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**Influence of Various Troposphere Modelling and Estimation Techniques on
Precise Position Estimation of Permanent GPS Arrays.**

by

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Presented in Fulfilment of the Requirements for the Award of the Degree
Master of Science in Engineering
School of Architecture, Planning and Geomatics
UNIVERSITY OF CAPE TOWN

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DEDICATION

"Ye knew nothing; and We gave you hearing and sight and intelligence and affection" (Qur'an, S16, verse 78)

for my loving wife

for her patience, love, support and assistance

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- Linda Fedder, the very helpful and professional librarian of Chief Directorate: Surveys and Mapping, for assisting me in sourcing research material.

DECLARATION

I, Aslam Parker, hereby declare that:

- This dissertation is the result of my personal effort and has never been submitted either wholly or partially for degree purposes at any other university.
- The views expressed are purely my original work (except where due acknowledgement is made in the text to all other material used) and should not be attributed to any other individual or entity.

Signed by candidate

Cape Town,
November 2003

ABSTRACT

A countrywide array of active GPS base stations (TrigNet) has been established in South Africa, which will supplement the existing passive network. This array is intended to serve as a fiducial network for South Africa, where the accurate and precise determination of station positions is essential. The Bernese GPS Software (version 4.2) was purchased to undertake routine processing, and co-ordination of the TrigNet network in a well-defined reference frame.

The troposphere is probably the ultimate accuracy-limiting factor for geodetic applications of the GPS today. This thesis investigates the effect of introducing low elevation data (down to 5°), various a priori tropospheric delay models, mapping functions as well as the influence of tropospheric gradient parameters estimation on station position, precision and accuracy, in order to ascertain the optimal combination to use in routine processing of TrigNet stations.

Data from eight TrigNet stations and two IGS stations were extracted in January and June 2002. Each campaign was processed using nine different strategies (where elevation, a priori troposphere model, mapping function or gradient estimation were varied). Constraining only one IGS station (HRAO) and comparing the computed value of the second IGS station (SUTH) to the official value validated the results. The precision of the Bernese software was also benchmarked by comparing the Bernese results to those returned by the AUSPOS and Auto-Gipsy (AG) services.

The results of the January processing were, in general, worse than the results obtained in June. This was attributed to decreased solar activity in June. The estimation of gradient parameters yielded no improvement in precision for both campaigns processed. Unlike the horizontal component, which was largely unaffected by the inclusion of low elevation data, the vertical component showed significantly improved repeatability when lowering the elevation mask down to 10° . In general, all strategies exhibited the least scatter at 10° elevation. The mean scatter (at 10°) in the horizontal component for the best performing strategy was 2.7 mm and

1.4 mm for the January and June campaigns respectively. The mean vertical scatter was 6.7 mm and 2.7 mm respectively.

Surprisingly, at 10° , the Saastamoinen a priori model with the simple $1/\sin(E)$ mapping function yielded more consistent results than the strategy using the Niell Mapping Function (NMF) to estimate the total delay. This was attributed to seasonal biases of the NMF in Northern winters.

The coordinates of SUTH, stemming from the most consistent strategy identified differed by only 1.0 mm, 1.4 mm and 1.0 mm in the North, East and Up components from the IGS (CODE) coordinates in January. Contrary to expectations, the June differences were 0.5 mm, 0.2 mm and 9.1 mm for the North, East and Up component. The large difference in height could not be explained. The results from the Bernese were consistently more precise than from the AUSPOS and AG services. Coordinate comparisons between the final Bernese solutions and AUSPOS and AG were not very consistent.

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LIST OF ABBREVIATIONS, ACRONYMS AND UNITS

AC's	Analysis Centre
AG	Auto-Gipsy
ARP	Antenna Reference Point
ARS	Ambiguity Resolution Strategy
AUIB	Astronomical Institute University of Berne
Bernese	Bernese GPS Software version 4.2
BPE	Bernese Processing Engine
CDDIS	Centre for Crustal Dynamics Data Information System
CDSM	Chief Directorate: Surveys and Mapping
CODE	Centre for Orbit Determination of Europe
ECEF	Earth Centred Earth Fixed
EDW	Elevation Dependent Weighting
EOP	Earth Orientation Parameters
ERP	Earth Rotation Parameters
EU	European Union
GIMs	Global Ionosphere Maps
GPS	Global Positioning Systems
GRS80	Geodetic Reference System 80
ICRS	International Celestial Reference Frame
IERS	International Earth Rotation Service
IGN	Institute Géographique National
ITRF	International Terrestrial Reference Frame
MF	Mapping Function
N	Refractivity
NCSN	National Control Survey Network
NGS	National Geodetic Survey
NIMA	National Imagery and Mapping Agency
NMF	Niell Mapping Function
NSWC	Naval Surface Warfare Centre
PCV	Phase Centre Variation

PGA	Permanent GPS Arrays
PRN	Pseudo Random Noise
QIF	Quasi Ionosphere Free
RINEX	Receiver INdependent EXchange Format
RMS	Root Mean Square
RTCM	Radio Technical Commission for Maritime
SAWB	South African Weather Bureau
SINEX	Solution INdependent EXchange Format
SIO	Scripps Institute of Oceanography
<i>t</i>	<i>Time</i>
T	Temperature
TEC	Total Electron Content
TECU	Total Electron Content Units
TZD	Total Zenith Delay
UNAVCO	University NAVstar COnsortium
UTC	Universal Time Coordinated
WGS84	World Geodetic System 1984
WVR	Water Vapour Radiometer
ZHD	Zenith Hydrostatic Delays
ZWD	Zenith Wet Delay

Chapter I

1. Introduction

Although modern technologies, especially space borne techniques, provoked revolutionary advances in geodetic sciences, atmospheric refraction remains a persistent problem (Geiger et al., 1995). In view of the fact that orbit errors must no longer be considered as an important error source (due to the availability of high accuracy orbits through the International GPS Service), propagation delays of the GPS code and phase signals due to the *troposphere*, probably are the *ultimate accuracy-limiting factor* for geodetic applications of the GPS (Hugentobler, Schaer and Fridez, 2001).

Although the GPS is clearly the most accurate worldwide navigation system yet developed, it still can exhibit significant error. The accuracy, with which a user receiver can determine its position, velocity and synchronise to GPS time, depends on a complicated interaction of various factors and processes. By understanding these processes and errors and factors, one can both hope to reduce and understand the limitations of the GPS system (Parkinson, 1996).

Chapter 2 deal with most of the known error sources and details steps taken to mitigate or model the effects. Chapter 3 deal with the effect and magnitude of tropospheric bias on GPS measurements and Chapter 4 examines the various models and functions that aim to estimate and model the troposphere in order to minimise its effect on the final position. Chapter 5 discusses the various processing options used and problems encountered during processing.

The results and analysis are contained in Chapter 6 with the conclusion and recommendations in Chapter 7.

1.1 RESEARCH OBJECTIVES

Using the Bernese GPS Software (version 4.2) as a processing tool, data from two campaigns with 10 stations were processed. The aim was to establish an optimal troposphere estimation strategy to derive high accuracy station positions, in both the horizontal and height components. Issues relating to various troposphere empirical models, mapping functions, variation of elevation angles cut-off, troposphere gradients and the inclusion of IGS tropospheric parameters as known in the estimation process were all of great interest and relevance to the Author.

However, to avoid the introduction of too many variables, and to focus the research, the following issues were concentrated on:

- a) Use of a priori troposphere models vs. total delay estimation.
- b) The effect of various mapping functions.
- c) The influence of tropospheric gradient estimation.
- d) The effect of introducing low elevation data.

Data were processed using nine troposphere estimation strategies, where either elevation or MF was varied and/or gradients were or were not estimated.

Although thirty TrigNet stations were up and running by January 2002, a spread of eight TrigNet stations and two IGS stations were selected for processing (see Figure 3.1). All the TrigNet and IGS stations are equipped with geodetic grade GPS receivers and choke ring antennas. Daily (24 hour) RINEX observation data spanning 6 days were extracted in January and June 2002. With the exception of SBOK, all stations had uninterrupted and continuous data. The quality of the data were generally very good, with the exception of stations GEOR and ELDN, which was characterised by significant multipath below 10°.

The Bernese is a sophisticated tool meeting highest quality and accuracy standards for geodetic applications using GPS and has countless advanced processing options. The accuracy, of which a user receiver can determine its position, depends on a complicated interaction of various factors and processes. By understanding

these processes, errors and factors, one can both hope to reduce and understand the limitations of the GPS system (Parkinson, 1996).

All non-TrigNet data products were obtained from the Centre for Orbit Determination in Europe (CODE). To ensure the best solution, only precise orbits, clocks, and consistent earth rotation parameters and station coordinates were downloaded. IGS antenna phase centre maps were used to model antenna phase centre variations. Ocean loading coefficients were generated for stations via a free service available from CODE. Baselines were formed using the “shortest” strategy (see Figure 1.1) to ensure identical baselines definition throughout the campaign. All phase data were pre-processed and cycle slips were automatically fixed.

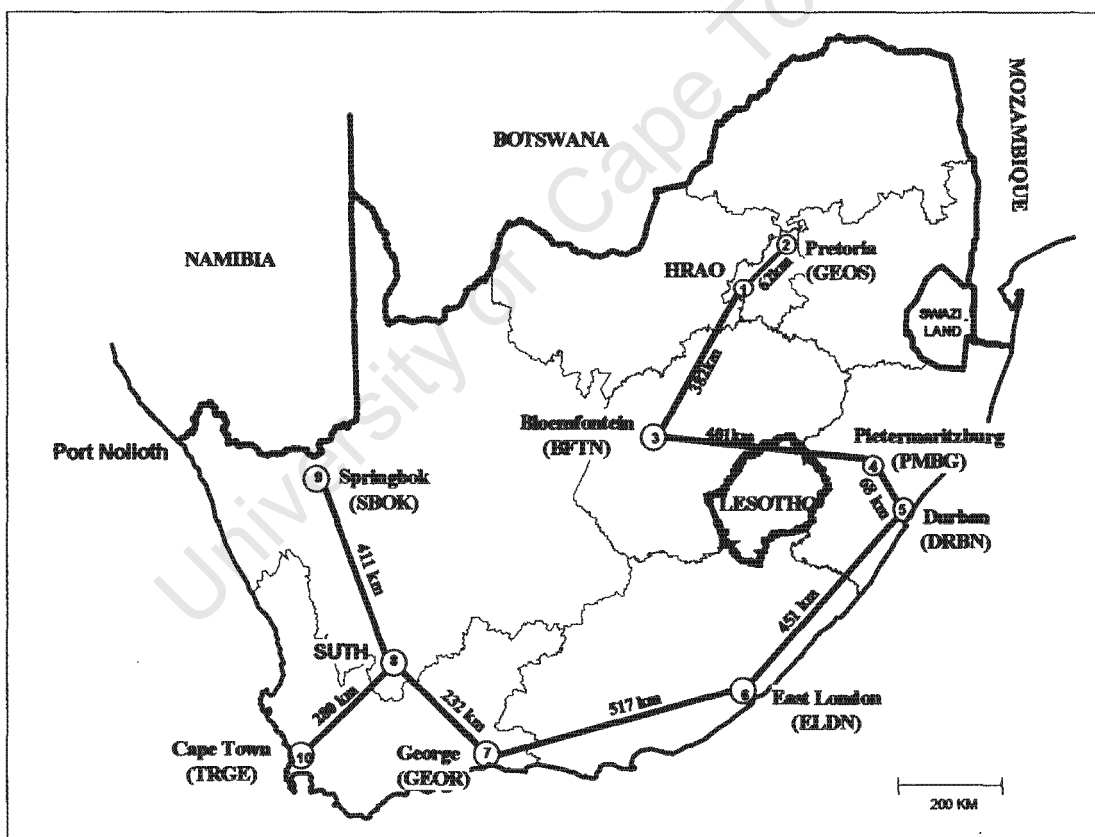


Figure 1.1 Location of stations and resultant baselines.

Site-specific tropospheric parameters were computed with 24 parameters set up per day. When estimating gradients, one set of parameters was set up per day. This was done for each of the 9 different estimation strategies. The tropospheric

parameters were then introduced during baselines processing. The Quasi-Ionosphere-Free (QIF) ambiguity resolution strategy, which allows one to directly resolve L1 and L2 ambiguities, even on long baselines was used during baseline processing in conjunction with Global Ionosphere Maps (GIMS). The correlations between all double-difference observations were correctly modelled. Multi-session (6 day) solutions were created for each strategy by forming normal equations from the statistically correct combination of a set of single-session (daily) solutions.

The results were validated by constraining only one IGS station (HRAO), and comparing the computed value of the second IGS station (SUTH) to the published CODE value. The precision of the results was benchmarked with results returned from free web-based processing software (AUSPOS and Auto Gipsy).

1.2 THE SOUTH AFRICAN NATIONAL CONTROL SURVEY NETWORK.

The Chief Directorate: Surveys and Mapping (CDSM) gets its mandate from the Land Survey Act (Act No 8 of 1997). One of its three primary functions is to maintain and further develop the National Control Survey Network (NCSN), a unique spatial reference framework. This network covers the entire country and now comprises of approximately 29 000 highly visible trigonometrical beacons on mountains, high buildings and water towers as well as approximately 20 000 easily accessible town survey marks.

1.2.1 Hartebeesthoek94, the New South African Datum

Until 31 December 1998, the co-ordinates of the NCSN, used in South Africa as the foundation for all surveying, engineering and geo-referenced projects and programs, used the **Cape Datum**. This datum is referenced to the modified Clarke 1880 ellipsoid and has its origin point at Buffelsfontein near Port Elizabeth.

As with other national control survey networks throughout the world, which were established using traditional surveying techniques, flaws and distortions in these

networks have become easily detectable using modern positioning techniques such as the Global Positioning System (GPS). In addition to these flaws and distortions, most national geodetic networks do not have the centre of their reference ellipsoids co-incident with the centre of the Earth, thus making them useful only to their area of application. The upgrading, recomputation and repositioning of the South African co-ordinate system has thus been driven by the advancement of modern positioning technologies and the globalisation of these techniques for navigation and surveying.

As from the 1st January 1999, the official datum for South Africa is based on the GRS80 ellipsoid, with the ITRF91 (epoch 1994.0) co-ordinates of Brit 44 (a trigonometrical beacon near the Hartebeesthoek Radio Astronomy Telescope) constrained for datum definition. This new system is known as the Hartebeesthoek94 Datum.

1.2.2 TrigNet, the South African Network of Active GPS Base Stations

With the increased use of GPS as a positioning tool for a variety of applications, a country-wide array of active GPS base stations have been established in South Africa which will supplement the current passive network of highly visible and easily accessible survey monuments and marks.

The array, which is known as **TrigNet**, will consist of approximately 40 active base stations that will provide both post-processing data and real time correction services upon completion. Besides providing a ground based GPS augmentation service, it is envisaged that data from the network could be used for atmospheric water vapour estimation, monitoring of short and long term geophysical disturbances, support the IGS programs, various GNSS initiatives and other scientific applications.

The general philosophy behind the establishment of TrigNet was to provide users of GPS equipment with a network of continuously operating GPS receivers, all set

on points whose position or co-ordinates are well established within the current National co-ordinate system (Parker and Wonnacott, 2001).

1.2.3 Readjustment and Redefinition of the South African Vertical Datum

The system of heights used in South Africa is termed 'spheroidal orthometric' heights. This height system, which has been gradually built up over the last century, is not a rigorous height system and deficiencies inherent in this system become apparent now that GPS is being used as a common tool for precise heighting. The Chief Directorate: Surveys and Mapping currently has a program to redefine the South African height system. The intention is to readjust the existing height network in a rigorous manner. The re-adjustment will be done in terms of geopotential numbers. Such an adjustment will have the advantage of transforming between the systems of normal heights, orthometric heights and dynamic heights depending on the application at hand. A by-product of this readjustment will be a South African geoid model, which needs precise GPS/levelled heights for validation and datum definition. For this reason, precise ellipsoidal heights are required on the TrigNet stations to serve as fiducial points when computing the GPS levelling network within a well defined datum.

Definition of the new vertical datum and the very high accuracy requirement (both in the horizontal and especially the vertical component) that is expected for a fiducial network such as TrigNet was the primary motivation for the Author's interest in high accuracy GPS data processing, and, the troposphere in particular.

1.3 REVIEW OF PREVIOUS RESEARCH

This part of the dissertation highlights a collection of papers and publications by researchers that had some influence on this research. Their motivations are summarised, and results and conclusions are drawn with the view of applying of the recommendations here. A large percentage of the theories and models presented in papers since the 1970's have undergone various levels of improvement and refinement. Where later models and theories were refinements of older ones, the Author considered these superfluous and did not expand on them in this section.

The effects of the troposphere on GPS signals and the numerous models to estimate and model it are dealt with extensively in chapter 3. However, certain literature and research were not expanded upon because it was outside the scope of the thesis. Where the Author thought that certain points were noteworthy, these points were highlighted, and, where applicable, were implemented in the processing. The titles of the summaries presented are keywords of issues the Author attempted to highlight and in most cases do not coincide with the title of the literature discussed.

1.3.1 Wet Tropospheric Effects on Precise Relative GPS Height Determination

Dodson et al. (1996), discusses atmospheric water vapour as a major source of error in GPS measurements. In order to achieve the high precision required for such applications such as absolute sea-level monitoring, improvement of the (then current) wet delay models is necessary. The results from GPS campaigns showed significant correlation (0.91) between the variability of the wet delay measured using Water Vapour Radiometers (WVRs) and the absolute value of the residual error in the height determination of a 134 km baseline. This correlation indicates that the atmospheric *variability*, as inferred from WVR data includes information

on the quality of GPS height estimate. Unfortunately, the Author does not have access to any WVR data, and further research is beyond the scope of this thesis.

1.3.2 Using Numerical Weather Products in the Absence of Tropospheric Modelling Capabilities.

Behrend et al. (2001) studied the effect of the choice of initial values for the zenith hydrostatic delay (ZHD) and the zenith wet delay (ZWD) in the evaluation of GPS data. As meteorological information they used 24-h dry and wet delay forecasts with an estimation interval of 1-hour derived from the numerical weather prediction (NWP) model HIRLAM. The a priori standard deviation values were contrasted to the default values that are derived from a standard atmosphere model.

The tests were performed for the IGS stations Villafranca (VILL), Wettzell (WTZR), and Zimmerwald (ZIMM). Results indicated that, in the absence of tropospheric modelling (as, for instance, possible in certain near real-time applications) the use of HIRLAM derived ZHD and ZWD a priori values furnish significantly **better** results than just using standard atmosphere values. The repeatability of the vertical coordinate component obtained values of 0.02m... 0.05m when NWP model was used, whereas the use of standard ZHD and ZWD a priori furnish repeatability of 0.1m...0.2m.

Although it is beyond the scope of this thesis to investigate the use of NWP models, it opens the question of the effect of using standard atmosphere values and the possible effect of variations in these values.

1.3.3 New CODE Processing Strategy for Regional Networks.

According to Rothacher et al., 1997, the main task of the **Centre for Orbit Determination of Europe (CODE)** Analysis Centre consists of daily generation of global products within the framework of the IGS. In addition, CODE is routinely processing regional GPS solutions for a dense network of European stations to improve and maintain EUREF. A by-product of this is that since the European

solutions are based on the global products from CODE (such as orbits, EOPs, etc.), these solutions provide a good check for the quality of the CODE products. Additionally, the network is ideal to perform tests with new processing strategies for regional networks.

Since March 1997, the CODE has adopted a new solution strategy pertaining to troposphere estimation during routine processing of the EUREF regional network in order to improve the height estimates. This was used as a guideline for the processing that Author undertook. The following options, all of which the Author have implemented throughout processing of thesis data, remained unchanged:

- The correlations between all double-difference observations are correctly modelled.
- The tropospheric zenith delay parameters are estimated once per hour for each station.
- Ambiguities are resolved to integers using the Quasi Ionosphere Free strategy.

The new strategies were developed with the idea, that low-elevation data (down from the conventional 15° elevation cut-off to 5°) should be included in the processing. The inclusion of low-elevation data has two major advantages:

- The number of observations increases by about 20 percent when going from 15° to 5°.
- A better decorrelation between the estimated height and troposphere delay parameters of the same station: the correlation coefficients changes from -0.96 to about -0.83 when going from 20° down to 5° elevation cut-off.

To ensure that the use of low-elevation data does not degrade the solution quality, three additional features were implemented in the processing using Bernese GPS software, namely:

- Niell mapping function discussed in section 4.3, (one for the dry and one for the wet part). During the processing of the GPS tropospheric delay, only the dry Niell mapping function is used to map the *total* delay. This was used instead of

the $1/\sin(E)$ mapping function implicit in the Saastamoinen delay model. Also, the residual tropospheric delays are precisely estimated.

- Due to the fact that tropospheric refraction and multipath are responsible for a considerable increase in scatter of observations at low elevations, a new model for an elevation dependent weighting (EDW) of the phase observations, namely a weighting function $w(z)$ where the noise increases in the same way.
- Azimuthal variations of the tropospheric delay, which play an increasingly important role at low elevations.

1.3.3.1 Results of New Strategy

To prove the accuracy of the new strategy, four different solution types were implemented by the CODE into routine processing of 143 daily solutions that have been accumulated since the start of the implementation of the new strategy. Two of the solution types are listed below:

Solution Type	Mapping Function	Elev-Dep Weighting	Elevation Cut-off	Gradient Estimation
A	Saastamoinen	No	15°	No
E	Niell (dry)	Yes	5°	Yes

Rothacher et al. (1997), further states that the results of a seven parameter Helmert's transformation between solution A and E above generated from 143 days of data showed a clear scale change of 1.9 ± 0.1 ppb with negligible rotations. The RMS of the transformation in the North, East and Up directions indicated that the major changes in the height coordinate occur when weighting the observations and by going down to low elevation data, whereas major scale changes occur when estimating tropospheric gradients. There was also a marked improvement in both vertical and horizontal coordinate repeatability.

1.3.4 Precise GPS Heighting Using National GPS Network of Great Britain

Penna et al. (2002) discusses the possibility of precise height determination using a single GPS receiver, following the establishment of GPS networks that include

active stations (more specifically the National GPS Network of Great Britain) with a typical separation of 100km. From the computation of the heights of 188 GPS stations distributed throughout the British mainland, a precision of 1.5cm was achieved using only 4 hours of dual frequency static GPS data, but with scientific software.

The tropospheric delay effects were mitigated in each daily network solution by modelling the ZHD using the Saastamoinen, and estimating, as an unknown, the residual ZWD at each station. To overcome the time varying nature of the troposphere, these were estimated as discrete parameters every 3 hours. It is not clear to the Author, why, if the session duration was 4 hours, such an odd interval was chosen (why not 2-hour, which is exactly divisible by 4?). The tropospheric delays were mapped to the relevant station to satellite elevation angle using the Niell mapping function. This just further reinforced the perception of the Author, that the Niell mapping function was the most widely accepted by users of GPS requiring the highest precision.

1.3.5 Effects of Atmosphere Modelling Errors on Estimates of Baseline Length.

Analysis of very long baseline interferometry data indicated that systematic errors in prior estimates of baseline length, of the order of 5cm for ~8000 km, were primarily due to mismodelling of the atmospheric delay. In this publication, Davis et al. (1985) discuss observational evidence for the existence of such errors in previously used models for the atmospheric delay and developed a new mapping function for the elevation dependence of the delay. According to the authors, the delay computed from this function, differed from ray-tracing by less than 5 mm at all elevations down to 5°, and introduces errors into the estimates of baseline length of < 1cm. A major downfall of this model is that is dependent on surface meteorological data, unlike the Niell function.

1.3.6 Estimation of the combined Zenith Wet and Dry Path Delays

Up to about 1990, only the zenith wet tropospheric path delay had been estimated simultaneously with geodetic parameters, either entirely or as a residual correction to an a priori calibration based on surface meteorological measurements or WVR data. Tralli and Lichten (1990) presented an argument for estimating the total, or combined wet and dry, delay at zenith without a priori wet or dry calibrations. The authors claim that normally, if the zenith dry path delay behaves comparably to the wet delay or shows smaller-scale fluctuations, the dry delay fluctuations are encompassed readily in the stochastic parameterisation of the corresponding wet path delay. The dry component of the troposphere typically behaves very stably, with uncertainties in ZHDs typically ranging from 1 mm to 2 mm.

1.3.7 Session Versus Baseline GPS Processing

Realising that many GPS users will have access only to baseline processing software, Craymer and Beck (1992) investigated processing strategies that could be used to provide results equivalent to session processing. The Bernese GPS Software uses session processing and treats all correlations correctly.

Many software packages used for static GPS surveying are based only on **baseline processing**, where mathematical correlations between simultaneous observed baselines are neglected. Moreover, all possible baselines, including so-called “trivial” baselines that are linear combinations of others, are often combined together in a 3D adjustment. In addition, baseline processing with all trivial baselines significantly distorts the formal accuracies by artificially increasing the redundancy in the model, resulting in overly optimistic covariance matrices.

In principle, **session processing**, which account for all mathematical correlations, is preferable since it also allows for orbit improvement, spatial modelling of the atmosphere and enables easier ambiguity resolution.

The authors demonstrates that using all possible baseline solutions (with the covariance matrix scaled by $n/2$, where n is the number of simultaneously observing receivers) is mathematically equivalent to session processing with all correlations only under certain conditions.

1.3.8 Impact of GPS Satellite Sky Distribution

Santerre (1991), in a summary of his Ph.D. dissertation studied the impact of the GPS satellite sky distribution on covariance matrix and the propagation of some important errors in precise static relative positioning. The study also provided a guide to know the tolerance values that systematic errors should not exceed in order to achieve a predetermined positioning accuracy level.

The results of the study can also be used for the selection of the most appropriate elevation mask angle. This means finding the best compromise between the need of decorrelation between station height, clock parameter and zenith delay parameter provided by low elevation observation angles and the effects of some systematic errors which get larger at lower elevation angles.

Santerre (1991) demonstrated that even with the deployment of the full GPS constellation of 24 satellites the distribution of the visible satellites in the observer's sky will not be uniform. Because of inclinations of 55° of all orbits, the satellite coverage will be a function of site latitude. For example, the satellite distribution over the sky at low latitudes will be almost uniform; at southern mid latitudes, practically no observations will be possible in the southern direction; and at high latitude sites, only observations between elevation angles 0° and 45° can be made. This is well demonstrated by figure 1.1 which shows a typical sky-plot of sites at the equator, Cape Town (latitude: 34°S) and the South Pole.

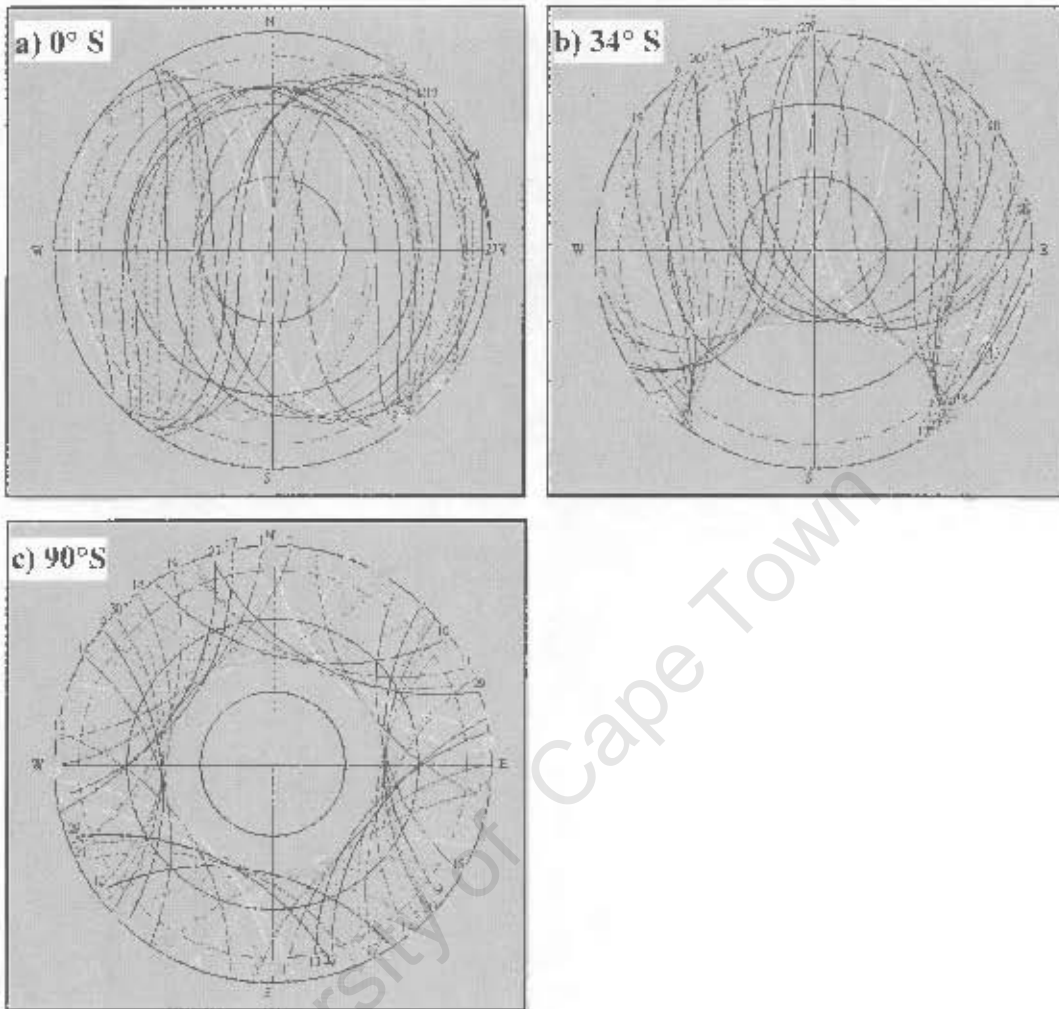


Figure 1.2 Polar plots of satellite configurations for 3 sites for a time span of 24 hours.

