1	11.58539	0	0	47.86373	0.903	0.024	33.2	0	1	11.58543	0	0	47.86369	0.886	-1	1	17
127	2	1200	1300	0.012	100.0	0	1	51.85384	0	1	49.23984	6.754	0.043	9.1	0	1	51.85385	0	1	49.23988	6.739	0	-1	15
127	2	0500	1200	0.019	92.9	0	4	50.52734	0	0	25.74526	8.415	0.039	1.3	0	4	50.53174	0	0	25.73419	8.515	-135	337	-100
127	2	0500	1300	0.020	96.1	0	2	58.67408	0	2	14.97804	1.606	0.056	1.3	0	2	58.67765	0	2	14.97385	1.782	-110	128	-176
128	1	0500	1300	0.012	99.9	0	2	58.67358	0	2	14.97905	1.683	0.056	1.9	0	2	58.67326	0	2	14.97846	1.779	10	18	-96
128	1	0500	0300	0.030	96.4	0	8	40.27373	0	3	13.47725	12.585	0.051	2.7	0	8	40.26214	0	3	13.48767	12.850	356	-317	-265
128	1	1300	0300	0.011	100.0	0	5	41.59997	0	0	58.49748	10.817	0.046	1.3	0	5	41.60235	0	0	58.50677	10.589	-73	-283	228
128	2	1200	0743	0.057	75.3	0	6	42.51985	0	0	17.13910	43.376	0.196	1.1	0	6	42.52174	0	0	17.12305	43.349	-58	489	27
128	2	0300	0743	0.071	85.1	0	2	52.76944	0	2	30.58606	39.441	0.173	1.0	0	2	52.76636	0	2	30.56251	39.705	95	717	-264
128	2	1200	0300	0.046	81.3	0	3	49.75024	0	2	47.72522	3.918	0.218	1.3	0	3	49.75176	0	2	47.73084	3.829	-47	-171	89
129	1	1300	0012	0.012	100.0	0	5	13.77661	0	4	27.23657	0.134	0.187	1.7	0	5	13.77705	0	4	27.23827	0.030	-14	-52	104
129	1	1300	0300	0.011	100.0	0	5	41.59936	0	0	58.49737	10.772	0.042	5.7	0	5	41.59943	0	0	58.49736	10.738	-2	0	34
129	1	0300	0012	0.009	100.0	0	0	27.82274	0	3	28.73912	10.912	0.038	9.7	0	0	27.82274	0	3	28.73910	10.903	0	1	9
129	2	0184	0743	0.022	99.9	0	7	44.76360	0	5	3.71501	26.223	0.086	3.0	0	7	44.76362	0	5	3.71504	26.228	-1	-1	-5
129	2	0184	1200	0.021	99.8	0	1	2.24940	0	4	46.56695	17.231	0.039	5.1	0	1	2.24930	0	4	46.56675	17.220	3	6	11
129	2	1200	0743	0.018	99.9	0	6	42.51420	0	0	17.14806	43.454	0.070	7.3	0	6	42.51422	0	0	17.14807	43.455	-1	0	-1
130	1	0184	0500	0.012	100.0	0	3	48.27888	0	4	20.82882	25.607	0.044	4.0	0	3	48.27881	0	4	20.82882	25.585	2	0	22
130	1	0184	1200	0.013	99.9	0	1	2.24904	0	4	46.56691	17.265	0.048	3.0	0	1	2.24900	0	4	46.56700	17.263	1	-3	3
130	1	0500	1200	0.014	96.5	0	4	50.52792	0	0	25.73809	8.342	0.044	2.3	0	4	50.52773	0	0	25.73822	8.308	6	-4	35
132	1	0100	0184	0.025	95.6	0	8	55.22561	0	1	14.29248	70.450	0.175	1.2	0	8	55.22651	0	1	14.28708	70.311	-28	164	139
132	1	0743	0184	0.023	82.0	0	7	44.76385	0	5	3.71080	26.211	0.167	1.3	0	7	44.76475	0	5	3.70937	26.180	-28	44	31
132	1	0100	0743	0.024	98.3	0	1	10.46298	0	3	49.42991	44.085	0.120	1.9	0	1	10.46175	0	3	49.42231	44.130	38	231	-44
132	2	0202	0184	0.015	100.0	0	1	6.33947	0	2	15.09299	26.256	0.053	5.5	0	1	6.33947	0	2	15.09298	26.259	0	0	-3
132	2	0202	0743	0.024	98.2	0	6	38.42161	0	7	18.81498	0.082	0.075	1.9	0	6	38.42138	0	7	18.81447	0.053	7	16	29
132	2	0184	0743	0.018	92.0	0	7	44.76140	0	5	3.71789	26.289	0.107	1.3	0	7	44.76292	0	5	3.71460	26.263	-47	100	26
133	1	0184	0600	0.019	100.0	0	6	50.96783	0	3	22.72104	13.161	0.059	4.9	0	6	50.96792	0	3	22.72111	13.157	-3	-2	4
133	1	0184	1010	0.014	99.9	0	4	41.60014	0	3	52.03861	24.624	0.048	5.0	0	4	41.60013	0	3	52.03862	24.611	0	0	13
133	1	1010	0600	0.016	100.0	0	2	9.36784	0	7	14.75954	11.448	0.061	2.8	0	2	9.36782	0	7	14.75956	11.431	1	-1	17
133	2	1010	1300	0.017	100.0	0	3	51.99466	0	2	43.76749	0.587	0.064	2.9	0	3	51.99466	0	2	43.76749	0.585	0	0	2

133	2	0500	1010	0.006	100.0	0	0	53.32194	0	0	28.78942	0.981	0.020	24.8	0	0	53.32196	0	0	28.78940	1.000	-1	1	-19
133	2	0500	1300	0.016	100.0	0	2	58.67272	0	2	14.97808	1.567	0.057	3.5	0	2	58.67272	0	2	14.97811	1.583	0	-1	-16
134	1	0600	2900	0.031	100.0	0	6	18.76813	0	3	38.40746	11.566	0.092	1.6	0	6	18.76792	0	3	38.40750	11.536	6	-1	30
134	1	0600	1010	0.044	99.9	0	2	9.36787	0	7	14.75465	11.622	0.148	1.4	0	2	9.36813	0	7	14.75885	11.413	-8	-128	209
134	1	2900	1010	0.046	100.0	0	8	28.13579	0	3	36.35136	0.115	0.133	1.4	0	8	28.13617	0	3	36.34505	0.019	-12	192	97
135	1	0600	0700	0.026	99.5	0	2	20.48359	0	5	3.13973	36.024	0.143	1.2	0	2	20.48258	0	5	3.13210	36.074	31	232	-50
135	1	0184	0700	0.055	98.3	0	4	30.48416	0	8	25.85497	23.090	0.197	1.1	0	4	30.48491	0	8	25.85448	23.040	-23	15	50
135	1	0184	0600	0.045	94.3	0	6	50.96815	0	3	22.71722	13.041	0.210	1.8	0	6	50.96889	0	3	22.71293	13.007	-23	131	34
136	1	0700	0600	0.022	99.6	0	2	20.48280	0	5	3.13962	36.045	0.090	6.4	0	2	20.48352	0	5	3.14728	36.025	-22	-233	20
136	1	0700	0800	0.022	95.3	0	2	31.50211	0	3	35.36442	12.951	0.085	3.4	0	2	31.50320	0	3	35.35792	13.079	-33	198	-128
136	1	0800	0600	0.021	94.8	0	0	11.01935	0	8	38.50426	49.086	0.062	1.4	0	0	11.01932	0	8	38.50559	49.094	1	-40	-8
136	2	0202	0600	0.016	75.6	0	7	57.31028	0	1	7.62794	39.262	0.114	1.3	0	7	57.31106	0	1	7.64476	39.155	-24	-512	107
136	2	0600	0900	0.019	89.5	0	5	18.29987	0	2	33.17816	5.103	0.086	1.5	0	5	18.29872	0	2	33.18265	5.239	35	-137	-136
136	2	0202	0900	0.033	92.6	0	13	15.61001	0	3	40.80521	44.373	0.123	1.1	0	13	15.61088	0	3	40.80964	44.479	-27	-135	-106
139	1	0600	2900	0.021	99.8	0	6	18.76810	0	3	38.40674	11.522	0.043	4.6	0	6	18.76812	0	3	38.40741	11.550	-1	-20	-28
139	1	0600	0011	0.020	98.1	0	7	12.68627	0	1	19.55968	11.509	0.045	4.1	0	7	12.68636	0	1	19.56040	11.541	-3	-22	-32
139	1	0011	2900	0.008	100.0	0	0	53.91821	0	2	18.84707	0.015	0.032	6.0	0	0	53.91823	0	2	18.84710	0.014	-1	-1	1
139	2	2900	0900	0.011	100.0	0	1	0.47014	0	6	11.58714	6.252	0.085	2.1	0	1	0.47032	0	6	11.58910	6.295	-6	-60	-43
139	2	0900	0011	0.013	98.1	0	1	54.38860	0	3	52.74180	6.294	0.051	5.3	0	1	54.38854	0	3	52.74181	6.277	2	0	17
139	2	2900	0011	0.013	100.0	0	0	53.91814	0	2	18.84725	0.015	0.049	5.6	0	0	53.91820	0	2	18.84727	0.018	-2	-1	-3
140	1	0800	0900	0.019	82.7	0	5	7.27757	0	6	5.32480	54.287	0.084	1.4	0	5	7.27815	0	6	5.32975	54.240	-18	-151	47
140	1	0800	1500	0.035	95.1	0	11	26.82121	0	0	44.33630	49.968	0.126	1.4	0	11	26.82120	0	0	44.33622	49.961	0	2	7
140	1	0900	1500	0.021	95.4	0	6	19.54400	0	5	20.98716	4.404	0.080	1.1	0	6	19.54426	0	5	20.98858	4.500	-8	-43	-96
140	2	0011	0900	0.010	100.0	0	1	54.38834	0	3	52.74245	6.276	0.038	7.6	0	1	54.38833	0	3	52.74240	6.262	0	2	14
140	2	1500	0900	0.022	100.0	0	6	19.54418	0	5	20.98896	4.525	0.077	1.9	0	6	19.54414	0	5	20.98900	4.517	1	-1	8
140	2	1500	0011	0.015	100.0	0	4	25.15555	0	9	13.73062	10.776	0.087	1.3	0	4	25.15581	0	9	13.73138	10.781	-8	-23	-5
141	1	0800	1500	0.024	97.8	0	11	26.82143	0	0	44.33353	49.726	0.098	1.4	0	11	26.82257	0	0	44.34117	49.686	-35	-233	40
141	1	0800	1600	0.022	90.9	0	7	5.64121	0	6	19.43730	57.025	0.095	1.1	0	7	5.64115	0	6	19.43717	57.042	2	4	-17
141	1	1600	1500	0.013	99.5	0	4	21.18022	0	7	3.77080	106.772	0.069	1.7	0	4	21.17916	0	7	3.76311	106.799	33	234	-26
141	2	1500	1600	0.009	100.0	0	4	21.18011	0	7	3.77177	106.807	0.038	11.0	0	4	21.18006	0	7	3.77177	106.806	2	0	1
141	2	1500	1000	0.016	99.3	0	3	57.04366	0	5	24.60440	26.230	0.130	1.4	0	3	57.04424	0	5	24.60601	26.106	-18	-49	124
141	2	1600	1000	0.018	100.0	0	8	18.22031	0	1	39.16726	80.740	0.207	2.1	0	8	18.22407	0	1	39.16979	80.863	-116	-77	-123

Table A2. 1993 GPPS L3 and TRIMMBP L0 solutions.
Baseline components in Phi/Lambda/Height, and software differences.

Day/ Sess		Stn. 1	Stn. 2	GPPS L3 fixed solutions. rms (m)	ISR	Delta Phi (dms)			Delta Lambda (dms)			dh (m)	TRIMMBP L0 fixed solutions. rms (cyc)	ISR	Delta Phi (dms)			Delta Lambda (dms)			dh (m)	Software Diff's. ϕ (mm)	λ (mm)	h (mm)
214	1	0014	0300	0.012	N/A	0	0	43.76254	0	4	16.60328	11.753	0.018	106.3	0	0	43.76268	0	4	16.60376	11.760	-4	-15	-7
214	1	0743	0300	0.014	N/A	0	2	52.76749	0	2	30.59059	39.478	0.019	93.3	0	2	52.76785	0	2	30.58991	39.485	-11	21	-7
214	1	0743	0014	0.013	N/A	0	2	9.00496	0	6	47.19370	51.232	0.018	95.2	0	2	9.00519	0	6	47.19369	51.246	-7	0	-14
214	3	0300	0012	0.021	N/A	0	0	27.82278	0	3	28.74092	10.931	0.024	13.2	0	0	27.82317	0	3	28.74009	10.898	-12	25	33
214	3	0300	0014	0.023	N/A	0	0	43.76282	0	4	16.60447	11.792	0.028	11.8	0	0	43.76295	0	4	16.60426	11.763	-4	6	29
214	3	0012	0014	0.016	N/A	0	1	11.58564	0	0	47.86380	0.879	0.021	17.8	0	1	11.58620	0	0	47.86442	0.851	-17	-19	28
215	1	1300	0012	0.012	N/A	0	5	13.77791	0	4	27.23668	0.187	0.017	100.8	0	5	13.77836	0	4	27.23743	0.204	-14	-23	-17
215	1	0300	0012	0.013	N/A	0	0	27.82310	0	3	28.73945	10.882	0.018	89.3	0	0	27.82343	0	3	28.73953	10.892	-10	-2	-10
215	1	0300	1300	0.013	N/A	0	5	41.60101	0	0	58.49723	10.696	0.017	105.8	0	5	41.60180	0	0	58.49790	10.687	-24	-20	9
215	3	0300	1200	0.018	N/A	0	3	49.74710	0	2	47.73620	3.999	0.025	41.4	0	3	49.74760	0	2	47.73874	4.022	-15	-77	-23
215	3	0300	1300	0.015	N/A	0	5	41.60094	0	0	58.49590	10.704	0.023	49.1	0	5	41.60231	0	0	58.49788	10.721	-42	-60	-17
215	3	1300	1200	0.015	N/A	0	1	51.85376	0	1	49.24013	6.720	0.023	53.0	0	1	51.85474	0	1	49.24079	6.699	-30	-20	21
216	1	1200	0300	0.018	N/A	0	3	49.74671	0	2	47.73930	4.037	0.022	47.0	0	3	49.74686	0	2	47.73862	4.027	-5	21	10
216	1	0743	0300	0.021	N/A	0	2	52.76771	0	2	30.58944	39.469	0.022	41.7	0	2	52.76802	0	2	30.59001	39.480	-10	-17	-11
216	1	0743	1200	0.016	N/A	0	6	42.51445	0	0	17.14997	43.508	0.021	53.0	0	6	42.51492	0	0	17.14862	43.507	-14	41	1
216	3	0743	1200	0.014	N/A	0	6	42.51434	0	0	17.14856	43.495	0.023	49.3	0	6	42.51603	0	0	17.14864	43.512	-52	-2	-17
216	3	0184	0743	0.017	N/A	0	7	44.76331	0	5	3.71634	26.235	0.027	38.3	0	7	44.76589	0	5	3.71656	26.208	-79	-7	27
216	3	0184	1200	0.017	N/A	0	1	2.24890	0	4	46.56774	17.259	0.023	50.3	0	1	2.24980	0	4	46.56779	17.308	-28	-2	-49
217	1	0202	0743	0.017	N/A	0	6	38.42456	0	7	18.80929	0.048	0.030	20.5	0	6	38.42549	0	7	18.80802	0.008	-29	39	40
217	1	0202	0184	0.015	N/A	0	1	6.33918	0	2	15.09277	26.233	0.020	55.0	0	1	6.33922	0	2	15.09288	26.253	-1	-3	-20
217	1	0184	0743	0.017	N/A	0	7	44.76374	0	5	3.71670	26.284	0.030	19.6	0	7	44.76465	0	5	3.71536	26.259	-28	41	25
217	3	0202	0743	0.023	N/A	0	6	38.42521	0	7	18.80724	0.049	0.037	19.9	0	6	38.42642	0	7	18.81032	0.074	-37	-94	-25
217	3	0202	0100	0.025	N/A	0	7	49.99714	0	3	28.22339	44.353												
217	3	0743	0100	0.023	N/A	0	1	11.57221	0	3	50.58356	44.401												
218	1	9201	0100	0.015	N/A	0	3	38.07054	0	4	27.41383	13.545	0.022	35.7	0	3	38.07092	0	4	27.41474	13.536	-12	-28	9

218	1	0202	0100	0.016	N/A	0	7	48.88765	0	3	29.37920	44.084	0.024	27.8	0	7	48.88834	0	3	29.37835	44.031	-21	26	53
218	1	0202	9201	0.014	N/A	0	11	26.95823	0	0	58.03430	57.630	0.025	28.0	0	11	26.95924	0	0	58.03649	57.573	-31	-67	58
218	3	0202	9202	0.020	N/A	0	2	59.74721	0	3	1.37714	29.552	0.027	37.6	0	2	59.74691	0	3	1.37530	29.569	9	56	-17
218	3	0202	9201	0.020	N/A	0	11	26.95790	0	0	58.03816	57.529												
218	3	9202	9201	0.017	N/A	0	8	27.21066	0	2	3.33881	27.976	0.032	33.1	0	8	27.21348	0	2	3.33924	28.001	-87	-13	-25
221	1	1300	0500	0.016	N/A	0	2	58.67423	0	2	14.97905	1.646	0.020	76.9	0	2	58.67421	0	2	14.97885	1.642	1	6	4
221	1	1200	0500	0.016	N/A	0	4	50.52796	0	0	25.73791	8.321	0.022	68.3	0	4	50.52816	0	0	25.73845	8.301	-6	-16	20
221	1	1200	1300	0.014	N/A	0	1	51.85373	0	1	49.24110	6.675	0.019	95.4	0	1	51.85398	0	1	49.24043	6.662	-8	20	13
221	3	0184	0500	0.020	N/A	0	3	48.27884	0	4	20.82857	25.566	0.027	38.3	0	3	48.27894	0	4	20.82950	25.552	-3	-28	14
221	3	0184	1200	0.022	N/A	0	1	2.24893	0	4	46.56648	17.242	0.025	45.0	0	1	2.24945	0	4	46.56780	17.233	-16	-40	9
221	3	0500	1200	0.020	N/A	0	4	50.52781	0	0	25.73791	8.330	0.026	41.4	0	4	50.52832	0	0	25.73820	8.318	-16	-9	12
222	1	0184	0500	0.016	N/A	0	3	48.27870	0	4	20.82731	25.552	0.024	47.3	0	3	48.27879	0	4	20.82908	25.544	-3	-54	8
222	1	0184	1010	0.014	N/A	0	4	41.60042	0	3	52.03829	24.568	0.021	63.8	0	4	41.60078	0	3	52.03979	24.570	-11	-46	-2
222	1	1010	0500	0.012	N/A	0	0	53.32172	0	0	28.78902	0.984	0.018	94.8	0	0	53.32199	0	0	28.78933	0.974	-8	-9	10
222	3	0184	0600	0.019	N/A	0	6	50.97078	0	3	22.72021	13.234	0.028	23.2	0	6	50.97175	0	3	22.72076	13.237	-30	-17	-3
222	3	0184	1010	0.017	N/A	0	4	41.60032	0	3	52.03868	24.597	0.036	14.8	0	4	41.60139	0	3	52.04035	24.613	-33	-51	-16
222	3	1010	0600	0.016	N/A	0	2	9.37043	0	7	14.75893	11.365	0.030	27.0	0	2	9.37065	0	7	14.76116	11.354	-7	-68	11
223	1	0600	0184	0.013	N/A	0	6	50.97103	0	3	22.71989	13.218	0.021	59.1	0	6	50.97122	0	3	22.71970	13.200	-6	6	18
223	1	0202	0184	0.013	N/A	0	1	6.33875	0	2	15.09310	26.230	0.020	80.4	0	1	6.33894	0	2	15.09299	26.242	-6	3	-11
223	1	0202	0600	0.012	N/A	0	7	57.30971	0	1	7.62690	39.446	0.019	67.1	0	7	57.31010	0	1	7.62672	39.444	-12	5	2
223	3	0202	0600	0.019	N/A	0	7	57.30974	0	1	7.62722	39.515	0.024	43.2	0	7	57.31116	0	1	7.62704	39.523	-44	5	-8
223	3	0202	0700	0.019	N/A	0	5	36.82547	0	6	10.76969	3.427	0.024	48.5	0	5	36.82652	0	6	10.77043	3.418	-32	-23	10
223	3	0700	0600	0.018	N/A	0	2	20.48424	0	5	3.14254	36.093	0.023	56.1	0	2	20.48465	0	5	3.14339	36.104	-13	-26	-11
223	5	0743	0100	0.017	N/A	0	1	10.46280	0	3	49.42966	44.013	0.025	38.3	0	1	10.46283	0	3	49.43157	44.050	-1	-58	-37
223	5	0202	0100	0.021	N/A	0	7	48.88805	0	3	29.37596	43.987	0.053	9.6	0	7	48.88942	0	3	29.37918	43.967	-42	-98	20
223	5	0202	0743	0.020	N/A	0	6	38.42528	0	7	18.80548	0.024	0.055	8.8	0	6	38.42659	0	7	18.81069	0.079	-40	-159	-55
224	1	0202	0700	0.014	N/A	0	5	36.82637	0	6	10.76897	3.405	0.018	77.6	0	5	36.82676	0	6	10.76960	3.371	-12	-19	34
224	1	0202	9203	0.015	N/A	0	2	48.94033	0	12	30.94438	86.070	0.024	40.4	0	2	48.94061	0	12	30.94616	86.118	-9	-54	-48
224	1	0700	9203	0.015	N/A	0	2	47.88607	0	6	20.17516	89.471	0.021	46.0	0	2	47.88616	0	6	20.17653	89.487	-3	-42	-16
224	3	0202	9202	0.020	N/A	0	2	59.74670	0	3	1.37383	29.673	0.025	47.0	0	2	59.74732	0	3	1.37522	29.660	-19	-42	13
224	3	0202	9203	0.024	N/A	0	2	48.94058	0	12	30.94488	86.123	0.031	27.2	0	2	48.94238	0	12	30.94724	86.066	-55	-72	57
224	3	9202	9203	0.038	N/A	0	5	48.68599	0	9	29.57872	56.356	0.034	27.3	0	5	48.68949	0	9	29.57201	56.411	-108	204	-55