Chapter II

2. GPS Error Sources

2.1 INTRODUCTION

Although the GPS is clearly the most accurate worldwide navigation system yet developed, it still can exhibit significant error. The accuracy, to which a user's receiver can determine its position, velocity and synchronise to GPS time, depends on a complicated interaction of various factors and processes. By understanding these processes, errors and factors, one can both hope to reduce and understand the limitations of the GPS system (Parkinson, 1996).

GPS errors are generally grouped into three categories (as shown in Figure 2.1):

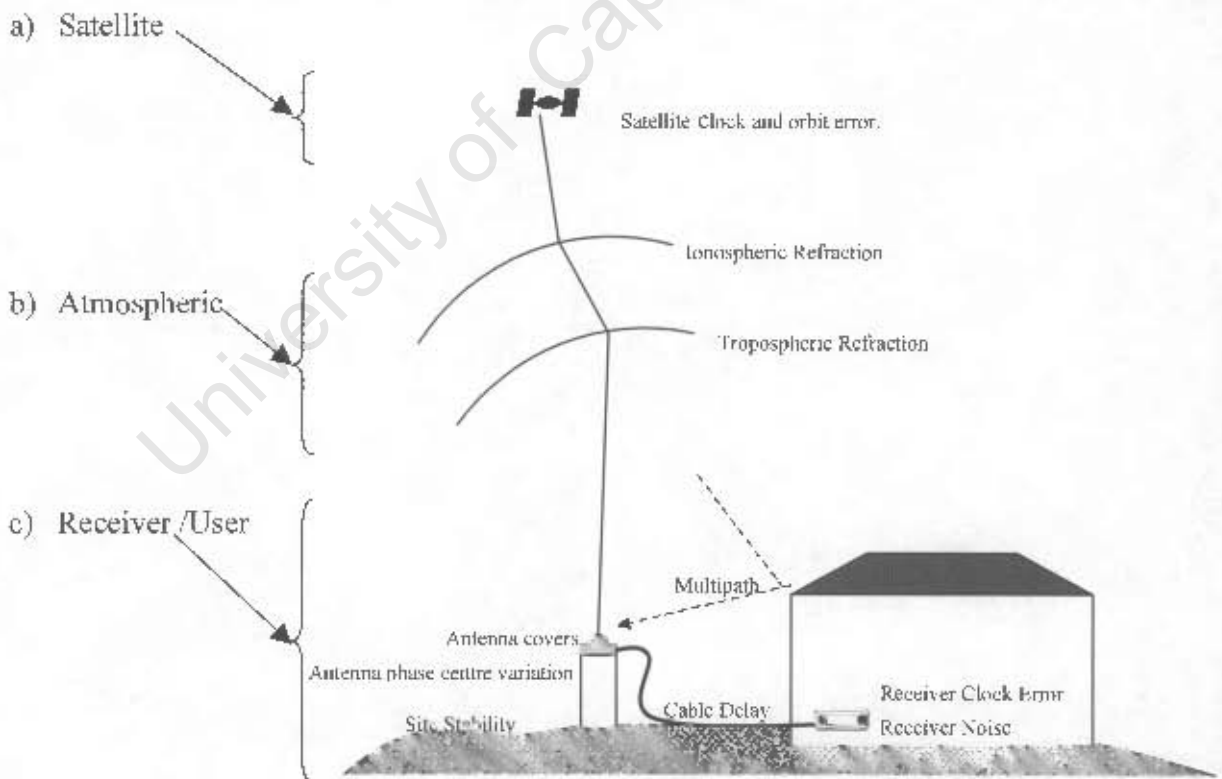


Figure 2.1 Categories of GPS error sources (non-exhaustive)

2.2 GPS OBSERVABLES AND OBSERVATION EQUATIONS

There are two types of GPS observations (observables): pseudoranges and carrier phases. Pseudoranges are often used in navigation and coarse positioning ($\approx 10\text{m}$ level). The carrier phases are sometimes called carrier beat phases in order to stress the measurement process of correlating the incoming carrier with the receiver-generated reference frequency. In high-precision surveying the carrier phase is favoured (see Figure 2.2). The phase observable is the difference between the received satellite carrier phase (as sensed by the receiver's antenna) and the phase of the internal receiver oscillator. The measurements are recorded at equally spaced nominal receiver clock epochs t (Leick, 1995).

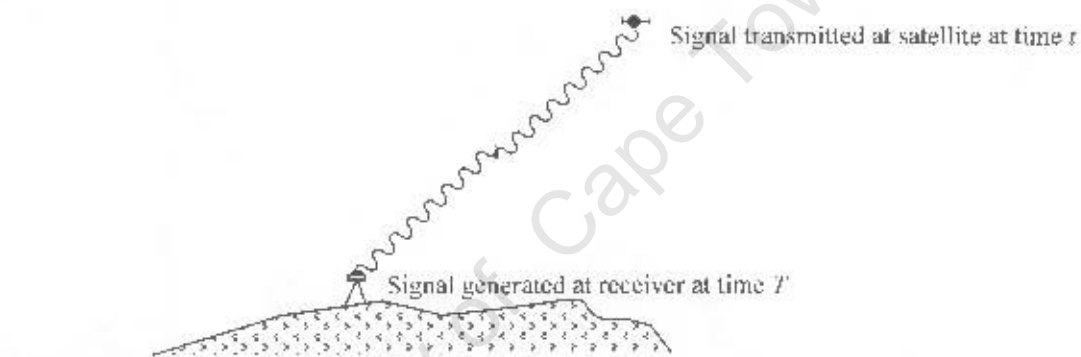


Figure 2.2 The carrier phase observable

Santerre and Beutler (1993), gives a comprehensive observation equation of the basic undifferenced carrier phase equation which can be written as follows:

$$\Phi_{Fj}^i = \rho_j^i - c \cdot dt - \lambda \cdot \phi^0 - d^{ec} - d^{ion} + d^{tro} + d^{mp} + d^{pc} + d^{an} + d^{ca} + d^{cc} + d^{ch} + c \cdot dT + \lambda \cdot \phi_0 - \lambda \cdot N + v \quad (2.1)$$

where:

- Φ_{Fj}^i : carrier phase observable (in length units) from satellite i at frequency F to receiver j .
- ρ : geometric range between satellite and receiver (or antenna)
- c : speed of light in a vacuum
- dt : satellite clock error
- λ : carrier wavelength
- ϕ^0 : initial phase of satellite oscillator
- d^{ec} : range error due to delay in satellite electrical circuit
- d^{ion} : range error due to ionospheric refraction
- d^{tro} : range error due to tropospheric refraction
- d^{mp} : range error due to multipath effect
- d^{pc} : range error due to antenna phase centre variation

d^{an}	:	range error due to delay in antenna (including amplifier)
d^{ca}	:	range error due to delay in antenna cable
d^{ec}	:	range error due to delay in receiver
d^{ch}	:	range error due to delay in receiver channel
dT	:	receiver clock error
ϕ_0	:	initial phase of receiver oscillator
N	:	integer carrier phase ambiguity
v	:	carrier phase observation noise

Most of the parameters above, such as receiver and satellite clock error and integer carrier phase ambiguity are unknowns and cannot be distinguished from each other for observations taken from a single receiver to single satellite. It is only by taking multiple observations from at least two ground stations to at least two satellites that a solution can be found (differencing). Prior to the late 1990s carrier phase measurements were only used in a differential sense, where the coordinates of one station was known and the second one was solved relative to the first. The JPL software (Gipsy-Oasis II) and the Bernese GPS software now have a single point-positioning algorithm that effectively uses carrier phase pseudo-ranges. Precise Point Positioning (PPP) is still very much in the developmental stages and is a very complicated process, requiring consistent earth rotation parameters and orbits of the highest accuracy.

2.2.1 Elimination /Reduction of Errors and Biases by Differencing

Differences between the original observations allows for eliminating or reducing some biases. Merry (1996) highlighted the various types of differences and effect on biases.

2.2.1.1 Single (between receiver) differences

Between receiver differencing, also known as single differencing is given by:

$$\Phi_{Fk-1}^i = \Phi_{Fk}^i - \Phi_{F1}^i \quad (2.2)$$

This leaves us with differences in phase, refraction, range, and receiver specific errors and cycle ambiguities. The advantage of single differences is that satellite clock error is eliminated entirely, effect of the orbit bias is reduced and effects of refraction are reduced.

2.2.1.2 Between satellite Differences

Here, simultaneous observations are made from a single receiver to two satellites effectively eliminating the receiver clock error.

$$\Phi_{Fk}^i = \Phi_{Fk}^i - \Phi_{Fk}^j \quad (2.3)$$

2.2.1.3 Double Differences

The combination of equations (2.2) and (2.3), i.e. simultaneous observations from two receivers to two satellites, yields a receiver-satellite double difference. More specifically, between-receiver single differences are formed for each of two satellites, and these two differences are again differenced, forming the so-called "double difference" (see Figure 2.3).

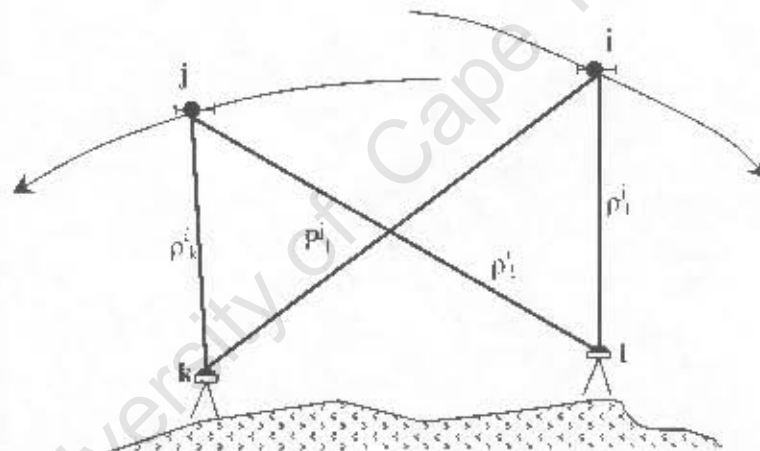


Figure 2.3 The double difference observation (adapted from Merry, 1996)

2.2.2 Initial Integer Carrier Phase Ambiguity

When switching on a receiver at epoch t_0 , the instantaneous fractional beat phase is measured. The receiver measures the total phase, which is the accumulated phase from the instant of locking on to a satellite. The initial integer number N of cycles between the satellite and receiver is unknown (see Figure 2.4).

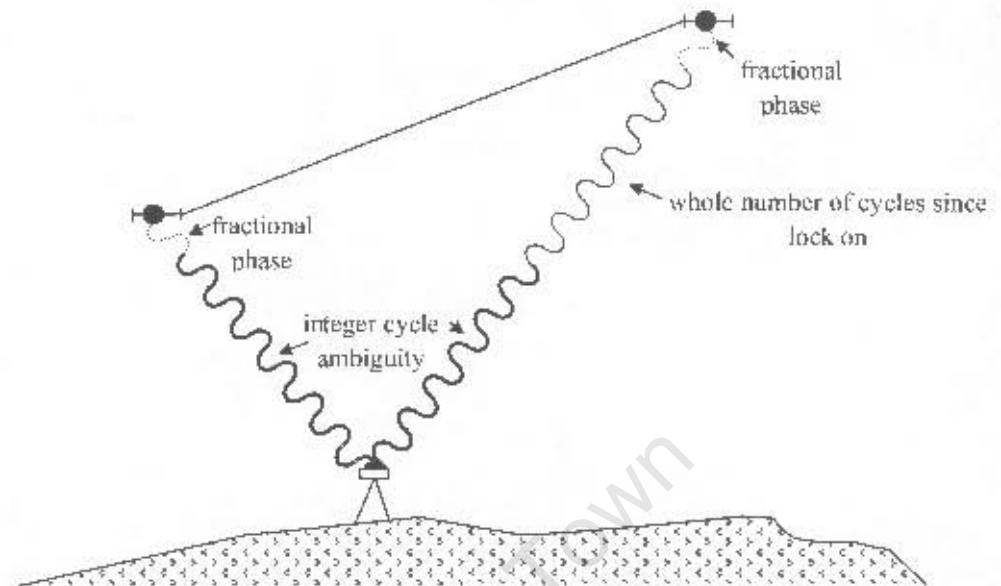


Figure 2.4 The concept of integer ambiguity (adapted from Merry, 1996)

The unknown number of cycles in the observation equation (2.1), i.e., the initial phase ambiguity parameter, has to be estimated in a first step as real valued parameters. However, it is known, that these parameters actually have to be ambiguities. Ambiguity resolution means (in GPS geodesy terminology) to assign the correct integer number to the real-valued estimates (Hugentobler, Schaer and Fridez, 2001)

There are many methods to resolve the ambiguities, some of them are very sophisticated and some simple. According to Hoffmann-Wellenhof, Lichtenegger and Collins (2001), most ambiguity resolution techniques involves three major steps:

- The first step is the generation of **potential** integer ambiguity **combinations** that should be considered by the algorithm. In order to determine these combinations, a search space is determined, which is the volume of uncertainty that surrounds the approximate coordinates of the unknown antenna location. In the case of static positioning, this search space is realised from the so-called float ambiguity solution.
- The second step is the identification of the **optimum** integer ambiguity **combination**. The criterion used by most integer ambiguity techniques is the selection of the integer combination that minimises the sum of the squared residuals (least squares).

- The third step in the ambiguity resolution should be a **validation** of the ambiguities by applying statistical tests.

As discussed, the initial phase ambiguities remain the same as long as no loss of signal has occurred. A loss of lock causes a jump in the instantaneous accumulated phase by an integer number of cycles. There are several possible causes for cycle slips (Hugentobler, Schaer and Fridez, 2001):

- Obstruction of the satellite signal due to trees, buildings, etc.,
- Low signal-to-noise ratio due to rapidly changing ionospheric conditions, multipath, high receiver dynamics, or low satellite elevation,
- Failure in the receiver software
- Malfunctioning of the satellite oscillator.

Availability of quality phase measurements, length of baselines and session length are factors that influence the selection of an ambiguity resolution strategy.

2.2.3 Orbit Bias and Error

There is a crude rule of thumb, giving the error Δx as a component of a baseline of length l as a function of an orbit error of size ΔX (Hugentobler, Schaer and Fridez, 2001):

$$\Delta x(m) \approx \frac{l}{\rho} \cdot \Delta X(m) \approx \frac{l(km)}{25'000(km)} \cdot \Delta X(m) \quad (2.4)$$

Prior to 1992, the orbit quality was considered as one of the primary accuracy limiting factors of GPS for Geodesy and Geodynamics. Hence, orbit computation and improvement of orbits was a prerequisite for precise geodetic computations.

Today, three sets of data are available to determine position and velocity vectors of the satellites in the terrestrial reference system at any instant in time, namely: almanac data, broadcast ephemeris and precise ephemeris (Hoffmann-Wellenhof, Lichtenegger and Collins, 2001). The data differ in accuracy and time it takes to be made available.

Orbit Type	Quality	Delay in Availability
Broadcast Orbits	5.00m	Real Time
IGS Predicted	0.50m	Real Time
IGS Ultra Rapid Orbits	0.20m	3 Hours
IGS Rapid Orbits	0.10m	19 Hours
IGS Final Orbits	0.05m	13 Days

Table 2.1 Accuracies and availability of various orbits (Kouba, 2001; Hugentobler, Schaer and Fridez, 2001).

The official **precise orbits** are produced by the Naval Surface Warfare Centre (NSWC) together with National Imaging and Mapping Agency (NIMA) and are based on observed data in the extended tracking network of the control segment (Hoffmann-Wellenhof, Lichtenegger and Collins, 2001). This orbital information is made available in the latest realisation of the World Geodetic System 1984 (WGS84) reference frame, which coincides with the ITRF at the 10cm level.

2.2.4 Using the Precise Ephemeris

The most accurate orbital information is provided from the International GPS Service (IGS). Since the IGS started its operation on June 21 1992, the orbit error contribution has virtually been eliminated. The IGS mission is to provide a service to support geodetic and geophysical research activities, through GPS data and data products. Using data from a network of about 200 stations equipped with permanent precision geodetic grade receivers, orbits of unprecedented accuracy (0.05m) are available less than 12 days after the observations and at least an order of magnitude better than the real time orbits (see Table 2.1) from the IGS and its analysis centres (Neilan, 2000).

The precise ephemerides consist of satellite positions and velocities at equidistant epochs. Typical spacing is 15 minutes. The SP3 format proposed by the National Geodetic Survey (NGS) is widely used. A description of the SP3 format can be obtained at http://www.ngs.noaa.gov/GPS/SP3_format.html.

Only precise orbits from the **Centre for Orbit Determination of Europe (CODE)** were used during computation and processing, hence ensuring orbit error contribution is minimised.

2.3 SATELLITE CLOCK ERROR

Each satellite is equipped with four atomic frequency standards, and uses the best of these for generating the fundamental frequencies and the time (GPS Time). The clocks do not keep exact time, but keep linear drift. The satellite time, as broadcast is kept within 1 ms of GPS Time. This represents $\pm 300\text{km}$ in range, so clock corrections are also broadcast by each satellite. After the application of this correction, the expected effect on range biases would be less than 5m (Merry, 1996). The IGS and all its associated analysis centres makes precise clocks available with the precise orbits. The accuracy of the final clocks is $\approx 0.3\text{ns}$, which, together with double differencing eliminates satellite clock error (Neilan, 2000). For this research, precise clock files were extracted from the precise orbit files during the pre-processing and preparatory stages.

2.4 IONOSPHERIC REFRACTION

The atmosphere is divided into two main shells, the troposphere and ionosphere, since the signal propagation conditions are quite different in these two shells. The **ionosphere** may be characterised as that part of the upper atmosphere where sufficient number of electrons and ions are present to affect the propagation of radio waves, thus signal from GPS satellites. It is located approximately between 50 and 1000 km above the Earth. The signal propagation is mainly effected by free charged particles. The state of the ionosphere may be described by the electron density n_e in units of electrons per cubic metre (Klobuchar, 1996).

2.4.1 Effect of the Ionosphere on GPS Signals

The ionosphere is an important source of range and range-rate errors for users of the GPS satellites who require high accuracy measurements. The ionospheric range error can vary from only a few metres to many tens of metres at zenith (Klobuchar, 1996).

The impact of the state of the ionosphere on the propagation of radio waves is characterised by the Total Electron Content (TEC) E :

$$E = \int_{\text{Receiver}}^{\text{Satellite}} n_e(s) ds \quad (2.5)$$

In geodetic terms, the TEC is measured in so-called **TEC Units (TECU)**, where one TECU corresponds to 10^{16} electrons/m² (Hugentobler, Schaer and Fridez, 2001).

For a group of waves with slightly different frequencies, the group velocity defines the propagation of the resultant energy. This velocity is considered for GPS code measurements since the PRN code signals employed in the pseudo ranging measurements are modulations superimposed upon the carrier signal, and as such are governed by the group velocity. This resultant **group delay** produces range errors, which can be expressed either in units of distance, or in units of time delay to GPS users. The apparent increase in pseudo-range is given by:

$$d_{ion} \approx \frac{40.3.N_T}{f^2} \cdot \sec \theta \quad (2.6)$$

Here, f is the carrier frequency in Hz, θ is the zenith angle of the satellite and N_T is the average electron density in the direction of the zenith. By measuring the group delay independently at the two, widely spaced GPS frequencies, the TEC along the path from the satellite to the receiver can be measured directly.

In the case of carrier phase measurements the effect of the ionosphere is to *advance*, not delay the signals. The relationship between group delay and carrier phase advance is

$$\Delta\phi = -f\Delta t \quad (2.7)$$

The minus sign in the above equation indicates that the differential code group delay and the carrier phase advance move in opposite directions. (Merry, 1996; Klobuchar, 1996).

The relationship between the density of the ionosphere and the sun's activity is clear in the mid-latitudes. The spatial distribution of electrons and ions is mainly determined by photochemical processes and transportation processes. The degree of ionisation shows large variations that are correlated with solar activity and geomagnetic influences. For example, during the daylight hours the ionospheric delay may be as much as five times greater than at night time. It is also four times greater in November, when the earth is nearing the closest approach to the sun, than in July, when the earth is the furthest. The effect of the ionosphere peaks in March, the time of the vernal equinox (Van Sickle, 1996). Ionospheric activity is also a function of sunspot activity, which has a 10-11 year cycle and has reached a high in March 2001. Thus, the ionosphere displays huge **temporal and spatial** variability.

2.4.2 Modelling the Ionosphere

One of the frames of the navigation message transmitted by the GPS satellites contains the parameters for an ionospheric correction model, which can be used to reduce the effect of the bias. However, it appears that this model can correct no more than 70% of the effect and could in some cases worsen it (Merry, 1996). Fortunately, the ionosphere is a dispersive medium as opposed to the troposphere. This implies the refractive index is a function of operating frequency and dual frequency GPS users can take advantage of this property of the ionosphere to measure and correct for the first-order ionospheric range and range-rate effects (Klobuchar, 1996).

The primary purpose of the second frequency in GPS satellites is to neutralise the effect the ionosphere on signal propagation. Functions of the dual-frequency observable are readily available that do not depend on the ionosphere (Leick, 1995).

In a first (but excellent) approximation, ionospheric refraction is proportional to $1/f^2$ where f is the carrier frequency. The linear combination, where I_1 and I_2 represent the phase observables (zero- or double-differences),

$$I_3 = \frac{1}{f_1^2 - f_2^2} (f_1^2 I_1 - f_2^2 I_2) \quad (2.8)$$

is often called “ionosphere-free” because the ionospheric path delay is virtually eliminated. The same is true for the corresponding combination of code measurements (Hugentobler, Schaer and Fridez, 2001).

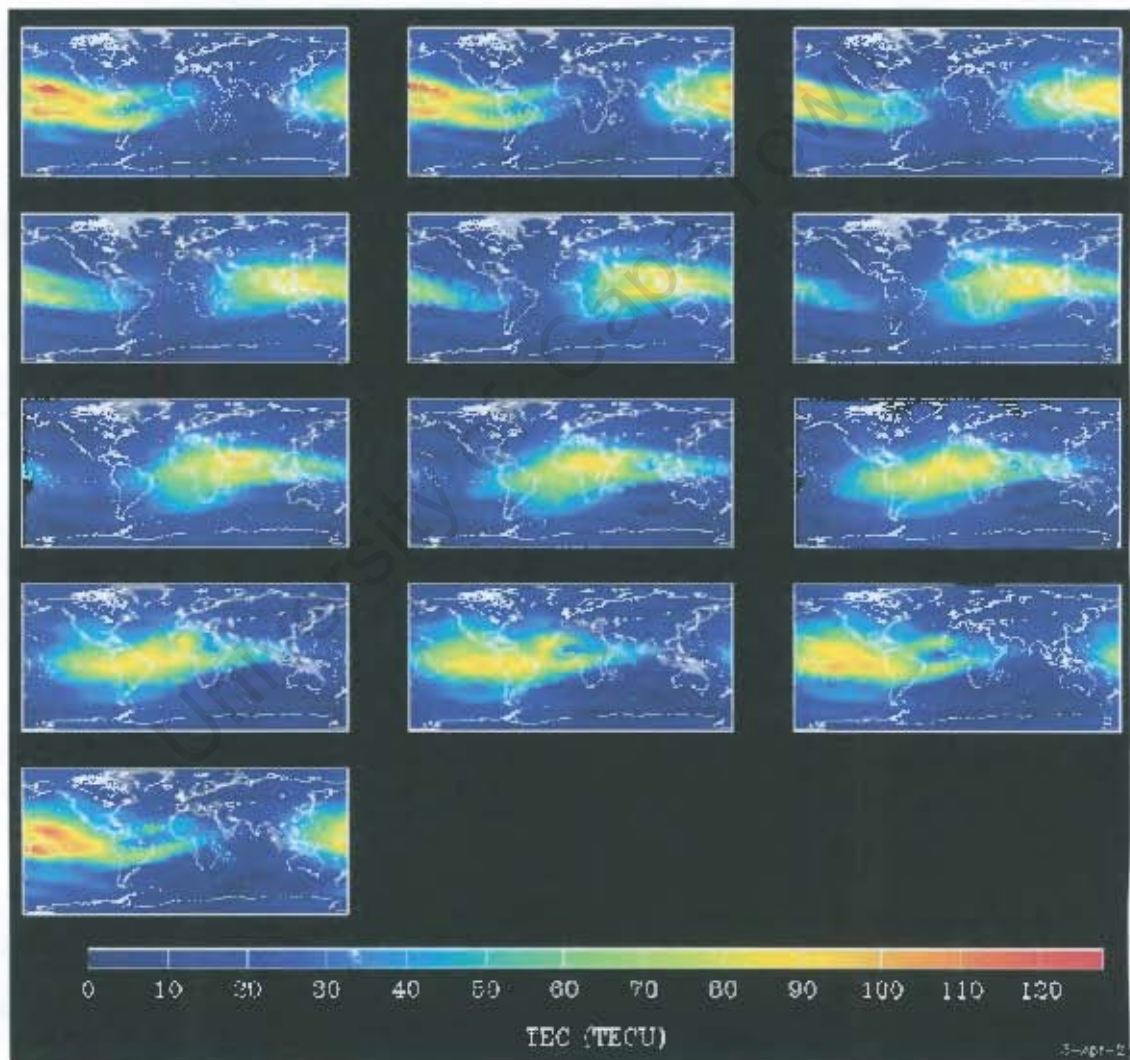


Figure 2.5 13 2-hourly snapshots of the Earth's total electron content (TEC) referring to times from 0:00 to 24:00 UT on day 087, 2003.

Figure 2.5 shows 13 2-hourly snapshots of the Earth's total electron content (TEC) referring to times from 0:00 to 24:00 UT on day 087, 2003 (AIUB, 2003). The blue areas indicate low TEC values (hence low ionospheric activity) and the green-yellow areas indicate high TEC values. Although the day-night cycles are the primary factor influencing TEC values, seasonal variations also play an important role.

During processing, all baselines were solved using the L3 linear combination. It must be pointed out that the L3 combination has 3 times more noise than the L1 and L2 frequencies. Since this research involved high level processing, aiming at mm level repeatability, a priori Global Ionosphere Maps (GIMS) were introduced to assist in ambiguity resolution, as recommended by Hugentobler, Schaer and Fridez (2001). This enabled more reliable ambiguity resolution by reducing the fractional parts of (L1, L2, or especially L5) ambiguities since precise dual-band code measurements were not used. These GIMS are extremely useful for single frequency users with longer baselines. For details, refer to Schaer, Beutler and Rothacher (1998), and a very useful overview of GIMS which can be found at <http://www.aiub.unibe.ch/ionosphere.html>.

2.5 TROPOSPHERIC REFRACTION

Tropospheric refraction will be dealt with extensively in Chapters 3 and 4. Suffice to say that, left uncompensated, the range equivalent of the delay caused by tropospheric refraction can vary from about 2.4m for a satellite at zenith and the user at sea level to about 25m for a satellite at an elevation of approximately 5° (Leva, Haag and Van Dyke, 1996).

2.6 MULTIPATH

Multipath is an indirect signal reflected off a nearby surface. The reflected signals always travel a longer path length than the direct signal. The direct and indirect (reflected) signals combine with one another, and introduce a bias into the time delay (for pseudo-range measurements) or into the phase difference (for carrier phase measurements). The impact of multipath depends on a variety of factors. These include

the strength and delay of the reflected signal compared to the direct signal attenuation characteristics of the antenna (Zimba, 2000).

The effect of multipath can neither be reduced nor eliminated by differencing. It has to be minimised at each end of the baseline. Site selection is clearly the best way of minimising the multipath. Analysis tools such as TEQC (Translate/Edit/Quality Check) software, available from UNAVCO are very handy in identifying the multipath characteristics, both of the receiver and the environment (UNAVCO, 2002). There are two techniques available to mitigate the effects of multipath, namely; signal processing techniques and multipath rejection antennas such as choke rings.

2.6.1 Signal Processing Techniques

In this method, the data is analysed to separate the direct signal from the indirect signal. Most geodetic receivers use advanced multipath rejection technology. The Ashtech Z-FX-CORS receivers, used at the TrigNet stations for example uses Enhanced Strobe Correlation. A detailed description of this technology performance is given in Garin and Roussseau (1997).

Far multipath occurs when there is reflecting surface at some distance from the antenna, such as building, a mast, mountain, etc. Metal surfaces cause the strongest reflections. Far multipath can very nearly be eliminated by good correlator-based multipath mitigation techniques. However, removing a multipath signal comes at the expense of removing part of the direct signal too, which in turn increases noise. (Magellan Corporation, 1998).

2.6.2 Multipath rejection choke rings

With GPS signals, the signal processing technique is ineffective if the difference between the direct path and the indirect path is less than a few metres. Oftentimes, the more we try to remove the short distance multipath, the more noise we add.

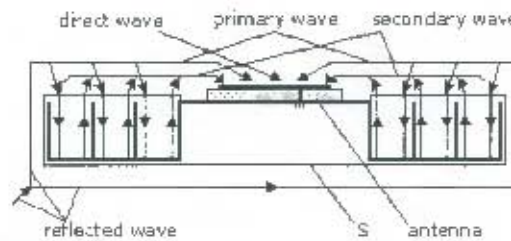


Figure 2.6 Choke ring antenna design (Topcon Positioning Systems, 2001)

Multipath rejection choke ring antennas (see Figures 2.6 and 2.7) works only for the multipath signals reflected from objects below the antenna. The reflected signal that hits the bottom side of the antenna can be rejected. For signals that are reflected off the ground, the multipath distance is in the order of a few metres and signal-processing techniques cannot do much to address them, but choke rings can. A choke ring ground plane consists of several concentric thin walls, or rings, around the centre where the antenna element is located. The area between the rings creates “grooves”.



Figure 2.7 Choke ring antenna

The signal that is received by the antenna is composed of two components of the “direct” signal and “reflected” signal. The grooves have no effect on the direct signal other than decreasing the antenna gain at low elevation angles. For high elevation angles the ground plane works almost like a flat ground plane. The grooves have significant effect from incoming signal at low elevation angles. Primary and secondary reflected signals propagate to the antenna element and contribute to the total signal that also includes direct signal from the satellite to the antenna element. The objective of the choke ring ground plane is for the primary and secondary reflected signals to

substantially cancel each other and the direct signal to the antenna to remain as the dominant signal (Topcon Positioning Systems, 2001).

Multipath can be reduced further by multiple observations, where the positions of the satellites changes with time, so the multipath effect will also change cyclically, and can be averaged out (Merry, 1996). All the observations used in this research spanned entire days (24 hours), except where data were unavailable or stations were down.

2.7 ANTENNA PHASE CENTRE OFFSET AND VARIATION

The antenna phase centre of the receiver is the point at which the radiation appears to be received and generally is not coincident with the geometric antenna centre. It is to this point to which the measurements and the position commonly refer. A GPS geodetic solution for a baseline fundamentally provides the vector between the phase centres of the antennae at either end of the baseline. To relate the vector to physical points on the ground, the exact location of the phase centre of each antenna relative to those points must be known. Standard GPS positioning procedures reduce all GPS observations from the antenna phase centre to the reference point, by way of measured vertical height (Merry, 1996; Zimba, 2000)

The **offset** depends on the elevation, the azimuth, and intensity of the satellite signal. Further, the L1 and L2 frequencies have different electrical phase centres, hence different offsets. The offsets must be set apart from antenna phase centre variation (PCV). Ultimately, the precision of an antenna should be based on antenna PCV's and not on offsets (Hoffmann-Wellenhof, Lichtenegger and Collins, 2001). A constant offset should however be determined and taken into account.

When processing GPS data without using a correction model for elevation dependent PCV's of GPS antennas two error types have to be considered, namely bias in the (relative) station height (up to 10 cm) if different antenna types are mixed, and a scale factor in the baseline length (up to 0.015 ppm), which can have a big impact on long

baselines even if antennas of the same type are used (Rothacher et al., 1995). The reasons for these are:

- a) The antenna pattern may not be azimuthally symmetrical, so that the phase centre is different for satellites at different azimuths. This effect can be reduced by always mounting the antenna in the same direction. Precautions were taken to ensure that all the TrigNet antennas were mounted in the same direction.
- b) The phase centre may be dependent upon the vertical angle to the satellites, which affects heights.

The elevation dependent PCV's also have an impact on the estimation of **tropospheric zenith delays** and ionosphere parameters (both effects relying on correct mapping).

It is important to remember that each GPS antenna has a character of its own. Even antennas that appear to be physically similar may have very different properties. These differences must be taken into account to achieve the highest accuracies. The true antenna phase centre may be different from the centre indicated by the manufacturer.

This antenna offset may simply arise from inaccurate production series. The antenna phase centre characteristics can even vary with different versions of the same antenna model. An example that the Author came across is the Ashtech L1/L2 marine antenna, where the L1 phase centre differs by as much as 1cm between 2 versions of the same model! Fortunately, it seems that an antenna with the same model and version number displays very similar characteristics, hence only a few of the same batch needs to be calibrated (Schupler and Clark, 1991).

Two independent methods are available to obtain antenna phase centre calibrations: the chamber tests and the estimation of phase centre corrections from the GPS data taken on short baselines. The **chamber** measurements are performed in anechoic chambers, where the final result yields the location of the centre of rotation with respect to a physical point on the test antenna, e.g. the antenna reference point (ARP) as defined by the IGS. The Bernese GPS Software 4.2 allow for the **estimation** of receiver antenna offset and phase centre variation using GPS data. Although the resulting accuracy is comparable to chamber tests, the disadvantage is that only relative corrections

(differences between antenna types) may be estimated. Therefore, at least one reference antenna has to be introduced as “known” phase centre offset and variation (Hugentobler, Schaer and Fridez, 2001). The Allen Osborne Dorne Margolin Model T dual frequency antenna has become the standard reference antenna when using GPS data to estimate PCV's.

This is important for this research as a mixture of antenna types were used. Fortunately all the TrigNet stations are equipped with identical antennas, (ASH701941.B: dual frequency GPS/GLONASS, model 701941-02 rev B). The PCV tables are obtainable from the IGS and other centres. The author used the PCV file in the AUIB ftp directory which contains the IGS tables in Bernese format. The IGS stations at Hartebeesthoek and Sutherland were both equipped with AOAD/M_T Dorne Margolin T choke ring (Turbo Rogue) antennas.

2.8 THE EFFECT OF ANTENNA COVERS

In an experiment conducted by UNAVCO (1997), it was shown that the addition of antenna covers causes an error to be introduced in the height component of baseline solutions. The main reason is that the effect of the cover on the GPS signal is often modelled as tropospheric delay. The magnitude of the error depends on the:

- Shape of the cover; the conical shape radomes produces errors as large as 44 mm in the L3 height solution with tropospheric parameters estimated, whereas the hemispherical antenna covers produce much smaller errors. If properly mounted, the spherical covers produce an error at the 2 mm level,
- Material the cover is constructed of,
- Thickness of the cover,
- How the cover is mounted around the antenna. To minimise errors, the radius of curvature must be centred near the mean electrical phase centre.

Ideally, it would be best if no cover were needed over an antenna. However, most PGA sites require their use to keep rain, snow and animals away. During the pilot phase of the TrigNet project when covers were not installed, the chambers of the choke ring antennas

were filled with bird excrement. Antenna covers are compulsory in regions that have snowfall.

As in the case with many errors in very high precision GPS applications, it is possible for the effect of the dome to cancel out at the single difference level. For very short baselines, using identical cover types, the common errors introduced at different stations are cancelled out. However, as baseline length increases, the two antennas observe a satellite at different azimuth and elevation angles, the errors no longer cancel out completely. Where stations are included, that either have no antenna cover or a different type of cover, the effect will not cancel out and this must be taken into consideration when highest precision is required.



Figure 2.8 SCIGN hemispherical radome used at all TrigNet installations

All TrigNet stations are equipped with identical “SCIGN” hemispherical radomes (see Figure 2.8 above), as used in the SCIGN network on the USA West Coast. The hemispheric design, concentric with the geometric centre of the antenna element means that the GPS signal is normally incident and delayed along the path only rather than refracted. The design should allow the radomes to perform such that no more than 0.1 mm of apparent phase centre variation due to motion of non-uniform paths through the radome material should occur (Magellan Corporation, 1998).

2.9 RECEIVER CLOCK ERROR

Similar to satellite clock errors, any error in the receiver clock causes inaccuracy in pseudo-range measurements. However, it is not practical to equip receivers with very accurate atomic clocks. Atomic clocks weigh more than 20 kilograms, cost about US\$50,000, and requires extensive care in temperature control.

Assume that at a given time our receiver clock has an error of one millisecond, causing a distance error of about 300,000 metres. If the distances to all satellites are measured exactly at the same time, then they are all off by the same amount of 300,000 metres. Therefore, we can include the receiver clock error as one of the unknowns that we must solve for (Topcon Positioning Systems, 2001). The GPS pseudo-range solution algorithm takes account of this and the clock is solved for independently at every epoch. Where carrier phase measurements are used, the receiver clock bias is eliminated in the double difference observation, which includes differencing across satellites (Merry, 1996).

2.10 SATELLITE CONSTELLATION AND GEOMETRY

The GPS satellite **constellation** was selected to satisfy many different conditions and provide worldwide three-dimensional navigation and positioning. The present full constellation provides global coverage, with at least four to eight simultaneously observable satellites above 15° elevation (in June 2002, 28 satellites were active). The satellites are located in six orbital planes on almost circular orbits of an altitude of about 20 200 km above the Earth, inclined 55° with respect to the equator and with orbital periods of approximately 11 hours and 58 minutes. The satellite constellation has been placed in an incline orbit at 55° to provide full earth coverage (Hugentobler, Schaer and Fridecz, 2001).

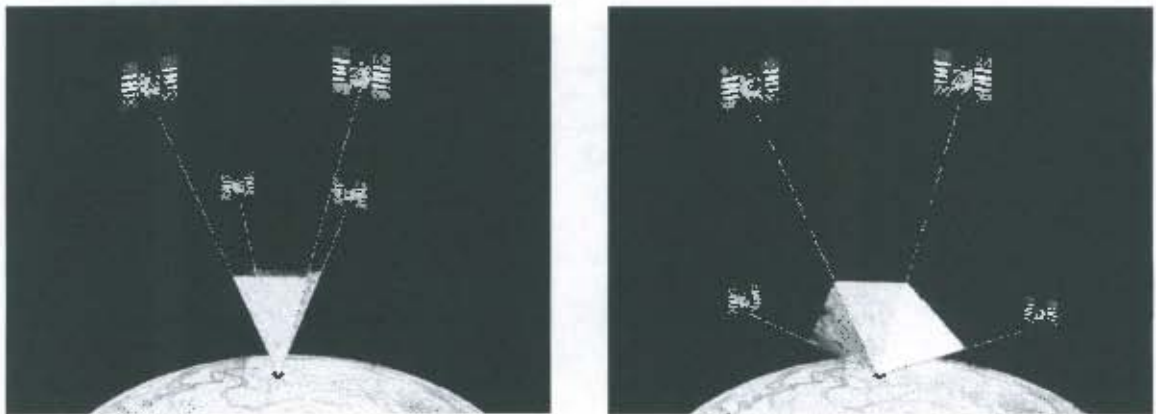


Figure 2.9 The effect of varying satellite distribution (Topcon Positioning Systems, 2001)

The effect of biases generated at the satellite (orbit, clock, etc) will be magnified by the geometry of the satellites used for position fix (see Figure 2.9). The magnitude of this is determined by the number and the geometry of the satellites observed. If four satellites are clustered near each other, then one metre of error in range may result in an error an order of magnitude larger than when many satellites are scattered around the sky.

For pseudo-ranging, the effect of the geometry of the satellites on the position error is called Geometric Dilution of Precision (**GDOP**), which can roughly be interpreted as the ratio of the position error to the range error. Ideally, the GDOP must be as small as possible. The reason to reject the use of a criteria based on GDOP value for static positioning analysis is that the GDOP parameter is uniquely based on a single epoch observations and it does not give any indication about the way that systematic errors propagate into station coordinates.

For differential carrier beat phase observations, the model is somewhat complicated by the unknown initial cycle ambiguity, which cannot be separated from the baseline components unless the satellite geometry changes during the course of the observations. All data used in this research was gathered in daily data sets, allowing for ample change in geometry (Topcon Positioning Systems, 2001; Merry, 1996).

2.11 INTERSTATION DISTANCE (BASELINE LENGTH)

The GPS has dramatically changed the way that surveyors, geodesists and others measure positions. Three-dimensional coordinates of a new point relative to a control point located several hundred (even thousands) kilometres away can now be determined. That control point may be associated with a GPS receiver that is continuously operated, such as TrigNet receivers. While perusing commercial GPS software manuals, static GPS baseline accuracy is normally quoted as " $a + b.ppm$ " where a (constant) and b (scalar error) normally ranges from 5 mm to 10 mm and 0.1 to 0.5 respectively.

After analysing ten days of GPS data from stations with separations up to 300km in 1998, Eckl et al. (2001) found that dependence of accuracy on baseline length is negligibly small when:

- a) IGS final orbits are used,
- b) Integer ambiguities are fixed (correctly),
- c) Tropospheric parameters are estimated,
- d) Baseline length < 300km and
- e) Session duration was > 4 hours.

All conditions, with the exception of baseline length were met during processing of data for this research. However, the availability of 24-hour datasets also improves the accuracy of the baseline estimate. When using software such as the Bernese, the " $a + b.ppm$ " baseline error/accuracy model does not hold, and coordinate precision is more a factor of station specific limitations such as multipath than baseline length.

2.12 SITE DISPLACEMENTS

2.12.1 Earth Rotation

The term "Earth orientation" refers to the direction in space of axes which have been defined on the Earth. It is usually measured using five quantities: two angles which identify the direction of the Earth's rotation axis within the Earth, an angle describing the rotational motion of the Earth, and two angles which characterise the direction of the

Earth's rotation axis in space. With these coordinates, the orientation of the Earth in space is fully described. The Rapid Service/Prediction Centre of the International Earth Rotation Service (IERS), located at the U.S. Naval Observatory (USNO), monitors the Earth's orientation and disseminates this information to many organisations on a continuous basis (U.S. Naval Observatory, 2001).

Earth Rotation Parameters (ERPs) is another of the official products of the IGS. Final ERPs, often called “poles”, are made available with a latency of 14 days by the IGS and accessible from any of the data centres. These files contains parameters for polar motion, polar motion rates, length-of-day with accuracies of 0.1 mas, 0.2 mas per day and 0.020 ms respectively (Neilan, 2000). The Author used final ERPs from the CODE analysis centre to ensure that the orbits, coordinates, poles and satellite clocks were consistent.

2.12.2 Solid Earth Tides

The gravitational attraction of moon and sun (and other bodies of the solar system) is responsible for what we call solid earth tides causing site displacements of up to several decimetres. The combined gravitational pull of the sun and the moon on the oceans causes them to deform and bulge, causing oceanic masses to continuously redistribute itself. What may come as a surprise is that the solid earth, despite having an average rigidity of about twice that of steel, is actually elastic and it too deforms and responds to tidal forces (Schüler, 2001). A person standing on the equator moves up and down with respect to the centre of the earth by about half a metre – twice a day! The Bernese GPS Software 4.2 implements a very precise algorithm (to model earth tides). Computation of solid earth tides requires knowledge of the positions of the disturbing bodies (sun and moon). The Bernese Software uses the JPL Planetary Ephemeris DE200 (Hugentobler, Schaer and Fridez, 2001).

2.12.3 Ocean Tide Loading

On top of this so-called body tide is an even more subtle displacement of the solid earth caused by the weight of the tidal water. A consequence of the accumulation along the coasts of water from tides has a secondary, geodetic/geophysical effect; the weight of this water deforms the supporting crust of the Earth. For example, sites along the East Coast of North America rise and fall 1 to 2 centimetres twice a day driven by the principle, semidiurnal lunar tide (Schenewerk and vanDam, 1999).

Site displacements due to ocean tide loading can be modelled if the amplitudes and phase angles of the partial tides are known. These are made available by CODE analysis centre via an automated service. The CODE analysis centre also makes available ocean loading coefficients of existing IGS stations via ftp on the AUIB site (<ftp://ftp.unibe.ch/aiub/BSWUSER/STA/ITRFCDL.BLQ>). All computations undertaken during this research used ocean-loading tables. Fortunately, this is not time varying (at least not at the bi-annual scale), so the Author used the same tables for all the campaigns processed.

2.13 REFERENCE FRAME: DEFINITION AND UPDATE

Reference systems are introduced in order to model geodetic observations as a function of unknown parameters of interest. The coordinate systems are defined in terms of orientation, metrics (unit of measure), and curvature, they are three dimensional in principle. A fourth dimension, time, enters through the mutual motion of the earth and other celestial bodies and the earth's deformations (Torge, 2001).

2.13.1 The International Terrestrial Reference Frame (ITRF)

Global reference systems are realised through reference frames, e.g., the ITRF, which is established and maintained by the International Earth Rotation Service (IERS). The ITRF represents the global basis for three-dimensional positioning. It is defined by the geocentric Cartesian coordinates and the horizontal velocities of a global set of space

geodetic observing sites, given for a certain epoch, within an accuracy of $\pm 1\text{cm}$ and $\pm 3\text{mm/year}$ respectively (Gendt, 2002).

The ITRF results are based on observations obtained by global networks employing different space techniques, which are combined within the frame of the International Earth Rotation Service (IERS). The stations participating in the ITRF carry out observations either continuously or at certain time intervals. Observations are made on twelve of the larger tectonic plates, which permit the derivation of station velocities relating to plate tectonics (Torge, 2001).

2.13.2 ITRF2000

The ITRF2000 solution is the densest and most accurate frame ever developed to date, containing about 800 stations located on about 500 different sites. It has been achieved by combination of positions and velocities using full variance/covariance matrices of the individual solutions provided by the IERS Analysis Centres. It includes core stations observed by Very Long Baseline Interferometry (VLBI), Lunar Laser Ranging (LLR), Satellite Laser Ranging (SLR), GPS and DORIS as well as regional GPS networks for its densification (Dick and Richter, 2001).

The ITRF2000 long term stability, evaluated over 10 years, is estimated to be better than 4 mm in origin and better than 0.5 ppb in scale, equivalent to a shift in station heights of approximately 3 mm and over the Earth's surface. According to Dick and Richter (2001), the ITRF2000 is intended to be a Standard and densified solution for a wide application community (geodesy, cartography, navigation, etc.)

2.13.3 Velocity Correction

The initial positions normally refer to a realisation of ITRF or a similar reference frame. The ITRF is a global reference frame. This means that effects like plate tectonics will make the positions of the ground-stations vary with **time**. Therefore, the epoch must be explicitly given for any coordinate solution and a position record does not only consist

of a coordinate triple, but of a velocity vector. The reference epoch is expressed in decimal years. The positions and velocities for the GPS stations that contributed to *ITRF2000* are referenced to the epoch 1997.0.

The position of these stations at any time other than the reference epoch can be obtained by applying the law of linear motion. The IERS prescribes the following method to translate/propagate coordinates to other than the reference epoch (Schüler, 2001):

$$X(t) = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \frac{X(t_{REF}) + (t - t_{REF}) \cdot v_x(t_{REF})}{1} \quad (2.9)$$

where:

- t : observation epoch in [years, decimal]
- t_{REF} : reference epoch in years as given in network solution file
- $X(t)$: ECEF position vector at the observation epoch
- $X(t_{REF})$: ECEF position vector at the reference epoch in [m]
- $v_x(t_{REF})$: velocity vector of station at reference epoch in [m/year]

The assumption of identical velocities at the reference epoch and the observation epoch is not strictly true, and the plates may display varying relative displacements over longer periods. It is for this reason that many geodesists prefer to use the weekly positions as computed as part of the IGS “free network” solution, normally denoted as, e.g. IGS97 instead of the ITRF97. This denotes that the coordinates/poles/orbits are computed in the IGS realisation of the ITRF instead of the position of the reference epoch updated to the observation epoch. The weekly SINEX coordinate files (from the IGS and analysis centres) give the coordinates of the station at the middle epoch of the week, i.e. Wednesday at 11:59:30 am UT (Sinex Working Group, 1996).

2.14 MONUMENT/GEODETIC SITE STABILITY

Monumentation is one of the most important aspects of geodetic installation, whether it be for VLBI, SLR or GPS installation. Site selection is not a factor of site stability alone. Depending on the country and infrastructure, factors such as vandalism, safety, access, power, low multipath, clear horizon and accessibility must all be considered. Currently a large number of different monument types, with varying designs, construction, quality and suitability are used in Permanent GPS Arrays (PGAs) and the IGS network. UNAVCO has an excellent website that contains a large amount of interesting and useful details on monumentation. Combrinck (2000) provides an excellent insight into the mechanics affecting geodetic site stability and monumentation. It is clear from all documentation relating to monumentation that the most suitable monument site, in terms of stability would be on shallow or even better, exposed bedrock.

The data used in this research stems from 2 IGS stations and TrigNet stations. Both IIRAO and SUTH are first class geodetic monuments set in bedrock. With the exception of the monuments at Bloemfontein and Springbok (which is built on gravel and compact shale respectively), all the TrigNet stations used in this research are located on **buildings**. Figure 2.10 shows a typical TrigNet monument at Bloemfontein.

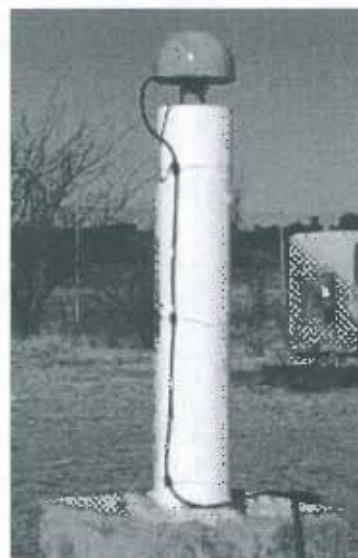


Figure 2.10 TrigNet antenna mounted at Bloemfontein weather office

During the reconnaissance phase of TrigNet stations, considerations such as convenience, accessibility, power, telecommunication infrastructure and most importantly, **security** and **safety** were paramount. These requirements were met at buildings such as Department of Environmental Affairs (weather office) buildings. In most cases, buildings were the only choice available and the establishment of many stations on buildings were sometimes at the expense of clear horizon and low multipath.

If one attaches a GPS antenna to a pole that is mounted against or on a building, neither the pole nor the mount are the monuments, instead, the building becomes the monument. Buildings are not necessarily bad monuments; they often meet requirements in terms of accessibility, safety, power and convenience. The load imposed by the structure at the foundations will always be accompanied by strain that results in settlement of structures. All building will show some settlement, the best will be those for which the piling are down to bedrock (Combrinck, 2000).

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Chapter III

3. Characteristics and Effects of the Troposphere

3.1 INTRODUCTION

GPS signals start travelling on their propagation path from a satellite to the receiver through space (essentially a vacuum) before entering the earth's atmospheric envelope (Brunner and Welsch, 1993). The ionosphere is the first atmospheric layer encountered relevant to GPS. After the ionosphere, GPS signals travels through the stratosphere and **troposphere** (see Figure 3.1).

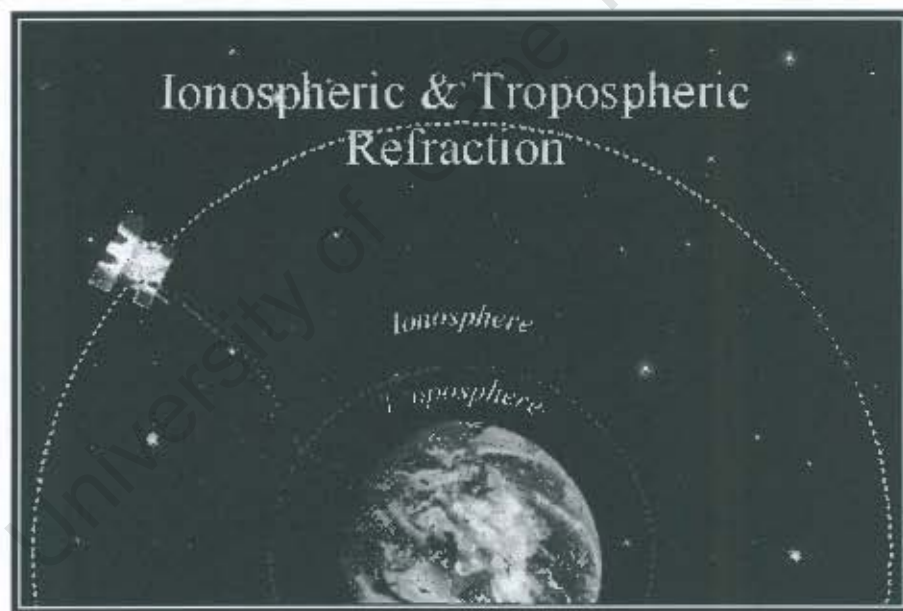


Figure 3.1 Atmospheric refraction (<http://www.montana.edu/places/gps>)

When describing the effects of atmospheric refraction on radio waves, it is convenient to separate the effects of **neutral** atoms and molecules, the bulk of which are contained in the **troposphere**, from those charged particles, primarily contained in the ionosphere (Langley, 1996). In this chapter the atmospheric **constituents** and

profile of the troposphere is detailed as well as the effect of the tropospheric refraction on GPS signals.

3.2 STRUCTURE, CONSTITUENTS AND CHARACTERISTICS

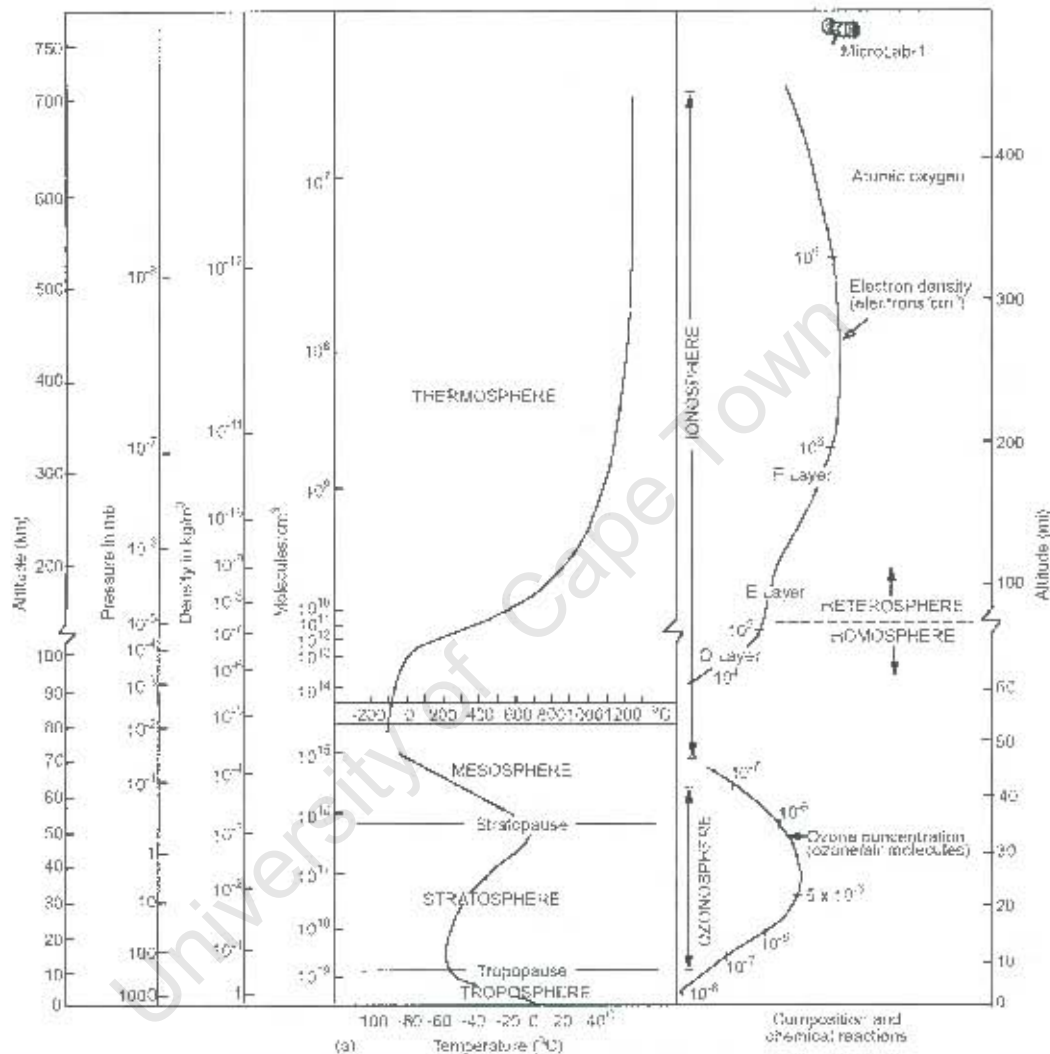


Figure 3.2 The mean vertical structure of the Earth's atmosphere. (Rocken et al, 1997, p52)

The troposphere is the lower part of the earth's atmosphere where temperature decreases with an increase in altitude. The thickness of the troposphere is not uniform. It extends to a height of less than 9km over the poles and in excess of 16km over the equator (Brunner and Welsch, 1993).

3.2.1 Water Vapour

Water vapour, which is confined to the troposphere, generally exists only below 12km above sea level, and most of the water vapour below 4km. Because the water vapour content is highly non-uniform, a total average fractional volume is not a very meaningful description of the water vapour content. Instead, a measure of water vapour often employed is the total amount of water in a vertical column of air one square cm in area:

$$W = \int_0^{\infty} \rho_w(h) dh \quad (3.1)$$

where W is the total integrated water vapour content and $\rho_w(h)$ is the water vapour density in g/cm^3 (Spilker, 1996, p518).

3.2.2 “Dry” Gas Constituents

Compared to the “wet” atmosphere (which is characterised by water vapour), the **dry atmosphere** is relatively uniform in its constituents. Typical dry gas constituents have molar weights and fractional densities. The major constituents of the “dry” air include N_2 , O_2 , Ar, CO_2 , Ne, He, Kr and Xe (Spilker, 1996).

3.2.3 Refractivity and Refractive Index of Air

The refractive index of air (n) is defined as the ratio of the speed of light in a vacuum (identical for radio waves) to the speed of propagation in the medium. The propagation direction is described in terms of the famous law of geometrical optics: Snell’s law of refraction. Because the refractive index of air is only slightly larger than 1, it is frequently convenient to use the refractivity N instead of n (Brunner and Welsch, 1993).

The refractivity (N) of a parcel of air, where $N=10^6.(n-1)$, is a function of its temperature (T) and partial pressures of the dry gasses (P_d) and water vapour (e).