225	1	0600	1010	0.010	N/A	0	2	9.37054	0	7	14.75947	11.378	0.021	25.9	0	2	9.37055	0	7	14.75962	11.376	0	-5	2
225	1	0600	2900	0.015	N/A	0	6	18.76687	0	3	38.40667	11.368	0.021	38.4	0	6	18.76776	0	3	38.40611	11.391	-27	17	-23
225	1	1010	2900	0.015	N/A	0	8	28.13741	0	3	36.35276	0.010	0.023	32.7	0	8	28.13826	0	3	36.35361	0.018	-26	-26	-8
225	3	0011	2900	0.011	N/A	0	0	53.91842	0	2	18.84728	0.016	0.022	61.6	0	0	53.91855	0	2	18.84849	0.003	-4	-37	13
225	3	0600	0011	0.016	N/A	0	7	12.68519	0	1	19.55608	11.493	0.027	42.0	0	7	12.68795	0	1	19.55814	11.459	-85	-63	34
225	3	0600	2900	0.016	N/A	0	6	18.76676	0	3	38.40332	11.478	0.032	29.7	0	6	18.76939	0	3	38.40664	11.457	-81	-101	21
228	1	0900	0011	0.018	N/A	0	1	54.38899	0	3	52.74252	6.287	0.024	57.8	0	1	54.38902	0	3	52.74277	6.327	-1	-8	-40
228	1	0600	0011	0.017	N/A	0	7	12.68688	0	1	19.55878	11.462	0.037	23.5	0	7	12.68755	0	1	19.55824	11.499	-21	16	-37
228	1	0600	0900	0.013	N/A	0	5	18.29785	0	2	33.18374	5.172	0.023	55.5	0	5	18.29850	0	2	33.18449	5.170	-20	-23	2
228	3	0600	0800	0.019	N/A	0	0	11.02014	0	8	38.50692	49.029	0.033	16.5	0	0	11.01887	0	8	38.50864	49.053	39	-52	-24
228	3	0600	0900	0.018	N/A	0	5	18.29846	0	2	33.18396	5.157	0.024	49.6	0	5	18.29848	0	2	33.18472	5.180	-1	-23	-23
228	3	0900	0800	0.016	N/A	0	5	7.27832	0	6	5.32300	54.185	0.036	15.0	0	5	7.27942	0	6	5.32396	54.218	-34	-29	-32
229	1	0600	0700	0.013	N/A	0	2	20.48381	0	5	3.14398	36.053	0.051	11.1	0	2	20.48355	0	5	3.14383	36.009	8	5	44
229	1	0600	0800	0.012	N/A	0	0	11.01888	0	8	38.50897	49.020	0.066	6.7	0	0	11.02041	0	8	38.51035	48.962	-47	-42	58
229	1	0800	0700	0.013	N/A	0	2	31.50265	0	3	35.36471	12.966	0.031	29.9	0	2	31.50385	0	3	35.36654	12.934	-37	-56	32
229	3	0700	0800	0.019	N/A	0	2	31.50258	0	3	35.36647	12.951	0.034	27.5	0	2	31.50257	0	3	35.36553	12.956	0	29	-5
229	3	0700	9203	0.017	N/A	0	2	47.88467	0	6	20.17426	89.402	0.053	12.5	0	2	47.88557	0	6	20.17586	89.385	-28	-49	17
229	3	9203	0800	0.018	N/A	0	5	19.38736	0	2	44.80811	76.458	0.035	26.3	0	5	19.38817	0	2	44.81033	76.443	-25	-68	16
230	1	0800	0900	0.013	N/A	0	5	7.27865	0	6	5.32426	54.165	0.019	66.9	0	5	7.27888	0	6	5.32358	54.190	-7	21	-25
230	1	0800	1000	0.013	N/A	0	15	23.86843	0	4	40.27156	23.481	0.022	28.4	0	15	23.86933	0	4	40.27155	23.472	-28	0	9
230	1	0900	1000	0.012	N/A	0	10	16.58978	0	10	45.59610	30.679	0.021	28.4	0	10	16.59044	0	10	45.59509	30.725	-20	31	-46
230	3	0014	bm8a	0.021	N/A	0	9	15.06312	0	4	10.49502	2.031	0.029	7.7	0	9	15.06336	0	4	10.50013	2.154	-7	-156	-123
230	3	0743	0014	0.022	N/A	0	2	9.00503	0	6	47.19247	51.323	0.027	14.8	0	2	9.00495	0	6	47.19373	51.274	2	-38	49
230	3	0743	bm8a	0.025	N/A	0	7	6.05806	0	10	57.68760	53.355	0.041	4.9	0	7	6.05833	0	10	57.69371	53.428	-8	-186	-73

Table A3. 1993 GPPS L3 and GPPS L1 solutions.
Baseline components in Phi/Lambda/Height, and software differences.

Day/ Sess		Stn. 1	Stn. 2	GPPS L3 float solutions. rms (m)	ISR	Delta Phi (dms)			Delta Lambda (dms)			dh (m)	GPPS L1 fixed solutions. rms (m)	ISR	Delta Phi (dms)			Delta Lambda (dms)			dh (m)	Software Diff's. φ (mm)	λ (mm)	h (mm)
214	1	0014	0300	0.012	N/A	0	0	43.76254	0	4	16.60328	11.753	0.009	100.0	0	0	43.76250	0	4	16.60339	11.748	1	-3	5
214	1	0743	0300	0.014	N/A	0	2	52.76749	0	2	30.59059	39.478	0.010	100.0	0	2	52.76746	0	2	30.58962	39.488	1	30	-10
214	1	0743	0014	0.013	N/A	0	2	9.00496	0	6	47.19370	51.232	0.011	100.0	0	2	9.00496	0	6	47.19301	51.236	0	21	-4
214	3	0300	0012	0.021	N/A	0	0	27.82278	0	3	28.74092	10.931	0.023	100.0	0	0	27.82282	0	3	28.73869	10.923	-1	68	8
214	3	0300	0014	0.023	N/A	0	0	43.76282	0	4	16.60447	11.792	0.022	100.0	0	0	43.76272	0	4	16.60289	11.789	3	48	3
214	3	0012	0014	0.016	N/A	0	1	11.58564	0	0	47.86380	0.879	0.014	100.0	0	1	11.58560	0	0	47.86412	0.864	1	-10	15
215	1	1300	0012	0.012	N/A	0	5	13.77791	0	4	27.23668	0.187	0.017	100.0	0	5	13.77708	0	4	27.23664	0.191	26	1	-4
215	1	0300	0012	0.013	N/A	0	0	27.82310	0	3	28.73945	10.882	0.013	100.0	0	0	27.82328	0	3	28.73880	10.876	-6	20	6
215	1	0300	1300	0.013	N/A	0	5	41.60101	0	0	58.49723	10.696	0.016	100.0	0	5	41.60033	0	0	58.49784	10.686	21	-19	10
215	3	0300	1200	0.018	N/A	0	3	49.74710	0	2	47.73620	3.999	0.023	100.0	0	3	49.74541	0	2	47.73710	4.025	52	-27	-26
215	3	0300	1300	0.015	N/A	0	5	41.60094	0	0	58.49590	10.704	0.027	100.0	0	5	41.59910	0	0	58.49705	10.707	57	-35	-3
215	3	1300	1200	0.015	N/A	0	1	51.85376	0	1	49.24013	6.720	0.020	100.0	0	1	51.85373	0	1	49.24009	6.683	1	1	37
216	1	1200	0300	0.018	N/A	0	3	49.74671	0	2	47.73930	4.037	0.016	100.0	0	3	49.74617	0	2	47.73822	4.033	17	33	4
216	1	0743	0300	0.021	N/A	0	2	52.76771	0	2	30.58944	39.469	0.019	100.0	0	2	52.76756	0	2	30.58984	39.485	5	-12	-16
216	1	0743	1200	0.016	N/A	0	6	42.51445	0	0	17.14997	43.508	0.015	100.0	0	6	42.51377	0	0	17.14838	43.518	21	48	-10
216	3	0743	1200	0.014	N/A	0	6	42.51434	0	0	17.14856	43.495	0.014	100.0	0	6	42.51301	0	0	17.14817	43.513	41	12	-18
216	3	0184	0743	0.017	N/A	0	7	44.76331	0	5	3.71634	26.235	0.017	100.0	0	7	44.76209	0	5	3.71393	26.222	37	73	13
216	3	0184	1200	0.017	N/A	0	1	2.24890	0	4	46.56774	17.259	0.015	100.0	0	1	2.24908	0	4	46.56576	17.292	-6	60	-33
217	1	0202	0743	0.017	N/A	0	6	38.42456	0	7	18.80929	0.048	0.030	100.0	0	6	38.42406	0	7	18.80854	0.042	15	23	6
217	1	0202	0184	0.015	N/A	0	1	6.33918	0	2	15.09277	26.233	0.013	100.0	0	1	6.33900	0	2	15.09306	26.247	6	-9	-14
217	1	0184	0743	0.017	N/A	0	7	44.76374	0	5	3.71670	26.284	0.030	100.0	0	7	44.76302	0	5	3.71548	26.290	22	37	-6
217	3	0202	0743	0.023	N/A	0	6	38.42521	0	7	18.80724	0.049	0.040	99.9	0	6	38.42338	0	7	18.80699	0.071	56	8	-22
217	3	0202	0100	0.025	N/A	0	7	49.99714	0	3	28.22339	44.353	0.038	99.9	0	7	49.99591	0	3	28.22443	44.300	38	-32	53
217	3	0743	0100	0.023	N/A	0	1	11.57221	0	3	50.58356	44.401	0.022	100.0	0	1	11.57254	0	3	50.58256	44.372	-10	30	29
218	1	9201	0100	0.015	N/A	0	3	38.07054	0	4	27.41383	13.545	0.014	100.0	0	3	38.07022	0	4	27.41372	13.568	10	3	-23

218	1	0202	0100	0.016	N/A	0	7	48.88765	0	3	29.37920	44.084	0.016	100.0	0	7	48.88704	0	3	29.37766	44.060	19	47	24
218	1	0202	9201	0.014	N/A	0	11	26.95823	0	0	58.03430	57.630	0.018	100.0	0	11	26.95726	0	0	58.03607	57.627	30	-54	3
218	3	0202	9202	0.020	N/A	0	2	59.74721	0	3	1.37714	29.552	0.026	100.0	0	2	59.74573	0	3	1.37448	29.595	45	81	-43
218	3	0202	9201	0.020	N/A	0	11	26.95790	0	0	58.03816	57.529	0.035	99.9	0	11	26.95502	0	0	58.03607	57.581	88	64	-52
218	3	9202	9201	0.017	N/A	0	8	27.21066	0	2	3.33881	27.976	0.023	100.0	0	8	27.20926	0	2	3.33845	27.985	43	11	-9
221	1	1300	0500	0.016	N/A	0	2	58.67423	0	2	14.97905	1.646	0.013	100.0	0	2	58.67405	0	2	14.97872	1.637	6	10	9
221	1	1200	0500	0.016	N/A	0	4	50.52796	0	0	25.73791	8.321	0.016	100.0	0	4	50.52781	0	0	25.73838	8.311	5	-14	10
221	1	1200	1300	0.014	N/A	0	1	51.85373	0	1	49.24110	6.675	0.011	100.0	0	1	51.85380	0	1	49.24038	6.675	-2	22	0
221	3	0184	0500	0.020	N/A	0	3	48.27884	0	4	20.82857	25.566	0.016	100.0	0	3	48.27812	0	4	20.82839	25.573	22	5	-7
221	3	0184	1200	0.022	N/A	0	1	2.24893	0	4	46.56648	17.242	0.022	100.0	0	1	2.24886	0	4	46.56652	17.261	2	-1	-19
221	3	0500	1200	0.020	N/A	0	4	50.52781	0	0	25.73791	8.330	0.018	100.0	0	4	50.52698	0	0	25.73809	8.311	26	-5	19
222	1	0184	0500	0.016	N/A	0	3	48.27870	0	4	20.82731	25.552	0.014	100.0	0	3	48.27845	0	4	20.82824	25.549	8	-28	3
222	1	0184	1010	0.014	N/A	0	4	41.60042	0	3	52.03829	24.568	0.014	100.0	0	4	41.60017	0	3	52.03897	24.571	8	-21	-3
222	1	1010	0500	0.012	N/A	0	0	53.32172	0	0	28.78902	0.984	0.006	100.0	0	0	53.32172	0	0	28.78927	0.978	0	-8	6
222	3	0184	0600	0.019	N/A	0	6	50.97078	0	3	22.72021	13.234	0.029	99.8	0	6	50.96956	0	3	22.71892	13.230	37	39	4
222	3	0184	1010	0.017	N/A	0	4	41.60032	0	3	52.03868	24.597	0.042	99.2	0	4	41.59952	0	3	52.03786	24.606	25	25	-9
222	3	1010	0600	0.016	N/A	0	2	9.37043	0	7	14.75893	11.365	0.029	100.0	0	2	9.36989	0	7	14.75681	11.387	17	65	-22
223	1	0600	0184	0.013	N/A	0	6	50.97103	0	3	22.71989	13.218	0.013	100.0	0	6	50.97071	0	3	22.71946	13.212	10	13	6
223	1	0202	0184	0.013	N/A	0	1	6.33875	0	2	15.09310	26.230	0.008	100.0	0	1	6.33886	0	2	15.09270	26.239	-3	12	-9
223	1	0202	0600	0.012	N/A	0	7	57.30971	0	1	7.62690	39.446	0.012	100.0	0	7	57.30953	0	1	7.62676	39.451	6	4	-5
223	3	0202	0600	0.019	N/A	0	7	57.30974	0	1	7.62722	39.515	0.019	100.0	0	7	57.30874	0	1	7.62676	39.510	31	14	5
223	3	0202	0700	0.019	N/A	0	5	36.82547	0	6	10.76969	3.427	0.024	100.0	0	5	36.82504	0	6	10.76886	3.397	13	25	30
223	3	0700	0600	0.018	N/A	0	2	20.48424	0	5	3.14254	36.093	0.020	100.0	0	2	20.48366	0	5	3.14207	36.115	18	14	-22
223	5	0743	0100	0.017	N/A	0	1	10.46280	0	3	49.42966	44.013	0.022	100.0	0	1	10.46251	0	3	49.42994	44.013	9	-9	0
223	5	0202	0100	0.021	N/A	0	7	48.88805	0	3	29.37596	43.987	0.051	98.4	0	7	48.88621	0	3	29.37697	43.986	57	-31	1
223	5	0202	0743	0.020	N/A	0	6	38.42528	0	7	18.80548	0.024	0.051	91.7	0	6	38.42399	0	7	18.80656	0.050	40	-33	-26
224	1	0202	0700	0.014	N/A	0	5	36.82637	0	6	10.76897	3.405	0.014	100.0	0	5	36.82583	0	6	10.76936	3.389	17	-12	16
224	1	0202	9203	0.015	N/A	0	2	48.94033	0	12	30.94438	86.070	0.018	100.0	0	2	48.94004	0	12	30.94510	86.080	9	-22	-10
224	1	0700	9203	0.015	N/A	0	2	47.88607	0	6	20.17516	89.471	0.014	100.0	0	2	47.88575	0	6	20.17577	89.468	10	-19	3
224	3	0202	9202	0.020	N/A	0	2	59.74670	0	3	1.37383	29.673	0.021	100.0	0	2	59.74624	0	3	1.37434	29.664	14	-16	9
224	3	0202	9203	0.024	N/A	0	2	48.94058	0	12	30.94488	86.123	0.031	100.0	0	2	48.93961	0	12	30.94250	86.159	30	72	-36
224	3	9202	9203	0.038	N/A	0	5	48.68599	0	9	29.57872	56.356	0.024	100.0	0	5	48.68578	0	9	29.56817	56.496	6	321	-140

225	1	0600	1010	0.010	N/A	0	2	9.37054	0	7	14.75947	11.378	0.015	100.0	0	2	9.37050	0	7	14.75846	11.397	1	31	-19
225	1	0600	2900	0.015	N/A	0	6	18.76687	0	3	38.40667	11.368	0.025	100.0	0	6	18.76662	0	3	38.40520	11.393	8	45	-25
225	1	1010	2900	0.015	N/A	0	8	28.13741	0	3	36.35276	0.010	0.023	100.0	0	8	28.13712	0	3	36.35305	0.004	9	-9	6
225	3	0011	2900	0.011	N/A	0	0	53.91842	0	2	18.84728	0.016	0.015	100.0	0	0	53.91835	0	2	18.84692	0.012	2	11	4
225	3	0600	0011	0.016	N/A	0	7	12.68519	0	1	19.55608	11.493	0.021	100.0	0	7	12.68425	0	1	19.55784	11.488	29	-54	5
225	3	0600	2900	0.016	N/A	0	6	18.76676	0	3	38.40332	11.478	0.026	100.0	0	6	18.76590	0	3	38.40480	11.475	26	-45	3
228	1	0900	0011	0.018	N/A	0	1	54.38899	0	3	52.74252	6.287	0.019	100.0	0	1	54.38816	0	3	52.74198	6.280	26	16	7
228	1	0600	0011	0.017	N/A	0	7	12.68688	0	1	19.55878	11.462	0.030	100.0	0	7	12.68562	0	1	19.55791	11.450	39	26	12
228	1	0600	0900	0.013	N/A	0	5	18.29785	0	2	33.18374	5.172	0.017	100.0	0	5	18.29746	0	2	33.18407	5.168	12	-10	4
228	3	0600	0800	0.019	N/A	0	0	11.02014	0	8	38.50692	49.029	0.033	100.0	0	0	11.01946	0	8	38.50699	48.999	21	-2	30
228	3	0600	0900	0.018	N/A	0	5	18.29846	0	2	33.18396	5.157	0.022	100.0	0	5	18.29749	0	2	33.18410	5.166	30	-4	-9
228	3	0900	0800	0.016	N/A	0	5	7.27832	0	6	5.32300	54.185	0.037	99.9	0	5	7.27804	0	6	5.32289	54.165	9	3	20
229	1	0600	0700	0.013	N/A	0	2	20.48381	0	5	3.14398	36.053	0.050	99.8	0	2	20.48413	0	5	3.14153	36.131	-10	75	-78
229	1	0600	0800	0.012	N/A	0	0	11.01888	0	8	38.50897	49.020	0.050	90.1	0	0	11.01920	0	8	38.51171	49.049	-10	-83	-29
229	1	0800	0700	0.013	N/A	0	2	31.50265	0	3	35.36471	12.966	0.024	100.0	0	2	31.50204	0	3	35.36456	12.965	19	5	1
229	3	0700	0800	0.019	N/A	0	2	31.50258	0	3	35.36647	12.951	0.025	100.0	0	2	31.50251	0	3	35.36482	12.924	2	50	27
229	3	0700	9203	0.017	N/A	0	2	47.88467	0	6	20.17426	89.402	0.032	99.7	0	2	47.88503	0	6	20.17490	89.460	-11	-19	-58
229	3	9203	0800	0.018	N/A	0	5	19.38736	0	2	44.80811	76.458	0.024	100.0	0	5	19.38757	0	2	44.81009	76.536	-6	-60	-78
230	1	0800	0900	0.013	N/A	0	5	7.27865	0	6	5.32426	54.165	0.013	100.0	0	5	7.27847	0	6	5.32361	54.176	6	20	-11
230	1	0800	1000	0.013	N/A	0	15	23.86843	0	4	40.27156	23.481	0.022	100.0	0	15	23.86768	0	4	40.27120	23.503	23	11	-22
230	1	0900	1000	0.012	N/A	0	10	16.58978	0	10	45.59610	30.679	0.023	100.0	0	10	16.58924	0	10	45.59480	30.674	17	40	5
230	3	0014	bm8a	0.021	N/A	0	9	15.06312	0	4	10.49502	2.031	0.033	100.0	0	9	15.06182	0	4	10.49657	2.023	40	-47	8
230	3	0743	0014	0.022	N/A	0	2	9.00503	0	6	47.19247	51.323	0.037	98.5	0	2	9.00510	0	6	47.19154	51.372	-2	28	-49
230	3	0743	bm8a	0.025	N/A	0	7	6.05806	0	10	57.68760	53.355	0.039	74.5	0	7	6.05687	0	10	57.68778	53.363	37	-5	-8

Table A4. 1994 GPPS L3 and TRIMMBP L0 solutions.
Baseline components in Phi/Lambda/Height, and software differences.

Day/ Sess		Stn. 1	Stn. 2	GPPS L3 float solutions.									TRIMMBP L0 fixed solutions.									Software Diff's.		
				rms (m)	ISR	Delta Phi (dms)			Delta Lambda (dms)			dh (m)	rms (cyc)	ISR	Delta Phi (dms)			Delta Lambda (dms)			dh (m)	ϕ (mm)	λ (mm)	h (mm)
110	1	0743	0014	0.009	N/A	0	2	9.00535	0	6	47.19348	51.260	0.028	4.8	0	2	9.00627	0	6	47.19447	51.218	-28	-30	42
110	1	0014	0801	0.010	N/A	0	9	15.06319	0	4	10.49956	2.142	0.035	3.4	0	9	15.06353	0	4	10.49780	2.137	-10	54	6
110	1	0743	0801	0.011	N/A	0	7	6.05788	0	10	57.69253	53.397	0.051	2.4	0	7	6.05742	0	10	57.69245	53.354	14	2	43
110	2	0743	0300	0.008	N/A	0	2	52.76731	0	2	30.58980	39.526	0.017	18.8	0	2	52.76748	0	2	30.59014	39.524	-5	-10	3
110	2	0014	0300	0.008	N/A	0	0	43.76203	0	4	16.60411	11.746	0.017	16.8	0	0	43.76222	0	4	16.60334	11.754	-6	23	-8
110	2	0012	0300	0.008	N/A	0	0	27.82354	0	3	28.73981	10.899	0.017	16.5	0	0	27.82339	0	3	28.73923	10.900	5	18	-1
110	2	0014	0012	0.007	N/A	0	1	11.58557	0	0	47.86430	0.847	0.013	29.6	0	1	11.58561	0	0	47.86411	0.855	-1	6	-8
110	2	0743	0012	0.008	N/A	0	3	20.59085	0	5	59.32964	50.425	0.020	11.3	0	3	20.59089	0	5	59.32937	50.422	-1	8	3
110	2	0743	0014	0.008	N/A	0	2	9.00528	0	6	47.19391	51.271	0.020	11.6	0	2	9.00530	0	6	47.19349	51.277	-1	13	-6
111	1	0012	1300	0.010	N/A	0	5	13.77719	0	4	27.23941	0.233	0.032	5.8	0	5	13.77707	0	4	27.23791	0.221	4	46	12
111	1	0300	0012	0.008	N/A	0	0	27.82418	0	3	28.74092	10.899	0.026	9.9	0	0	27.82440	0	3	28.74052	10.889	-7	12	10
111	1	1300	1200	0.010	N/A	0	1	51.85420	0	1	49.24031	6.672	0.022	10.8	0	1	51.85420	0	1	49.24120	6.663	0	-27	9
111	1	0012	1200	0.012	N/A	0	3	21.92299	0	6	16.47976	6.902	0.036	4.3	0	3	21.92270	0	6	16.47904	6.878	9	22	24
111	1	0300	1200	0.012	N/A	0	3	49.74710	0	2	47.73894	3.989	0.023	9.3	0	3	49.74717	0	2	47.73853	4.010	-2	12	-21
111	1	0300	1300	0.010	N/A	0	5	41.60141	0	0	58.49838	10.665	0.024	11.3	0	5	41.60155	0	0	58.49742	10.670	-4	29	-5
111	2	1200	0184	0.014	N/A	0	1	1.38227	0	4	46.57800	17.554	0.023	20.3	0	1	1.38268	0	4	46.57804	17.570	-13	-1	-16
111	2	0300	1200	0.011	N/A	0	3	49.74721	0	2	47.73764	4.019	0.019	31.6	0	3	49.74724	0	2	47.73834	4.009	-1	-21	10
111	2	0743	0184	0.015	N/A	0	7	43.89661	0	5	3.72667	25.995	0.023	20.4	0	7	43.89725	0	5	3.72614	25.969	-20	16	26
111	2	0300	0184	0.013	N/A	0	4	51.12952	0	7	34.31575	13.533	0.023	20.2	0	4	51.12991	0	7	34.31631	13.567	-12	-17	-34
111	2	0743	1200	0.012	N/A	0	6	42.51427	0	0	17.14828	43.541	0.020	24.6	0	6	42.51450	0	0	17.14810	43.535	-7	5	6
111	2	0743	0300	0.010	N/A	0	2	52.76710	0	2	30.58915	39.526	0.017	41.9	0	2	52.76729	0	2	30.59027	39.525	-6	-34	1
112	1	9201	0100	0.012	N/A	0	3	38.07000	0	4	27.41236	13.524	0.024	10.6	0	3	38.07013	0	4	27.41442	13.491	-4	-63	33
112	1	9201	9202	0.012	N/A	0	8	27.21163	0	2	3.33542	27.951	0.023	8.5	0	8	27.21140	0	2	3.33803	27.922	7	-79	29
112	1	0202	9201	0.012	N/A	0	11	26.95736	0	0	58.03582	57.541	0.026	9.3	0	11	26.95807	0	0	58.03714	57.499	-22	-40	42
112	1	0100	9202	0.015	N/A	0	4	49.14163	0	6	30.74789	14.430	0.024	5.4	0	4	49.14104	0	6	30.75230	14.415	18	-134	15
112	1	0202	0100	0.013	N/A	0	7	48.88736	0	3	29.37676	44.018	0.023	13.0	0	7	48.88780	0	3	29.37723	44.003	-14	-14	15