According to (Langley, 1996), we can express the refractivity (N) of a particular parcel of air as the sum of two terms:

$$N = N_d + N_w \quad (3.2)$$

where, N_d is proportional to the total density of air, and N_w is mainly determined by the density of the water vapour contained in the air parcel. More specifically,

$$N = K_1 \left(\frac{P_d}{T} \right) Z_d^{-1} + \left[K_2 \left(\frac{e}{T} \right) + K_3 \left(\frac{e}{T^2} \right) \right] Z_w^{-1} \quad (3.3)$$

where K_1 , K_2 , K_3 are empirically determined coefficients and Z_d and Z_w is the compressibility factors for dry air and water vapour respectively. The compressibility factors are corrections to account for the departure of the air behaviour from that of perfect gas (Langley, 1996). The first term in Eq. (3.3) is referred to as the dry term and the second two terms as the wet terms. Typically the dry term represents 90% of the total effect and is relatively well predicted by surface pressure measurements. The wet term, although small, cannot be easily predicted, and water vapour effects vary considerably with position, elevation angle and time (Spilker, 1996).

The above Eq. (3.3) express N mainly in terms of temperature (T). The pressure P and the density ρ for the dry and wet air are related by the gas law as follows:

$$P_d = \left[\rho_d \frac{R}{M_d} T Z_d \right] \quad e = \left[\rho_w \frac{R}{M_w} T Z_w \right] \quad (3.4)$$

where R is the universal gas constant and M_w and M_d denote the molar mass of moist and dry air respectively. The formulation is useful as the hydrostatic component is not influenced by the water vapour content (Langley, 1996). This allows Eq. (3.3) to be re-written as:

$$N = \left[K_1 \frac{R \rho_d}{M_d} \right] + \left[\left(K_2 - K_1 \frac{M_w}{M_d} \right) \frac{e}{T} + K_3 \left(\frac{e}{T^2} \right) \right] Z_w^{-1} \quad (3.5)$$

The Figure 3.3 below shows the height profile of N_d and N_w , the shaded area indicates the overall variability of the wet component.

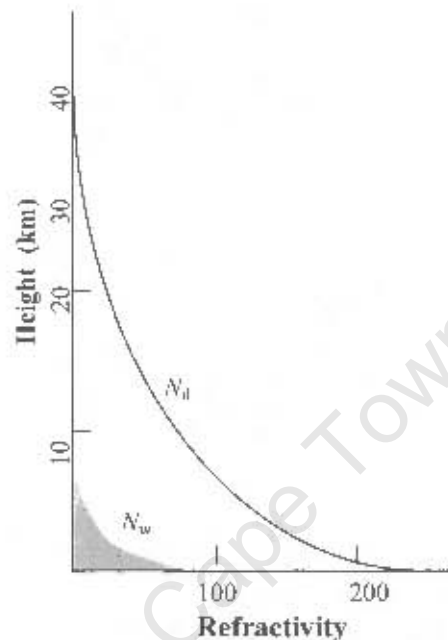


Figure 3.3 Typical height profiles of refractivities N_d and N_w (Brunner & Welsch, 1993, p44)

The Figure 3.3 above reveals some interesting points (Brunner and Welsch, 1993):

- First, the variability of N_d is very small within the troposphere because of the nearly constant mixing ratio of the constituents of air (see section Figure 3.2), with the exception of water vapour and condensed water. This makes modelling and predicting the N_d a relatively uncomplicated task.
- The N_d is negligible at heights of about 40km and above. Therefore only the troposphere and the stratosphere are important as electrically neutral propagation medium for satellite signals.
- The wet refractivity is only significant at heights below the troposphere (<12km).

The mixing of dry air and water vapour is a rather complicated process and depends mainly on weather conditions, which, in turn, makes the N_w difficult to predict. The

N_w shows strong variations with time, location, season and frontal systems (both high and low pressure systems), thus very difficult to predict and almost impossible to model accurately. "This variability of the wet refractivity is highest in the atmospheric boundary layer, which extends from the ground up to a height of about 1.5 kilometres, and to the cloud layers that do not extend much beyond a height of about 4 kilometres" (Brunner and Welsch, 1993, p44).

3.2.4 Temperature and Pressure Profile of the Troposphere

The **temperature** profile of a highly simplified model of the earth's atmosphere shows a linear decrease with altitude at constant lapse rate of -5 to -7°C per km of altitude increase from sea level up to the tropopause. The tropopause region is characterised by approximately constant temperature and has an altitude of 8-12km in winter, or 10-12km in summer.

The atmospheric **pressure** at sea level is roughly 1013mb and decreases with altitude to approximately 200-300mb at the tropopause over the pole, and 70-150mb over the equator. In meteorology, one atmosphere of pressure (also known as standard pressure) is defined as 1013.25mb (Spilker, 1996).

3.3 EFFECT OF THE TROPOSPHERE ON GPS SIGNALS.

The presence of neutral atoms and molecules in the troposphere affects the propagation of electromagnetic signals. To be precise, the term “tropospheric” used throughout this dissertation is somewhat of a misnomer because roughly 25% of the delay effect is caused by atmospheric gasses above the troposphere, especially in the tropopause and stratosphere (see Figure 3.2), where atoms and molecules in the stratosphere also exist in sufficient numbers to affect the propagation of signals. However, since the bulk of the neutral atmosphere lies within the troposphere, the whole neutral atmosphere is often loosely referred to as the troposphere (Spilker, 1996).

“The neutral atmosphere changes the **speed** and **direction** of the propagation of radio waves” (Brunner and Welsch, 1993, p42). This causes the signal received from a GPS satellite to be refracted by the atmosphere as it travels to the user on or near the Earth’s surface. The **delay** caused by atmospheric refraction depends upon the actual path of the ray and refractive index of the gasses along the path. For an atmosphere symmetric in azimuth about the user antenna, the delay depends only upon the vertical profile of the atmosphere and the elevation angle to the satellite (Spilker, 1996). The effect of assuming atmospheric symmetries is discussed in section 4.5.

3.3.1 Delay Effects of the Troposphere

This tropospheric delay is caused by, and is a function of the larger refractive index n ($n > 1$) of the atmospheric gases than that of free space (where $n = 1$). This causes the speed of light (group velocity) in the medium to decrease below its value in a vacuum (normally denoted as c). Since this part of the atmosphere is non-dispersive (for radio wavelengths), the phase and group velocities associated with GPS carrier and signal information on both L1 and L2 are equally delayed with respect to free-space propagation (Leva, de Haag and Van Dyke, 1996).

There are two main delay effects of the troposphere. The delay or excess path length introduced by the refractivity of the Earth's troposphere is usually separated into a hydrostatic (dry) and wet component. The first and larger effect is a **dry** atmosphere excess delay caused primarily by N_2 and O_2 . The dry atmosphere zenith excess delay is about 2.3m (at zenith (sea-level)) and varies with temperature and pressure. Fortunately, the dry component (which gives rise to about 90% of the tropospheric delay) is reasonably predictable as its effect varies by less than 1% in a few hours (Spilker, 1996).

The **wet** atmosphere (water vapour effect) is generally smaller, 0.01 to 0.3 m at zenith. Although it is roughly 10% the size of the dry atmosphere delay effect, it varies markedly, 10-20%, in a few hours and is less predictable even with surface measurements. The wet delay varies roughly from a few centimetres to 30 cm between the poles and the equator and from a few cm to about 20 cm during the year at mid-latitudes (Davis et al., 1993). Dual frequency (22 and 31GHz) water vapour radiometers (WVRs) can be used to make predictions that are more precise. However, these measurements are fairly complicated, expensive and not feasible for most navigation purposes (Spilker, 1996). WVRs are described in more detail in section 3.8.

3.3.2 Curvature of the Signal Path

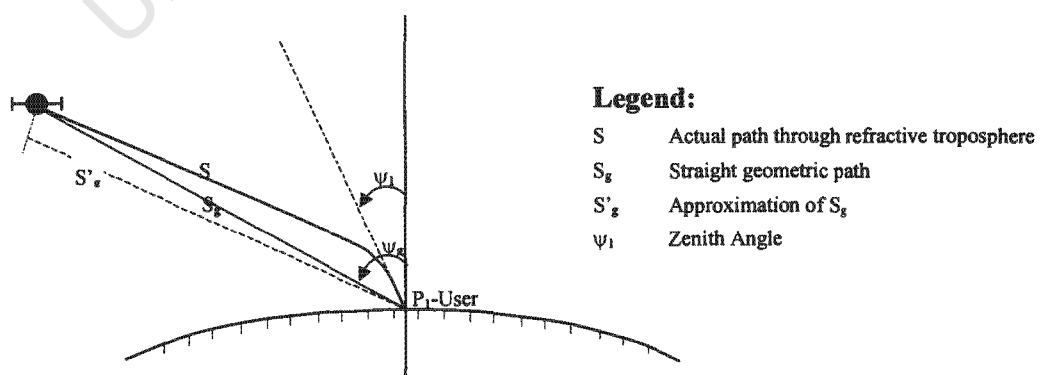


Figure 3.4 Actual slightly curved path S and the straight geometric paths through the refractive atmosphere (Spilker, 1996, p525)

The spatially varying refractive index causes the signal path to have a slight curvature (see Figure 3.4) with respect to the geometric straight-line path. Thus, the actual satellite to user path is a slightly curved path, as shown in Figure 3.4, where the path curvature has been greatly exaggerated for clarity. The total length of the actual path from the user to the satellite is as follows:

$$S = \int_{Actual} n(s) ds \quad (3.6)$$

and is clearly longer than the straight geometric path S_g (at elevation angles less than 90°) that the ray would take in a vacuum. Fermat's principle of least time states that the actual path travelled is that which minimises the total delay from user to satellite. Therefore, the actual curved path of length S , which is longer than the geometric path length S_g is still shorter in time delay. The difference between the length of the actual curved path and the straight line path is typically quite small $S - S_g < 0.1\text{m}$, except at low elevation angles (Spilker, 1996).

To summarise, the curved path, although physically slightly longer, has a slightly shorter delay than would a path travelling in a straight line through the troposphere. The difference between the actual curved delay and the straight-line geometric distance (rectilinear coordinates) is as follows:

$$\Delta = \tau - S_g = \int_{Actual} n(s) ds - \int_{geometric} ds \quad (3.7)$$

where τ is the delay along the actual path (Spilker, 1996). The curvature and the delay effects will have to be accounted for in any tropospheric delay model.

3.3.3 Elevation Dependence of Tropospheric Refraction

The lower the elevation angle of the incoming GPS signal, the more it is adversely affected because it must travel a longer path through the atmosphere, and more specifically the troposphere (see Figure 3.5).

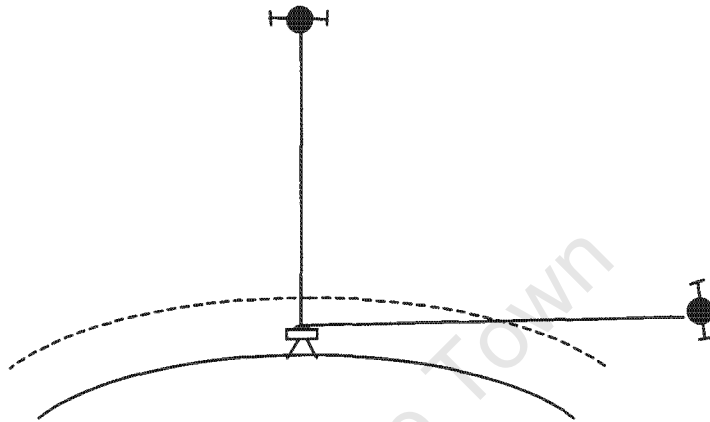


Figure 3.5 Elevation dependence of tropospheric refraction

Observations at low elevations are generally more corrupted by tropospheric refraction and various unmodelled systematic effects (especially multipath) than those at high elevations. These unmodelled systematic errors decrease the quality of the results. For this reason the cut-off elevation angle for most classical surveys and even geodetic surveys using GPS are recommended at 15° and even 20° in some cases. However, this contributes to a worsened height estimate and increases the already high correlation between the tropospheric parameters and the height component.

Using low-elevation observations may improve the estimation of troposphere zenith delays, resulting in de-correlation of the height and tropospheric parameters and, consequently, improve the vertical component of the station position. In order to optimise the usage of low-elevation observations, the option of elevation dependent weighting of the observation was introduced into many high-level GPS processing software suites. The Bernese GPS Software uses the weighting function $w(z)$ where

the noise increases with elevation decrease, in the same way as the troposphere delay, namely:

$$w(z) = \cos^2(z) \quad (3.8)$$

where z is the zenith angle of the satellite. Thus, an observation at zenith is assumed to have a unit weight. Figure 3.6 clearly shows how the weight attached to each observation decreases as elevation angle decreases.

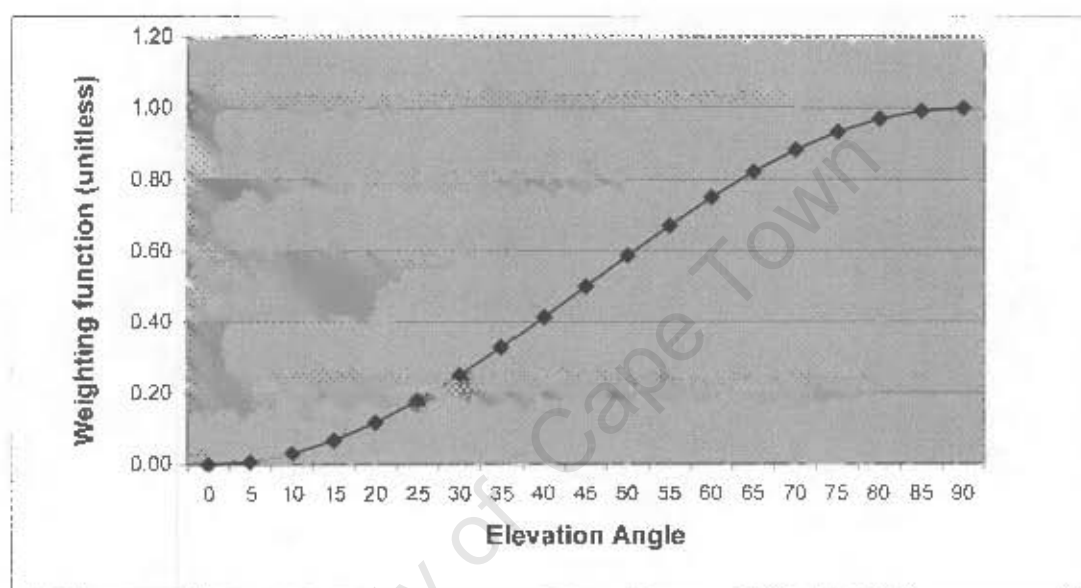


Figure 3.6 Graph indicating elevation dependence and weight assigned to observations using the $|\cos^2 z|$ weight model.

3.4 TWO BIAS CLASSES AND THEIR INFLUENCE ON BASELINE ESTIMATES

Beutler et al. (1988), in a very interesting publication illustrates how **relative** troposphere biases caused by errors of (mismodelled) tropospheric refraction at one of the endpoints of a baseline relative to the other endpoint invoke primarily biased station **heights**. On the other hand, absolute troposphere biases caused by errors of (mismodelled) tropospheric refraction common to **both** endpoints of baseline produce primarily **scale** biases of the estimated baseline lengths.

Legend:

- S: Satellite at observation time t
- P_i : Receiver locations at observation time t
- ρ_i : Distance from satellite to receiver at P_i
- $\Delta\rho$: Single difference observable
- b : Baseline to be estimated

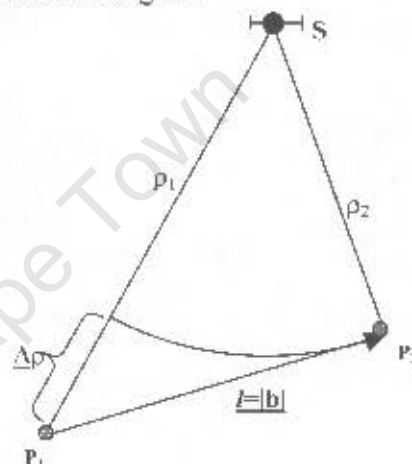


Figure 3.7 The single difference observable (Beutler et al., 1988, p16)

As mentioned in section 2.2, geodesists use carrier beat phase measurements in a relative mode with the double difference as the basic observable. More specifically, between-receiver single differences are formed for each of two satellites, and these two differences are again differenced, forming the so-called "double difference"

To study the influence of a bias ε on the baseline b , Beutler et al. (1988) made the following simple assumptions in addition to the initial assumption that the ambiguity resolution process was successful:

- For each observation (single difference) $\Delta\rho$ to a satellite S made at zenith angle z and azimuth a , there exists an observation $\Delta\rho^*$ to a satellite S^* made

at the same zenith angle but at the azimuth $(a+180^\circ)$. So approximately we have $\Delta\rho = \Delta\rho^*$.

- The height difference between receivers at P1 and P2 is small compared to the baseline length.
- Baseline length l is small compared to ρ_i .
- Let $\bar{\Delta\rho}$, $\Delta\rho^*$, stand for the biased observations of $\Delta\rho = \Delta\rho^*$,

3.4.1 Relative Troposphere Bias (Class1)

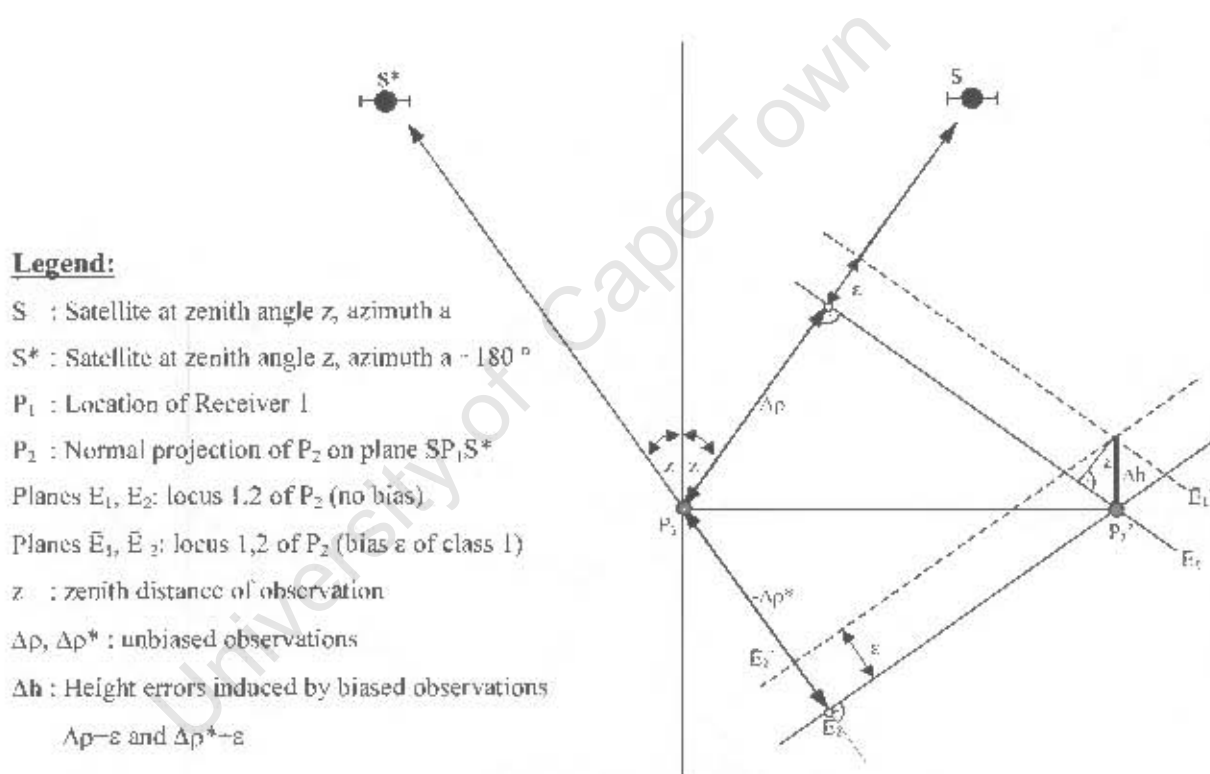


Figure 3.8 Influence of a Class 1 bias ϵ on baseline $\underline{b}$ (Beutler et al., 1988, p17)

In this bias class, observations Δp and Δp^* , biased by the same ε (which is caused by relative troposphere error), was shown by Beutler et al. (1988) to primarily induce a biased station height. The authors summarise the effect of relative troposphere error on height with the following very simple formula:

$$\Delta h = \frac{1}{\cos \alpha_{mag}} \cdot \Delta d_{prop}^{relative} \quad (3.9)$$

This means that relative troposphere errors cause height errors which are amplified by the factor $\cos z_{\max}$ (2.9 for $z_{\max} = 70^\circ$) in the estimated receiver height. Relative troposphere errors also induce scalar errors, depending on the inclination of the baseline. This is only of importance if the height difference is large relative to horizontal station separation.

3.4.2 Absolute Troposphere Bias (Class 2)

In this case observations $\Delta\rho$ and $\Delta\rho^*$ are biased by $+\varepsilon$ and $-\varepsilon$ respectively

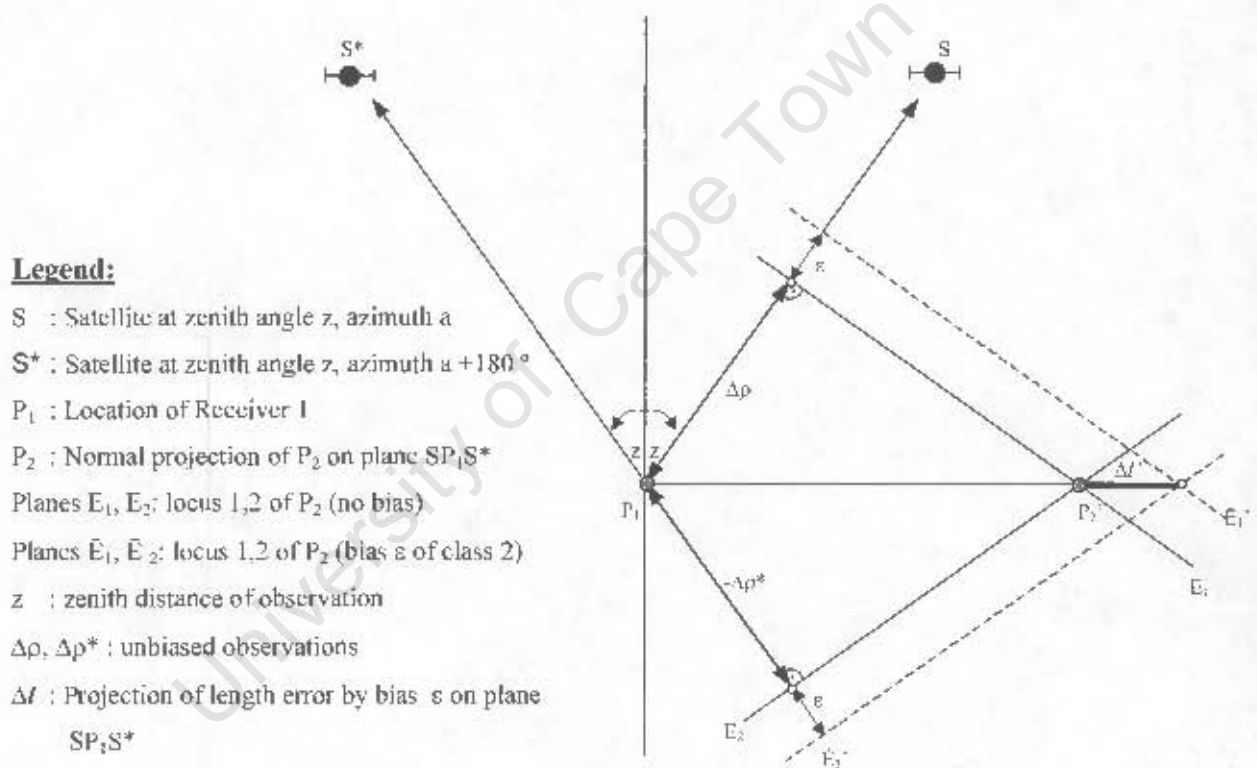


Figure 3.9 Influence of a Class 2 bias ε on baseline b (Beutler et al., 1988, p19)

This class (class 2) of bias induces a scale bias. Beutler et al. (1988) again proves that a neglected troposphere error (a common error at both ends of the baseline) will cause a class2 bias in the observations. So neglecting the tropospheric refraction lengthens the GPS derived baselines.

$$\frac{\Delta l}{l} = \frac{\Delta d_{trop}^{absolute}}{R_1} \cdot \frac{1}{\cos z_{max}} \quad (3.10)$$

Since the entire troposphere effect is of the order of 2.25 metres and since for $z_{max} = 70^\circ$, $\cos z_{max} \approx 2.9$, we may expect a scalar error of the order of $\approx 1.10^{-6}$ if we neglect tropospheric refraction completely. "It should be stated however, that relative troposphere errors are a much greater danger for GPS results" (Beutler et al., 1988, 26).

3.5 USING GROUND BASED METEOROLOGICAL DATA

Many meteorological models have been developed to calculate the zenith delays from meteorological observations made near the ground at the time of GPS observations. This approach is especially useful for determination of zenith hydrostatic delay which is related to the total air mass contained in the vertical column above a GPS station, and thus directly proportionate to the barometric pressure and antenna height. Consequently, the accuracy attainable with meteorological measurements controls the attainable accuracy of the hydrostatic delay. For example, a pressure error of 0.5mb, gives rise to a 1.2 mm error in zenith hydrostatic delay (Brunner and Welsch, 1993).

The zenith wet delay on the other hand is only weakly related to the surface meteorological conditions, which generally are poor indicators of the humidity distribution above the receiver. All known models suffer from serious inaccuracies because of this fact. According to Brunner and Welsch (1993), the tropospheric delay models using meteorological ground observations have produced rather poor, and in most cases worse, results compared with the results from the default model values that replaced the actual meteorological values. This surprising finding can be attributed to the following (Brunner and Welsch, 1993 ; Dodson et al., 1996):

- The difficulty of taking accurate meteorological observations and the frequency at which significant observation errors can occur.
- The closeness of very local microclimatological conditions.

- The dynamic processes of the atmosphere start to smooth the ground proximity effects at heights of about 50-100m.
- The combination of observation errors and the ground proximity effects on temperature and humidity significantly affect the wet refractivity profile.
- Localised effects also exhibit strong diurnal structure, related to conditions of inversion and convection, making the effect even more complex.

Hugentobler, Schaer and Fridez (2001), discussed the implications of small biases in ground-met data (pressure, temperature, humidity) on the estimated station heights.

T °C	P mbar	H %	$\left \frac{\partial \Delta d_{\text{trop}}}{\partial T} \right $ mm/°C	$\left \frac{\partial \Delta d_{\text{trop}}}{\partial P} \right $ mm/mbar	$\left \frac{\partial \Delta d_{\text{trop}}}{\partial H} \right $ mm/1%
0	1000	50	3	2	0.6
30	1000	50	14	2	4
0	1000	100	5	2	0.6
30	1000	100	27	2	4

Table 3.1 Tropospheric zenith delay as a function of temperature T , pressure P and relative humidity H . (Hugentobler, Schaer and Fridez, 2001, p189)

The Table 3.1 gives an impression of the sensitivity of the estimated station height (independent of baseline length) on biases in surface meteorological for different atmospheric conditions. From the above table, together with equation 3.9, it can be seen that, e.g., on a hot and humid environment an error of only 1% in the relative humidity will induce a bias of 4 mm in tropospheric zenith delay. In turn, this will produce a height bias of more than one centimetre!

It is common knowledge that it is virtually impossible to measure relative humidity to that accuracy; moreover, the measured humidity is not representative for the entire environment of the site. Similar remarks are true for temperature measurements. It

should however be possible to measure pressure to the accuracy level necessary (0.1mb) to render pressure-induced height errors harmless.

As mentioned above, meteorological observations at GPS sites frequently are not representative of the propagation path of the satellite and applying them has been detrimental to GPS results. As a remedy, meteorological data of a standard atmosphere are used. Usually, such a standard atmosphere is created by defining a reference pressure, temperature and humidity at sea level and then use the height (and, in certain models, latitude) of the GPS site as the sole variable to calculate meteorological values for a site. These values are obviously independent of time and actual weather conditions. Excellent results have been obtained using such standard atmospheric data as inputs for the Saastamoinen model in GPS data processing (Brunner and Welsch, 1993,p49)

The Bernese GPS 4.2 software uses the following values as reference:

H_r	=	0.	Reference Height for Meteo Model M
P_r	=	1013.25	Pressure at h_r in Mbar
T_r	=	18.	Temperature at h_r in Deg. Celsius
h_r	=	50.	Humidity at h_r in %

Table 3.2 Standard values used by the Bernese GPS 4.2 software as reference (source: Hugentobler, Schaer and Fridez, 2001, p189)

Hugentobler, Schaer and Fridez (2001), strongly recommend not changing these parameters.

3.6 TROPOSPHERIC GRADIENTS

Davis et al. (1993) investigated the local temporal and spatial variation of the wet propagation delay for a site using WVRs (see section 3.8.2). The data were obtained from a wide range of azimuths and from elevation angles greater than 23.6° . Visual inspection of the data suggested a “cosine azimuth” variation, implying that a first-order gradient model was required. Gradient and gradient rate vectors showed preferred directions, which indicates a prevailing structure in the three-dimensional temperature and humidity fields, possibly related to systematic behaviour in large-scale weather systems and/or local air-land-sea interactions at sites.

Coster et al. (1997) reported on a campaign designed to measure spatial and temporal variability of precipitable water vapour. This time GPS data were compared to WVR data and the GPS data were analysed for correlations with time for large gradients. The authors commented that differences in GPS and WVR zenith wet delays could, amongst other factors, be explained by the presence of gradients (horizontal) in the water vapour distribution. “Gradients in the water vapour distribution around a site do exist, and their presence will affect the estimated zenith wet delay” (Coster et al., 1997, p2).

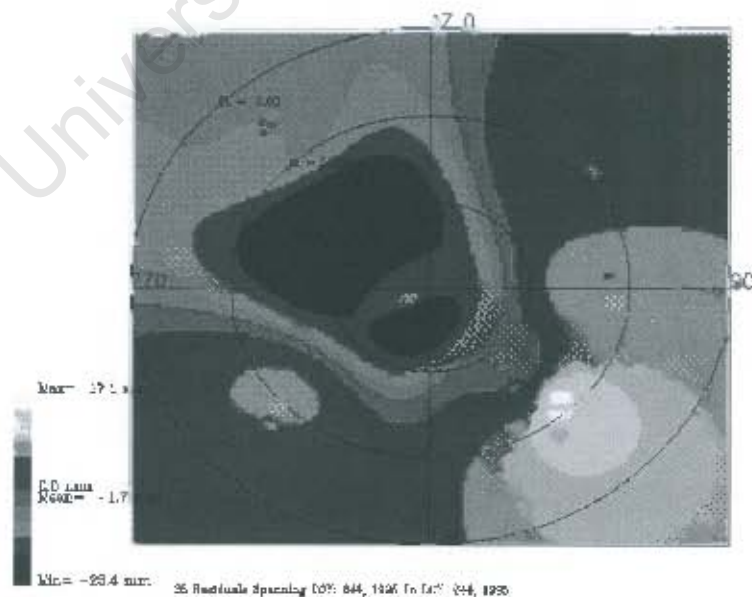


Figure 3.10 WVR Measurement of zenith wet delay as a function of azimuth and elevation (Coster et al., 1997, p5)

Chen and Herring (1997) observed that although the effects of atmospheric gradients on zenith delay are much smaller than that of elevation (usually <30mm), they do affect modern GPS/VLBI measurements. Their research indicated that the north-south gradient effects have average values over month-long periods of up to 20 mm delay at 10° elevation for sites in mid-latitudes. The east-west gradients do not show such large average values over most of the Earth. The effects of these gradients on geodetic position estimates are to cause ~2 mm mean latitude change at mid-latitudes sites.

Independent research by Bar-Sever, Krogerand and Borjesson (1998), found that using low elevation angle cut-off, a good mapping function combined with atmospheric delay gradients leads to 19.5% and 15% average improvement in radial and horizontal site position repeatability respectively. This was relative to a then current (JPL's Auto Gypsy) state of the art estimation strategy that does not model horizontal gradients and imposes a high elevation angle cut-off. The agreement between estimated values of the zenith wet delay from collocated GPS receivers and WVRs was improved by at least 25%. Bar-Sever, Krogerand and Borjesson (1998), demonstrated that utilisation of the troposphere gradient model with a proper estimation strategy leads to improvements in precision and accuracy for precise point positioning. The improvement in precision was inferred from a significant reduction in position repeatability. The improvement in accuracy was inferred from direct comparison of ZWD estimates with the independent technique of water vapour radiometry.

According to Hugentobler, Schaer and Fridez (2001), estimation of gradients may considerably improve the repeatability of the estimated horizontal station coordinates. This indicates that ignoring the effect of azimuthal asymmetry induces an absolute troposphere bias (class 2, scale bias). "At low elevation angles, the impact of gradients on the observable becomes very significant, and the prevailing gradients will have systematic effects on geodetic quantities. The emerging rule is that a reduction in elevation from 15° or 20° to the 5°-10° range should be

accompanied by modelling the troposphere gradients, especially if good horizontal repeatability is desired”(Bar-Sever, Krogerand and Borjesson, 1998, p5033).

Since all the TrigNet stations record data at 5°, and, the software used for processing could compute troposphere gradients, the Author saw opportunity in investigating the impact of gradients on station positions. However, it must be mentioned that all the research to date has found anomalous sites where there was degradation in repeatability and accuracy when using data at such low elevations. The behaviour at most of the anomalous sites was explained by relatively high multipath environments.

3.7 THE EFFECT OF WEATHER FRONTS ON GPS MEASUREMENTS

Although most GPS users are familiar with atmospheric delay and how it contributes to positioning error, they are generally unfamiliar with the concept of a weather front. A weather front is a boundary between two air masses that display differences, especially in temperature, wind direction and humidity. Depending on the front's direction of motion, it is denoted either as warm or cold. Weather fronts are an important meteorological phenomenon that not only bring change in weather, but can also significantly disturb GPS observations. Because they occur in the troposphere, they affect tropospheric propagation delay (Gregorius and Blewitt, 1998).

Weather fronts can cause rapid variations in tropospheric delay. Their passage usually stands out as a peak in the tropospheric delay time series. Therefore, it is no surprise that such rapid variations can introduce a form of systematic error in the GPS station position (especially in height).

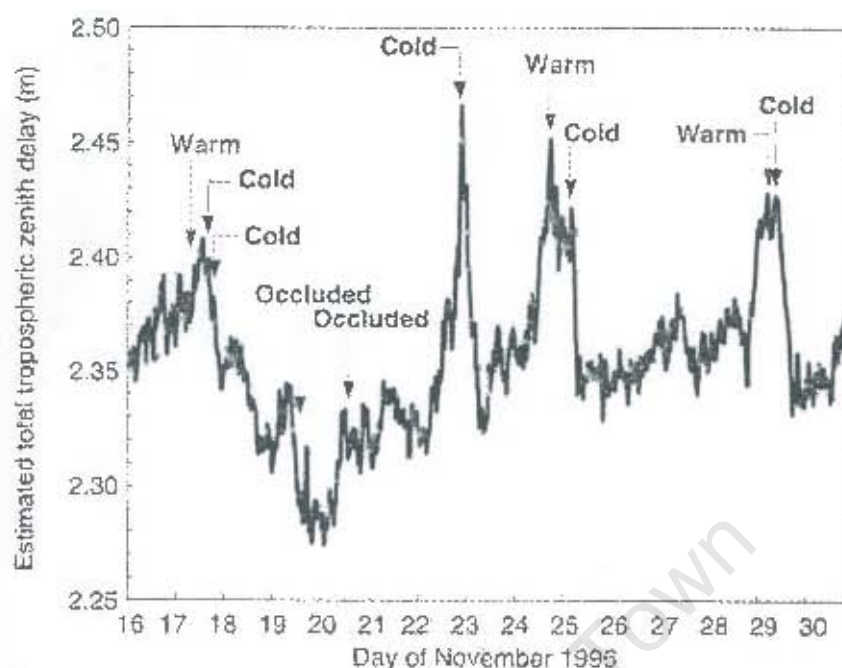


Figure 3.11 Tropospheric zenith delay at Herstmonceux, southern England. (Gregorius and Blewitt, 1998, p 55)

The weather fronts cause rapid variations in the tropospheric delay which can be clearly be seen in the above figure (3.11). According to Brunner and Welsch (1993), in extreme cases, the tropospheric delay caused by the wet part can vary by more than 30 mm per hour during the passage of a weather front. Depending on the weather front's intensity and the estimation strategy used, a front can degrade the heights in regional networks, (where station separation is greater than 10km) by as much as several millimetres. Gregorius and Blewitt (1998) explains in more detail why fronts cause such rapid variations in the delay and consequential effect on GPS precision and what can be done to reduce or eliminate the problem.

3.8 INDEPENDENT TECHNIQUES AND TOOLS FOR TROPOSPHERE MODELLING AND ANALYSIS.

This section briefly describes certain meteorological tools and techniques used to determine tropospheric and related parameters as well as verifying troposphere estimation techniques and models.

3.8.1 Radiosondes



Figure 3.12 Picture of a radiosondes before release (Coster et al., 1997, p5)

The radiosonde is a balloon-borne instrument platform with radio transmitting capabilities (see Figure 3.12). The radiosonde contains instruments capable of making direct in-situ measurements of air temperature, humidity and pressure with height, typically to altitudes of approximately 30 km. These observed data are transmitted immediately to the ground station by a radio transmitter located within the instrument package. The ascent of a radiosonde provides an indirect measure of the wind speed and direction at various levels throughout the troposphere (Coster et al., 1997).

Ray tracing of radiosonde data is extensively used to examine the accuracy of several models for tropospheric delay prediction under various atmospheric conditions (Janes, Langley and Newby, 1991). Radiosondes have been the backbone of the global upper air observing system since the 1940s. In 1991 there were more than

1000 radiosondes stations operated by 92 nations using 39 different types of radiosondes. Under ideal conditions, and with careful calibration, radiosondes temperatures are accurate to within 0.5°C and relative humidities are accurate to within a few percent. Radiosondes provide data from near the surface to an altitude of about 20 to 30km, with accuracy decreasing with an increase in altitude. Although radiosondes produce sounding of high vertical resolution, the coverage of radiosondes is uneven over the Earth, with very few stations in oceanic regions. The temporal frequency is also fairly low (12hr at best, with many countries taking one observation per day). Nevertheless, radiosondes are the most accurate source of data influencing global atmosphere data, and has been used extensively for troposphere refraction analysis and development of subsequent models (Rocken et al., 1997).

3.8.2 Water Vapour Radiometers (WVRs)

As previously mentioned, whereas the hydrostatic component of the vertical delay can generally be well modelled using accurate surface values of total pressure, the same is not true for the wet component due to the spatial and temporal inhomogeneous nature of the water vapour. Microwave WVRs have been developed in an effort to remotely sense the amount of water vapour along a ray path. A WVR measures atmospheric black body radiation, which is affected by the presence of water vapour (Dodson et al., 1996).

Various observing procedures are possible ranging from a complete scan of the atmosphere to a scan of a single position. Complete scans are useful during GPS observations, since multiple pointing to each satellite at an instant in time is not always practical. The latter is used in very long baseline interferometry when the telescope points towards an extra-galactic radio source at the time in a sequential mode (Dodson et al., 1996).

The radiometer provides sky brightness temperatures by measuring the microwave emissions of the atmosphere at frequencies around the water vapour spectral line centred at 22.235 GHz. Measurements are taken at two frequencies to separate the

effect of liquid water from water vapour in the atmosphere. This allows in-situ measurements of the path delay distribution and its temporal and spatial variations. With this information, the GPS microwave measurements obtained can be corrected.

WVRs are also extensively used to evaluate the accuracy of new tropospheric delay models and various mapping functions. An example is the completed EU-project WAVEFRONT (WATER Vapour Experiment For Regional Network Trials) evaluated the feasibility of the Global Positioning System (GPS) as a remote sensing tool for the determination of tropospheric water vapour. In this context the WVRs served as an independent technique for the validation of GPS meteorology.

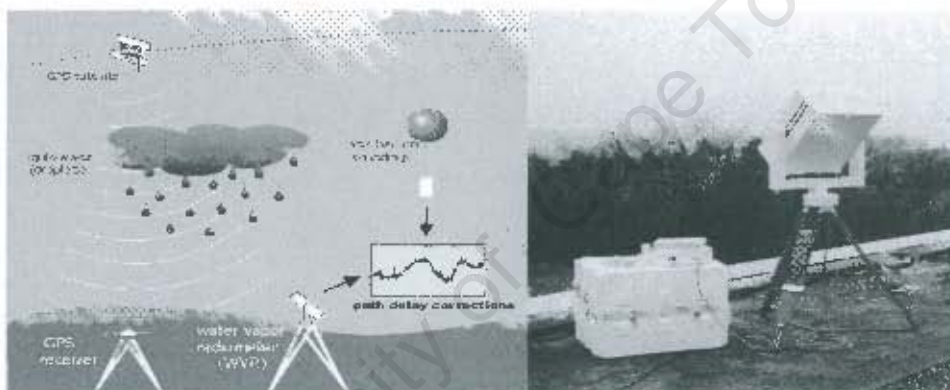


Figure 3.13 WVRs in operation (<http://www.ggl.baug.ethz.ch/>)

Chapter IV

4. Tropospheric Delay Models

4.1 INTRODUCTION

Today, the delay of electromagnetic waves as it traverses through the neutral atmosphere is the dominant source of error for high precision geodetic computations for both very long baseline interferometry and GPS measurements (Niell, 1996). With present state of the art GPS data analysis in geodesy, positioning accuracy is at the level of 1-2 mm in the horizontal component and 5-10 mm in the vertical component. The poorer accuracy in the vertical is two-fold. Firstly, there is the theoretical limit due to satellite sky distribution (Santerre, 1991). Secondly, the main error source for high accuracy height determination is still due to tropospheric refraction, especially that part of the path delay due to water vapour (Bock and Doerflinger, 2001). With regard to GPS, the troposphere biases are orders of magnitude above the noise level of the phase observable.

The GPS L1 and L2 carrier frequencies have wavelengths of 1.57542 and 1.22760 GHz respectively. Since the troposphere is a non-dispersive medium for radio waves up to frequencies of about 15GHz, tropospheric refraction is identical for both GPS carriers, both code and phase measurements. Because of this non-dispersive nature of the troposphere, it **cannot** be eliminated by various linear combinations of the carrier and code measurements (Hugentobler, Schaer and Fridez, 2001).

In addition to differencing, the influences must be reduced to make full use of the accuracy of the observables by either of the following three methods which have been used to remove the effect of tropospheric delay/refraction on geodetic data from GPS (Hugentobler, Schaer and Fridez, 2001; Ifadis, 1993):

- The first and simplest of these is to compute the wet and dry delays from surface measurements of pressure, temperature and humidity using atmospheric mapping functions. Although this method is very effective for estimating the dry delay, it

- yields poor results for the computation of the wet delay, because of the unpredictable temperature and pressure profiles (see section 3.5).
- The second method for determining the wet path delay of geodetic signals is to use a Water Vapour Radiometer (see section 3.8). This method models the tropospheric refraction without using the GPS observable (the alternative to WVRs are the use of traditional ground meteorological measurements).
 - The third method is to directly estimate the tropospheric zenith delays in the general GPS parameter estimation process. Results indicate that estimation of the tropospheric zenith delay parameters yields baseline accuracies that are comparable to those obtained with WVR corrections.

Early efforts to determine corrections for radio propagation delay by the atmosphere were prompted by the need for improvements in satellite tracking by ground stations. Hopfield (1969), Saastamoinen (1972 & 1973), Marini (1972) and Chao (1974) made very significant contributions to the study of range corrections. Saastamoinen's zenith hydrostatic delay and the form of Marini's approximation for the mapping function for a horizontally stratified refractive medium are incorporated in many current models used for accurate space-based geodetic measurements (Niell, 1996).

This chapter outlines the principles on which tropospheric delay modelling is based, outlines the development of delay models and discusses some of the common models used in today. It should be emphasised that the term *tropospheric propagation* delay is used here despite the fact that gasses above the troposphere also influence the hydrostatic component.

4.2 MODELLING THE ZENITH DELAY

According to Langley (1996), a first approximation to the range bias (due to the troposphere) experienced by signal propagation from a GPS satellite to the ground may be expressed by the integral equation

$$d_{trop} = \int_{r_s}^{r_a} [n(r) - 1] \csc \theta(r) dr + \left[\int_{r_s}^{r_a} \csc \theta(r) dr - \int_{r_s}^{r_a} \csc \varepsilon(r) dr \right] \quad (4.1)$$

where n is the refractive index, r is the geocentric radius with r_s the radius of the earth's surface and r_a the radius of the top of the neutral atmosphere, and θ and ε denote the refracted (apparent) and non refracted (geometric or true) satellite elevation angle.

This equation holds for a spherically symmetric atmosphere for which n varies only as a geocentric radius (height). The first integral accounts for the difference in the electromagnetic and geometric length of the refracted transmission path. The bracketed integral accounts for the difference in refracted and rectilinear path lengths (path curvature).

The integral can be evaluated given knowledge of the refractive index profile of the column of air or it may be approximated by an analytical function. In most cases, water vapour and the hydrostatic component are considered separately (due to the nature of the refractivity of the atmosphere). Each component is usually written as a product of a zenith delay term, approximating the integral of the refractive index profile in the vertical direction, and a mapping function which maps the increase in delay with decreasing elevation angle (see section 4.3). Langley (1996) has the general form as

$$d_{trop} = d_h^z m_h(E_s) + d_{wv}^z m_{wv}(E_s) \quad (4.2)$$

where

d_h^z	is the zenith delay due to the hydrostatic component
d_{wv}^z	is the zenith delay due to water vapour
m_h	is the hydrostatic mapping function
m_{wv}	is the water vapour(wet) mapping function
E_s	is the non-refracted elevation angle at the ground station.

For a signal coming from the direction of zenith, equation 4.2.2 becomes:

$$d_{trop}^z = 10^{-6} \int_{r_s}^{r_t} N(r) dr \quad (4.3)$$

This is the total tropospheric zenith delay. At sea level the total tropospheric delay in the zenith direction is of the order of 2.3 to 2.6 metres. The zenith delay can be expressed as the sum of a hydrostatic and wet component. The zenith delay is very close to hydrostatic equilibrium meaning that surface pressure is given by the vertical integration of density.

4.2.1 Zenith Hydrostatic Delay

The two most common hydrostatic delay models will be discussed in this section. The Hopfield and the Saastamoinen model are discussed and compared with each other.

4.2.1.1 Hopfield hydrostatic (two-quartic) delay model

“Hopfield has developed a dual quartic zenith delay model of the refraction, different quartics for dry and wet atmospheric profiles” (Spilker, 1996, p534). This model is based upon a single-layer polytropic model atmosphere extending from the surface to an altitude of approximately 40km. The zenith hydrostatic delay of the Hopfield model can be written (without derivation) in closed form as:

$$ZHD = \left(\frac{0.62291}{T_0} + 0.0023081 \right) \cdot p_0 \quad (4.4)$$

T: Temperature in [K], T_0 denotes the surface temperature

ρ : pressure in [hPa], ρ_0 denotes the surface pressure

and can be computed with knowledge of surface temperature and pressure, or, to be more precise, with knowledge of these meteorological quantities at the antenna site.

A number of approximations lead to this simple formula. Apart from the fact that the air is treated as an ideal gas, which is not too critical, the assumption of a constant temperature lapse rate is one important approximation that should be stressed as well as the fact that the gravity is not modelled with dependence on the height (Schüler, 2001).

4.2.1.2 Saastamoinen Hydrostatic Delay Model

In a series of papers, Saastamoinen (1972; 1973) presented one of the first models of the refraction of the troposphere that estimates delay versus elevation angle (E). In this model, the dry pressure is modelled using a constant lapse rate model for the troposphere and an isothermal model above the tropopause (Spilker, 1996). The starting point for the development of this model is identical to the approach accomplished to derive the Hopfield model. Again, the assumption is that the dry atmosphere is in hydrostatic equilibrium and the equation of state is true. However, this time, the gravity acceleration is treated as a function of height. At first instance, it is possible to treat the gravity as constant again. Schüler (2001), gives the zenith hydrostatic delay (Saastamoinen) in closed form as:

$$\text{ZHD} = \frac{0.0022767 \cdot \rho_0}{1 - 0.00266 \cdot \cos^2 \varphi - 0.000280 \cdot h} \quad (4.5)$$

φ : ellipsoidal latitude

h: surface/antenna height above the ellipsoid in [km]

p : pressure in [hPa], p_0 denotes the surface pressure

This model has become very popular due to its high accuracy. Elgered et al. (1991), gives the following RMS error budget; the error in the refractivity constant contributes to about 2.4 mm, the uncertainty of the gravity reduction has a marginal influence of 0.2 mm as well as the uncertainty of the universal gas constant (0.1mm) and the variability of the dry mean molar mass (0.1mm). Furthermore, it should be noted that no temperature measurements are needed (in contrast to the Hopfield model), but instead, the height of the station and its latitude are used for the computation of the gravity correction. The Saastamoinen hydrostatic delay model is considered superior to the Hopfield model (Schüler, 2001).

4.2.2 Zenith Wet Delay

Zenith wet delays are those components of the neutral delay which both geodesists as well as meteorologists are most interested in. The average value of this quantity is between 1 and 3 decimetre with a variability of 40% (Schüler, 2001). The wet component can be derived in a similar form as it has been demonstrated for the hydrostatic component, but the inherent approximations are more problematic. Schüler (2001) compares the Hopfield, with other ZWD models.

The zenith wet delay of the Hopfield model can be written in closed form as

$$\text{ZWD} = \left(555.7 + 1.792 \cdot 10^{-4} \cdot \exp\left(\frac{t_0}{22.90}\right) \right) \cdot \frac{e_0}{T_0^2} \quad (4.6)$$

e_0 : partial water vapour pressure at surface/antenna in [hPa]

t_0 : temperature at surface/antenna in [°C]

T_0 : temperature at surface/antenna in [K]

This can be computed with knowledge of surface (antenna) temperature and relative humidity. (Schüler, 2001).

Ifadis (1986, p. 76) proposes to model the zenith wet delay as a function of the surface pressure, partial water vapour pressure and temperature.

$$\text{ZWD} = 0.554 \cdot 10^{-2} - 0.880 \cdot 10^{-4} (p - 1000) + 0.272 \cdot 10^{-4} \cdot e + 2.771 \cdot \frac{e}{t} \quad (4.7)$$

Zenith wet delays are affected by the distribution of water vapour. It is very difficult to derive highly accurate models using only surface measurements for this component. However, it is possible to estimate zenith wet delays as additional parameters during network filtering /processing.

4.3 MAPPING FUNCTIONS

Over the past 30 years, geodesists and radio meteorologists have developed a variety of model profiles and functions for the evaluation of the delay experienced by signals propagating through the troposphere at arbitrary elevation angles. The above-mentioned zenith delay models calculates either the total zenith delay or constituent dry and wet delays for a signal coming directly from the direction of the zenith (90° elevation). Obviously, only a fraction (if any) of the GPS observations are made at zenith. (Langley, 1996). “The zenith delay can be transformed or mapped to the delay that a signal would experience at an arbitrary elevation angle through the use of **mapping functions**” (Bisnath, Mendes and Langley, 1997,p2).

Mapping functions can be used in conjunction with other models for zenith delay (e.g. Hopfield and Saastamoinen). Since mapping functions are dimensionless factors, it is useful when discussing their effect on geodetic measurements to multiply the hydrostatic mapping function by 2300 mm, a nominal hydrostatic delay for a site at sea level, and the wet mapping function by 100 mm, a nominal wet zenith delay (Niell, 1996).

4.3.1 The $1/\sin(E)$ Mapping Function

The simplest mapping function is the cosecant of the elevation which assumes that spherical constant-height surfaces can be approximated as plane surfaces (ignores curvature of the earth). This is reasonably accurate approximation only for high elevation angles and with small degree of bending. However, at lower elevation angles ($< 15^\circ$), the non-uniform and finite width spherical shell model troposphere make this simple model inadequate (Langley, 1996).

4.3.2 The Marini Mapping Function, (Continued Fraction Form)

Various empirical models have been put forward based upon a **continued fraction** approximation to the elevation angle dependence. Marini (1972) was the first to develop this form with the generalised expression given as:

$$m(E) = \frac{1}{\sin E + \frac{a}{\sin E + \frac{b}{\sin E + \frac{c}{\sin E + \dots}}}} \quad (4.8)$$

where E is the geometric (unrefracted) satellite elevation angle, and $a, b, c, \dots$ are profile dependent coefficients. The major limitation of this is that the resulting numerical coefficients do not lend themselves easily to physical interpretation, and hence cannot be readily varied to suit local and seasonal departures from the representative profiles from which they were derived (Janes et al, 1989).

4.3.3 The Chao Mapping Functions

Chao employed a model of this form for the excess delay Δ that utilises separate mapping functions for the wet and dry components. This mapping function is the same as the continued fraction form (see equation 4.8), except that the first two terms are used and the second $\sin E$ has been replaced by $\tan E$ so as to make $m(90^\circ) = 1$, i.e. this will assign a unit weight to an observation at zenith. The specific dry and wet mapping functions used by Chao are as follows (Spilker, 1996):

$$m_d(E) = \frac{1}{\sin E + \frac{0.00143}{\tan E + 0.0445}}$$

$$m_w(E) = \frac{1}{\sin E + \frac{0.00035}{\tan E + 0.017}} \quad (4.9)$$

4.3.4 Davis (Cfa 2.2) "Modified Hopfield" Mapping Function

The Marini and Chao mapping functions are generalised forms and as such subject to the influence of variability in the refractivity profile and lateral gradient. They are thought to be accurate to perhaps 1-2% of the total delay for elevation angles above 5° . Davis et al. (1985), in an effort to improve accuracy at low elevation angles and better accommodate local and seasonal variations in the profile structure, introduced a revised continued fraction expression for the hydrostatic delay of the form (Janes et al., 1989):

$$m(E) = \frac{1}{\sin E + \frac{a}{\tan E + \frac{b}{\tan E + c}}} \quad (4.10)$$

where a , b and c are dependent on actual measurements and estimates such as the tropospheric temperature lapse rate, height of the tropopause, surface temperature and surface pressure (Spilker, 1996).

4.3.5 The Niell Mapping Function (1996)

The NMF is most commonly used in space geodesy because it is presently believed to be the most accurate at elevation angles below 10° and it does not require any meteorological observations (Rocken et al., 2001).

All the above mapping functions are limited in their accuracy ultimately by the dependence on surface temperature, which causes three problems, all related to the fact that there is more variability in temperature in the boundary layer (from surface up to $\sim 2000\text{m}$) than above (Niell, 1996):

- First, diurnal changes in surface temperature produce much smaller variations in the true mapping function than are calculated,
- Second, seasonal changes in surface temperature are larger than upper atmosphere changes, causing artificially large seasonal variations in the calculated mapping functions. The calculated mapping function for warm winter days and cold summer days may not be significantly different, although the actual mapping function may be quite different due to the difference in lapse rates and heights of the tropopause.

Because of the above limitations, Niell (1996) investigated and developed a mapping function based on **temporal** changes (season and time of day) and geographic location rather than on surface meteorological parameters. Niell (1996) presented the NMF as a global mapping function, since the function was validated over a large range of latitudes, and in both Hemispheres. The NMF assumes that (1) the southern and Northern Hemispheres are antisymmetric in time, i.e. the seasonal behaviour is the same, (2) the equatorial region is described by the 15° north/south latitude profile, and (3) the polar regions are described by the 75° north/south latitude.

According to Niell (2000), the form adopted by the NMF is the continued fraction of Marini (1972) with three coefficients, but normalised to unity at the zenith as used by Herring (1992).

$$m(E) = \frac{1 + \frac{a}{1 + \frac{b}{1 + c}}}{\sin E + \frac{a}{\sin E + \frac{b}{\sin E + c}}} \quad (4.11)$$

Here, the three-term continued fraction uses coefficients that depend linearly on temperature (nominally the surface temperature), the cosine of the station latitude, and the height of the station above the geoid. Using radiosonde data at sites spread across various latitudes, Niell (1996) developed coefficients that are only **time** and **location** specific that can be interpolated for any site on the planet. These coefficients are different for the hydrostatic component and the wet component. The specific versions for which Niell (1996) tabulated the coefficients are nmfh2.0 and nmfw2.0, respectively (see Table 4.1 and 4.2 below).

Niell (1996) was not able to find any simple analytic expression that describes the **latitude** dependence of all of the coefficients. Instead, the interpolation in latitude was chosen to be linear, with the exception from the equator to 15°, where the 15° coefficients are used, and from 75° to the poles, where the 75° values of the coefficients are used. This is the case for both the hydrostatic and wet mapping functions.

The **temporal** variation of the hydrostatic mapping functions to be sinusoidal within the scatter of the data that was analysed. Therefore, at each latitude, the coefficients are modelled as sinusoids in time with a period of 365.25 days. Since no data from the Southern Hemisphere were used in developing this mapping function, the inversion of the seasons has been accounted for simply by adding half a year to the phase for southern latitudes. No temporal dependence is included in the wet mapping functions.

For the hydrostatic mapping function the parameter a at tabular latitude λ at time t from January 0.0 (in UT days) is calculated as:

$$a(\lambda_i, t) = a_{\text{avg}}(\lambda_i) - a_{\text{amp}}(\lambda_i) \cos \left[2\pi \frac{t - T_0}{365.25} \right] \quad (4.12)$$

where :

T_0 is the adopted phase, DOY 28, as described above. The value of $a(\lambda, t)$ is obtained by interpolating linearly between the nearest $a(\lambda_i, t)$. A similar procedure is followed for the parameters b and c (Niell, 2000).

In addition to a latitude and season dependence due to varying solar illumination, the hydrostatic mapping function should also be dependent on the **height** above the geoid of the point of observation because the ratio of the atmosphere "thickness" to the radius of curvature decreases with height. This does not apply to the wet mapping function since the water vapour is not in hydrostatic equilibrium, and the height distribution of the water vapour is not expected to be predictable from the station height. Niell (1996) gives the height correction to the MF as

$$\Delta m(E) = \left(\frac{1}{\sin(E)} - f(E, a_{ht}, b_{ht}, c_{ht}) \right) \cdot H \quad (4.13)$$

E : is the elevation angle

f : is the three term continued fraction (see equation 4.11)

H : is the height of the site above sea level in kilometres

The NMF was used extensively during processing of data for this thesis. It is also the preferred mapping function of the CODE, JPL, BKG and other analysis centres.

4.3.5.1 Coefficients of the NMF

Niell (1996, p24) published the following coefficients to use in the equation 4.11. As mentioned above, both the hydrostatic and wet mapping functions are

latitude dependent, but the wet mapping function has no temporal dependence or height correction.