112	1	0202	9202	0.013	N/A	0	2	59.74577	0	3	1.37120	29.589	0.026	6.6	0	2	59.74666	0	3	1.37531	29.573	-27	-125	16
112	2	0743	0100	0.011	N/A	0	1	10.46262	0	3	49.43063	44.000	0.018	33.6	0	1	10.46232	0	3	49.43012	44.003	9	16	-3
112	2	0100	0184	0.013	N/A	0	8	54.35959	0	1	14.29612	70.007	0.021	21.0	0	8	54.35991	0	1	14.29572	70.005	-10	12	2
112	2	0202	0100	0.011	N/A	0	7	48.88672	0	3	29.37730	44.009	0.019	28.8	0	7	48.88681	0	3	29.37723	44.004	-3	2	5
112	2	0202	0184	0.012	N/A	0	1	5.47288	0	2	15.08122	25.994	0.019	36.2	0	1	5.47310	0	2	15.08154	25.997	-7	-10	-3
112	2	0202	0743	0.010	N/A	0	6	38.42410	0	7	18.80800	0.007	0.020	24.3	0	6	38.42451	0	7	18.80734	0.003	-13	20	4
112	2	0743	0184	0.013	N/A	0	7	43.89697	0	5	3.72682	26.006	0.022	21.0	0	7	43.89760	0	5	3.72580	26.001	-19	31	5
115	1	0202	9202	0.013	N/A	0	2	59.74663	0	3	1.37380	29.639	0.021	12.1	0	2	59.74724	0	3	1.37426	29.640	-19	-14	-1
115	1	0202	0700	0.011	N/A	0	5	36.82597	0	6	10.76836	3.410	0.021	10.4	0	5	36.82543	0	6	10.76917	3.415	17	-25	-5
115	1	0202	9203	0.012	N/A	0	2	48.94091	0	12	30.94510	86.046	0.028	6.4	0	2	48.93988	0	12	30.94525	86.033	32	-5	13
115	1	9203	9202	0.012	N/A	0	5	48.68758	0	9	29.57130	56.398	0.023	8.6	0	5	48.68719	0	9	29.57101	56.388	12	9	10
115	1	0700	9202	0.011	N/A	0	8	36.57264	0	3	9.39460	33.052	0.023	8.8	0	8	36.57266	0	3	9.39493	33.052	-1	-10	0
115	1	0700	9203	0.009	N/A	0	2	47.88506	0	6	20.17667	89.453	0.021	14.6	0	2	47.88553	0	6	20.17604	89.453	-14	19	0
115	2	0700	0600	0.009	N/A	0	2	20.48438	0	5	3.14329	36.128	0.016	17.8	0	2	20.48433	0	5	3.14358	36.142	2	-9	-14
115	2	0202	0184	0.011	N/A	0	1	5.47255	0	2	15.08194	25.984	0.019	11.0	0	1	5.47220	0	2	15.08240	25.984	11	-14	0
115	2	0202	0600	0.010	N/A	0	7	57.31007	0	1	7.62560	39.500	0.018	12.7	0	7	57.30984	0	1	7.62525	39.509	7	11	-9
115	2	0202	0700	0.009	N/A	0	5	36.82568	0	6	10.76904	3.365	0.017	12.7	0	5	36.82551	0	6	10.76879	3.362	5	8	3
115	2	0600	0184	0.012	N/A	0	6	51.83755	0	3	22.70747	13.519	0.020	10.8	0	6	51.83766	0	3	22.70760	13.520	-3	-4	-1
115	2	0700	0184	0.011	N/A	0	4	31.35313	0	8	25.85094	22.614	0.020	9.2	0	4	31.35336	0	8	25.85117	22.621	-7	-7	-7
116	1	0184	1300	0.015	N/A	0	0	50.47128	0	6	35.82054	24.182	0.027	8.0	0	0	50.47092	0	6	35.81952	24.183	11	31	-1
116	1	1200	1300	0.012	N/A	0	1	51.85452	0	1	49.24110	6.637	0.020	18.6	0	1	51.85451	0	1	49.24057	6.637	0	16	0
116	1	0184	1200	0.014	N/A	0	1	1.38306	0	4	46.57998	17.545	0.027	8.3	0	1	1.38347	0	4	46.57902	17.556	-13	29	-11
116	1	1200	212A	0.021	N/A	0	4	33.91662	0	0	53.06663	14.053	0.039	4.1	0	4	33.91593	0	0	53.06462	14.054	21	61	-1
116	1	1300	212A	0.021	N/A	0	2	42.06192	0	2	42.30996	7.413	0.075	3.4	0	2	42.06111	0	2	42.32097	7.444	25	-335	-31
116	1	0184	212A	0.022	N/A	0	3	32.53316	0	3	53.51044	31.604	0.043	3.7	0	3	32.53248	0	3	53.51449	31.598	21	-123	6
116	2	1010	212A	0.020	N/A	0	1	9.93349	0	0	1.46210	6.755	0.035	8.1	0	1	9.93413	0	0	1.46254	6.732	-20	-13	23
116	2	0184	1010	0.011	N/A	0	4	42.46687	0	3	52.05186	24.938	0.020	29.8	0	4	42.46630	0	3	52.05048	24.855	18	42	83
116	2	0184	212A	0.022	N/A	0	3	32.53360	0	3	53.51454	31.689	0.039	7.2	0	3	32.53213	0	3	53.51294	31.592	45	49	97
117	1	1010	2900	0.009	N/A	0	8	28.13816	0	3	36.35384	0.051	0.021	16.3	0	8	28.13794	0	3	36.35344	0.043	7	12	8
117	1	0600	1010	0.011	N/A	0	2	9.37108	0	7	14.75915	11.347	0.023	14.4	0	2	9.37094	0	7	14.75818	11.354	4	30	-7
117	1	1010	0184	0.012	N/A	0	4	42.46640	0	3	52.05100	24.859	0.024	14.4	0	4	42.46626	0	3	52.05058	24.872	4	13	-13
117	1	0600	2900	0.011	N/A	0	6	18.76709	0	3	38.40566	11.400	0.022	13.8	0	6	18.76698	0	3	38.40476	11.400	3	27	0

117	1	2900	0184	0.013	N/A	0	13	10.60457	0	0	15.69744	24.911	0.025	11.0	0	13	10.60419	0	0	15.69718	24.918	12	8	-7
117	1	0600	0184	0.014	N/A	0	6	51.83748	0	3	22.70848	13.509	0.022	14.7	0	6	51.83727	0	3	22.70747	13.511	6	31	-2
117	2	0011	2900	0.008	N/A	0	0	53.91896	0	2	18.84664	0.016	0.014	33.1	0	0	53.91875	0	2	18.84752	0.014	6	-27	2
117	2	0600	2900	0.010	N/A	0	6	18.76694	0	3	38.40358	11.423	0.017	24.9	0	6	18.76716	0	3	38.40429	11.422	-7	-22	1
117	2	0600	0900	0.010	N/A	0	5	18.29746	0	2	33.18565	5.122	0.015	33.1	0	5	18.29769	0	2	33.18504	5.110	-7	19	12
117	2	0011	0900	0.008	N/A	0	1	54.38845	0	3	52.74245	6.286	0.012	45.1	0	1	54.38823	0	3	52.74180	6.300	7	20	-14
117	2	0600	0011	0.009	N/A	0	7	12.68587	0	1	19.55690	11.409	0.015	24.3	0	7	12.68592	0	1	19.55680	11.411	-2	3	-2
117	2	0900	2900	0.008	N/A	0	1	0.46949	0	6	11.58923	6.300	0.013	44.8	0	1	0.46948	0	6	11.58932	6.312	0	-3	-12
118	1	9203	9202	0.012	N/A	0	5	48.68722	0	9	29.57083	56.471	0.029	7.4	0	5	48.68805	0	9	29.57044	56.456	-26	12	15
118	1	0700	9202	0.012	N/A	0	8	36.57246	0	3	9.39456	33.020	0.023	11.8	0	8	36.57342	0	3	9.39478	33.024	-29	-7	-3
118	1	0700	9203	0.010	N/A	0	2	47.88524	0	6	20.17652	89.494	0.023	8.8	0	2	47.88538	0	6	20.17569	89.479	-4	25	15
118	1	0800	9202	0.012	N/A	0	11	8.07554	0	6	44.75948	20.065	0.025	7.0	0	11	8.07673	0	6	44.76018	20.083	-37	-21	-18
118	1	0800	0700	0.009	N/A	0	2	31.50316	0	3	35.36507	12.962	0.019	17.9	0	2	31.50335	0	3	35.36542	12.945	-6	-11	17
118	1	0800	9203	0.009	N/A	0	5	19.38840	0	2	44.81110	76.531	0.021	13.0	0	5	19.38871	0	2	44.81022	76.535	-10	27	-3
118	2	0600	0700	0.009	N/A	0	2	20.48456	0	5	3.14282	36.133	0.016	10.6	0	2	20.48493	0	5	3.14368	36.137	-11	-26	-4
118	2	0600	0900	0.008	N/A	0	5	18.29735	0	2	33.18508	5.121	0.013	34.6	0	5	18.29759	0	2	33.18478	5.118	-7	9	3
118	2	0800	0700	0.009	N/A	0	2	31.50276	0	3	35.36557	12.948	0.016	11.3	0	2	31.50292	0	3	35.36547	12.951	-5	3	-3
118	2	0600	0800	0.009	N/A	0	0	11.01816	0	8	38.50840	49.087	0.018	16.7	0	0	11.01812	0	8	38.50914	49.087	1	-23	0
118	2	0900	0700	0.008	N/A	0	7	38.78188	0	2	29.95757	41.256	0.015	12.6	0	7	38.78248	0	2	29.95888	41.253	-18	-40	3
118	2	0900	0800	0.008	N/A	0	5	7.27919	0	6	5.32339	54.207	0.016	27.0	0	5	7.27950	0	6	5.32438	54.203	-10	-30	4
119	1	0800	0900	0.008	N/A	0	5	7.27876	0	6	5.32361	54.200	0.021	14.2	0	5	7.27907	0	6	5.32439	54.175	-10	-24	25
119	1	0900	1000	0.010	N/A	0	10	16.59018	0	10	45.59444	30.666	0.031	4.5	0	10	16.59112	0	10	45.59602	30.566	-29	-48	100
119	1	0900	0011	0.009	N/A	0	1	54.38795	0	3	52.74241	6.279	0.018	20.0	0	1	54.38809	0	3	52.74214	6.265	-4	8	14
119	1	0800	0011	0.009	N/A	0	7	1.66670	0	9	58.06609	60.480	0.030	7.3	0	7	1.66724	0	9	58.06658	60.442	-17	-15	38
119	1	0800	1000	0.009	N/A	0	15	23.86897	0	4	40.27051	23.536	0.028	6.6	0	15	23.87022	0	4	40.27160	23.606	-38	-33	-70
119	1	0011	1000	0.010	N/A	0	8	22.20227	0	14	38.33646	36.943	0.038	2.9	0	8	22.20291	0	14	38.33823	36.834	-20	-54	109
119	2	0800	0900	0.014	N/A	0	5	7.27872	0	6	5.32267	54.207	0.016	51.1	0	5	7.27902	0	6	5.32422	54.205	-9	-47	2
119	2	0011	1000	0.012	N/A	0	8	22.20169	0	14	38.33783	36.989	0.023	18.3	0	8	22.20197	0	14	38.33713	36.989	-9	21	0
119	2	0011	0900	0.011	N/A	0	1	54.38834	0	3	52.74212	6.295	0.015	54.9	0	1	54.38808	0	3	52.74192	6.296	8	6	-1
119	2	0800	1000	0.014	N/A	0	15	23.86865	0	4	40.27321	23.522	0.022	22.8	0	15	23.86905	0	4	40.27099	23.513	-12	68	9
119	2	0800	0011	0.012	N/A	0	7	1.66703	0	9	58.06480	60.502	0.018	34.4	0	7	1.66707	0	9	58.06614	60.500	-1	-41	2
119	2	0900	1000	0.012	N/A	0	10	16.59000	0	10	45.59563	30.688	0.022	22.0	0	10	16.59008	0	10	45.59520	30.684	-2	13	4

Appendix B

Final Adjusted Co-ordinates and Displacements, 1990 to 1994

This appendix contains tables of the final adjusted co-ordinates and plots of the displacements, for the the years 1990 to 1994.

Tables B1 to B9, contain the adjusted coordinates from the minimum constraints adjustment, holding station 0202 fixed.

Figures B1 to B7, contain the displacements from the minimum constraints adjustment, holding station 0202 fixed.

Figures B8 to B14, contain the displacements after the removal of the systematic biases.

Table B1.
Venezuela GPS 1990 (TRIMMBP L1 solution)
Adjusted PLH Coordinates:

		STN	LATITUDE (dms)				LONGITUDE (dms)				HEIGHT (m)
PLH	000	0011	N	9	57	21.81375	W	71	9	23.58173	2.894
PLH	000	0012	N	10	15	49.64273	W	71	22	29.78773	3.410
PLH	000	0014	N	10	17	1.22897	W	71	23	17.65134	2.506
PLH	000	0100	N	10	20	20.69631	W	71	12	41.02891	97.811
PLH	000	0184	N	10	11	25.47059	W	71	11	26.74378	27.517
PLH	111	0202	N	10	12	31.80970	W	71	9	11.65150	53.773
PLH	000	0300	N	10	16	17.46514	W	71	19	1.04827	14.293
PLH	000	0500	N	10	7	37.19225	W	71	15	47.57222	2.057
PLH	000	0600	N	10	4	34.50319	W	71	8	4.01744	14.482
PLH	000	0700	N	10	6	54.98378	W	71	3	0.88174	50.353
PLH	000	0743	N	10	19	10.23386	W	71	16	30.45894	53.752
PLH	000	0800	N	10	4	23.48113	W	70	59	25.51654	63.314
PLH	000	0801	N	10	26	16.29107	W	71	27	28.14877	0.446
PLH	000	0900	N	9	59	16.20242	W	71	5	30.83900	9.117
PLH	000	1000	N	9	48	59.61495	W	70	54	45.24560	39.833
PLH	000	1010	N	10	5	57.86459	W	71	14	59.60156	3.033
PLH	000	1200	N	10	12	27.71933	W	71	16	13.31076	10.365
PLH	000	1300	N	10	10	35.86609	W	71	18	2.55062	3.566
PLH	000	1400	N	10	19	39.68363	W	71	24	22.15540	10.964
PLH	000	1500	N	9	52	55.97047	W	71	0	8.64427	13.426
PLH	000	1600	N	9	57	21.65529	W	70	53	3.65404	127.140
PLH	000	2900	N	9	58	15.73243	W	71	11	42.42906	2.936

Table B2.
Venezuela GPS 1991 (TRIMMBP L1 solution)
Adjusted PLH Coordinates:

		STN	LATITUDE (dms)				LONGITUDE (dms)				HEIGHT (m)
PLH	000	0011	N	9	57	21.81763	W	71	9	23.58281	3.021
PLH	000	0012	N	10	15	49.64288	W	71	22	29.78581	3.391
PLH	000	0014	N	10	17	1.22808	W	71	23	17.64937	2.475
PLH	000	0100	N	10	20	20.69523	W	71	12	41.02882	97.706
PLH	000	0184	N	10	11	25.47068	W	71	11	26.74386	27.504
PLH	111	0202	N	10	12	31.80970	W	71	9	11.65150	53.773
PLH	000	0300	N	10	16	17.46496	W	71	19	1.04738	14.268
PLH	000	0600	N	10	4	34.50465	W	71	8	4.01973	14.516
PLH	000	0700	N	10	6	54.98508	W	71	3	0.88323	50.426
PLH	000	0743	N	10	19	10.23268	W	71	16	30.45862	53.736
PLH	000	0800	N	10	4	23.48313	W	70	59	25.51865	63.385
PLH	000	0801	N	10	26	16.28941	W	71	27	28.14661	0.356
PLH	000	0900	N	9	59	16.20584	W	71	5	30.84083	9.275
PLH	000	1010	N	10	5	57.86636	W	71	14	59.60162	3.055
PLH	000	1200	N	10	12	27.71960	W	71	16	13.31026	10.326
PLH	000	1300	N	10	10	35.86604	W	71	18	2.55030	3.585
PLH	000	2900	N	9	58	15.73571	W	71	11	42.42977	2.999

Table B3.
Venezuela GPS 1992 (TRIMMBP L1 solution)
Adjusted PLH Coordinates:

		STN	LATITUDE (dms)				LONGITUDE (dms)				HEIGHT (m)
PLO	000	0011	N	9	57	21.81513	W	71	9	23.58382	2.787
PLO	000	0012	N	10	15	49.64193	W	71	22	29.78810	3.331
PLO	000	0014	N	10	17	1.22736	W	71	23	17.65182	2.442
PLO	000	0100	N	10	20	20.69618	W	71	12	41.02876	97.842
PLO	000	0184	N	10	11	25.46993	W	71	11	26.74425	27.489
PLO	111	0202	N	10	12	31.80970	W	71	9	11.65150	53.773
PLO	000	0300	N	10	16	17.46462	W	71	19	1.04879	14.243
PLO	000	0500	N	10	7	37.19144	W	71	15	47.57279	1.895
PLO	000	0600	N	10	4	34.50159	W	71	8	4.02374	14.300
PLO	000	0700	N	10	6	54.98491	W	71	3	0.88298	50.405
PLO	000	0743	N	10	19	10.23275	W	71	16	30.45873	53.734
PLO	000	0800	N	10	4	23.48213	W	70	59	25.51810	63.355
PLO	000	0900	N	9	59	16.20341	W	71	5	30.84142	9.055
PLO	000	1010	N	10	6	43.86955	W	71	15	18.78333	2.892
PLO	000	1200	N	10	12	27.71902	W	71	16	13.31107	10.256
PLO	000	1300	N	10	10	35.86509	W	71	18	2.55107	3.509
PLO	000	2900	N	9	58	15.73337	W	71	11	42.43095	2.769
PLO	000	9201	N	10	23	58.76621	W	71	8	13.61572	111.469
PLO	000	9202	N	10	15	31.55605	W	71	6	10.27720	83.471
PLO	000	9203	N	10	9	42.86995	W	70	56	40.70769	139.915

Table B4.
Venezuela 1992 GPS (GPPS L1 solution)
Adjusted PLH Coordinates:

		STN	LATITUDE (dms)				LONGITUDE (dms)				HEIGHT (m)
PLO	000	0011	N	9	57	21.81547	W	71	9	23.58389	2.781
PLO	000	0012	N	10	15	49.64150	W	71	22	29.78880	3.351
PLO	000	0014	N	10	17	1.22688	W	71	23	17.65263	2.436
PLO	000	0100	N	10	20	20.69585	W	71	12	41.02923	97.839
PLO	000	0184	N	10	11	25.47012	W	71	11	26.74381	27.500
PLO	111	0202	N	10	12	31.80970	W	71	9	11.65150	53.773
PLO	000	0300	N	10	16	17.46455	W	71	19	1.04886	14.332
PLO	000	0500	N	10	7	37.19145	W	71	15	47.57245	1.916
PLO	000	0600	N	10	4	34.50153	W	71	8	4.02317	14.330
PLO	000	0700	N	10	6	54.98452	W	71	3	0.88276	50.352
PLO	000	0743	N	10	19	10.23225	W	71	16	30.45974	53.753
PLO	000	0800	N	10	4	23.48171	W	70	59	25.51770	63.290
PLO	000	0900	N	9	59	16.20385	W	71	5	30.84238	9.032
PLO	000	1010	N	10	6	43.86953	W	71	15	18.78289	2.891
PLO	000	1200	N	10	12	27.71891	W	71	16	13.31119	10.270
PLO	000	1300	N	10	10	35.86491	W	71	18	2.55141	3.541
PLO	000	2900	N	9	58	15.73364	W	71	11	42.43056	2.769
PLO	000	9201	N	10	23	58.76595	W	71	8	13.61613	111.471
PLO	000	9202	N	10	15	31.55579	W	71	6	10.27716	83.461
PLO	000	9203	N	10	9	42.86930	W	70	56	40.70774	139.884

Table B5.
Venezuela 1993 GPS (GPPS L1 solution)
Adjusted PLH Coordinates:

		STN	LATITUDE (dms)				LONGITUDE (dms)				HEIGHT (m)
PLO	000	0011	N	9	57	21.81560	W	71	9	23.58283	2.864
PLO	000	0012	N	10	15	49.64287	W	71	22	29.78742	3.411
PLO	000	0014	N	10	17	1.22854	W	71	23	17.65166	2.534
PLO	000	0100	N	10	20	20.69620	W	71	12	41.02906	97.825
PLO	000	0184	N	10	11	25.47082	W	71	11	26.74427	27.528
PLO	111	0202	N	10	12	31.80970	W	71	9	11.65150	53.773
PLO	000	0300	N	10	16	17.46606	W	71	19	1.04859	14.293
PLO	000	0500	N	10	7	37.19251	W	71	15	47.57228	1.952
PLO	000	0600	N	10	4	34.50051	W	71	8	4.02485	14.316
PLO	000	0700	N	10	6	54.98405	W	71	3	0.88248	50.387
PLO	000	0743	N	10	19	10.23346	W	71	16	30.45887	53.781
PLO	000	0800	N	10	4	23.48178	W	70	59	25.51745	63.332
PLO	000	0900	N	9	59	16.20329	W	71	5	30.84094	9.152
PLO	000	1010	N	10	6	43.87080	W	71	15	18.78301	2.926
PLO	000	1200	N	10	12	27.72001	W	71	16	13.31054	10.262
PLO	000	1300	N	10	10	35.86623	W	71	18	2.55089	3.591
PLO	000	2900	N	9	58	15.73391	W	71	11	42.42980	2.897
PLO	000	9201	N	10	23	58.76609	W	71	8	13.61530	111.396
PLO	000	9202	N	10	15	31.55599	W	71	6	10.27665	83.401
PLO	000	9203	N	10	9	42.86971	W	70	56	40.70723	139.866

Table B6.
Venezuela 1993 GPS (GPPS L3 solution)
Adjusted PLH Coordinates:

		STN	LATITUDE (dms)				LONGITUDE (dms)				HEIGHT (m)
PLO	000	0011	N	9	57	21.81364	W	71	9	23.58228	2.902
PLO	000	0012	N	10	15	49.64367	W	71	22	29.78868	3.417
PLO	000	0014	N	10	17	1.22924	W	71	23	17.65206	2.540
PLO	000	0100	N	10	20	20.69719	W	71	12	41.02890	97.816
PLO	000	0184	N	10	11	25.47075	W	71	11	26.74431	27.531
PLO	111	0202	N	10	12	31.80970	W	71	9	11.65150	53.773
PLO	000	0300	N	10	16	17.46677	W	71	19	1.04889	14.307
PLO	000	0500	N	10	7	37.19190	W	71	15	47.57289	1.961
PLO	000	0600	N	10	4	34.49978	W	71	8	4.02466	14.323
PLO	000	0700	N	10	6	54.98357	W	71	3	0.88193	50.380
PLO	000	0743	N	10	19	10.23438	W	71	16	30.45941	53.793
PLO	000	0800	N	10	4	23.48075	W	70	59	25.51656	63.334
PLO	000	0900	N	9	59	16.20209	W	71	5	30.84039	9.165
PLO	000	1010	N	10	6	43.87021	W	71	15	18.78338	2.943
PLO	000	1200	N	10	12	27.71986	W	71	16	13.31117	10.285
PLO	000	1300	N	10	10	35.86594	W	71	18	2.55182	3.606
PLO	000	2900	N	9	58	15.73240	W	71	11	42.42932	2.917
PLO	000	9201	N	10	23	58.76763	W	71	8	13.61483	111.357
PLO	000	9202	N	10	15	31.55678	W	71	6	10.27605	83.383
PLO	000	9203	N	10	9	42.86943	W	70	56	40.70613	139.849

Table B7.
Venezuela GPS 1993 (TRIMMBP L0 solution)
Adjusted PLH Coordinates:

		STN	LATITUDE (dms)				LONGITUDE (dms)				HEIGHT (m)
PLO	000	0011	N	9	57	21.81185	W	71	9	23.58247	2.862
PLO	000	0012	N	10	15	49.64427	W	71	22	29.79063	3.402
PLO	000	0014	N	10	17	1.23039	W	71	23	17.65487	2.539
PLO	000	0100	N	10	20	20.69850	W	71	12	41.02986	97.816
PLO	000	0184	N	10	11	25.47065	W	71	11	26.74476	27.531
PLO	111	0202	N	10	12	31.80970	W	71	9	11.65150	53.773
PLO	000	0300	N	10	16	17.46764	W	71	19	1.05100	14.298
PLO	000	0500	N	10	7	37.19175	W	71	15	47.57412	1.969
PLO	000	0600	N	10	4	34.49917	W	71	8	4.02454	14.319
PLO	000	0700	N	10	6	54.98309	W	71	3	0.88151	50.388
PLO	000	0743	N	10	19	10.23568	W	71	16	30.46103	53.785
PLO	000	0800	N	10	4	23.47988	W	70	59	25.51578	63.349
PLO	000	0900	N	9	59	16.20085	W	71	5	30.83965	9.159
PLO	000	1010	N	10	6	43.86976	W	71	15	18.78469	2.950
PLO	000	1200	N	10	12	27.72020	W	71	16	13.31242	10.274
PLO	000	1300	N	10	10	35.86591	W	71	18	2.55303	3.609
PLO	000	2900	N	9	58	15.73093	W	71	11	42.43083	2.906
PLO	000	9201	N	10	23	58.76972	W	71	8	13.61521	111.362
PLO	000	9202	N	10	15	31.55693	W	71	6	10.27631	83.395
PLO	000	9203	N	10	9	42.86869	W	70	56	40.70495	139.856

Table B8.
Venezuela GPS 1994 (TRIMMBP L0 solution)
Adjusted PLH Coordinates:

		STN	LATITUDE (dms)				LONGITUDE (dms)				HEIGHT (m)
PLH	000	0011	N	9	57	21.81378	W	71	9	23.58314	2.852
PLH	000	0012	N	10	15	49.64380	W	71	22	29.78931	3.371
PLH	000	0014	N	10	17	1.22936	W	71	23	17.65340	2.522
PLH	000	0100	N	10	20	20.69750	W	71	12	41.02948	97.800
PLH	000	0184	N	10	11	26.33707	W	71	11	26.73348	27.783
PLH	111	0202	N	10	12	31.80970	W	71	9	11.65150	53.773
PLH	000	0300	N	10	16	17.46750	W	71	19	1.04982	14.262
PLH	000	0600	N	10	4	34.49954	W	71	8	4.02614	14.261
PLH	000	0700	N	10	6	54.98408	W	71	3	0.88246	50.386
PLH	000	0743	N	10	19	10.23496	W	71	16	30.45955	53.785
PLH	000	0800	N	10	4	23.48099	W	70	59	25.51693	63.329
PLH	000	0900	N	9	59	16.20194	W	71	5	30.84130	9.145
PLH	000	1010	N	10	6	43.87045	W	71	15	18.78417	2.897
PLH	000	1200	N	10	12	27.72022	W	71	16	13.31158	10.239
PLH	000	1300	N	10	10	35.86593	W	71	18	2.55251	3.593
PLH	000	2900	N	9	58	15.73249	W	71	11	42.43059	2.842
PLH	000	9201	N	10	23	58.76802	W	71	8	13.61504	111.302
PLH	000	9202	N	10	15	31.55700	W	71	6	10.27702	83.392
PLH	000	9203	N	10	9	42.86950	W	70	56	40.70659	139.851

Table B9.
Venezuela GPS 1994 (GPPS L3 solution)
Adjusted PLH Coordinates:

		STN	LATITUDE (dms)				LONGITUDE (dms)				HEIGHT (m)
PLH	000	0011	N	9	57	21.81375	W	71	9	23.58330	2.846
PLH	000	0012	N	10	15	49.64287	W	71	22	29.78972	3.369
PLH	000	0014	N	10	17	1.22847	W	71	23	17.65388	2.523
PLH	000	0100	N	10	20	20.69662	W	71	12	41.02881	97.789
PLH	000	0184	N	10	11	26.33708	W	71	11	26.73289	27.785
PLH	111	0202	N	10	12	31.80970	W	71	9	11.65150	53.773
PLH	000	0300	N	10	16	17.46668	W	71	19	1.04942	14.266
PLH	000	0600	N	10	4	34.49944	W	71	8	4.02611	14.250
PLH	000	0700	N	10	6	54.98377	W	71	3	0.88311	50.378
PLH	000	0743	N	10	19	10.23394	W	71	16	30.45963	53.787
PLH	000	0800	N	10	4	23.48076	W	70	59	25.51762	63.324
PLH	000	0900	N	9	59	16.20198	W	71	5	30.84082	9.128
PLH	000	1010	N	10	6	43.87052	W	71	15	18.78532	2.886
PLH	000	1200	N	10	12	27.71965	W	71	16	13.31143	10.251
PLH	000	1300	N	10	10	35.86551	W	71	18	2.55177	3.598
PLH	000	2900	N	9	58	15.73255	W	71	11	42.43005	2.832
PLH	000	9201	N	10	23	58.76710	W	71	8	13.61531	111.321
PLH	000	9202	N	10	15	31.55610	W	71	6	10.27801	83.390
PLH	000	9203	N	10	9	42.86902	W	70	56	40.70649	139.850

Figure (B1). Trimble L1 1990 – Trimble L1 1991. Minimum Constraints, using GPS weights.

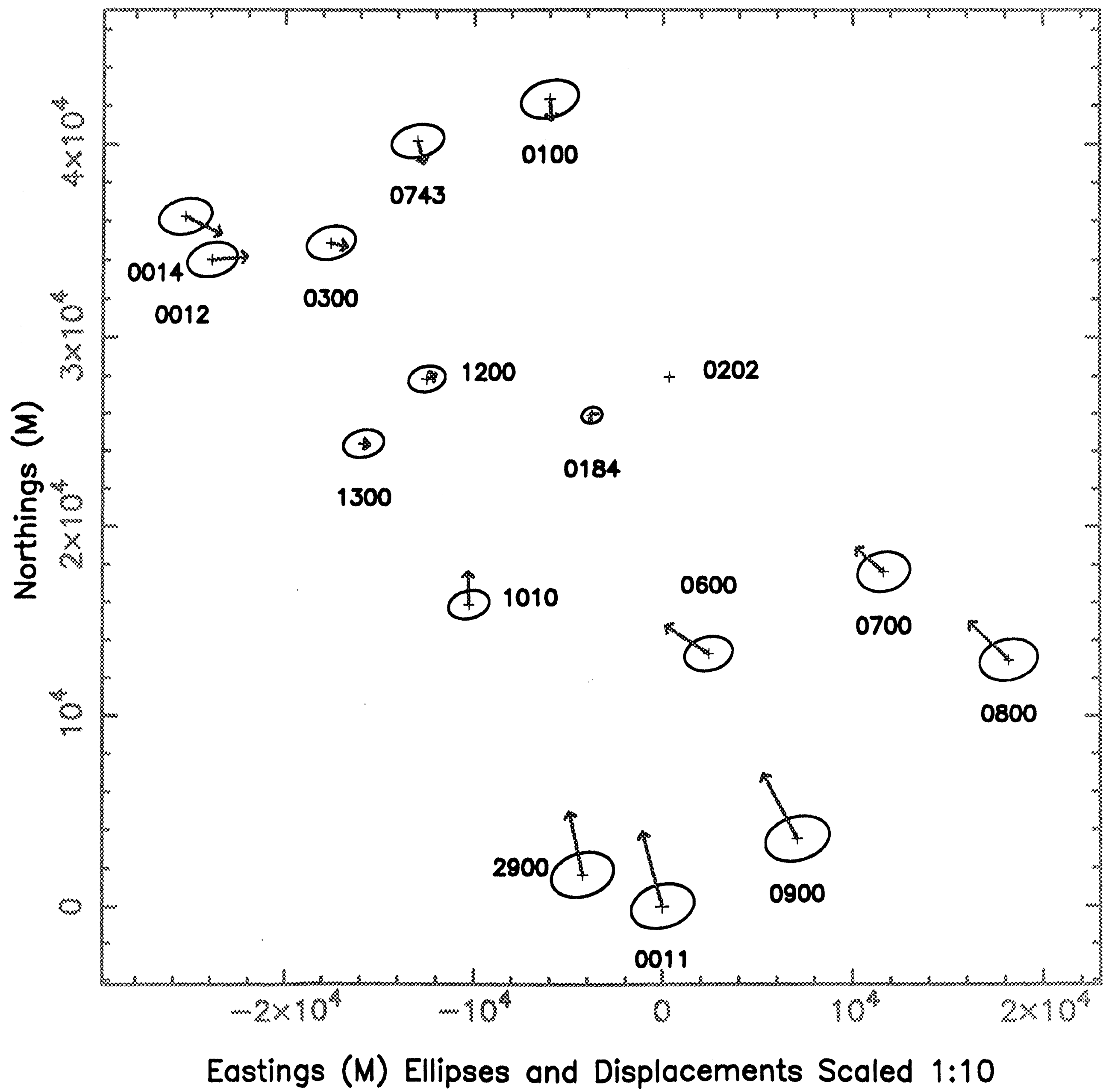


Figure (B2). Trimble L1 1991 — Trimble L1 1992. Minimum Constraints, using GPS weights.

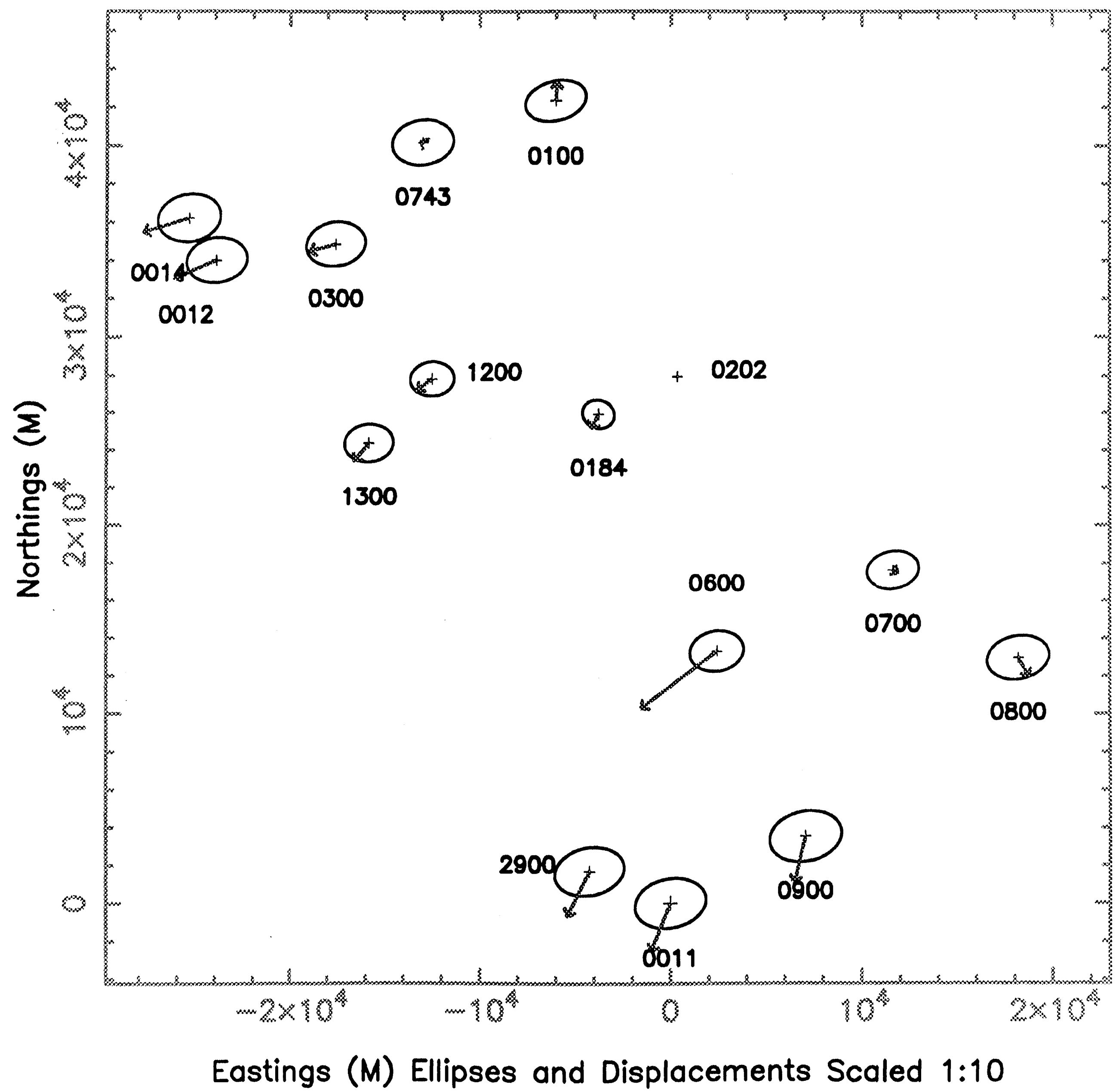


Figure (β3). Ashtech L1 1992 – Ashtech L1 1993. Minimum Constraints, using GPS weights.

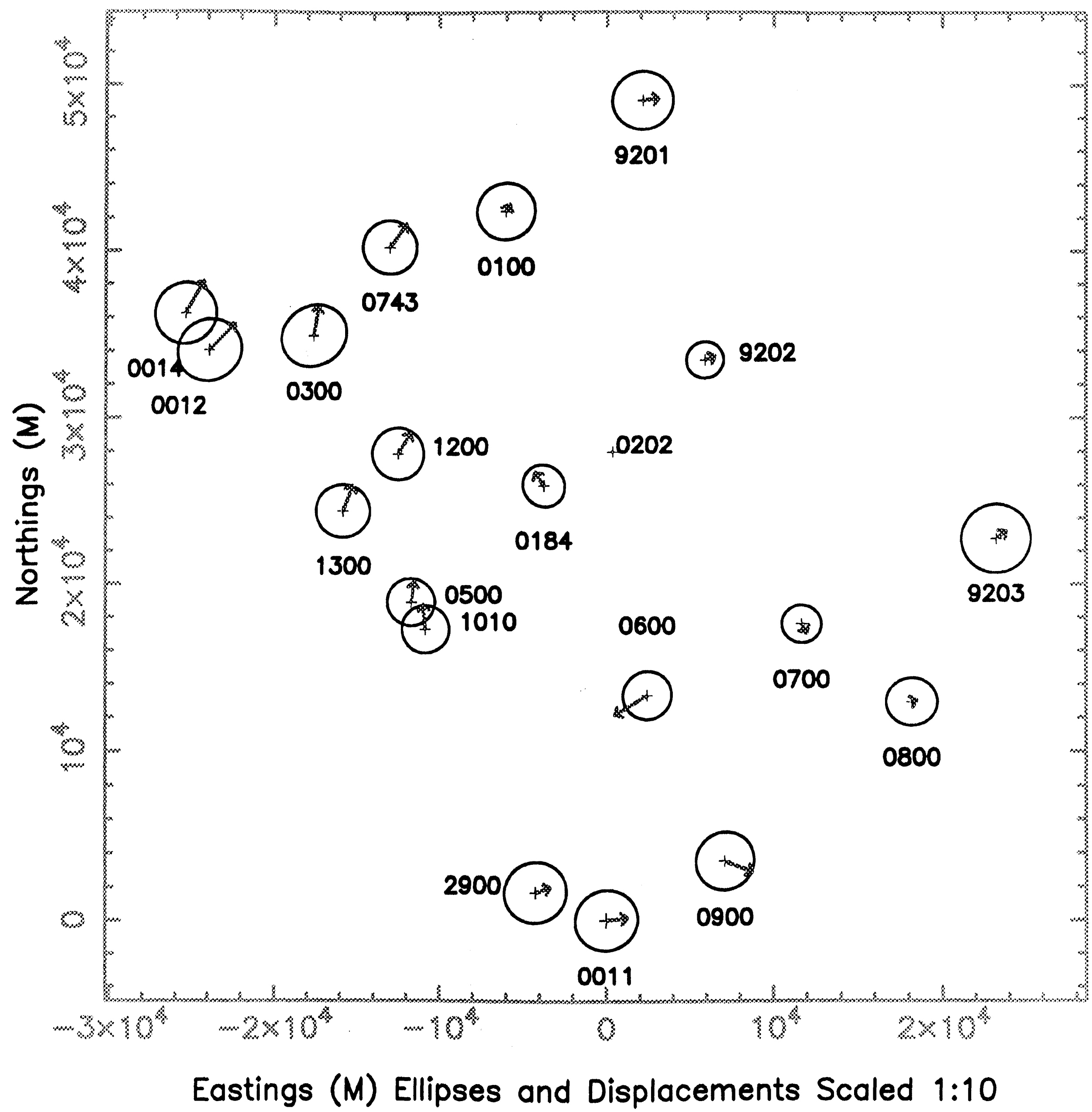


Figure (B4). Trimble L1 1992 – Trimble L0 1993. Minimum Constraints, using GPS weights.

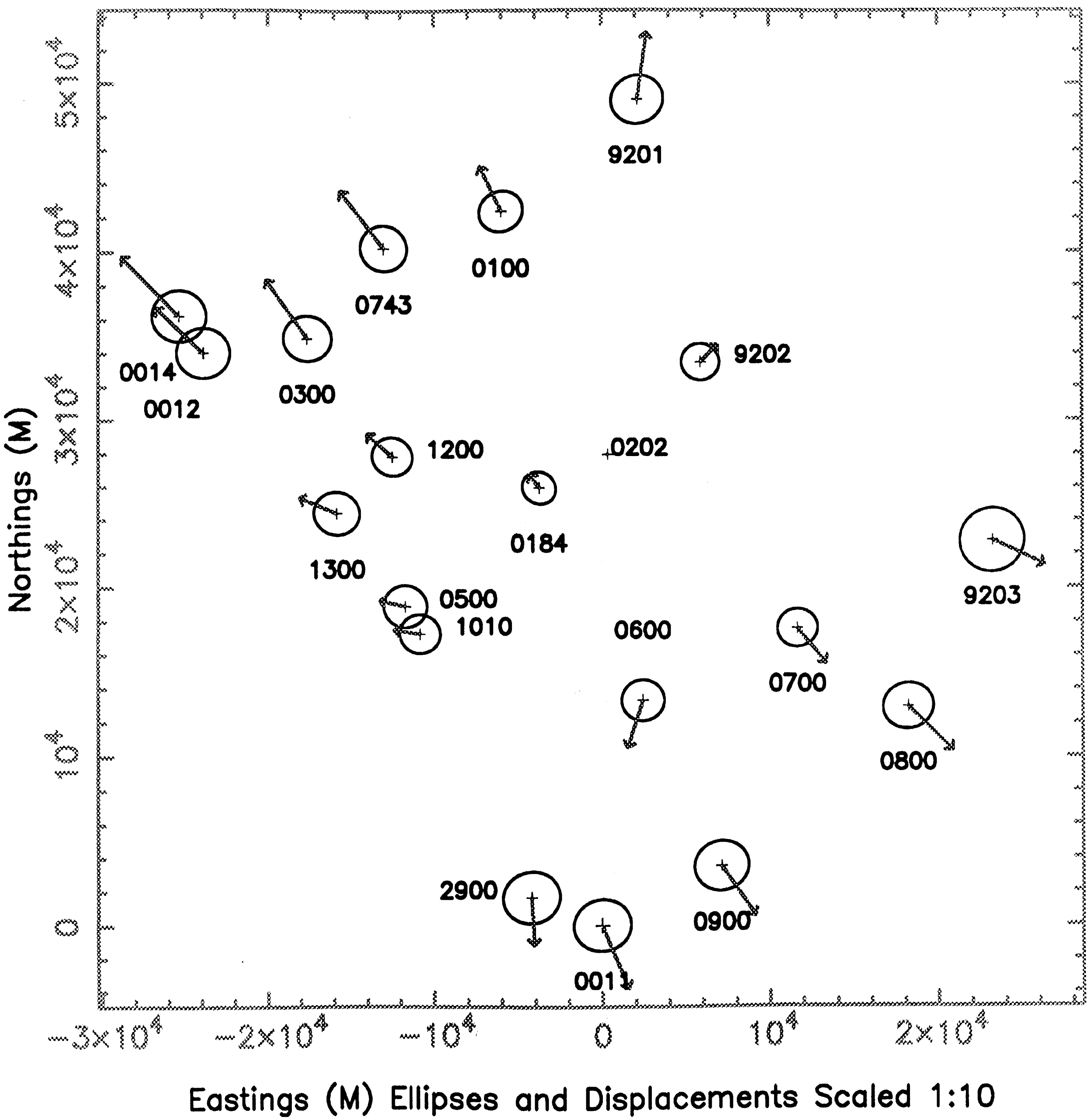


Figure (BS). Ashtech L1 1992 – Ashtech L3 1993. Minimum Constraints, using GPS weights.