Coefficient	Latitude				
	15°	30°	45°	60°	75°
Average					
a	1.2769934e-3	1.2683230e-3	1.2465397e-3	1.2196049e-3	1.2045996e-3
b	2.9153695e-3	2.9152299e-3	2.9288445e-3	2.9022565e-3	2.9024912e-3
c	62.610505e-3	62.837393e-3	63.721774e-3	63.824265e-3	64.258455e-3
Amplitude					
a	0.0	1.2709626e-5	2.6523662e-5	3.4000452e-5	4.1202191e-5
b	0.0	2.1414979e-5	3.0160779e-5	7.2562722e-5	11.723375e-5
c	0.0	9.0128400e-5	4.3497037e-5	84.795348e-5	170.37206e-5
Height correction					
	a_{ht} 2.53e-5, b_{ht} 5.49e-3, c_{ht} 1.14e-3				

Table 4.1 Coefficients of the hydrostatic mapping function (nmfh2.0)

Coefficient	Latitude				
	15°	30°	45°	60°	75°
a	5.8021897e-4	5.6794847e-4	5.8118019e-4	5.9727542e-4	6.1641693e-4
b	1.4275268e-3	1.5138625e-3	1.4572752e-3	1.5007428e-3	1.7599082e-3
c	4.3472961e-2	4.6729510e-2	4.3908931e-2	4.4626982e-2	5.4736038e-2

Table 4.2 Coefficients of the wet mapping function (nmfw2.0).

4.3.5.2 Latitudinal (Southern) and seasonal biases of the NMF

Rocken et al. (2001), compared several methods to map the a priori tropospheric delay of GPS signals from the zenith direction to lower elevations. The authors compared the following mapping techniques against ray-traced delays computed from radiosondes profiles assuming azimuthal symmetry:

- Niell Function, which by 2000 has become the most commonly used in space geodesy because it is believed to be the most accurate at elevations below 10° and does not require any meteorological observations. This mapping function is classified as parameterised mapping function.
- Mapping through the COSPAR International Reference Atmosphere with added water vapour metrology.
- Same as in b) but with added use of surface meteorological temperature, pressure and humidity.

- d) Use of numerical reanalysis model of the National Centres for Environmental prediction.
- The authors refer to the above 3 (b to d) as direct mapping differing from a in that it requires an atmospheric profile of temperature, pressure, and humidity for a specific location and time.

Based on the comparisons with all available global radiosondes (~1000 per day) for every fifth day of 1997, the authors found that dry mapping based on d) above performed 2-4 time better for elevations 15° and below, with b) and c) yielding a 50% improvement. Smaller improvements also shown for wet delay mapping by b), c) and d) above compared to a).

At 5° and below the Niell dry mapping function has biases that vary with season by 1% and displays significant systematic errors (2%-4% at 5° elevation) between 30°S and 90°S (South Africa lies between 22°S and 34°S) in the northern winter months.

This document is the first significant research that indicates weakness in the Niell mapping function and model. What was of special concern/interest to the Author was the bias in the Southern Hemisphere. This is probably attributable to the fact that the Niell mapping function was developed in the Northern Hemisphere, primarily with Northern Hemisphere data.

4.3.6 Classification of Various Mapping Functions

O' Keefe (2001), categorised most of the widely used mapping functions as well as indicating its dependence on meteorological data

Mapping Function	Type of Mapping Function				Parameters required	Dependence on meteorological data
	Quartic	Continued Fraction (Marini)	Expansion of Snell's Law	Empirical		
1/sin(E)					none	none
Black & Eisner (1984)	✓				Surface temp.	Depends slightly on surface temp.
Chao (1974)	✓	✓				none
Davis (1985)	✓	✓			Surface temp., pressure and relative humidity & height	Surface temp., pressure and relative humidity
Ifadis (1986)		✓		✓	Surface temp., pressure and relative humidity	none (empirically derived)
Herring (1992)		✓		✓	Latitude, height, surface temp.	none
Niell (1996)		✓		✓	Latitude, day of year, height	none

Table 4.3 Classification of Mapping Functions

The findings of Bisnath, Mendes and Langley (1997), seem to be an expansion of the findings of Mendes and Langley (1994) documented results of inter-comparison of mapping functions and zenith hydrostatic and wet delays models with extensive radiosondes data sets. The research analysed the performance of fifteen tropospheric delay mapping functions compared against ray tracing through radiosondes data as well as investigating how the errors of these mapping functions propagate into station coordinates.

The mapping functions evaluated were: Baby et al. (1988), Black (1978), Black and Eisner (1984), Chao (1972), Davis et al. (1985), Goad and Goodman (1974), Herring (1992), Moffett (1973), Ifadis (1986), Lanyi (1984), Marini and Murray (1973), Niell (1993, 1994), Saastamoinen (1973), Santerre (1987) and Yionoulis (1970). The radiosondes data were all from the North America, both at low and high latitudes.

The results indicated that for elevation angles above 30° , virtually all mapping functions yield errors of less than 5mm. Nearly all mapping functions provide sub-centimetre accuracy for angles down to 15° . For elevation angles less than 10° , only a few of the functions were found to adequately meet the requirements required by space geodetic techniques.

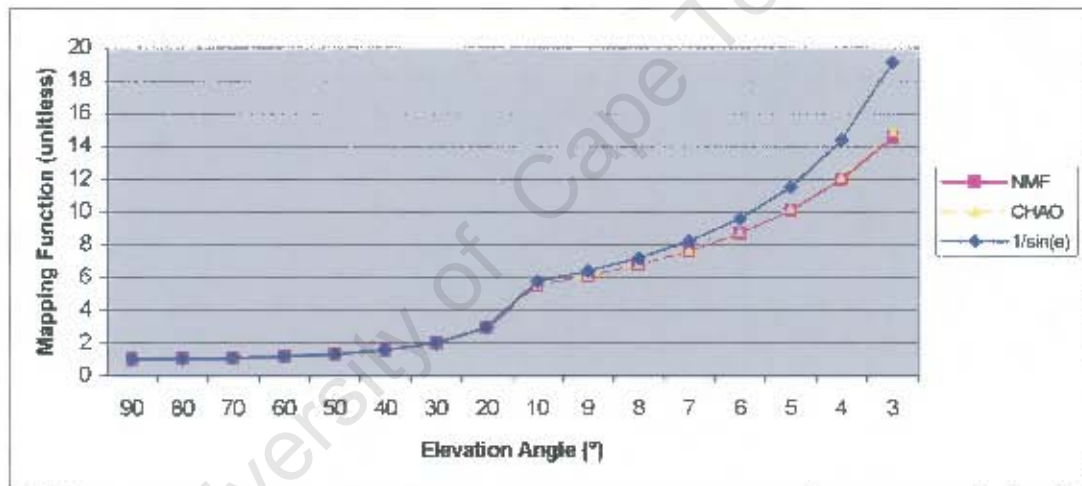


Figure 4.1 Comparison of three mapping functions.

The Niell, Herring and Ifadis mapping functions are quite accurate at elevation angles above 10° . The above figure further demonstrates that mapping functions only shows significant departure below 10° . The same three functions are also quite accurate at very low elevation angles (less than 10°) as compared to ray tracing data. It was recommended that for high precision applications, the newer mapping functions derived by Lanyi, Herring, Ifadis or Niell should be used. In terms of their impact on station coordinates, when compared to the Herring mapping functions, the functions of Niell, Ifadis and Lanyi give comparable results (Bisnath, Mendes and Langley, 1997).

4.3.7 Effects of Different Tropospheric Mapping Functions on Station Coordinates

It is clear from the previous sections (4.3.1- 4.3.6) that different mapping functions produce different tropospheric delay errors. Santerre et al. (1995) looked at the effect of tropospheric propagation delays $d\bar{x}$ computed from zenith delays and mapping functions at station coordinate level with values computed from ray-tracing radiosonde data at different elevations. The following parameters were highlighted which influence the way the tropospheric error propagate into station coordinate:

- a) the elevation mask,
- b) satellite sky distribution as a function of the observing site latitude,
- c) duration of the GPS session, and
- d) with / without ambiguity parameters solved for.

The aim of the research was to assess whether the impact of different mapping functions on station coordinates (especially the height component) is significantly different or not. This was done by propagating the tropospheric delay error from simulated GPS observations into station coordinates by solving the following set of normal equations of the least-squares adjustment:

$$d\bar{x} = (A^T P A)^{-1} (A^T P A d_{\text{trop}}) = N^{-1} U \quad (4.14)$$

where $d\bar{x}$ is the estimated increment to the initial value of the position vector

A is the design matrix of the problem,

P is the weight matrix of the observations, and

d_{trop} is the tropospheric error

The matrix N and the vector U are accumulated epoch by epoch for a complete session. The dx vector is augmented by the carrier phase ambiguity parameters for “float solution” processing.

Santerre et al. (1995), with further analysis by Bisnath, Mendes and Langley (1997) found that:

- In relative positioning, the effect of an error in the tropospheric delay on baseline length will be less harmful if the zenith delays are similar at both sites. Generally,

the shorter the baseline length and the smaller the height difference between the two sites, the more probable the zenith tropospheric delay will be similar.

- The tropospheric delay mainly affects the station height determination. However, the effect on horizontal coordinates can also be significant (more so than for the vertical component) if the integer ambiguities are incorrectly resolved in the least-squares adjustment, the time series is short, and the elevation angle is low.
- Some mapping functions perform exceptionally well at very low mask angles (3°), in fact, better than they do at higher elevation mask angles. This exceptional performance was seen as an artifact and explained by the fact that those models under-(or over) estimate the tropospheric delay at lower elevations angles (e.g., at 5° and 3°).

4.4 ESTIMATION OF TROPOSPHERIC PARAMETERS FOR INDIVIDUAL STATIONS

The estimation of tropospheric parameters for *individual stations* is much more common than the estimation of local troposphere models. The equation for total tropospheric delay correction can be written as (Hugentobler, Schaer and Fridez, 2001).

$$d_{k \text{ trop}}^i = m_{apr}(z_k^i) d_{\text{trop}(apr,k)} + m(z_k^i) d_{\text{trop}(t)} \quad (4.15)$$

where

$d_{k \text{ trop}(apr,k)}^i$ is the tropospheric zenith delay according to the a priori model specified.

If a standard atmosphere is used (no met files), this delay is time-invariant (depends on the station height only), $d_{k \text{ trop}}^i$ may be zero.

z_k^i is the zenith distance (satellite i , station k),

m_{apr} is the mapping function of the a priori model (each a priori model has its mapping function),

$d_{\text{trop}(t)}$ is the (time-dependent) zenith troposphere parameter for station k , and

$m(z_k^i)$ is the mapping function used for the parameter estimation. This mapping function may be different from m_{apr} .

Hugentobler, Schaer and Fridez (2001) make the following recommendations concerning the estimation of tropospheric parameters for individual stations:

- For *regional* or *global* campaigns, it is recommended to estimate tropospheric parameters for *all* stations.
- For *local* campaigns, it is recommended to estimate tropospheric parameters for *all but one* stations (due to strong correlations between the tropospheric parameters of the stations included).

4.5 ESTIMATION OF TROPOSPHERIC GRADIENTS

“During the last 20 years, the sophistication of the estimation strategies used for the determining the atmospheric zenith delays improved greatly, but the assumption of azimuthal symmetry of the atmospheric delay has been largely retained” (Chen and Herring, 1997).

Based on analysis of VLBI data and three-dimensional atmospheric pressure, temperature and relative humidity fields from the National Centre for Environmental Prediction (NCEP), two distinct methods for determining the propagation delay due to gradients in the Earth’s atmosphere were presented by Chen and Herring (1997). The inferences about the magnitudes and time dependence were very similar.

Until recently, water vapour **gradients** as discussed in section 3.6 have not typically been modelled in the GPS estimation of ZWD’s. The reported occurrence of atmospheric azimuthal asymmetry has prompted some researchers to include a parameterisation of the azimuthal asymmetry into their analysis programs. The Bernese GPS Software and other high level GPS processing software such GIPSY/OASIS, GAMIT have included gradient estimation as part of the parameter estimation process.

4.5.1 Tilting of the Zenith

One way to represent azimuthal asymmetries is **tilting** of the zenith the mapping function refers to (see Figure 4.2 below). The troposphere gradient parameters then

comply with the fact that the so-called tropospheric zenith (the direction with minimal tropospheric delay) and the corresponding tropospheric zenith distance z might not be identical to the geometric zenith distance z (Hugentobler, Schaer and Fridez, 2001).

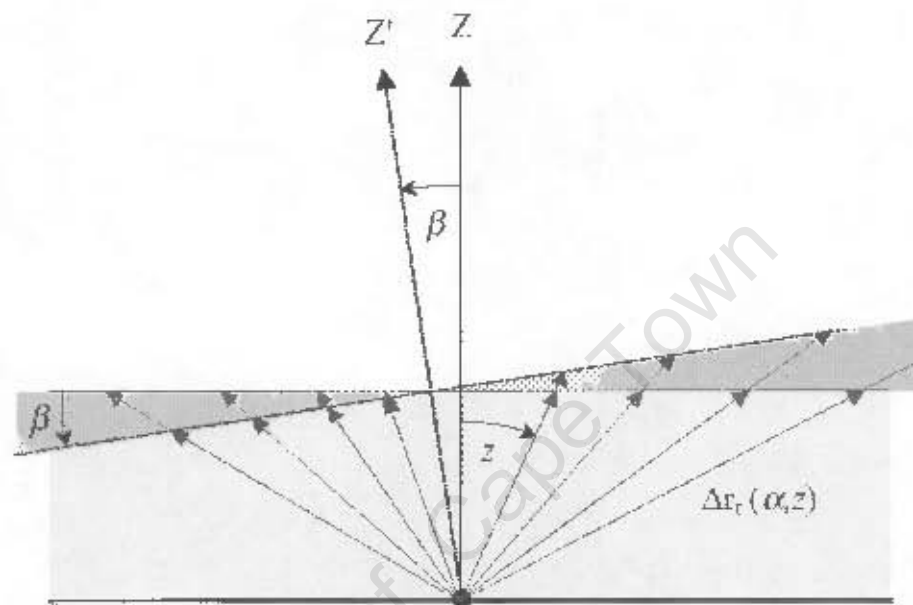


Figure 4.2 Tilting of the “tropospheric” zenith by angle β .
(Hugentobler, Schaer and Fridez, 2001, p 201)

Having introduced the tropospheric zenith angle as a parameter of the mapping functions (discussed in section 4.4), tropospheric delay would now include not only a zenith delay parameter, but also a gradient parameter in north-south direction, and in east-west direction (see Appendix B for an example).

This represents the adopted and refined tropospheric model as used in the Bernese GPS Software used for analysis. This model may be selected by specifying "TILTING" for gradient estimation model. The number of gradient parameters per session are usually much lower than the number of zenith delay parameters. (Hugentobler, Schaer and Fridez, 2001). Typically, one set of gradient parameters is estimated for a 24-hour session. The Author did not investigate the effect of estimating more than one gradient parameter for a 24-hour gradient.

4.6 MAGNITUDE OF RESIDUAL TROPOSPHERIC PROPAGATION DELAY

Collins and Langley (1998), in a paper reports on the residual range error due to incompletely modelled tropospheric propagation delay to the average user of wide-area differential and real time kinematic GPS. Cases where the atmosphere exhibits unusual conditions when the vertical profiles of total pressure or water vapour pressure are significantly different from average profiles have been documented. Extreme surface pressure differences of the order of 80mb from global averages have been recorded in the past. The author discusses the ability of WVRs to sense gradients as well as the spatial and temporal nature of water vapour.

According to Collins and Langley (1998), to obtain the highest precision in GPS measurement, there is definite advantage in estimating the residual tropospheric delay, which removes biases of many centimetres in height. An interesting observation made by the authors was that there is a general rule that the amount of vertical position bias due to unmodelled tropospheric range error is approximately the same value as the maximum residual tropospheric delay present in the solution. If no WVR data is available for a GPS campaign, data can be regarded as less accurate if there is an indication of unstable atmospheric conditions. Due to the elevation angle dependence of the tropospheric delay, this will essentially be the delay error on the lowest-elevation angle satellite.

4.7 IGS TROPOSPHERIC ZENITH PATH DELAY ESTIMATES

Continuous and well-distributed measurements of water vapour are of great interest for numerical weather forecast, climate research and atmospheric studies. According to Gendt (1998), ground-based GPS receivers can provide continuous information on integrated water at the site. Tropospheric parameters, in form of zenith path delay (ZPD) corrections, are estimated by all IGS Analysis Centres in their routine daily work. Since the additional effort to make these estimates available is marginal, these estimates are made available (since 1998) as a new official IGS product. The product is a weekly file for each IGS site. Weekly combination reports summarise some statistics on the differences of each Analysis Centre to the IGS Mean. The product is archived at the Global Data Centres and the Central Bureau Information System. The ZPD estimates archived at the CDDIS can be found at <ftp://cddis.gsfc.nasa.gov/pub/gps/products/www/trop/> as weekly files.

For ZPD estimates to be converted to integrated precipitable water vapour (PWV), it is necessary that the GPS receivers are equipped with meteorological sensors of high quality, precision and reliability. Unfortunately, the number of instruments available now is not sufficient. Even today (2002), most IGS sites are not equipped with meteorological equipment. Although the ZPD estimates of IGS sites is an official product, the conversion into PWV is postponed until a sufficient number of surface meteorological packages are available. Currently, it is left to the customer to convert the ZPD by relying on the existing RINEX met files (that accompanies the observation files) and on interpolation within global or regional meteorological fields (Gendt, 1998).

According to Hugentobler, Schaer and Fridez (2001), it is a good idea to introduce IGS ZPD estimates into your solutions when using stations from the IGS network in your processing (aiming at a correct, ITRF-conform reference frame for your local network). When making consistent use of IGS coordinates, orbits, EOPs and troposphere estimates for the IGS stations included in your network, it is possible to get results almost identical to those you would obtain by processing your (local)

network data together with the global data set. Since the IGS estimates are the mean of numerous analysis centres, the most consistent results will be achieved if estimates are obtained from the same analysis centre (e.g. CODE estimates). In the initial stages of processing, the Author downloaded the troposphere estimates for the IGS stations relevant to the research from the AIUB ftp site. However, this would have introduced an additional variable to the many that the Author were focussing on and it was decided that the introduction of IGS troposphere estimates into processing was beyond the scope of this research.

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Chapter V

5. Processing Options and Methodologies

5.1 INTRODUCTION

Differencing, modelling the tropospheric effects and **estimation** of tropospheric parameters are the primary methods used to reduce tropospheric biases. A priori models of the tropospheric delay are not sufficient if the highest accuracy is required. Therefore, it is necessary to either estimate the residual or total tropospheric delay (Hugentobler, Schaer and Fridez, 2001). Advanced troposphere estimation options, and the ability to estimate residual tropospheric delay parameters are some of the features that separates commercial GPS processing software from the scientific/academic software suites such as Bernese, GAMIT and GIPSY-OASIS II.

Using the Bernese GPS Software (version 4.2) as a processing tool, data from two campaigns with 10 stations were processed. The aim was to derive high accuracy station positions, in both the horizontal and height components. Issues relating to various troposphere empirical models, mapping functions, variation of elevation angles cut-off, troposphere gradients and the inclusion of IGS tropospheric parameters as known in the estimation process were all of great interest and relevance to the Author. However, to avoid the introduction of too many variables, and to focus the research, the following issues were concentrated on:

- e) Use of a priori troposphere models vs. total delay estimation.
- f) The effect of various mapping functions.
- g) The influence of tropospheric gradient estimation.
- h) The effect of introducing low elevation data.

This chapter outlines the extent of the campaign, the software used to do the processing, steps involved, options used and challenges and problems faced during processing.

5.2 STATIONS PARTICIPATING IN THE CAMPAIGN

Although thirty TrigNet stations were up and running by January 2002, a spread of eight TrigNet stations and two IGS stations were selected for processing. It is noteworthy that six of the selected stations are located on buildings and four are on the ground. The HRAO and SUTH stations are on bedrock.

No.	City / Centre	Code Name	Specific Location	Instrument Type	Antenna Type
1	Bloemfontein	BFTN	South African Weather Bureau (SAWB) office, on ground	Ashtech UZ-12	ASH701941.B
2	Durban	DRBN	SAWB office, on airport build.	Ashtech UZ-12	ASH701941.B
3	East London	ELDN	SAWB office, on airport build.	Ashtech UZ-12	ASH701941.B
4	Pretoria	GEOS	Council for Geoscience , on building	Ashtech UZ-12	ASH701941.B
5	George	GEOR	SAWB office, on airport build.	Ashtech UZ-12	ASH701941.B
6	Hartebeesthoek	HRAO	HRAO Radio Astronomy Observatory (bedrock)	Ashtech Z-XII3	ASH701941.B
7	Pietermaritzburg	PMBG	KZN Provincial Administration ,on building	Ashtech UZ-12	ASH701941.B
8	Springbok	SBOK	SAWB office (on shale)	Ashtech UZ-12	ASH701941.B
9	Sutherland (Jan)	SUTH	Sutherland Astronomic Observatory (bedrock)	Rogue SNR-8000	AOAD/M_T
	Sutherland (Jun)			Ashtech UZ-12	ASH701945C M
10	Cape Town	TRGE	Chief Directorate: Surveys and Mapping on building	Ashtech UZ-12	ASH701941.B

Table 5.1 List of stations, code names, GPS receivers and antenna types used

5.3 THE BERNESE GPS SOFTWARE VERSION 4.2

The Bernese GPS Software (version 4.2, hereafter referred to as the “Bernese”) was used for all processing undertaken by the Author. The Bernese is a sophisticated tool meeting highest quality and accuracy standards for geodetic and further applications using GPS as well as GLONASS. Typical users include scientists (for research and education), survey agencies responsible for high accuracy GPS surveys, agencies responsible to maintain arrays of permanent GPS receivers and commercial users with complex applications demanding high accuracy, reliability and productivity.

The software package is particularly well suited for rapid processing of small-size single and dual frequency surveys, permanent network processing (such as TrigNet), ambiguity resolution on long baselines, ionosphere and troposphere modelling, clock estimation and time transfer, simulation studies, orbit determinations and estimation of ERPs and meets highest accuracy requirements (Hugentobler, Schaer and Fridez, 2001).

5.3.1 The Bernese Software: Interface and Program Structure

Primary	Bernese GPS Software Version 4.2	
S:Y C:0		
0 ..	DEFAULTS	: Defaults for Processing, Program and File Names
1 ..	CAMPAIGNS	: Informations and Update of Campaigns
2 ..	TRANSFER	: Data Transfer to Bernese Format; Simulation
3 ..	ORBITS	: Orbit Computation, Check and Update
4 ..	PROCESSING	: Preprocessing and Processing of Observations
5 ..	SERVICES	: Service Programs
6 ..	BPE	: Bernese Processing Engine
7 ..	DOCU	: Documentation, Help Panels
9 ..	USER	: Individual User Programs
=H	HELP	: Get Help Panel
=X	EXIT	: Terminate GPS Processing

Figure 5.1 Illustration of the Bernese Interface

The processing part of the Bernese consists of more than 100 Fortran programs. All program options, lists of data files and auxiliary files (e.g., the file containing Earth potential parameters) have to be prepared and made available to the programs in special input files. The ordering of the top-level menu represents the steps involved in GPS processing and analysis grouped logically in a hierarchical structure. The top-level menu is the major division into the first sub-levels and so on.

It was quite a challenge for the Author to become adequately proficient in the use of the software. Unlike commercial software, where most processing phases are done in the background, the Bernese has a manual interface (when scripts are not used). This had the advantage of reinforcing numerous concepts relating to GPS processing and data analysis.

5.4 PREPARATORY AND PROCESSING STEPS

The preparatory and processing steps are best demonstrated by the functional flow diagram below.

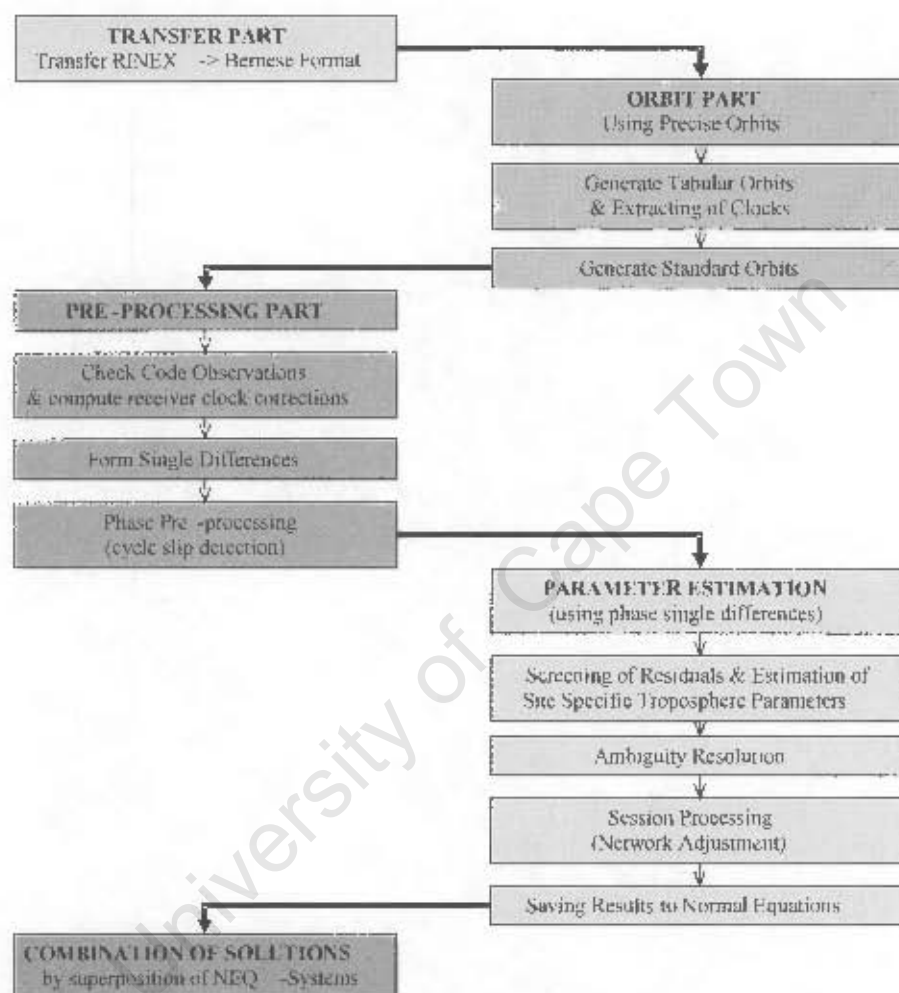


Figure 5.2 Functional flow diagram of Bernese processing

5.4.1 Retrieval of Observation and Auxiliary Data

It was decided to process data stemming from two campaigns; one in January 2002 and one in June 2002, each spanning 6 days. In order to process each campaign, the following (± 80) data files had to be downloaded/extracted:

- 60 RINEX (6 days, 10 stations) observation files had to be downloaded.
- 6 Precise orbit files corresponding to each day of the respective campaign
- 6 GIM files

- 1 Weekly IGS station coordinate file
- 1 Weekly ERP file
- 1 Satellite Problem file
- 1 Ocean Loading Coefficients file
- 1 Antenna phase centre file
- 2 IGS zenith delay estimate files (for validation/comparison only)

Appendix A lists in detail all files downloaded and the source of the respective files.

5.4.2 Observation Sessions

January 2002 Campaign							
No.	Code Name	13 Jan.	14 Jan.	15 Jan.	16 Jan.	17 Jan.	18 Jan.
1	BFTN						
2	DRBN						
3	FLDN						
4	GEOS						
4	GEOR						
6	HRAO						
7	PMBG						
8	SBOK						
9	SUTH						
10	TRGE						
		0h	0h	0h	0h	0h	0h
June 2002 Campaign							
No.	Code Name	24 June	25 June	26 June	27 June	28 June	29 June
1	BFTN						
2	DRBN						
3	FLDN						
4	GEOS						
4	GEOR						
6	HRAO						
7	PMBG						
8	SBOK						
9	SUTH						
10	TRGE						
		0h	0h	0h	0h	0h	0h

Table 5.2 Observation sessions of the January and June 2002 campaigns

All stations had continuous/uninterrupted reception with the exception of Springbok (from 18:35 on 26th June to 5:35 on 27th June 2002, UTC).

5.4.3 Campaign Creation and Data/Environment Preparation

The two campaigns were defined for the 13th - 18th Jan 2002 and 24th-29th June 2002 respectively. All the necessary "environmental" files were defined, such as the corresponding ERP, satellite problem, phase centre offset files, etc.

5.4.4 Orbit Computation

There are two orbit related steps needed before commencing with processing. The first step involved the creation of tabular files for all the days of the respective campaigns that transforms the precise orbits (in "sp3/eph" format) from the terrestrial into the celestial reference frames. The relevant satellite clock files were also extracted at this stage. RMS errors were between 1cm and 2cm since consistent orbit and pole information were used. The next step involved the creation of standard orbits using satellite positions in tabular orbits files as pseudo-observations for a least square adjustment (Hugentobler, Schaer and Fridez, 2001).

5.4.5 Code Pre-processing

This stage of processing involved storing the receiver clock corrections in the phase observation file. This was the last stage where code observations were used. All subsequent procedures only used phase observations.

5.4.6 Formation of Single Differences

The Bernese has various strategies for forming the single differences (baselines). The "obs-max" strategy, which optimises the baselines according to the number of common observations for both stations, is the ideal strategy. However, the "shortest" strategy was chosen, where an independent set of the shortest baselines are created, because the "obs-max" strategy did not yield the same baselines over the campaign

duration. In order to force the same baselines throughout the two campaigns, a baseline definition file formed after the first session (day) for all subsequent files.