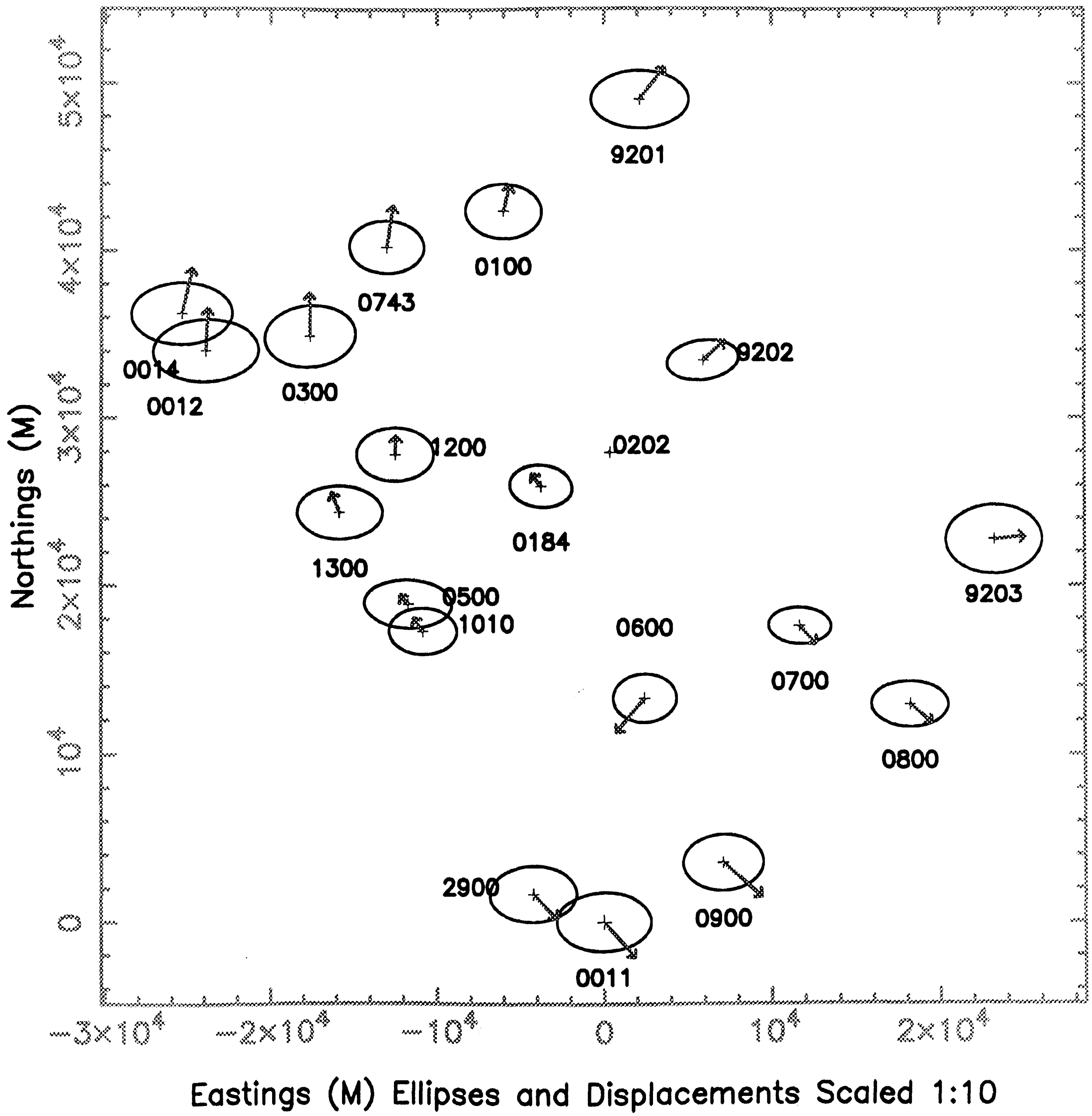


Figure (β6). Trimble LO 1993 – Trimble LO 1994. Minimum Constraints, using GPS weights.

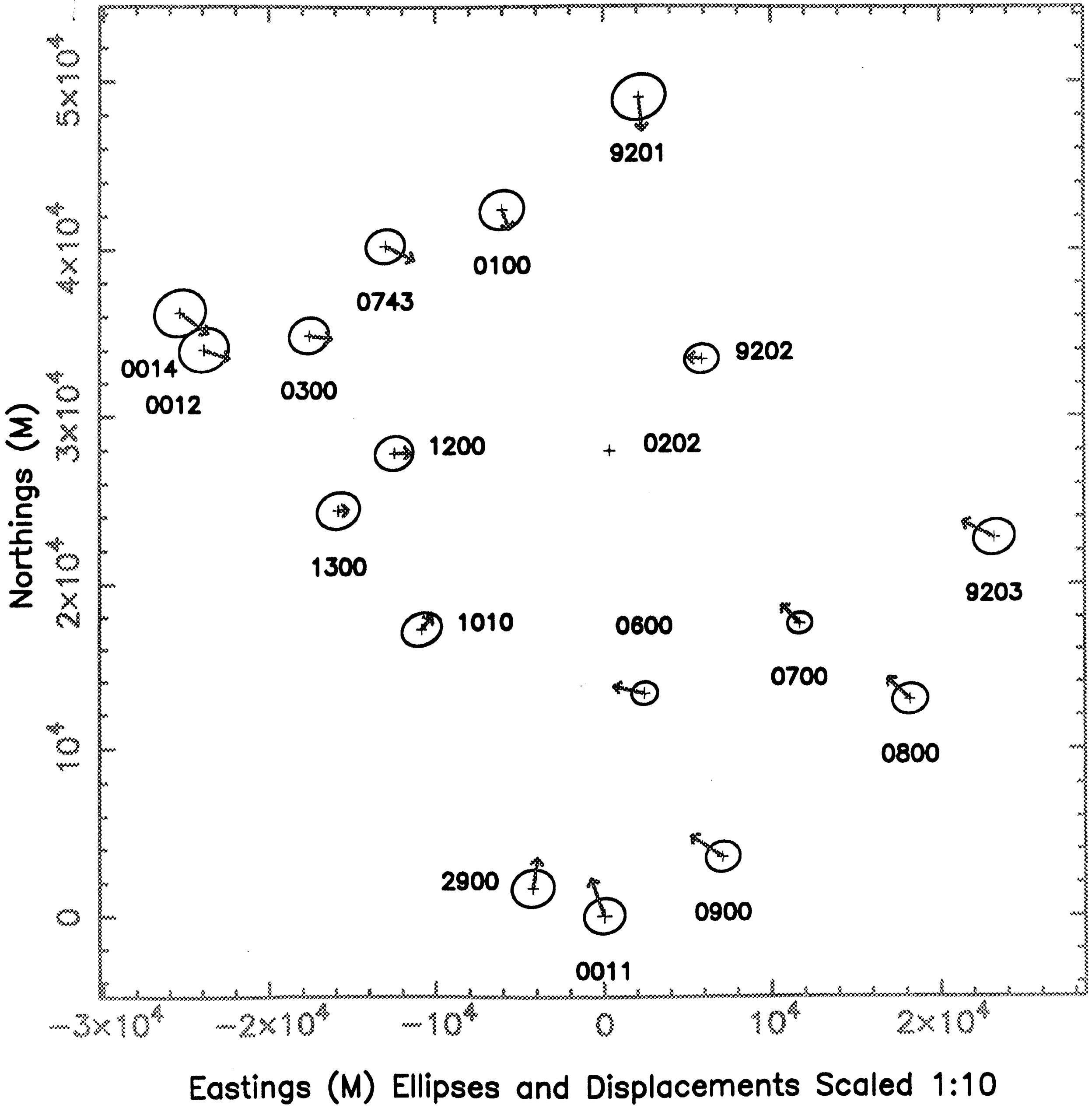


Figure (B7). Ashtech L3 1993 – Ashtech L3 1994. Minimum Constraints, using GPS weights.

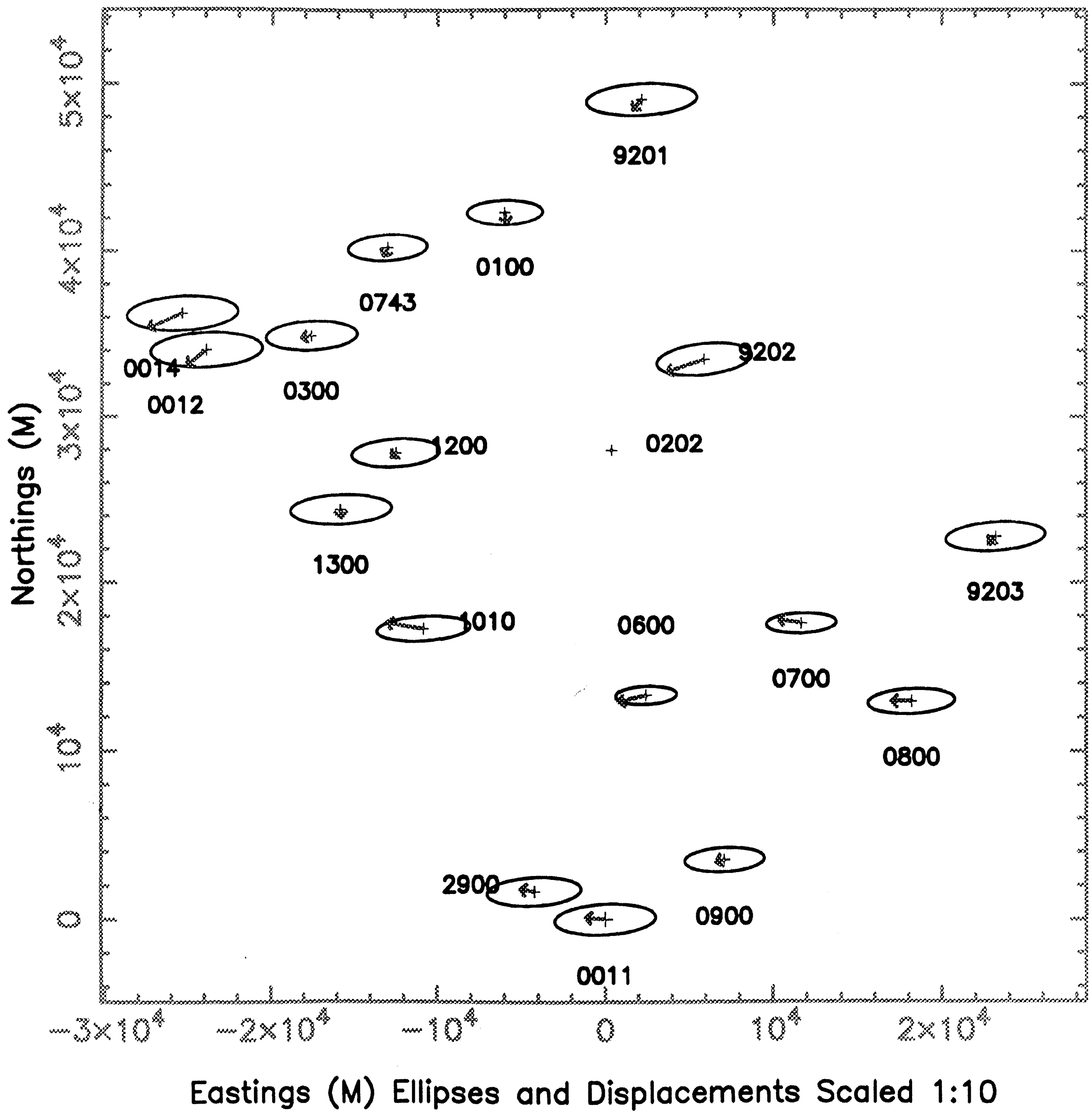
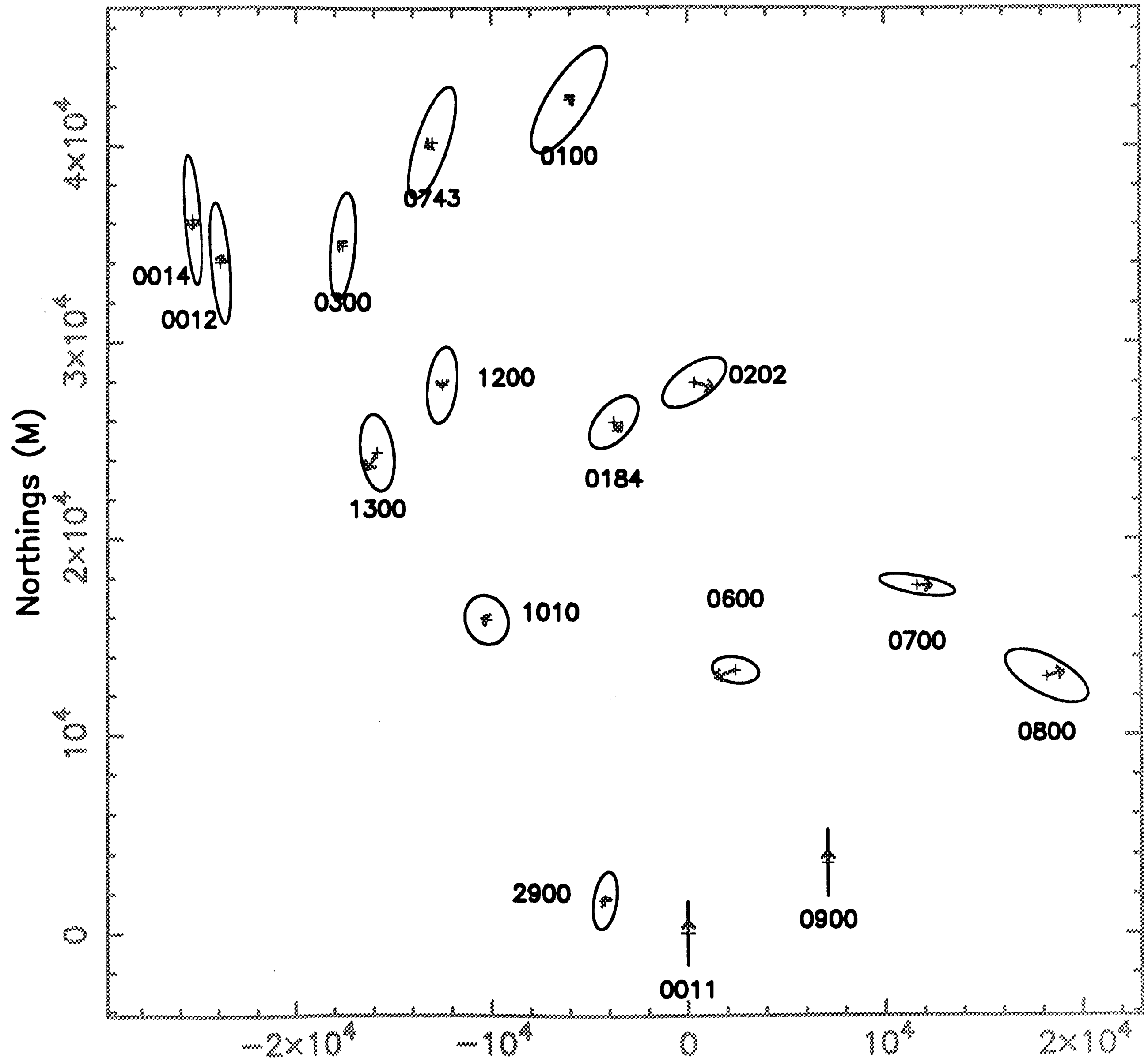


Figure (B8). Trimble L1 1990 – Trimble L1 1991. IWST using GPS weights. Scale + Rotation defects.



Eastings (M) Ellipses and Displacements Scaled 1:10

Figure (β9). Trimble L1 1991 – Trimble L1 1992. IWST using GPS weights. Scale + Rotation defects.

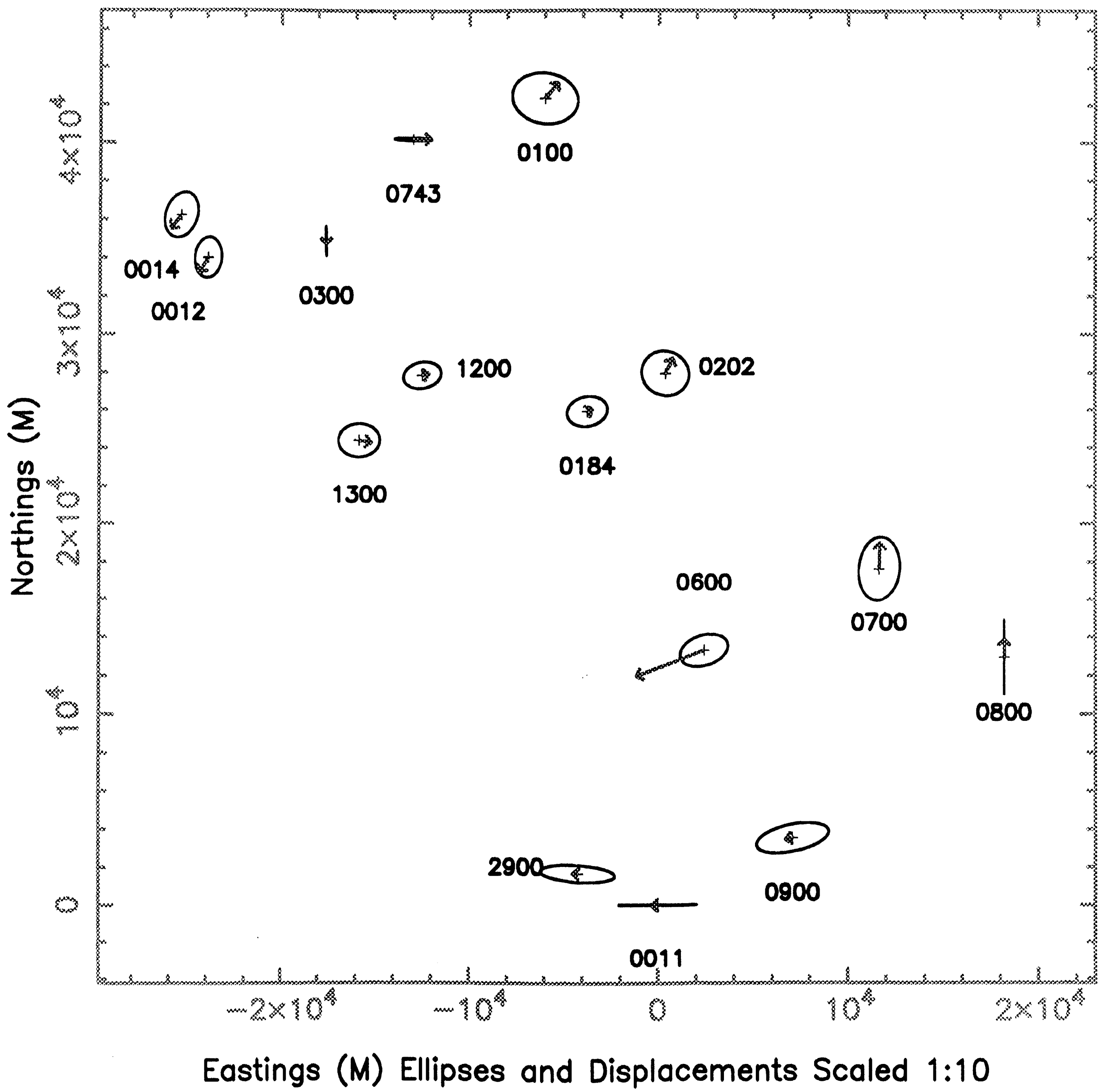


Figure (B10). Ashtech L1 1992 – Ashtech L1 1993. IWST using GPS weights. Scale + Rotation defects.

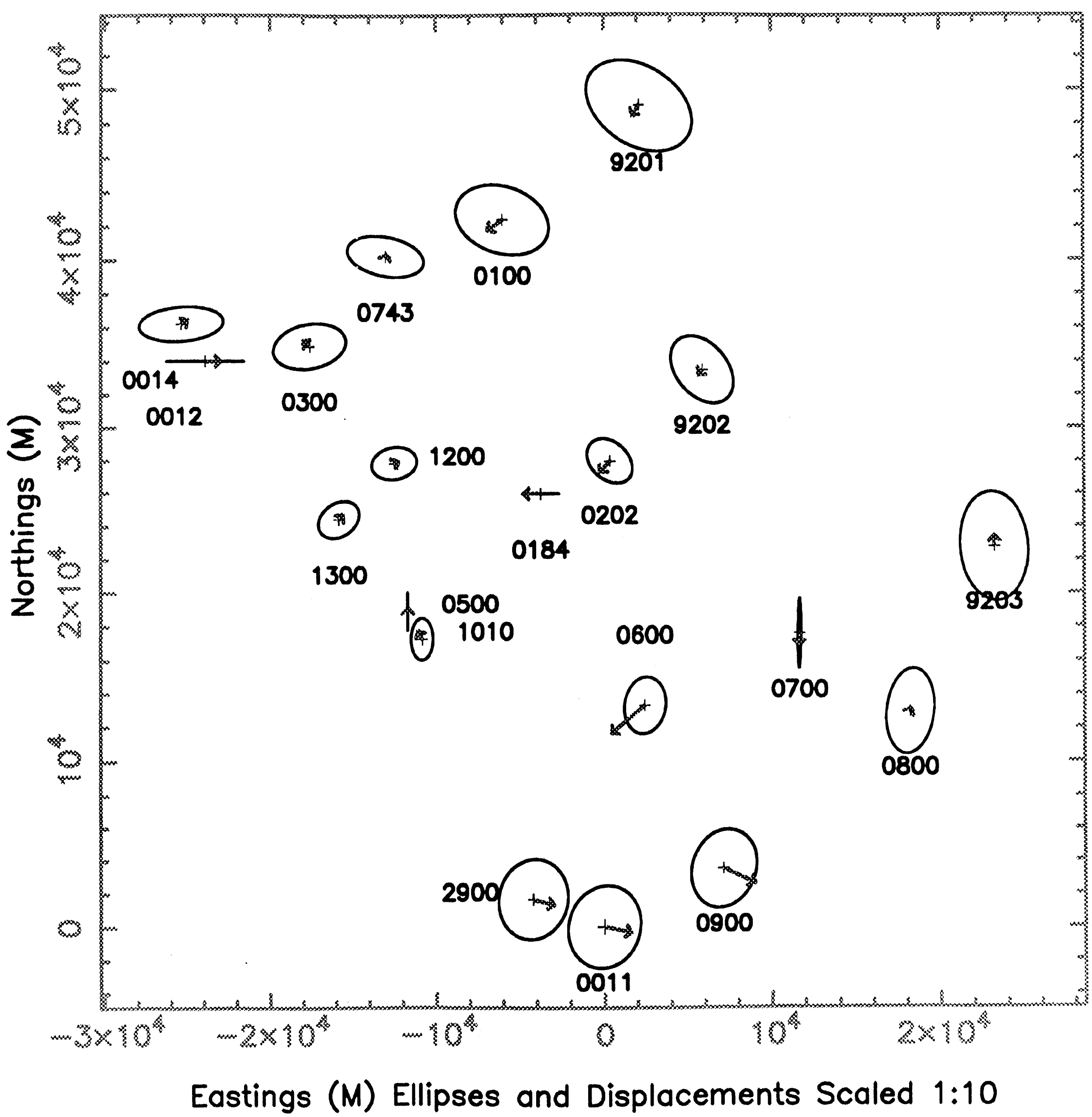


Figure (B11). Trimble L1 1992 – Trimble L0 1993. IWST using GPS weights. Scale + Rotation defects.

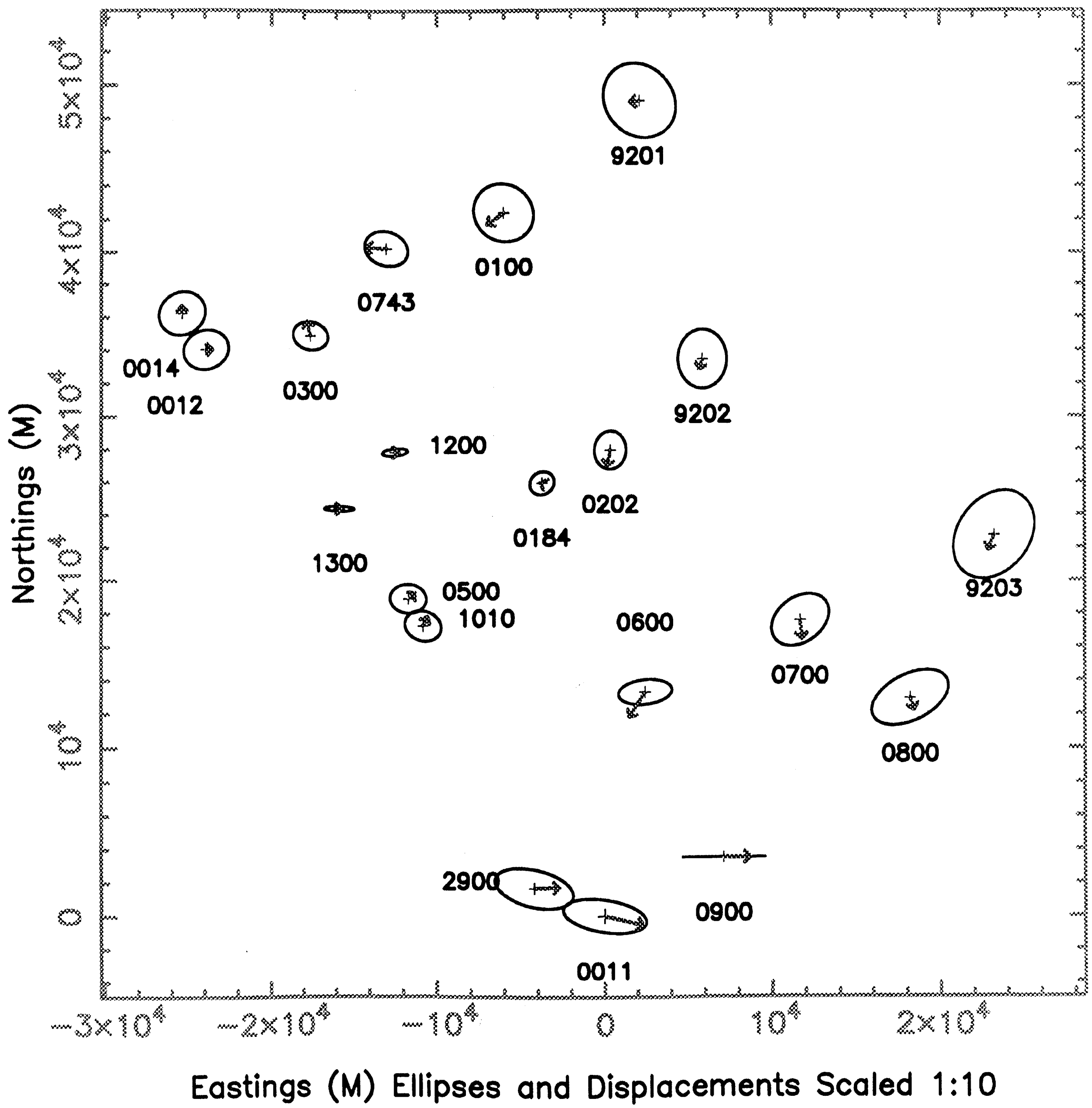


Figure (B12). Ashtech L1 1992 – Ashtech L3 1993. IWST using GPS weights. Scale + Rotation defects.

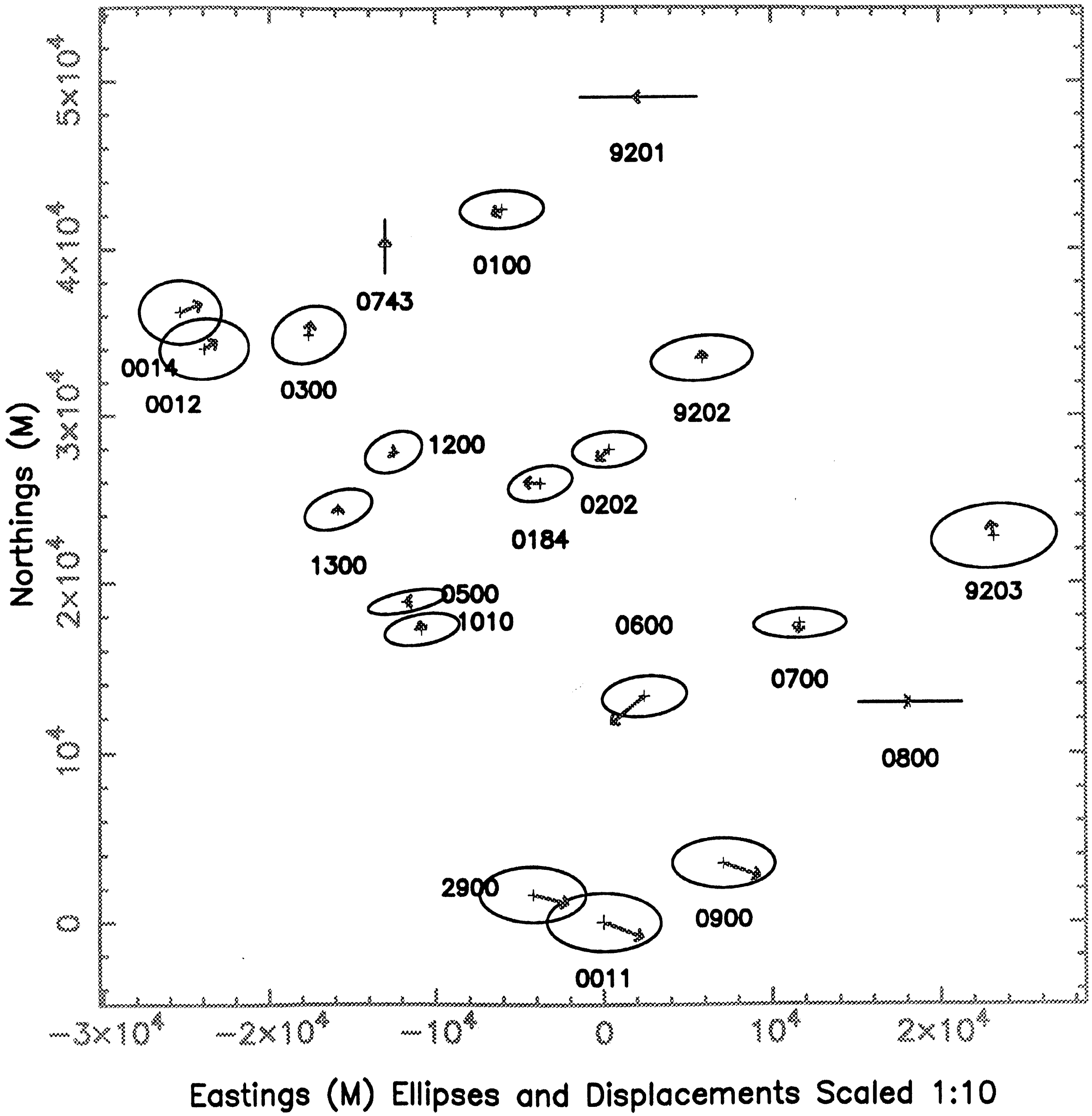


Figure (B13). Trimble LO 1993 – Trimble LO 1994. IWST using GPS weights. Scale + Rotation defects.

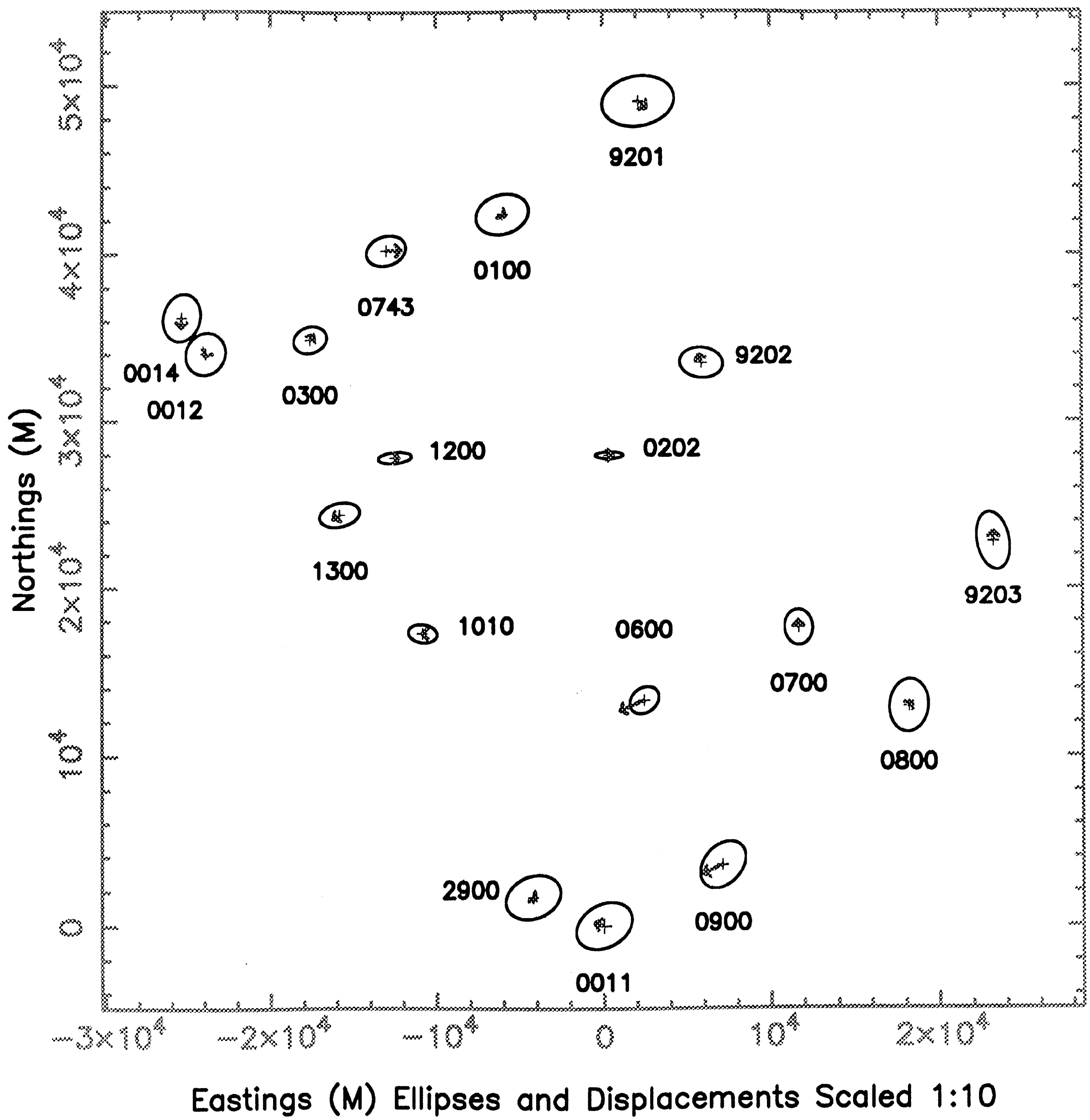
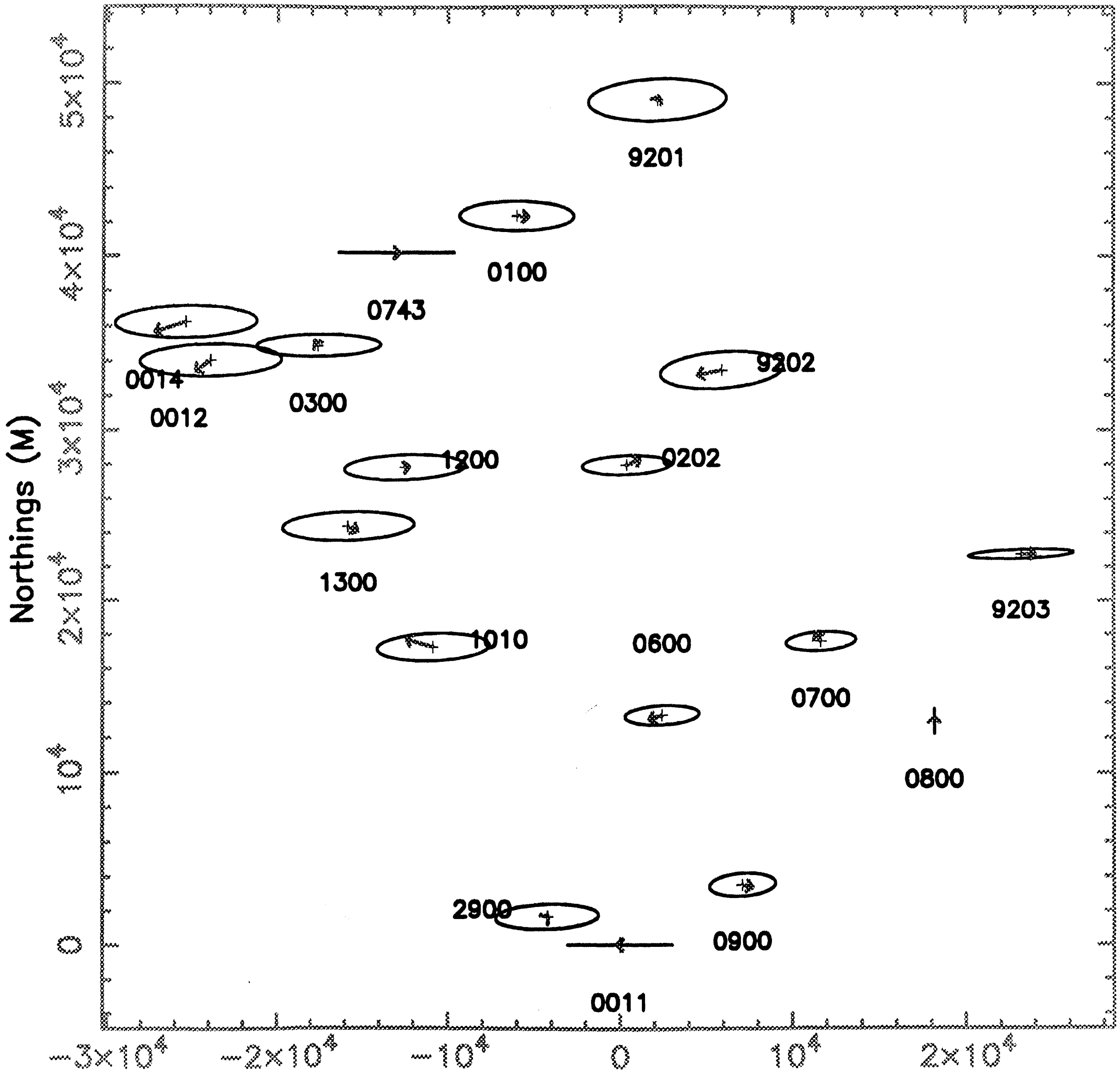


Figure (B14). Ashtech L3 1993 – Ashtech L3 1994. IWST using GPS weights. Scale + Rotation defects.



Eastings (M) Ellipses and Displacements Scaled 1:10

Appendix C

Comparison of Solution Types

This appendix contains tables and plots, comparing the results of different solution types for the same year.

Table C1.
1992. Solution Differences. GPPS L1 - TRIMMBP L1.

		STN	Delta Lat. (dms)				Delta Long. (dms)				Delta H (m)
PLO	000	0011		0	0	0.00034		0	0	0.00007	-0.006
PLO	000	0012		0	0	-0.00043		0	0	0.00070	0.020
PLO	000	0014		0	0	-0.00048		0	0	0.00081	-0.006
PLO	000	0100		0	0	-0.00033		0	0	0.00047	-0.003
PLO	000	0184		0	0	0.00019		0	0	-0.00044	0.011
PLO	111	0202		0	0	0.00000		0	0	0.00000	0.000
PLO	000	0300		0	0	-0.00007		0	0	0.00007	0.089
PLO	000	0500		0	0	0.00001		0	0	-0.00034	0.021
PLO	000	0600		0	0	-0.00006		0	0	-0.00057	0.030
PLO	000	0700		0	0	-0.00039		0	0	-0.00022	-0.053
PLO	000	0743		0	0	-0.00050		0	0	0.00101	0.019
PLO	000	0800		0	0	-0.00042		0	0	-0.00040	-0.065
PLO	000	0900		0	0	0.00044		0	0	0.00096	-0.023
PLO	000	1010		0	0	-0.00002		0	0	-0.00044	-0.001
PLO	000	1200		0	0	-0.00011		0	0	0.00012	0.014
PLO	000	1300		0	0	-0.00018		0	0	0.00034	0.032
PLO	000	2900		0	0	0.00027		0	0	-0.00039	0.000
PLO	000	9201		0	0	-0.00026		0	0	0.00041	0.002
PLO	000	9202		0	0	-0.00026		0	0	-0.00004	-0.010
PLO	000	9203		0	0	-0.00065		0	0	0.00005	-0.031

Table C2.
1993. Solution Differences. GPPS L3 - TRIMMBP L0.

		STN	Delta Lat. (dms)				Delta Long. (dms)				Delta H (m)
PLO	000	0011		0	0	0.00179		0	0	-0.00019	0.040
PLO	000	0012		0	0	-0.00060		0	0	-0.00195	0.015
PLO	000	0014		0	0	-0.00115		0	0	-0.00281	0.001
PLO	000	0100		0	0	-0.00131		0	0	-0.00096	0.000
PLO	000	0184		0	0	0.00010		0	0	-0.00045	0.000
PLO	111	0202		0	0	0.00000		0	0	0.00000	0.000
PLO	000	0300		0	0	-0.00087		0	0	-0.00211	0.009
PLO	000	0500		0	0	0.00015		0	0	-0.00123	-0.008
PLO	000	0600		0	0	0.00061		0	0	0.00012	0.004
PLO	000	0700		0	0	0.00048		0	0	0.00042	-0.008
PLO	000	0743		0	0	-0.00130		0	0	-0.00162	0.008
PLO	000	0800		0	0	0.00087		0	0	0.00078	-0.015
PLO	000	0900		0	0	0.00124		0	0	0.00074	0.006
PLO	000	1010		0	0	0.00045		0	0	-0.00131	-0.007
PLO	000	1200		0	0	-0.00034		0	0	-0.00125	0.011
PLO	000	1300		0	0	0.00003		0	0	-0.00121	-0.003
PLO	000	2900		0	0	0.00147		0	0	-0.00151	0.011
PLO	000	9201		0	0	-0.00209		0	0	-0.00038	-0.005
PLO	000	9202		0	0	-0.00015		0	0	-0.00026	-0.012
PLO	000	9203		0	0	0.00074		0	0	0.00118	-0.007

Table C3.
1994. Solution Differences. GPPS L3 - TRIMMBP L0.

		STN	Delta Lat. (dms)				Delta Long. (dms)				Delta H (m)
PLO	000	0011		0	0	-0.00003		0	0	0.00016	-0.006
PLO	000	0012		0	0	-0.00093		0	0	0.00041	-0.002
PLO	000	0014		0	0	-0.00089		0	0	0.00048	0.001
PLO	000	0100		0	0	-0.00088		0	0	-0.00067	-0.011
PLO	000	0184		0	0	0.00001		0	0	-0.00059	0.002
PLO	111	0202		0	0	0.00000		0	0	0.00000	0.000
PLO	000	0300		0	0	-0.00082		0	0	-0.00040	0.004
PLO	000	0600		0	0	-0.00010		0	0	-0.00003	-0.011
PLO	000	0700		0	0	-0.00031		0	0	0.00065	-0.008
PLO	000	0743		0	0	-0.00102		0	0	0.00008	0.002
PLO	000	0800		0	0	-0.00023		0	0	0.00069	-0.005
PLO	000	0900		0	0	0.00004		0	0	-0.00048	-0.017
PLO	000	1010		0	0	0.00007		0	0	0.00115	-0.011
PLO	000	1200		0	0	-0.00057		0	0	-0.00015	0.012
PLO	000	1300		0	0	-0.00042		0	0	-0.00074	0.005
PLO	000	2900		0	0	0.00006		0	0	-0.00054	-0.010
PLO	000	9201		0	0	-0.00092		0	0	0.00027	0.019
PLO	000	9202		0	0	-0.00090		0	0	0.00099	-0.002
PLO	000	9203		0	0	-0.00048		0	0	-0.00010	-0.001

Figure (C1). Ashtech L1 1992 – Trimble L1 1992. Minimum Constraints, using GPS weights.

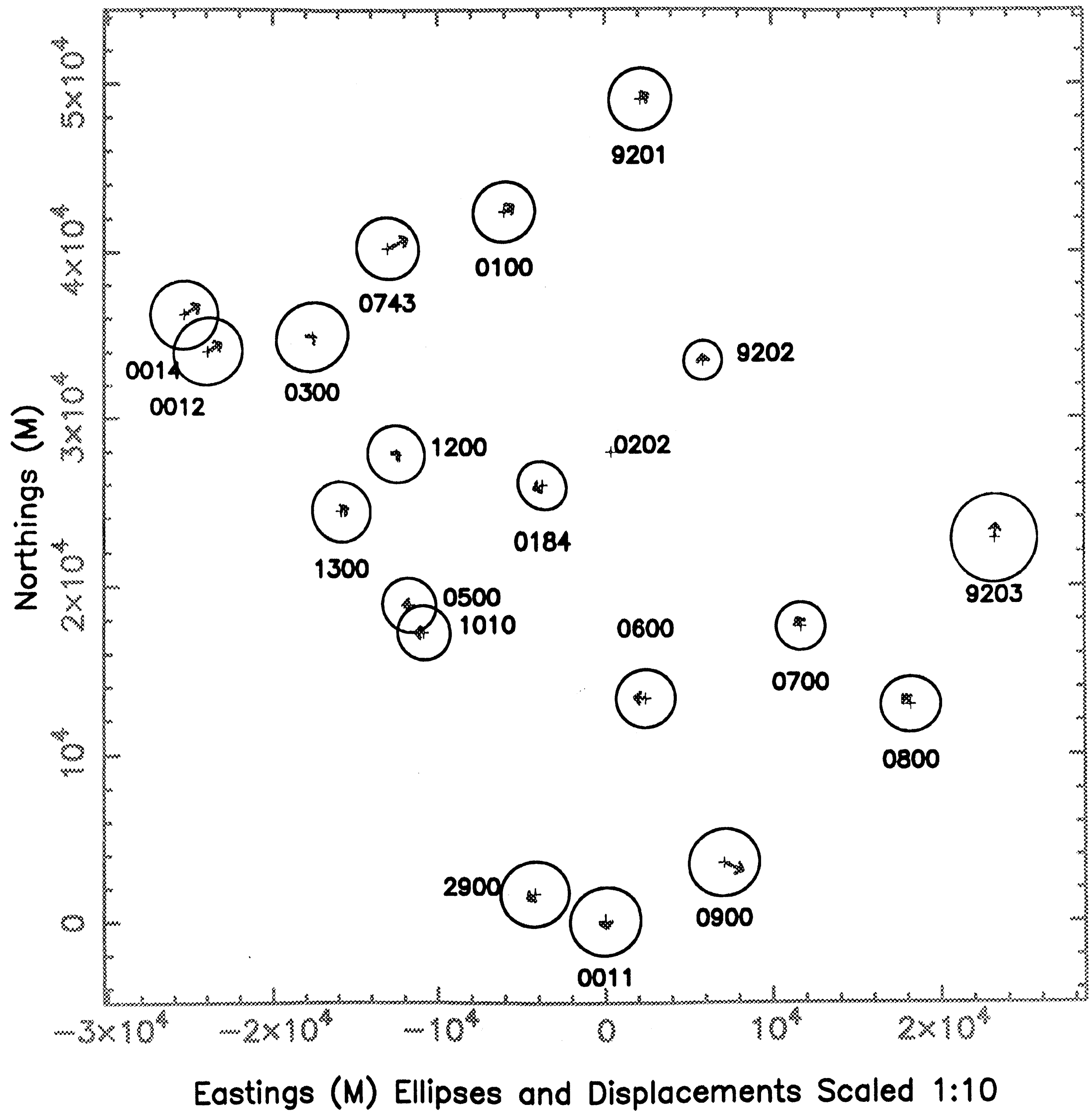


Figure (C2). Ashtech L1 1993 – Ashtech L3 1993. Minimum Constraints, using GPS weights.