GEOSCIENCE	< ----- >	HRAO 30302M004
HRAO 30302M004	< ----- >	BLOEMFONTEIN
BLOEMFONTEIN	< ----- >	PIETERMARITZBURG
PIETERMARITZBURG	< ----- >	DURBAN
DURBAN	< ----- >	EASTLONDON
EASTLONDON	< ----- >	GEORGE
GEORGE	< ----- >	SUTH 30314M002
SUTH 30314M002	< ----- >	SPRINGBOK
SUTH 30314M002	< ----- >	TRGEMOWBRAY

Table 5.3 Baseline definition using the "shortest" strategy.

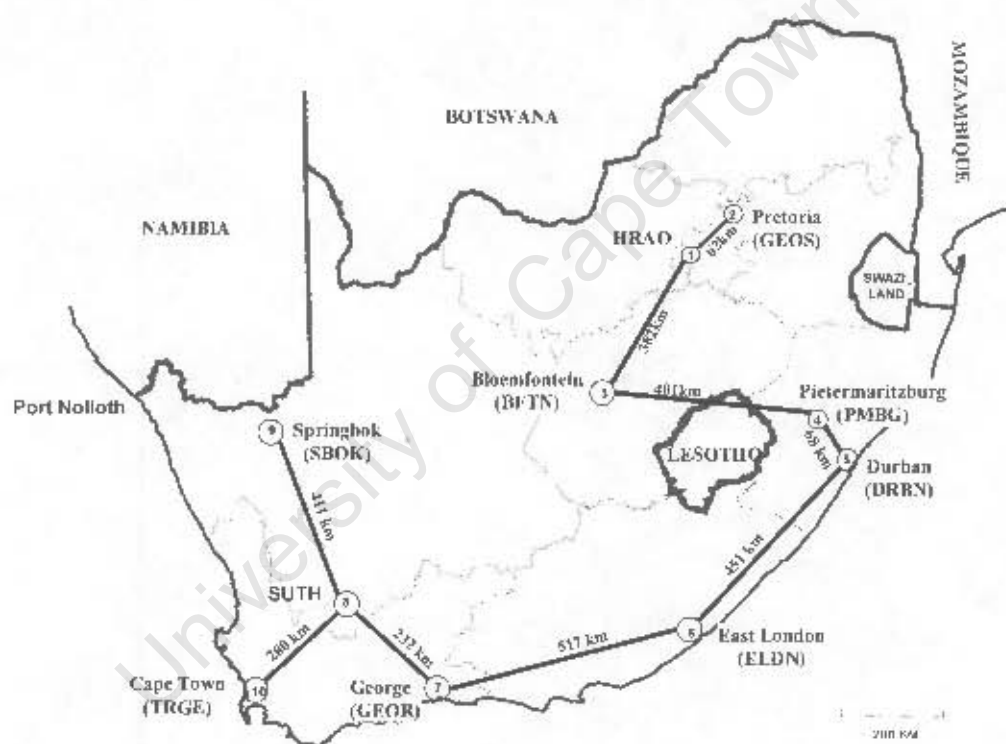


Figure 5.3 Baseline length between chosen terminals.

5.4.7 Data Pre-processing (cycle slip detection and fixing)

During pre-processing the following tasks were accomplished:

- All the phase observations are checked and time interval $\langle t_1, t_2 \rangle$ which were corrupted by cycle slips identified.
- If possible, cycle slips were repaired. The differences in cycles were estimated and all observations corrected that followed the instant of the cycle slip.
- If it was not possible to estimate the difference in a reliable way, the observation at time t_2 was marked as an outlier or a new ambiguity parameter was introduced.

The Bernese uses smoothing, triple differencing (where the main advantage is that cycle slips only affects one triple-difference and not all double differences thereafter) and a new automated cycle slip algorithm to fix cycle slips. All the observation data were screened (and cycle slips fixed where possible) down to 5°. No cycle slips were fixed manually. The RMS of the triple-difference solutions (for both campaigns) ranged from 0.007m to 0.014m. The baseline between DRBN and ELDN consistently had the most cycle slips.

The observations of short intervals (a few epochs only) are in general not important for the quality of the final solution. On the contrary, small pieces of data might indicate tracking problems and introducing many new ambiguity parameters leads to greater a-posteriori mean errors of the estimated parameters. It seems to be safer to mark (not use) observations with very short intervals. Since the Bernese recommends a time interval which covers approximately 10 epochs, and the observation were recorded at 30 seconds, the minimum time interval for continuous observations were set to 300 seconds.

5.4.8 Estimation of Site Specific Tropospheric Parameters

All the data stemming from the previous processing steps were valid for all the envisaged strategies. A master copy of cleaned phase single differences was made, and all subsequent processing strategies used this data.

Since this dissertation focused on the effect of various troposphere modelling and estimation techniques, each campaign was processed 9 times (independently), where, either the a priori troposphere model / mapping function combination, elevation angle or tropospheric gradient estimation (toggle) were varied.

Strategy		A Priori Model	Mapping Function	Elevation Dependent Weighting	Elevation Cut-Off	Gradient Estimation
No	Name					
1	SANG05	Saastamoinen	1/sin(E)	Yes	5°	No
2	SANG10	Saastamoinen	1/sin(E)	Yes	10°	No
3	SANG15	Saastamoinen	1/sin(E)	Yes	15°	No
4	NENG05	No	Niell (dry)	Yes	5°	No
5	NENG10	No	Niell (dry)	Yes	10°	No
6	NENG15	No	Niell (dry)	Yes	15°	No
7	NEWG05	No	Niell (dry)	Yes	5°	Yes
8	NEWG10	No	Niell (dry)	Yes	10°	Yes
9	NEWG15	No	Niell (dry)	Yes	15°	Yes

Table 5.4 Summary of the options used for each of the nine estimation strategies.

The processing strategies were named using the following convention:

MMGGEE, where

MM : denotes the a priori troposphere model / MF combination used

SA denotes Saastamoinen a priori model and 1/sin(E) mapping function

NE denotes no a priori model and NMF (dry)

GG : denotes whether additional tropospheric gradient parameters to model azimuthal asymmetries were estimated.

NG denotes that no gradient parameters were estimated

WG denotes that gradient parameters were estimated

EE : denotes the elevation cut-off used to process the data

When using the Saastamoinen troposphere model, the $1/\sin(E)$ mapping function was used when estimating the troposphere parameter. No a priori troposphere model was used when using the NMF (dry), in which case the total delay is estimated instead of a residual delay, as recommended by Hugentobler, Schaer and Fridez (2001).

In the case of the NEWG strategies, the option to estimate additional tropospheric parameters to model azimuthal asymmetries was activated. In this case, the North and East components were set up in addition to the zenith component. The zenith to which the mapping function is related to is tilted. The tilting angles are implicitly described by two gradient parameters in North and East directions. When this option is not specified, as in the NENG strategies, only zenith path delay parameters are set up. No gradient estimation was done when the $1/\sin(E)$ mapping function was used.

Only one gradient parameter was estimated per day for the NEWG strategies whereas 24 zenith delay parameters were estimated for all strategies, as recommended by Rothacher, Schaer, & Beutler (2001). All the a priori model/mapping functions and gradient combinations were processed at 5°, 10° and 15° elevation respectively.

5.4.9 Ambiguity Resolution

The Quasi-Ionosphere-Free (QIF) ambiguity resolution strategy was used as recommended in the Bernese documentation for all the baselines longer than 100km. The QIF strategy allows one to directly resolve L1 and L2 ambiguities even on long baselines (with lengths up to 2000 kilometres) without using the code measurements. This requires, in addition, the estimation of stochastic ionosphere parameters. L1 and L2 observations have to be processed in parallel. Hugentobler, Schaer and Fridez (2001), provides a detail theory of the QIF algorithm.

All baselines were processed separately when resolving ambiguities. This mode was necessary because of the tremendous number of parameters. This manual processing can be prevented by using the Bernese Processing Engine (BPE) to automate this processing step.

During this stage, the troposphere estimates were introduced from the previous stage and the integer values of resolved ambiguities (L1/L2 or L5) were saved in the corresponding single difference header files. All unresolved ambiguities were treated as real values in all subsequent program runs. Here, the troposphere estimates resulting from each of the 9 different strategies were introduced.

5.4.10 Session Processing

After the loop over all baselines were completed and the ambiguities were resolved, the baselines were processed in session mode. The baselines resulting from each daily session (nine baselines per day) were adjusted simultaneously in order to correctly correlate the individually processed baselines. The result is written to a normal equation file which were combined later for multi-session solutions. This was done not only for each of the six sessions (1 day), but also for each of the nine strategies spanning the two campaigns. Since each of the two campaigns consisted of 6 daily sessions, and each session had to be processed in 9 different ways, this resulted in 108 different normal equation files. This required well thought out naming conventions in order not to confuse the results and muddle up files.

During the session processing stage, the ionosphere-free linear combination was processed. Any unresolved ambiguities (estimated as real valued parameters) were pre-eliminated (as integer-valued parameters). In order to retain the flexibility for later changes in reference frame definition, no station was kept fixed. Instead, HRAO was heavily constrained to 0.0001m. The estimation of tropospheric parameters is mandatory for a campaign of this type. At this stage the user can change the number of estimated parameters (e.g., 12 instead of 24 parameters per station and session). In order to keep the size of the resulting normal equation files within reasonable limits, the parameters were pre-eliminated “after inversion”. In cases where tropospheric delays are not of interest, one may even go for “before inversion” (Hugentobler, Schaer and Fridez, 2001).

5.4.11 Combination of Solutions (normal equations)

Since each campaign spanned 6 days (sessions), the Bernese program ADDNEQ was used to compute the multi-session solutions from the (statistically correct) combination of a set of single-session solutions. The result of stacking normal equations resulting from 1-day sessions would have been identical if all six days were adjusted simultaneously in the previous step. However, for logistical reasons and computational efficiency, each day was treated as one session.

It is only at this stage that the datum is actually defined. In the previous step, the coordinate of HRAO was heavily constrained (0.0001m). The result obtained from the program ADDNEQ differs from the arithmetic mean of the 6 coordinate sets (from the daily solutions). This is simply due to the fact that ADDNEQ takes full covariance information of the daily solutions into account (Hugentobler, Schaer and Fridez, 2001). The tropospheric parameters saved in the NEQs in the session adjustment stage and estimated again as part of a multi-session combination using ADDNEQ.

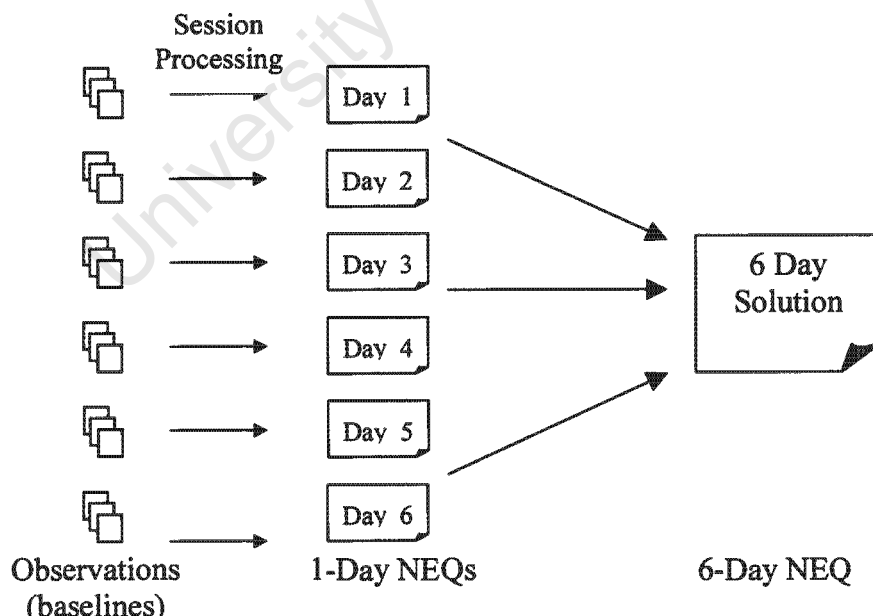


Figure 5.4 Combination of the normal equations

5.5 VALIDATION OF RESULTS

Although the Bernese GPS software gives a good indication of internal precision, it was difficult to benchmark the “absolute” accuracy of the results obtained by processing with various strategies. To benchmark the accuracy of the results, the Author used the following approaches:

5.5.1 Minimally Constrained Network

Only the coordinates of HRAO at the middle of each campaign was constrained during the session processing stage and when adding the normal equations of the respective campaigns. Although SUTH is an IGS station, the coordinate was at no time constrained. This was done so that the computed coordinate could be compared to the official value (CODE estimate), since all other stations' coordinates were unknown. When the final (optimal) processing strategy was identified, the coordinates of HRAO and SUTH were fixed to define the datum.

5.5.2 Independent Processing

The TrigNet observation data spanning both campaigns were processed using third party web-based processing software available free of charge to users.

5.5.2.1 AUSPOS

The user friendly AUSPOS online GPS Processing Service, provided by the Space Geodesy Analysis Centre, National Mapping Division (NMD) of Geoscience Australia provides a useful web-based interface. More details of the service can be found at <http://www.auslig.gov.au>. Although the service used different processing software (Microcosm) instead of the Bernese, it was designed to deliver accuracies of the same order aimed at in this research. Important processing defaults to note are that the AUSPOS services uses an elevation cut-off of 15°, the Hopfield tropospheric delay model as a priori model and the NMF when estimating the troposphere parameter.

5.5.2.2 Auto-Gipsy

NASA's Jet Propulsion laboratory makes use of Gipsy-Oasis II software to process GPS baselines. For more information, see <http://gipsy.jpl.nasa.gov/go/>. Unlike the very user-friendly AUSPOS, the Auto-Gipsy does not have a web interface. Data have to be tediously submitted via an email message of the location of the data on an FTP server. The positions computed by the service are of the electrical phase centre of the antenna and reduction to the ARP has to be done after the position is returned. This reduction was done manually by the Author by subtracting the 0.108m (corresponding to the height of the L1 electrical phase centre of the TrigNet ASH701941.B antenna) from the returned ellipsoidal height.

ELDN	LAT	02JAN18	-33.038130892	+- 0.0007	-0.288552	0.090845
ELDN	LON	02JAN18	27.828680320	+- 0.0016	-0.072200	
ELDN	RAD	02JAN18	164.2249	+- 0.0040		

Table 5.5 Sample file returned by JPL's Auto-Gipsy service

According to Zumberge et al. (1997), the Auto-Gipsy uses precise point positioning technique. Precise orbits and clocks are used to estimate receiver-specific parameters with receiver-specific data. Solutions are not constrained by fiducial/IGS stations (as in the case with the AUSPOS and the processing strategy used in this thesis).

5.6 DATUM DEFINITION

The ITRF division of the IERS publishes the coordinates (with its associated velocities) of all IGS stations at a reference epoch. The official ITRF station coordinates are often updated using the velocities obtained in the ITRF2000_GPS.SNX file. This accuracy of the station coordinates (relative) decreases with time due to this linear extrapolation. In Table 5.6, the ITRF coordinates of HRAO and SUTH are updated from the 1997.0 reference epoch to the middle of the January and June campaigns.

Point	Datum	Epoch	Time since Reference Epoch (years)	Position at Reference Epoch		
				X	Y	Z
				Velocities (m/m/y)		
				X/V _x	Y/V _y	Z/V _z
30302M004 HARTEBEEST -HOEK GPS HRAO	ITRF 2000	1997.000	0	5085352.4890	2668395.6700	-2768731.6760
		(15 Jan)		-0.0012	0.0198	0.0159
		2002.041	5.041	5085352.4830	2668395.7698	-2768731.5958
		(26 June)		-0.0060	0.0998	0.0802
		2002.484	5.484	5085352.4824	2668395.7786	-2768731.5888
				-0.0066	0.1086	0.0872
30314M002 SUTHERLAND GPS SUTH	ITRF 2000	1997.000	0	5041274.8080	1916053.9920	-3397076.0740
		(15 Jan)		0.0057	0.0197	0.0146
		2002.041	5.041	5041274.8367	1916054.0913	-3397076.0004
		(26 June)		0.0287	0.0993	0.0736
		2002.484	5.484	5041274.8393	1916054.1000	-3397075.9939
				0.0313	0.1080	0.0801

Table 5.6 ITRF2000 coordinates of HRAO and SUTH using velocities based on ITRF2000_GPS.SNX.

The official IGS final products (including coordinates/velocities) are given in the IGS realisation of the ITRF (see 2.13.3). The ITRF coordinates (updated) differed significantly (up to 8cm) from the IGS realisation of the ITRF, given by the weekly solution, and from each of the analysis centre contributions. Table 5.7 compares the ITRF2000 "official" coordinates to those stemming from the IGS combined weekly

solution (weekly SINEX files with the "IGS" prefix") and the CODE weekly solution. It is clear that, depending on which coordinates were used to constrain the network, the datum definition would be different.

Point	Datum	Epoch	Time since reference epoch (years)	X	Y	Z
30302M004 HARTEBEEST -HOEK GPS HRAO	ITRF2000	2002.041	5.041	5085352.4830	2668395.7698	-2768731.5958
	CODE			5085352.4675	2668395.7481	-2768731.5755
	IGS		ITRF-CODE	-0.0155	-0.0217	0.0203
			ITRF-IGS	5085352.4881	2668395.6914	-2768731.6626
30314M002 SUTHERLAND GPS SUTH	ITRF2000		5.041	5041274.8367	1916054.0913	-3397076.0004
	CODE			5041274.8246	1916054.0756	-3397075.9826
	IGS		ITRF-CODE	-0.0121	-0.0157	0.0178
			ITRF-IGS	5041274.7971	1916054.0060	-3397076.0503
				-0.0396	0.0853	0.0499

30302M004 HARTEBEEST -HOEK GPS HRAO	ITRF2000	2002.484	5.484	5085352.4824	2668395.7786	-2768731.5888
	CODE			5085352.4830	2668395.7790	-2768731.5910
	IGS		ITRF-CODE	0.0006	0.0004	-0.0022
			ITRF-IGS	5085352.4886	2668395.6918	-2768731.6627
30314M002 SUTHERLAND GPS SUTH	ITRF2000		5.484	5041274.8393	1916054.1000	-3397075.9939
	CODE			5041274.8480	1916054.1060	-3397076.0020
	IGS		ITRF-CODE	0.0087	0.0060	-0.0081
			ITRF-IGS	5041274.7975	1916054.0082	-3397076.0502
				0.0418	0.0918	0.0563

Table 5.7 Comparison of ITRF2000, CODE, and the IGS combined solution.

Table 5.7 compares the updated ITRF2000 coordinates of HRAO and SUTH to the IGS00 (combined solution) weekly coordinates for both the January and July Campaigns. The same comparison is made with the CODE values. Although the ITRF coordinates of HRAO and SUTH, and the IGS values differed by up to 91 mm in one component, the difference very similar in January and June.

This was not the case with the CODE coordinates. As an example, whereas the ITRF-CODE differences were -15.7 mm, -20.7 mm and 20.3 mm in January, and 8.7 mm, 6 mm and -8.1 mm in June in the X, Y and Z components respectively. This was probably due to different processing strategies, station coordinates, processed

network size and geometry etc. Further inspection of the SINEX files submitted by other Analysis Centres (AC) revealed that each AC had a unique solution.

The Author only used the CODE submission for station positions, since all poles and orbits used were the CODE submissions.

University of Cape Town

Chapter VI

6. Results and Analysis

6.1 INTRODUCTION

During all the pre-processing, processing and adjustment stages, huge volumes of output files were generated. All output files were renamed so that during all stages of processing, the strategy and session could be identified. The analysis was focused on answering the key research questions highlighted in section 5.1.

6.2 OVERALL QUALITY OF OBSERVATION DATA USED

An analysis of the quality of the observation data were done using the TEQC software. A quality check was done on all observation files. In general, the quality of the data were very good with the exception of ELDN and GEOR, which had relatively high multipath. The best station, in terms of number of cycle slips and multipath, was HRAO followed by SUTH and BFTN. The data stemming from the stations at ELDN and GEOR had significant multipath at low elevations ($<10^\circ$). This is due to the increasing number of transmitters that are located in close proximity to those stations. All stations had continuous/uninterrupted reception with the exception of Springbok (from 18:35 on 26th June to 5:35 on 27th June UTC).

6.3 STATISTICAL QUANTITIES USED IN THIS ANALYSIS

In this chapter, certain statistical quantities that were used in the analysis are expanded upon. The Bernese *COMPAR* program was used extensively to compare daily coordinates files stemming from the daily session adjustments of the same strategy.

COMPARISON OF COORDINATES (IN NORTH, EAST, AND HEIGHT COMPONENT)										
RMS: UNWEIGHTED RMS OF THE ESTIMATION OF ONE COORDINATE COMPONENT IN MM										
NUM	STATION	#FIL	C	RMS	1	2	3	4	5	6
1	BLOEMFONTEIN	6	N	2.5	-2.6	0.5	-3.2	3.5	0.8	1.1
			E	1.6	-0.2	0.6	0.7	-1.5	-2.1	2.5
			U	4.0	2.6	-6.7	-1.8	-0.3	1.1	5.1
2	DURBAN	6	N	2.4	-3.3	0.7	-2.6	2.3	2.1	0.9
			E	1.6	-2.2	-0.4	0.8	-1.0	0.4	2.5
			U	8.4	-1.7	-15.5	2.3	9.1	1.6	4.3
3	EASTLONDON	6	N	2.8	-4.6	-0.3	-1.8	2.2	1.6	2.8
			E	2.1	-0.6	0.3	0.3	-2.4	-1.3	3.7
			U	6.4	0.7	-11.3	-1.6	7.9	1.7	2.5
.	.	.	.	.	.	.	.	.	.	.
10	TRGEMOWBRAY	6	N	2.7	-1.5	5.2	-1.6	-1.3	-1.6	0.8
			E	2.1	-2.4	-1.3	1.2	3.1	-1.6	1.0
			U	7.9	-10.4	-0.4	7.8	-7.1	0.8	9.4
RMS OF UNIT WEIGHT FOR COORDINATE COMPARISON : 0.0044										

Table 6.1 Sample output from the Bernese COMPAR program

Five quantities were used from the output of this program (see Table 6.1); namely:

- "Unweighted RMS of the estimation of one coordinate component", hereafter referred to as "**RMS^{1D}**". This is nothing more than the standard deviation of a single coordinate component (N, E or U). The Author used this quantity as a measure of the **scatter/repeatability** of the coordinate components (instead of the daily residuals).

$$\text{RMS}^{1D} = \sqrt{\frac{\sum_{i=1}^n v_i^2}{(n-1)}} \quad (6.1)$$

where

v_i : are the residuals of each coordinate component (average-actual)

n : is the number of files compared (sessions in this case)

b) The RMS of the baseline length (RMS^{bl}) were computed in the same way as RMS^{1D}

$$RMS^{bl} = \sqrt{\frac{\sum_{i=1}^n v_i^2}{(n-1)}} \quad (6.2)$$

where

v_i : are the residuals of each daily baseline length.

n : is the number of baselines compared (sessions in this case)

c) Bernese uses a statistical quantity called the “RMS of unit weight for coordinate comparison” (hereafter referred to as RMS^{3D}), which in as indication of the overall 3 dimensional precision of all the coordinates compared (i.e., of the entire campaign)

$$RMS^{3D} = \sqrt{\frac{\sum_1^{nsta \cdot nfile} (resN^2 + resE^2 + resU^2)}{(nres - 3 * nsta)}} \quad (6.3)$$

where:

$resN, E, U$: are the individual (daily) coordinate residuals of each station in the respective components.

$nsta$: are the number of stations per coordinate file

$nfile$: is the number of files (sessions)

$nres$: is the number of residuals values , i.e. if no station is missing on one of the files, $nres = nsta * nfile$.

d) In certain situations (such as lowering the elevation mask), it was important to separately analyse the effect on the horizontal and vertical component. The RMS^{1D} values were used to calculate the mean horizontal repeatability (mean RMS^{2D}), where

$$\text{mean RMS}^{2D} = \frac{\sum_{i=1}^{nsta} \sqrt{(\text{RMS}^{1D(N)})^2 + (\text{RMS}^{1D(E)})^2}}{(nsta)} \quad (6.4)$$

and the mean vertical repeatability (mean RMS^U)

$$\text{mean RMS}^U = \frac{\sum_{i=1}^{nsta} \text{RMS}^{1D(U)}}{(nsta)} \quad (6.5)$$

- e) When comparing the combined coordinates of two campaigns (same strategy), the Bernese program *HELMRI* was used to compute Helmert transformation parameters between the coordinates stemming from the respective campaigns. The RMS resulting from this output, hereafter referred to as “RMS^b”, refers to the square root of the variance of unit weight, which indicates the quality of the fit between the two coordinate sets.

6.4 AMBIGUITY RESOLUTION

According to Rothacher et al. (1997), successful ambiguity resolution is a prerequisite in obtaining an improvement in horizontal and height estimation when using low elevation data and estimating tropospheric gradients.

Interestingly, although the number of ambiguities set up for the different estimation strategies were identical at the same elevation (5° , 10° , 15°), the number of ambiguities resolved varied with strategy (although slightly). The SANG strategy consistently had slightly more ambiguities resolved, generally within 1% of the success rate of the NENG and NEWG strategies

An examination of the results of the ambiguity resolution stage of the NENG05 (which was typical of all the other strategies) shows that the January and June campaigns exhibited significant differences in the number of ambiguities set up and the percentage of the ambiguities resolved to integers.

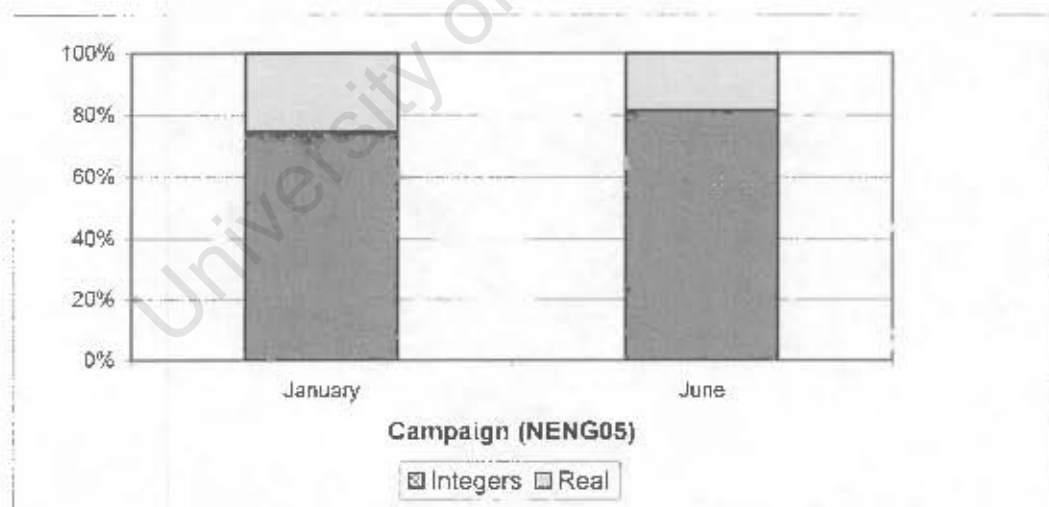


Figure 6.1 Percentage of ambiguities resolved to integers per campaign

Of the 10342 ambiguities set up in January, only 7720 (74.6%) were resolved to integers. In June of the 7598 ambiguities set up, 6198 (81.6%) were resolved to integers. This represents a 26.5% decrease in number of ambiguities and a 9.4% increase in ambiguity resolution success rate.

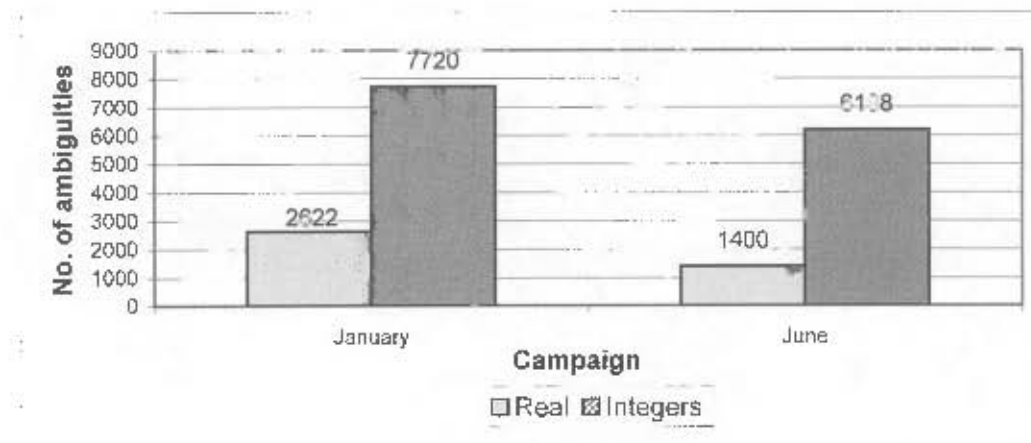


Figure 6.2 Number of ambiguities resolved to integers during campaign.