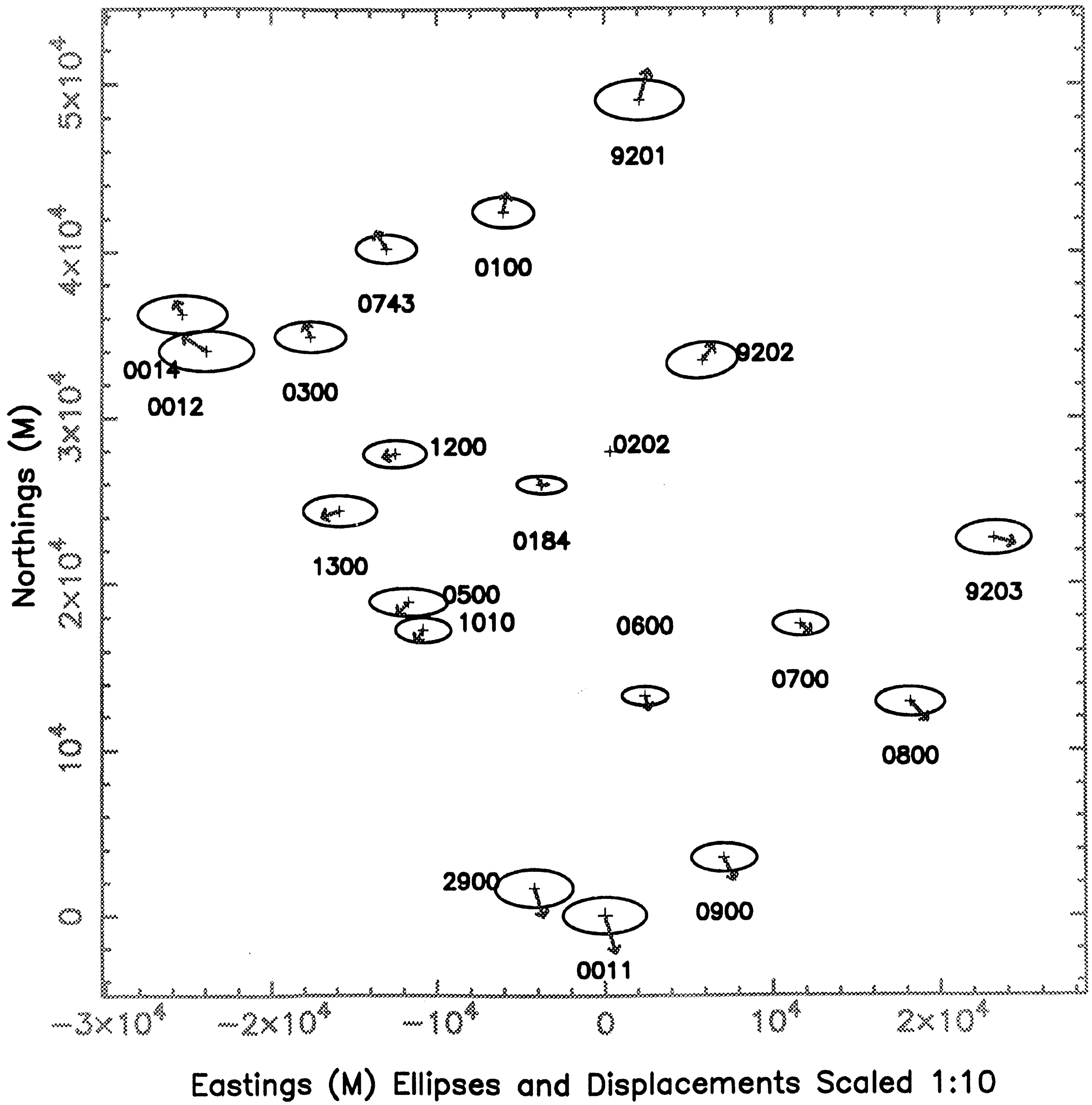
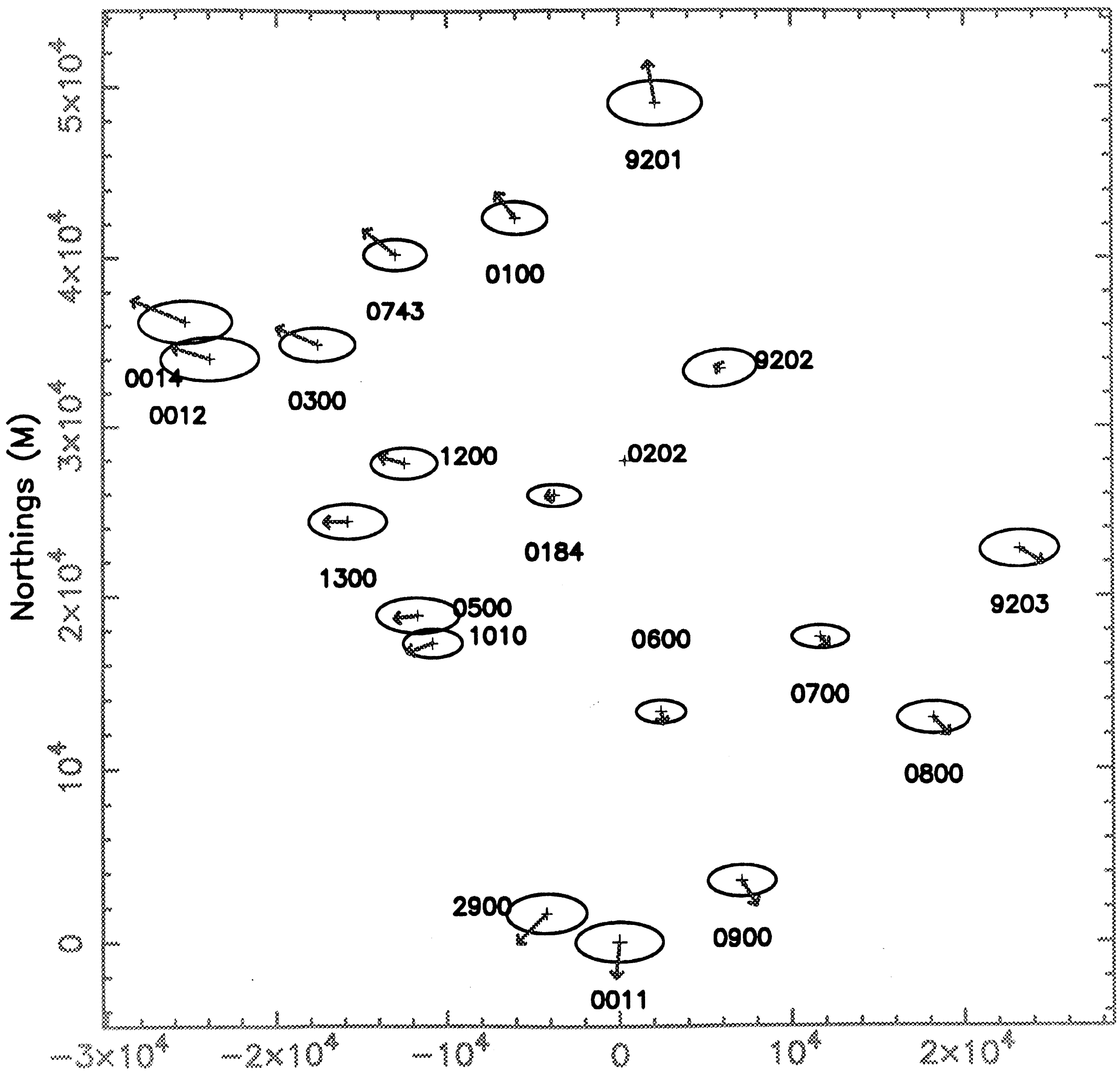
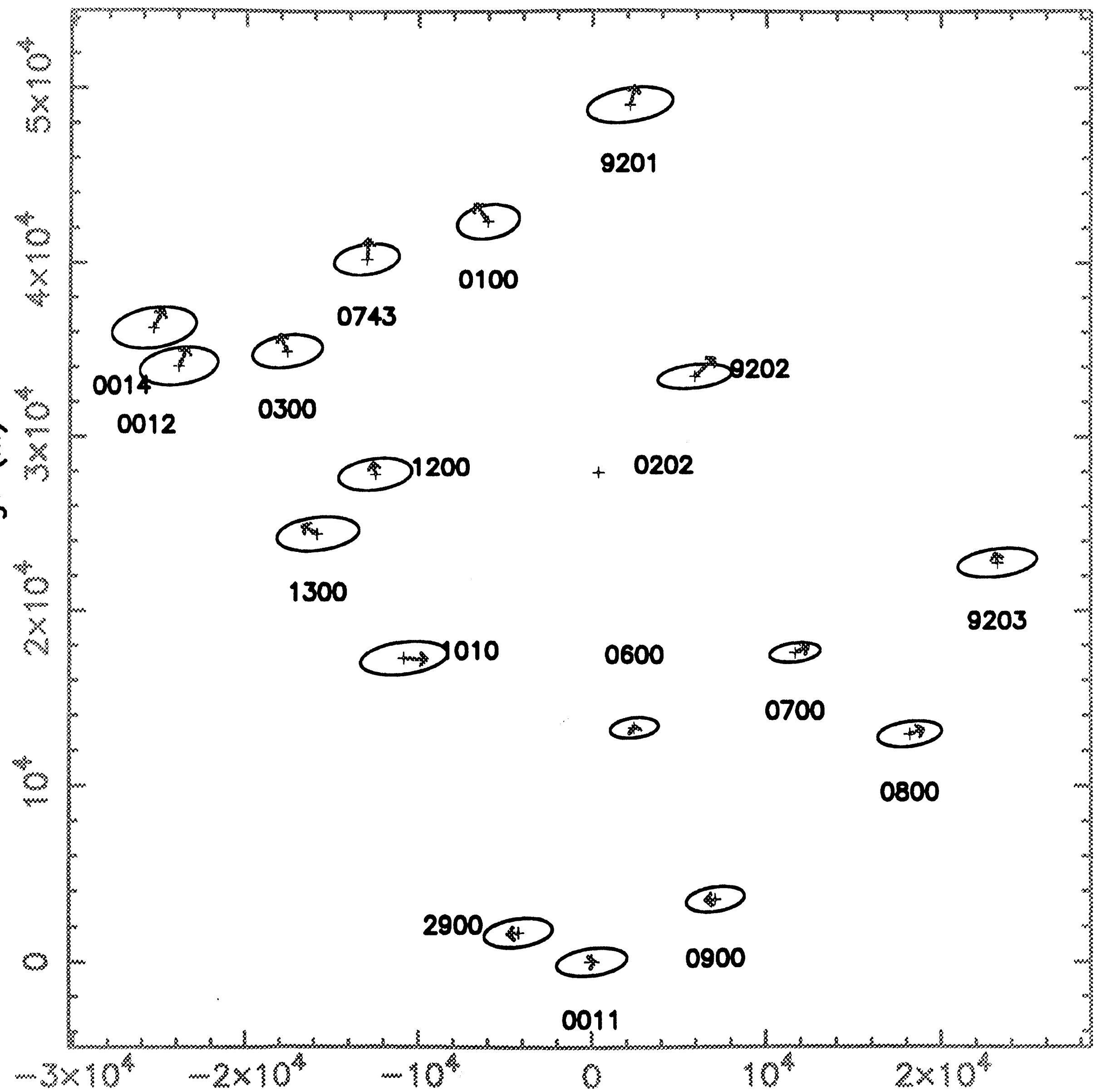


Figure (C3). Ashtech L3 1993 - Trimble L0 1993. Minimum Constraints, using GPS weights.



Eastings (M) Ellipses and Displacements Scaled 1:10

Figure (C4). Ashtech L3 1994 – Trimble L0 1994. Minimum Constraints, using GPS weights.



Eastings (M) Ellipses and Displacements Scaled 1:10

Appendix D

Examples of Residual Plots

This appendix contains some double difference residual plots for the years 1992 and 1993. An example of the worst and best plots are given.

According to Ashtech [1993], an L1 cycle is 19cm and an L3 cycle is 48cm.

Figure (D!). 1992. Baseline 0184 to 0600. Day 135-1
SVs 13 14 15 16 18 19 24 - 02 (L1)

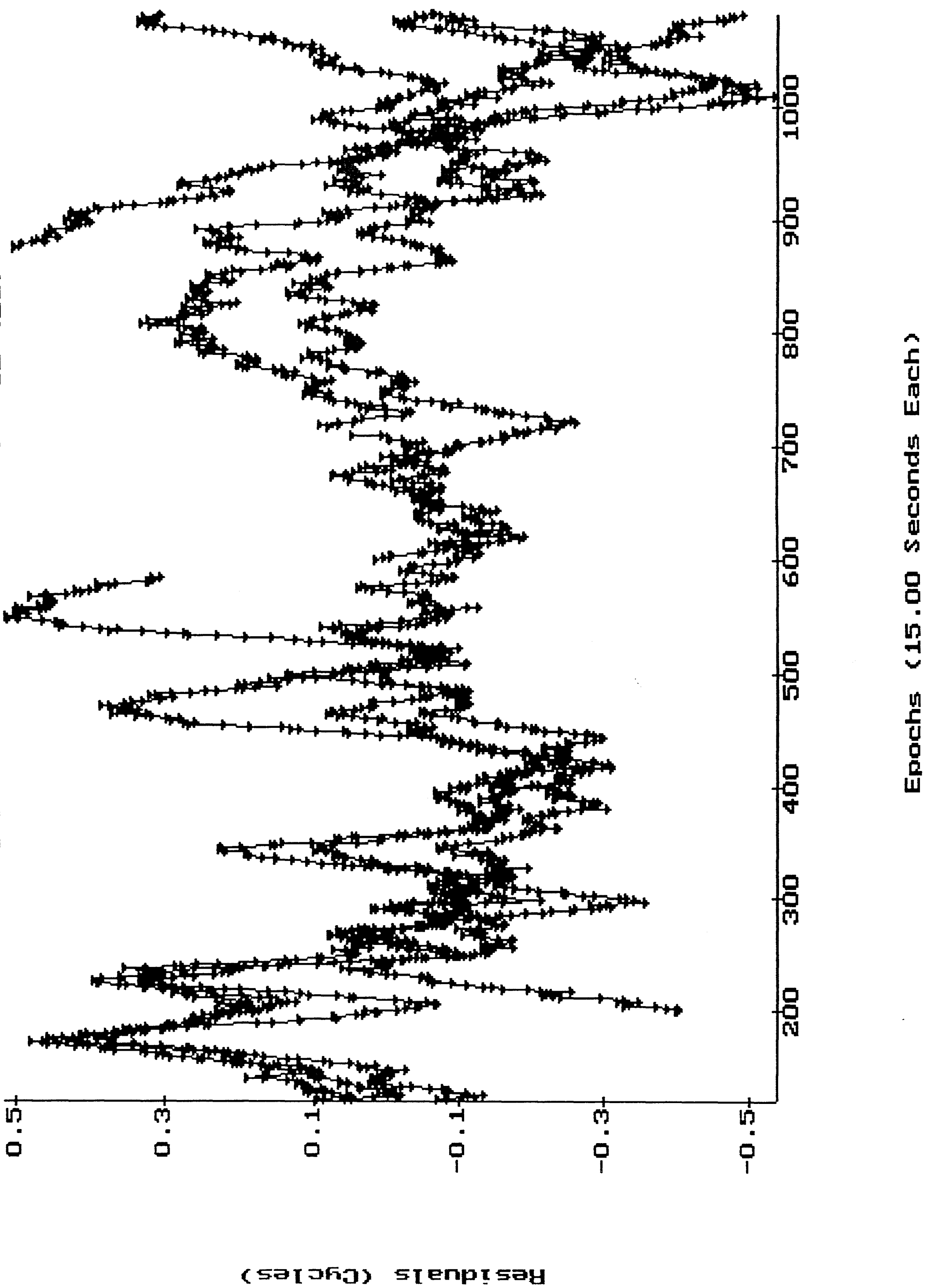
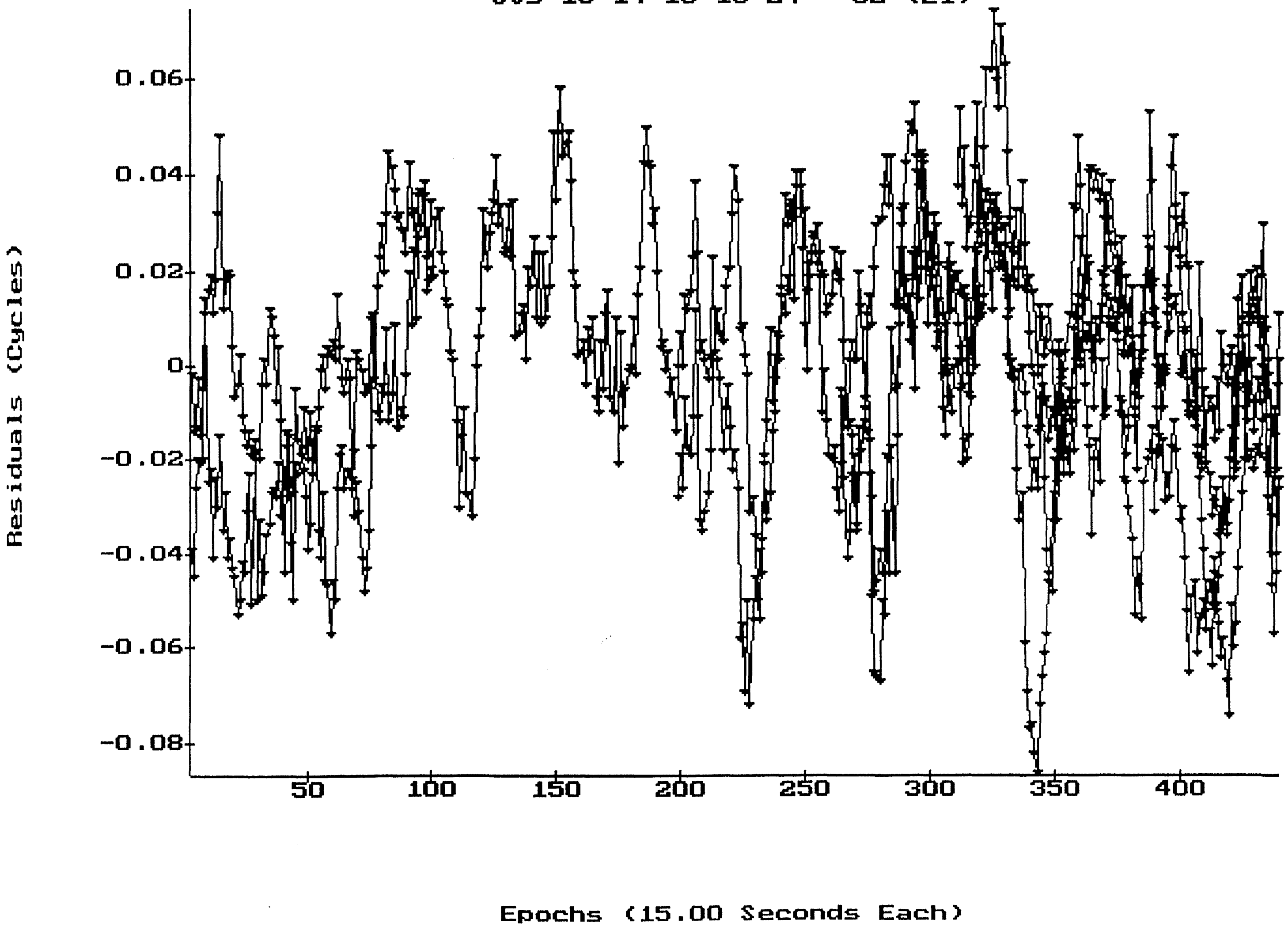


Figure (D2). 1992. Baseline 0500 to 1010. Day 133-2
SVs 13 14 16 18 24 - 02 (L1)



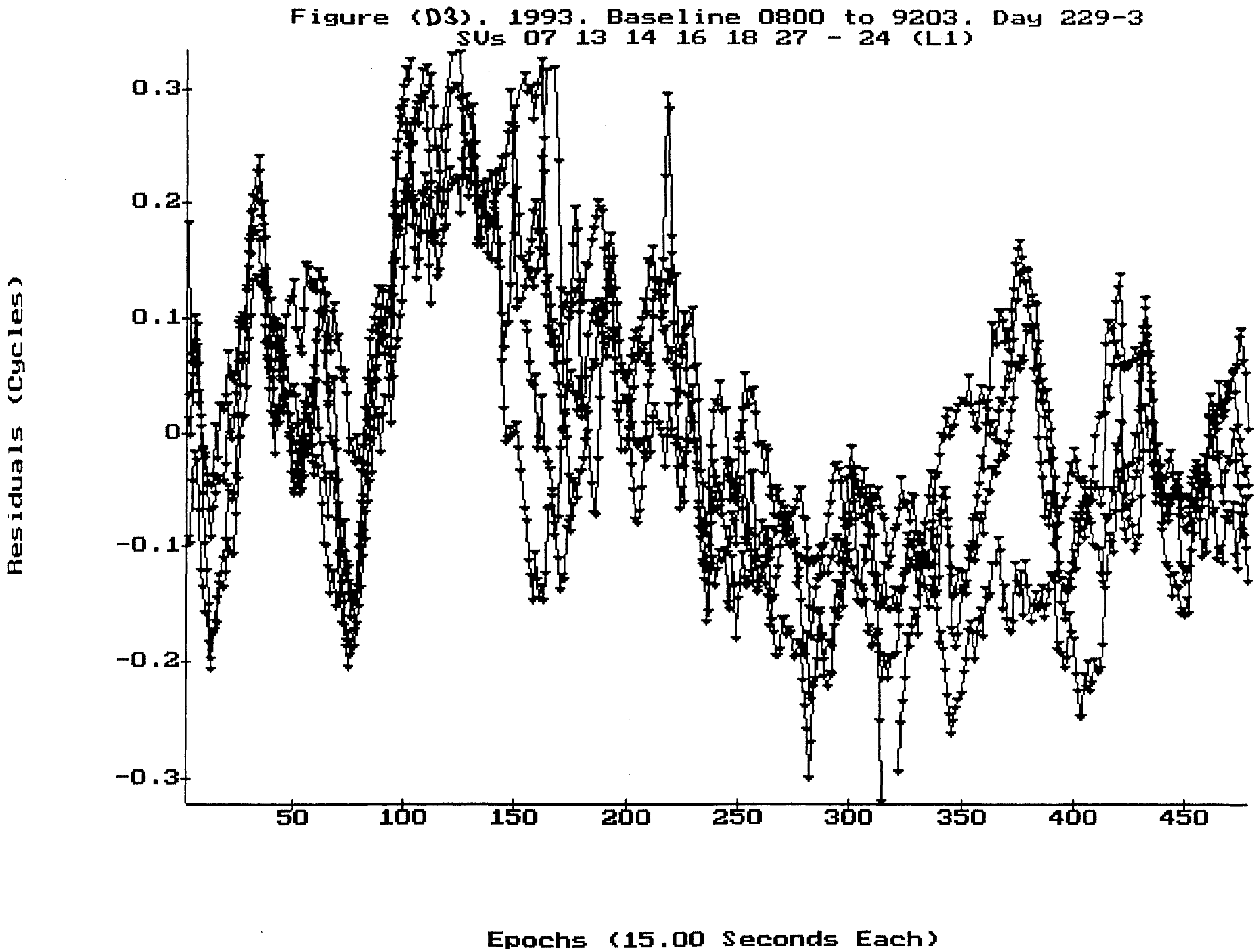


Figure (D3). 1993. Baseline 0800 to 9203. Day 229-3
SVs 07 13 14 16 18 27 - 24 (L1)
Residuals (Cycles)
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
50
100
150
200
250
300
350
400
450
Epochs (15.00 Seconds Each)

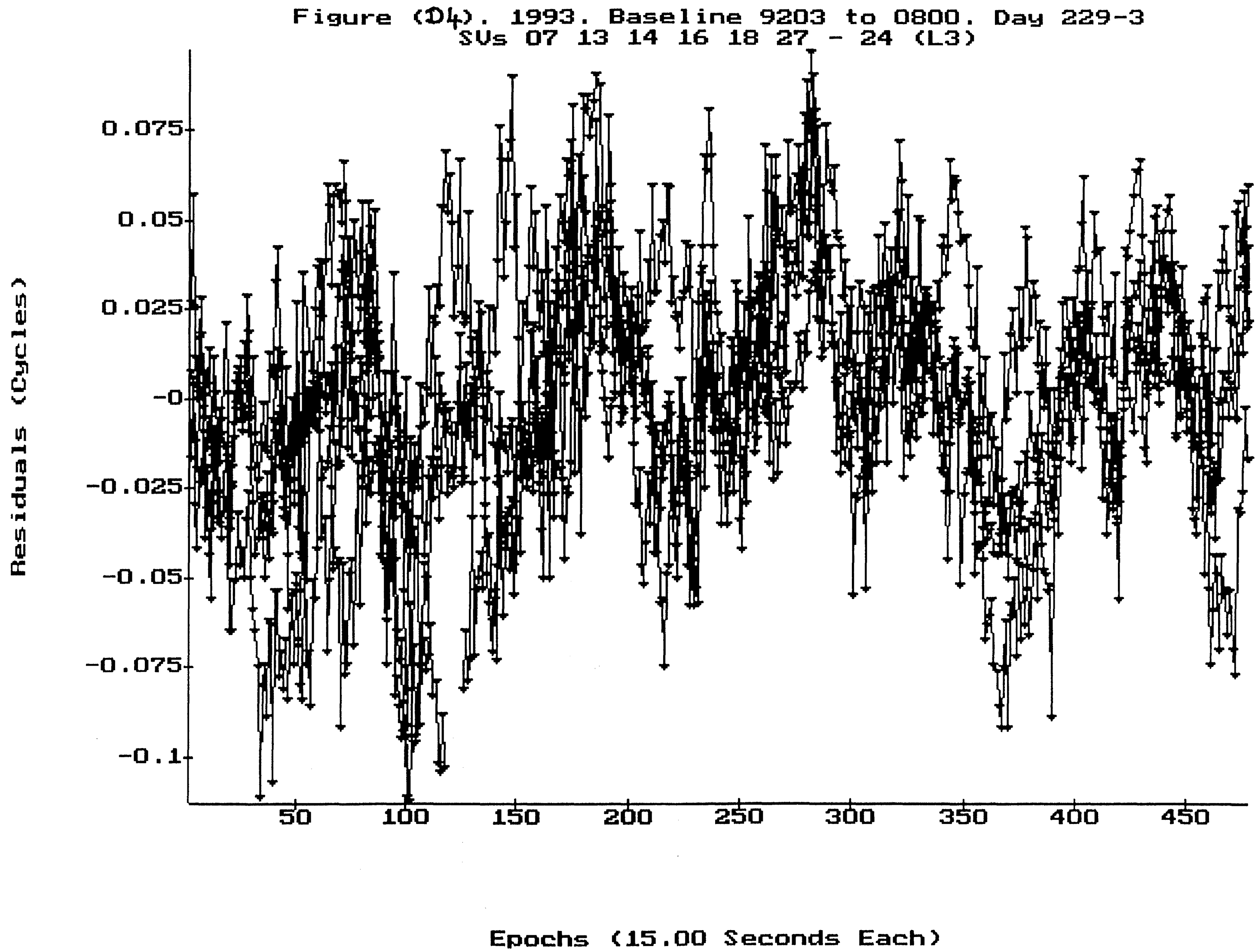


Figure (D4). 1993. Baseline 9203 to 0800. Day 229-3
SVs 07 13 14 16 18 27 - 24 (L3)
Residuals (Cycles)
0.075
0.05
0.025
-0
-0.025
-0.05
-0.075
-0.1
50
100
150
200
250
300
350
400
450
Epochs (15.00 Seconds Each)

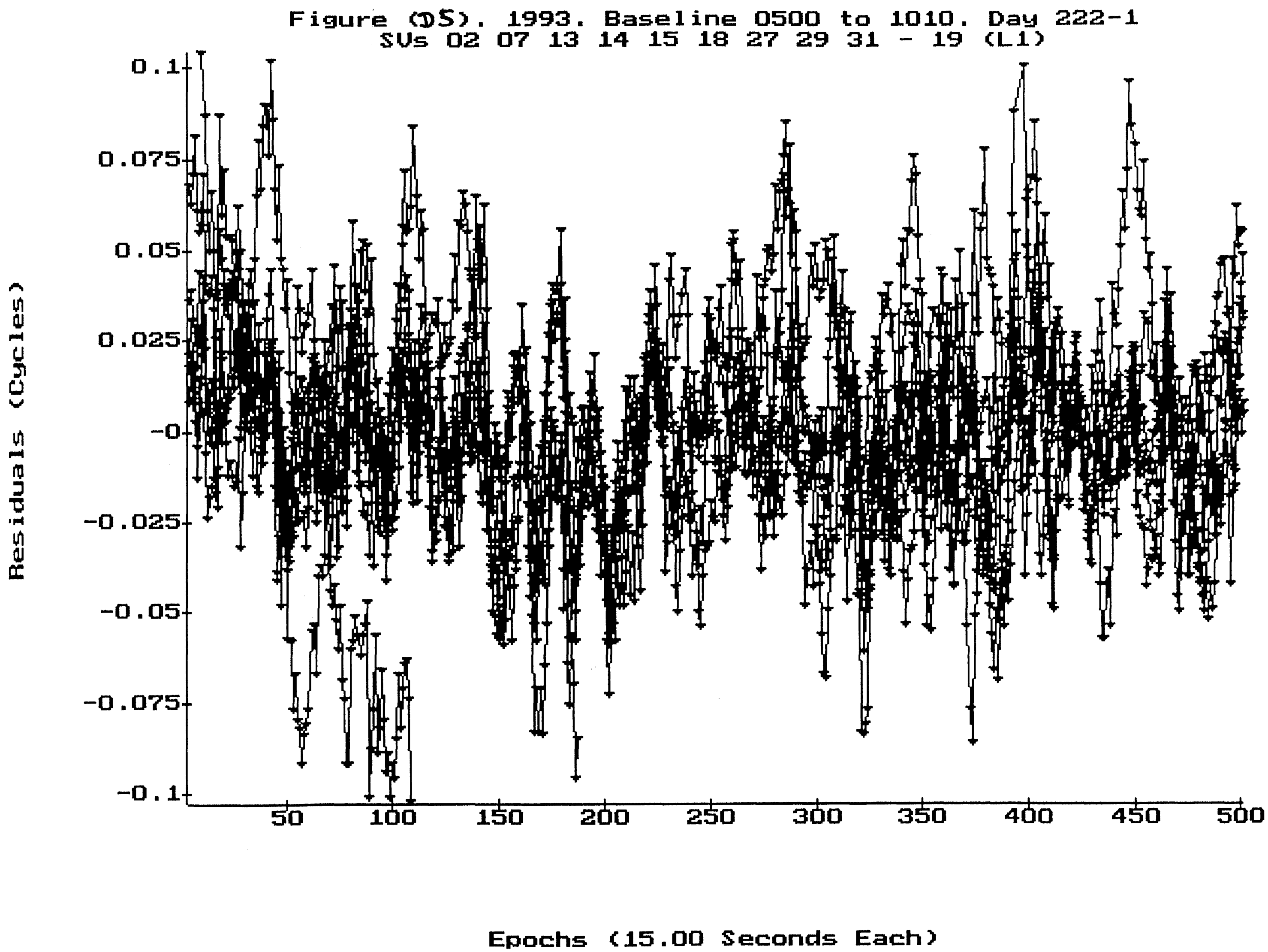
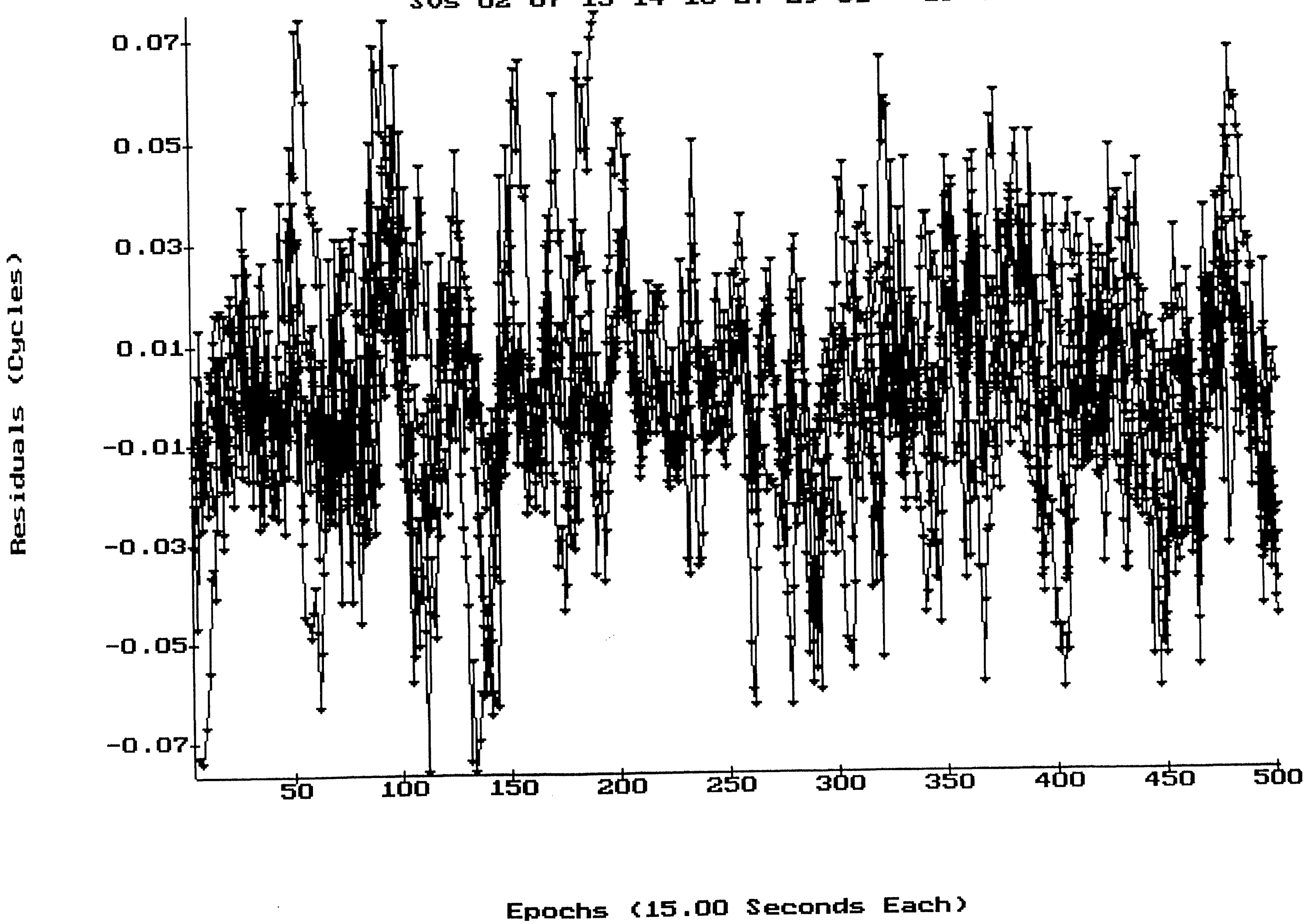


Figure (15). 1993. Baseline 0500 to 1010. Day 222-1
SVs 02 07 13 14 15 18 27 29 31 - 19 (L1)
Residuals (Cycles)
0.1
0.075
0.05
0.025
-0
-0.025
-0.05
-0.075
-0.1
50
100
150
200
250
300
350
400
450
500
Epochs (15.00 Seconds Each)

Figure (D6). 1993. Baseline 1010 to 0500. Day 222-1
SVs 02 07 13 14 15 27 29 31 - 19 (L3)



Appendix E

Software Comparison to DIPOP

This appendix contains the results of the Texas data set. A table of individual results for each software is given, followed by tables of day to repeatability and internal and external loop misclosures.

Table E1, contains a comparison of baseline solutions from the three processors.

Tables E2 to E7, contain the 3D loop misclosures (external), calculated using independent baseline solutions.

Table E8, contains the 3D loop misclosures (internal), calculated from the baselines within a session.

Processor	Day	Session No.	From Stn.	To Stn.	Sol'n Type	Dx (m)	Dy (m)	Dz (m)	Length (m)
GPPS	47	1	5	7	L0	18801.266	-749.246	2240.595	18949.123
GPPS	47	1	5	7	L1	18801.261	-749.236	2240.585	18949.116
GPPS	47	1	5	7	L3	18801.280	-749.259	2240.582	18949.135
DIPOP	47	1	5	7	L3	18801.290	-749.256	2240.587	18949.145
TRIMMBP	47	1	5	7	L0	18801.282	-749.266	2240.613	18949.141
TRIMMBP	47	1	5	7	L1	18801.261	-749.235	2240.585	18949.116
TRIMMBP	47	1	5	7	L3	18800.801	-749.269	2240.644	18948.668
GPPS	49	2	5	7	L0	18801.270	-749.243	2240.584	18949.125
GPPS	49	2	5	7	L1	18801.264	-749.228	2240.574	18949.118
GPPS	49	2	5	7	L3	18801.315	-749.224	2240.579	18949.168
DIPOP	49	2	5	7	L3	18801.306	-749.232	2240.596	18949.162
TRIMMBP	49	2	5	7	L0	18801.279	-749.250	2240.598	18949.136
TRIMMBP	49	2	5	7	L1	18801.262	-749.224	2240.574	18949.115
TRIMMBP	49	2	5	7	L3	18801.317	-749.247	2240.612	18949.175
GPPS	47	1	5	10	L0	18515.204	-13287.640	-17474.626	28718.230
GPPS	47	1	5	10	L1	18515.204	-13287.619	-17474.621	28718.217
GPPS	47	1	5	10	L3	18515.209	-13287.657	-17474.620	28718.237
DIPOP	47	1	5	10	L3	18515.235	-13287.662	-17474.628	28718.261
TRIMMBP	47	1	5	10	L0	18515.772	-13288.068	-17474.616	28718.788
TRIMMBP	47	1	5	10	L1	18515.109	-13287.615	-17474.707	28718.206
TRIMMBP	47	1	5	10	L3	18515.220	-13287.842	-17474.663	28718.356
GPPS	49	2	5	10	L0	18515.197	-13287.659	-17474.613	28718.226
GPPS	49	2	5	10	L1	18515.200	-13287.627	-17474.644	28718.232
GPPS	49	2	5	10	L3	18515.207	-13287.639	-17474.616	28718.224
DIPOP	49	2	5	10	L3	18515.254	-13287.620	-17474.644	28718.264
TRIMMBP	49	2	5	10	L0	18515.201	-13287.674	-17474.586	28718.219
TRIMMBP	49	2	5	10	L1	18514.889	-13287.775	-17474.607	28718.077
TRIMMBP	49	2	5	10	L3	18515.070	-13287.726	-17474.593	28718.163
GPPS	47	1	7	10	L0	-286.063	-12538.393	-19715.221	23366.280
GPPS	47	1	7	10	L1	-286.057	-12538.380	-19715.224	23366.276
GPPS	47	1	7	10	L3	-286.080	-12538.402	-19715.204	23366.271
DIPOP	47	1	7	10	L3	-286.073	-12538.386	-19715.209	23366.267
TRIMMBP	47	1	7	10	L0	-286.066	-12538.397	-19715.261	23366.317
TRIMMBP	47	1	7	10	L1	-286.128	-12538.401	-19715.367	23366.409
TRIMMBP	47	1	7	10	L3	-285.391	-12538.479	-19715.225	23366.322
GPPS	49	2	7	10	L0	-286.070	-12538.407	-19715.206	23366.276
GPPS	49	2	7	10	L1	-286.065	-12538.403	-19715.215	23366.281
GPPS	49	2	7	10	L3	-286.058	-12538.381	-19715.221	23366.274
DIPOP	49	2	7	10	L3	-286.055	-12538.387	-19715.227	23366.282
TRIMMBP	49	2	7	10	L0	-286.073	-12538.403	-19715.205	23366.272
TRIMMBP	49	2	7	10	L1	-286.065	-12538.398	-19715.220	23366.282
TRIMMBP	49	2	7	10	L3	-286.148	-12538.704	-19715.023	23366.281

Table E1. Comparison of software solutions. Texas data set.

Processor	Sol. Type	Sessions	Misclosures			3d misc	3d misc
			dx	dy	dz	(m)	ppm
GPPS	L0	2+1+1	0.003	0.005	-0.010	0.012	0.16
GPPS	L1	2+1+1	0.003	0.011	-0.029	0.031	0.44
GPPS	L3	2+1+1	0.026	0.031	-0.005	0.041	0.57
DIPOP	L3	2+1+1	-0.002	0.044	0.015	0.047	0.66
TRIMVEC	L0	2+1+1	-0.559	0.421	-0.047	0.701	9.87
TRIMVEC	L1	2+1+1	0.025	-0.010	-0.086	0.090	1.27
TRIMVEC	L3	2+1+1	0.706	0.116	0.050	0.717	10.10

Table E2. Texas data set. External loop misclosures.

Processor	Sol. Type	Sessions	Misclosures			3d misc	3d misc
			dx	dy	dz	(m)	ppm
GPPS	L0	1+2+1	-0.007	-0.012	0.014	0.020	0.28
GPPS	L1	1+2+1	-0.008	-0.020	-0.009	0.023	0.33
GPPS	L3	1+2+1	0.013	0.017	-0.019	0.029	0.41
DIPOP	L3	1+2+1	0.000	0.020	-0.011	0.022	0.32
TRIMVEC	L0	1+2+1	-0.563	0.399	0.024	0.690	9.72
TRIMVEC	L1	1+2+1	0.087	-0.018	0.072	0.114	1.61
TRIMVEC	L3	1+2+1	-0.567	-0.131	0.284	0.648	9.12

Table E3. Texas data set. External loop misclosures.

Processor	Sol. Type	Sessions	Misclosures			3d misc	3d misc
			dx	dy	dz	(m)	ppm
GPPS	L0	1+1+2	0.006	0.021	-0.013	0.025	0.35
GPPS	L1	1+1+2	0.004	0.011	0.005	0.013	0.18
GPPS	L3	1+1+2	-0.007	-0.022	-0.006	0.024	0.34
DIPOP	L3	1+1+2	-0.038	-0.023	0.022	0.049	0.70
TRIMVEC	L0	1+1+2	0.015	0.011	-0.062	0.065	0.91
TRIMVEC	L1	1+1+2	0.244	0.139	-0.175	0.331	4.66
TRIMVEC	L3	1+1+2	0.340	-0.022	0.012	0.341	4.80

Table E4. Texas data set. External loop misclosures.

Processor	Sol. Type	Sessions	Misclosures			3d misc	3d misc
			dx	dy	dz	(m)	ppm
GPPS	L0	1+2+2	0.000	0.007	0.001	0.007	0.10
GPPS	L1	1+2+2	-0.004	-0.012	0.014	0.019	0.27
GPPS	L3	1+2+2	0.016	-0.001	-0.023	0.028	0.40
DIPOP	L3	1+2+2	-0.020	-0.023	0.005	0.031	0.43
TRIMVEC	L0	1+2+2	0.008	0.005	-0.006	0.011	0.16
TRIMVEC	L1	1+2+2	0.307	0.142	-0.028	0.339	4.78
TRIMVEC	L3	1+2+2	-0.417	-0.247	0.214	0.530	7.46

Table E5. Texas data set. External loop misclosures.

Processor	Sol. Type	Sessions	Misclosures			3d misc (m)	3d misc ppm
			dx	dy	dz		
GPPS	L0	2+1+2	0.010	0.024	-0.023	0.035	0.49
GPPS	L1	2+1+2	0.007	0.019	-0.006	0.021	0.30
GPPS	L3	2+1+2	0.028	0.013	-0.009	0.033	0.46
DIPOP	L3	2+1+2	-0.021	0.002	0.031	0.038	0.53
TRIMVEC	L0	2+1+2	0.012	0.027	-0.077	0.082	1.16
TRIMVEC	L1	2+1+2	0.245	0.150	-0.186	0.342	4.82
TRIMVEC	L3	2+1+2	0.856	0.000	-0.020	0.856	12.05

Table E6. Texas data set. External loop misclosures.

Processor	Sol. Type	Sessions	Misclosures			3d misc (m)	3d misc ppm
			dx	dy	dz		
GPPS	L0	2+2+1	-0.003	-0.009	0.004	0.010	0.14
GPPS	L1	2+2+1	-0.005	-0.012	-0.020	0.024	0.34
GPPS	L3	2+2+1	0.048	0.053	-0.022	0.075	1.05
DIPOP	L3	2+2+1	0.017	0.044	-0.002	0.047	0.66
TRIMVEC	L0	2+2+1	-0.566	0.415	0.009	0.702	9.88
TRIMVEC	L1	2+2+1	0.088	-0.007	0.061	0.107	1.51
TRIMVEC	L3	2+2+1	-0.051	-0.109	0.252	0.279	3.93

Table E7. Texas data set. External loop misclosures.

Processor	Sol. Type	Session	Misclosures			3d misc (m)	3d misc ppm
			dx	dy	dz		
GPPS	L0	1	-0.001	0.002	0.000	0.002	0.03
GPPS	L1	1	0.000	0.003	-0.018	0.018	0.26
GPPS	L3	1	-0.009	-0.004	-0.002	0.010	0.14
DIPOP	L3	1	-0.018	0.020	0.006	0.028	0.39
TRIMVEC	L0	1	-0.556	0.405	-0.032	0.689	9.69
TRIMVEC	L1	1	0.024	-0.021	-0.075	0.081	1.15
TRIMVEC	L3	1	0.190	0.094	0.082	0.227	3.20
GPPS	L0	2	0.004	0.010	-0.009	0.014	0.20
GPPS	L1	2	-0.001	-0.004	0.003	0.005	0.07
GPPS	L3	2	0.051	0.034	-0.026	0.067	0.94
DIPOP	L3	2	-0.003	0.001	0.014	0.014	0.20
TRIMVEC	L0	2	0.005	0.021	-0.021	0.030	0.42
TRIMVEC	L1	2	0.308	0.153	-0.039	0.346	4.87
TRIMVEC	L3	2	0.099	-0.225	0.182	0.306	4.31

Table E8. Texas data set. Internal loop misclosures.