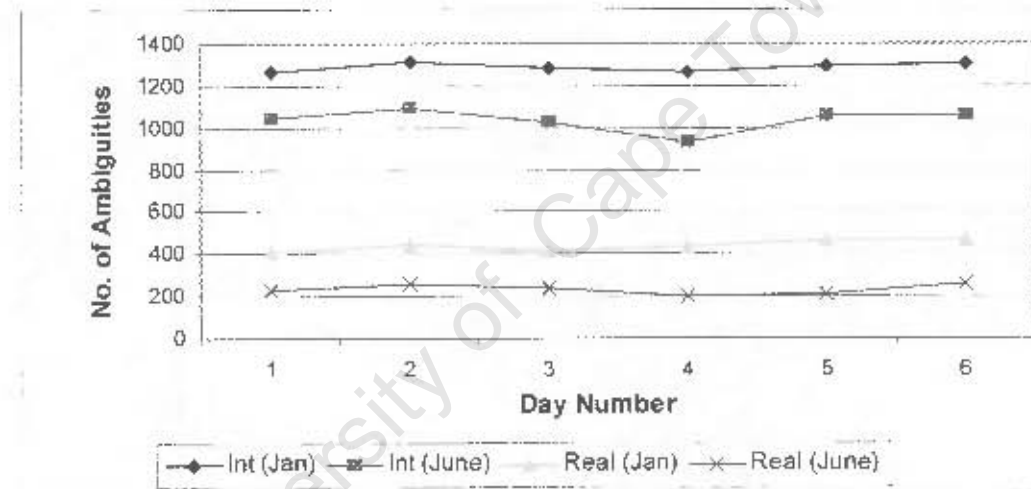


Figure 6.3 Daily number of ambiguities resolved to integers/unresolved for both campaigns.

It is clear from Figure. 6.3 that there was a fairly constant number of ambiguities set up for each session of the January and June campaigns respectively. This indicates that overall, no single day had an extra-ordinary number of ambiguities. However, the January sessions show not only a higher number of ambiguities, but also unresolved (real) ambiguities (see Figures 6.1 and 6.2).

As we know, increased ionospheric activity, multipath and other environmental factors increases the number of cycle slips and hence the number of ambiguities. TEQC analysis showed that the multipath environment were very similar during the

respective campaigns, and does not account for the difference in number of ambiguities set up.

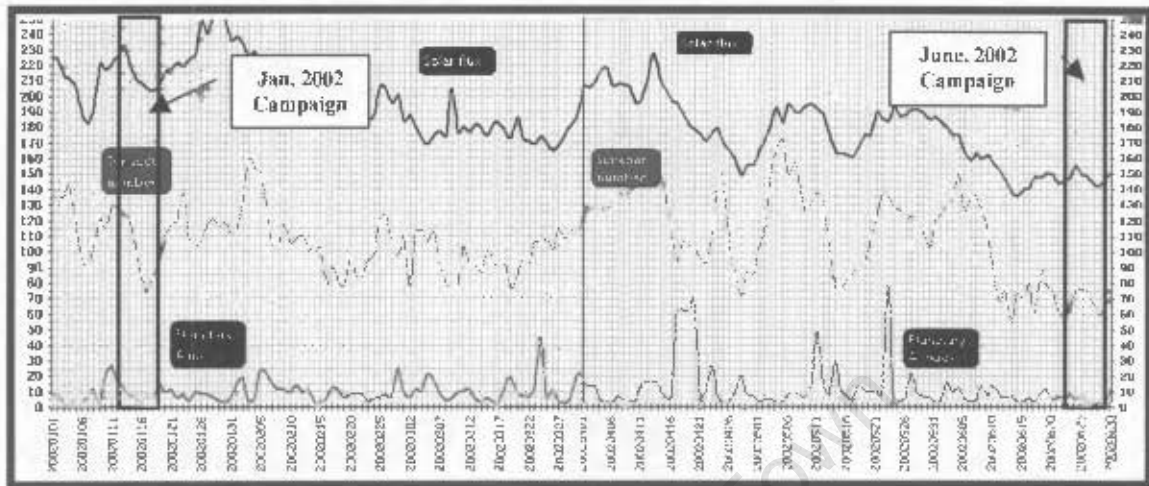


Figure 6.4 Solar Activity during the 1st and 2nd quarter of 2002
(<http://www.dxlc.com/solar/history/hist2002.html>)

Analysis of the solar and geomagnetic activity (see Figure 6.4) over the periods spanning the campaigns reveals that solar flux levels were 34% less during the June campaign compared to January. Sunspot numbers averaged ± 100 during the January campaign whereas the sunspots during June averaged ± 70 (30% reduction). The only deduction that the Author can make is that the greater ambiguity resolution success rate in June could be ascribed to reduced levels of solar flux, which resulted in less ionospheric refraction (because June falls in southern hemisphere winter) and less noise in the data.

6.5 ESTIMATION OF SITE SPECIFIC TROPOSPHERIC PARAMETERS

As discussed in section 5.4.8, site-specific tropospheric parameters were estimated for all the stations and for each of the estimation strategies identified in Table 5.4 during both the campaigns.

Where an a priori tropospheric delay model was selected (Saastamoinen), the a priori delay was inversely proportional to the height of the station (see section 4.2). The estimated parameters were the corrections to the a priori values. The correction to the

a priori zenith delay was mostly at the sub 0.1 m level and never exceeded 0.20 m for all elevations tested. Here, the total zenith delay (TZD) was the sum of the a priori delay and the correction.

Where no a priori model was specified (as with the NENG strategies), the total delay was estimated. In this case, the a priori delay was always set to zero and the parameter estimated was the TZD. Where gradient parameters were estimated, the total zenith delay as well as gradient parameters were estimated. Here, the delay parameters are estimated in the North and East and Up components (see Appendix B for examples of troposphere estimate files).

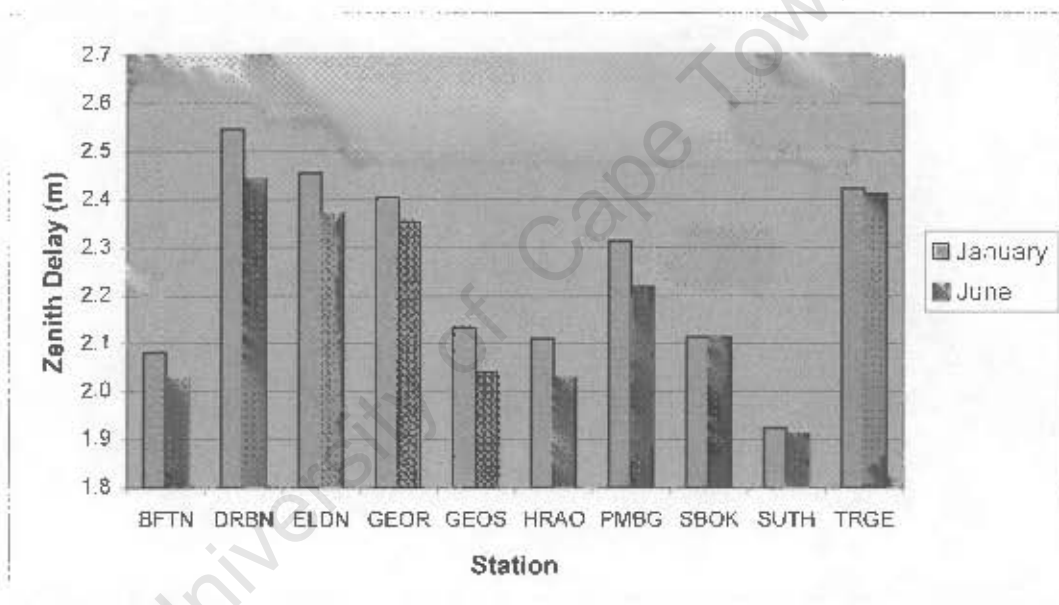


Figure 6.5 Average (6-day) TZD estimates at stations.

Figure 6.5 shows the average zenith delays at stations calculated by averaging the hourly TZD estimates of the SANG10 strategy over each campaign. The average zenith delays were greater in January than in June at all stations. This trend was regardless of estimation strategy. However, this difference was less pronounced at stations located in the western part of the country (see stations TRGE, SBOK and SUTH) and it seems that the differences increase in an easterly direction. This can be attributed to the markedly different climate and pressure profiles and rainfall regimes that characterise South Africa, which varies primarily in an east-west direction (Preston-Whyte and Tyson, 1988).

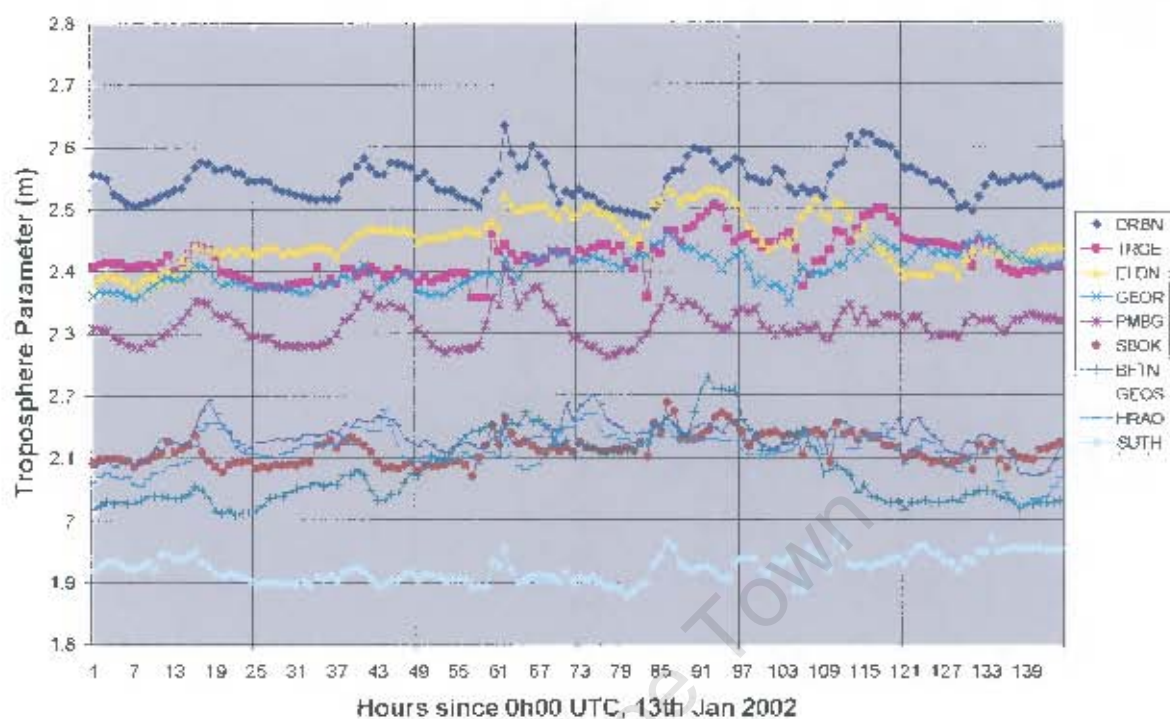


Figure 6.6 Magnitude of TZD at various stations during the six-day campaign in January 2002

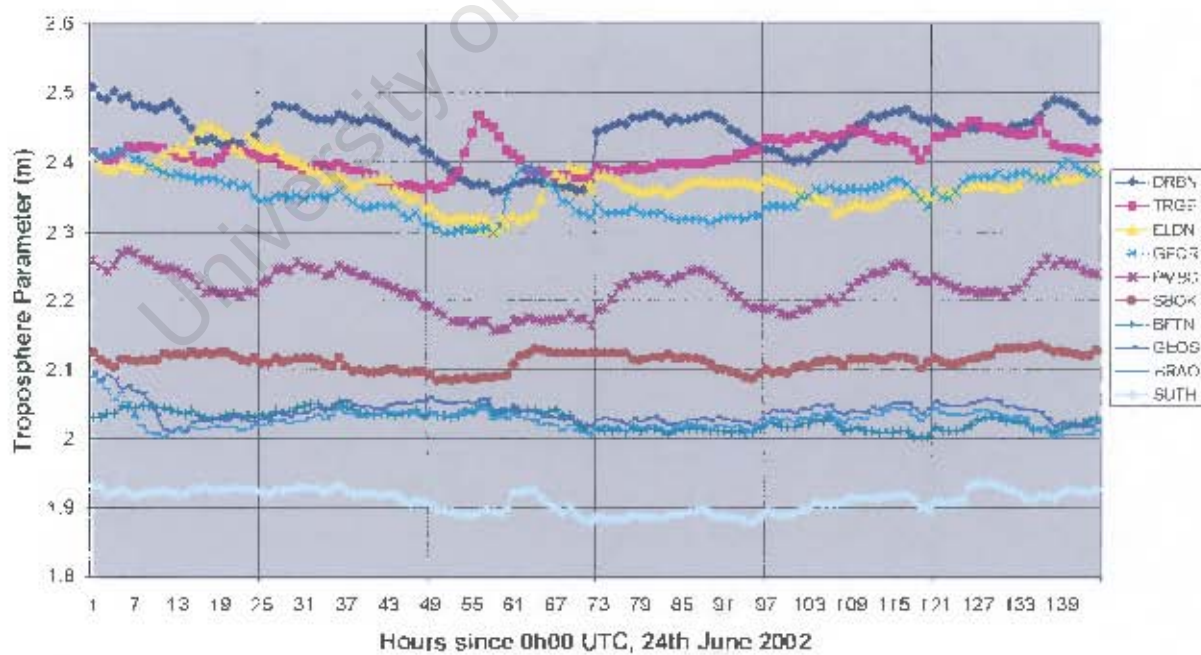


Figure 6.7 Magnitude of TZD at various stations during the six-day campaign in June 2002

Figures 6.6 and 6.7 are plots of the TZD estimates of all stations stemming from the SANG10 strategy. It is quite clear that stations in close proximity to each other (such as PMBG and DRBN) display remarkably similar profiles, although vertically offset. On the other hand, a lateral displacement of profiles is noticeable between stations with primarily east-west separations (such as TRGE and GEOR). There is evidence of a weather front passing progressively through TRGF, GFOR and ELDN between hours 55 to 69 in the June campaign.

There are certain spikes that are noticeable on the plots. The sudden increase in TZD on the 15th January 2002 (see hour 62) at almost all stations, and for DRBN on the 27th July 2002 (see hour 73), could not be explained. It is extremely unlikely that a weather system could have resulted in such rapid simultaneous countrywide troposphere variation.

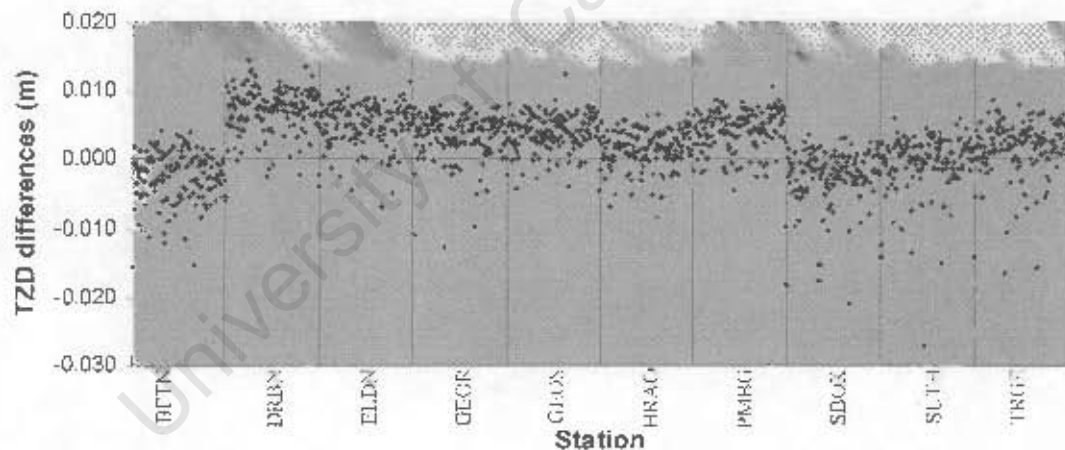


Figure 6.8 TZD differences between the NENG10 and SANG10 strategies (January)

The Figures 6.8 and 6.9 shows the differences between the TZD as estimated by the NENG10 and SANG10 strategies for January and June respectively. The differences are plotted per station, where 144 differences are plotted over the six-day campaign, corresponding to each hour.

In January, the differences ranged from +15 mm to -27 mm and show a very strong correlation with stations. Both graphs shows that the TZD stemming from the above two strategies are far more consistent (close to zero) at certain stations compared to others. In addition, the TZD estimates resulting from the strategies are very consistent at some stations (see HRAO), whereas the differences are more pronounced at others (see BFTN).

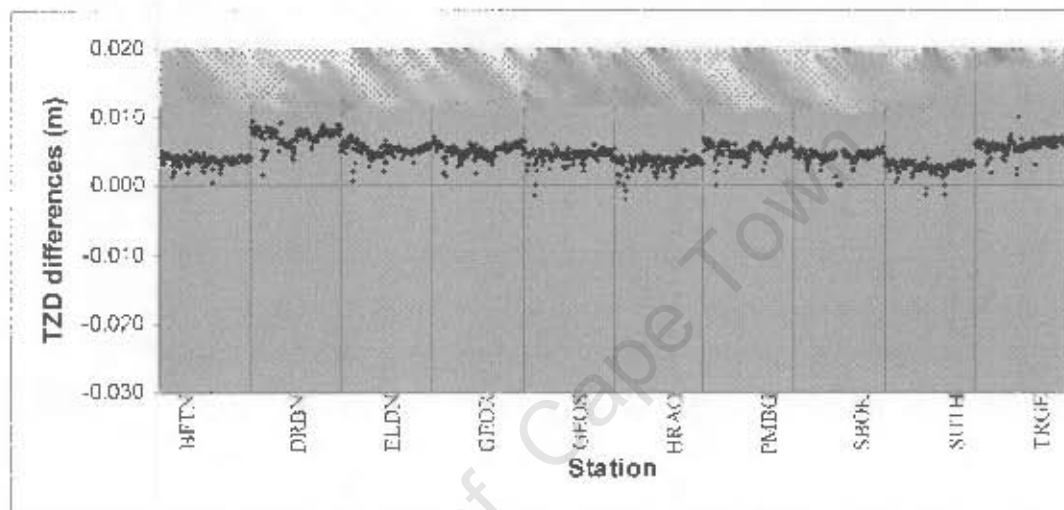


Figure 6.9 TZD differences between the NENG10 and SANG10 strategies (June).

In June, the TZD estimates from the two strategies were not only far more consistent but also displayed significantly less scatter. For example, the differences at SUTH ranged from -0.1 mm to 5.0 mm in June, whereas the differences ranged from -26 mm to 6 mm in January. Although Figures 6.8 and 6.9 cannot reveal which strategy yielded the most accurate TZD estimates, it is clear that the estimates from NENG10 and SANG10 strategies are far more consistent in June (winter). Unfortunately, it is difficult to benchmark these values, since using external validation techniques (such as WVRs) was beyond the scope of this research.

6.6 IMPACT OF TROPOSPHERIC GRADIENT ESTIMATION

Since it is not recommended to estimate gradient parameters with the $1/\sin(E)$ mapping function (as used in the SANG strategies), only the NEWG and NENG strategies are compared in this section.

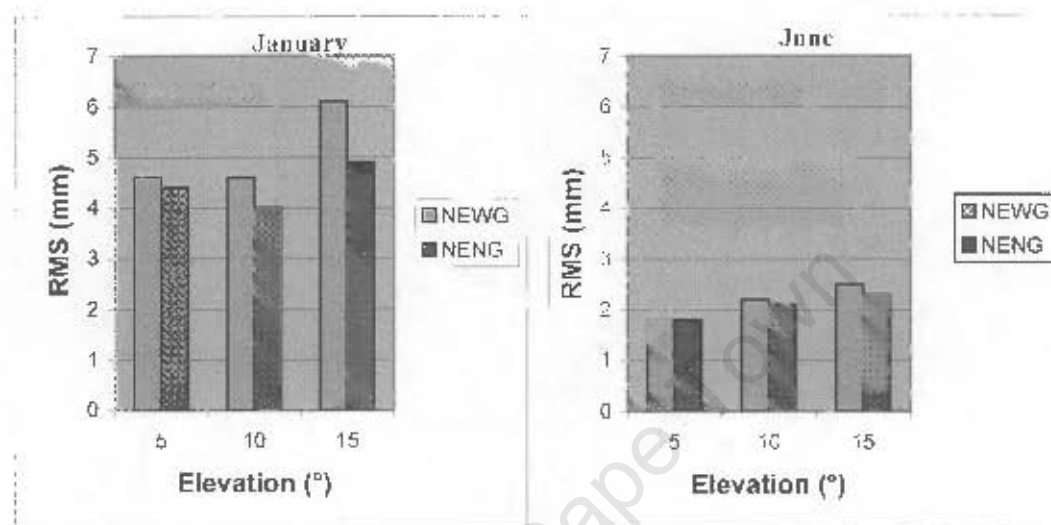


Figure 6.10 RMS^{3D} for January and June campaigns respectively.

The estimation of tropospheric gradients did not yield the improvements as demonstrated by Rothacher et al. (1997). It is clear from the Figure 6.10 that there was **no** improvement in overall 3D precision when estimating additional troposphere gradient parameters at all elevations tested. At 5°, where the improvement was most expected (when estimating gradients), the precision was very similar. With the exception of June (5°), there was an improvement in all cases when **no** gradients were estimated. This was more pronounced as the elevation increased. The improvement in precision was computed with the following formula:

$$\text{Improvement} = \left(\frac{\text{RMS}_{\text{NI-NGEE}}^{\text{DW}} - \text{RMS}_{\text{NI-WGEE}}^{\text{DW}}}{\text{RMS}_{\text{NENGEE}}^{\text{DW}}} \right) \quad (6.6)$$

Elevation	January	June
5°	4%	0%
10°	14%	0%
15°	20%	8%

Table 6.2 Improvement (%) in RMS^{3D} when not estimating gradients.

The horizontal components, as well as the vertical component exhibited the same improvement in precision when **no** tropospheric gradients are estimated. The reasons for this are not too obvious. Possible explanations are that the quality of the data used were not sufficient, and that the additional noise caused by the inclusion of low elevation data worsened the results, and did not offset any potential benefits from estimating gradients. *“One has to emphasise in this context that the availability of good quality is crucial to obtain the results as shown above”* (Rothacher et al., 1997, p97).

6.7 IMPACT OF ELEVATION CUT-OFF ON STATION COORDINATES.

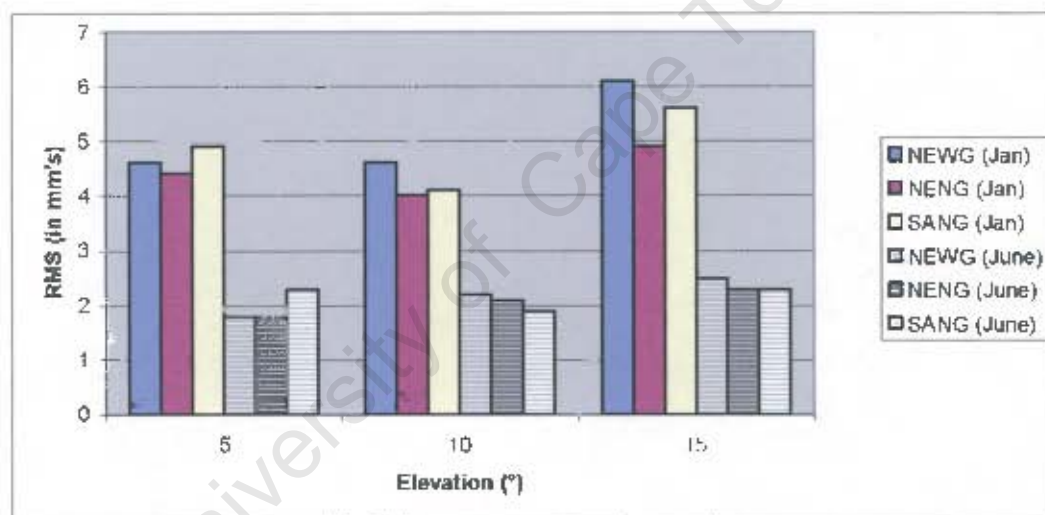


Figure 6.11 RMS^{3D} comparison during both campaigns for all strategies.

The Figure 6.11 compares the RMS^{3D} of all the strategies tested at various elevations. What is immediately obvious is the substantial improvement in overall precision in June (regardless of strategy and elevation). This is probably due to the more successful ambiguity resolution due to decreased solar activity in June, and not due to mapping function, since all strategies showed the same improvement.

The results stemming from the January and June campaigns exhibited similar effects on position with the introduction of low-elevation data together with an elevation-dependent weighting model of the observations. In section 6.6, it was shown that for

both the campaigns, there was no increase in precision when estimating the gradients. It is for this reason that the NEWG strategy was not used for further analysis/comparison.

Campaign	Elevation	Mean RMS ^{2D} (±mm)	
		NENG	SANG
January	5°	3.0	2.9
	10°	2.8	2.7
	15°	2.5	2.7
June	5°	1.5	1.5
	10°	1.4	1.4

Table 6.3 Mean RMS^{2D} of coordinate estimation

Table 6.3 lists the mean RMS^{2D} (see equation 6.5) of the NENG and SANG strategies. To simplify the analysis, the mean of all the stations were compared instead of the RMS^{1D} of each individual station. An analysis of the individual station repeatability indicates that there were no stations with significant deviations from this mean RMS^{2D} shown above.

Both the NENG and SANG strategies seems to perform best at 15° (horizontal component only). The inclusion of data at very low elevations (down to 10°) degraded the horizontal positions very slightly (in terms of RMS^{2D}). This is consistent with what Rothacher (1997) found. The mean RMS^{2D} degraded more significantly when lowering the elevation mask from 10° to 5° than from 15° to 10°. This is probably due to the ever-increasing multipath down to 5°.

Campaign	Elevation	Mean RMS ¹ (±mm)	
		NENG	SANG
January	5°	7.0	8.3
	10°	6.3	6.7
	15°	8.4	9.6
June	5°	2.6	3.7
	10°	3.1	2.7
	15°	3.3	3.2

Table 6.4 Mean RMS¹ of coordinate estimation

As expected, the effect of variation of the elevation cut-off propagates mainly to the vertical component. Table 6.4 lists the mean RMS^U of the NENG and SANG strategies at various elevations. An analysis of the individual station repeatability indicates that there were no stations with significant deviations from this mean RMS^U shown above.

The NENG strategy had the best RMS^U at 10° in January and at 5° in June. However, the NENG strategy seems more stable at 10° (less spikes when looking at individual station $\text{RMS}^{(X,U)}$), which, in both campaigns, yielded better RMS^U than at 15° . Using low elevation data with the Saastamoinen- $1/\sin(E)$ combination yielded the poorest RMS^U at 5° . This is probably due to the fact the $1/\sin(E)$ model breaks up at elevations lower than 10° . Again, the best results were obtained using data at 10° and the worst results at 15° .

There is a definite improvement in mean RMS^U regardless of strategy when lowering the elevation mask down from 15° to 10° . When lowering the mask to 5° , the results does not concur with Rothacher et al. (1997), who found an improvement in the Up component. The low quality of the data at 5° is the most likely cause of this.

6.8 IMPACT OF MAPPING FUNCTION ON STATION COORDINATES

Since the NMF is widely used by various analysis centres, it was expected to produce results with the best repeatability, especially at low elevations. Only the NENG and SANG strategies were compared here (for the same reasons as in section 6.7). In section 6.5, we discussed the difference in site-specific troposphere estimates generated by the NENG10 and SANG10 strategies. It was found that the estimates were far less consistent in January than June.

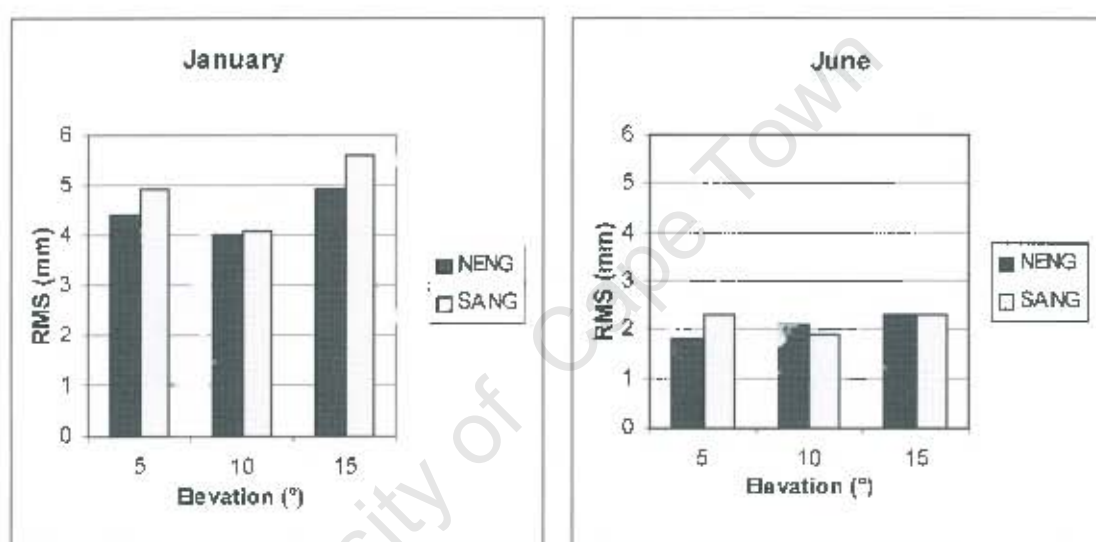


Figure 6.12 RMS^{3D} for the NENG and SANG strategies during both campaigns.

The NENG strategy performed better than the SANG strategy at 5° during both campaigns (see Figure 6.12). This was expected, since the $1/\sin(E)$ mapping function breaks up at this low elevation (O'Keefe, 2001). On average, the NENG strategy performs better (RMS^{3D}), when elevation mask was set to 15°. Since both the strategies perform best at 10°, only the NENG10 and SANG10 strategies will be compared further.

It was not easy to only look at the RMS^{3D} to decide which strategy performs best at 10°, since in January the NENG strategy had a better RMS^{3D} whereas in June the SANG strategy performed better. For this reason the performance at station level was analysed.

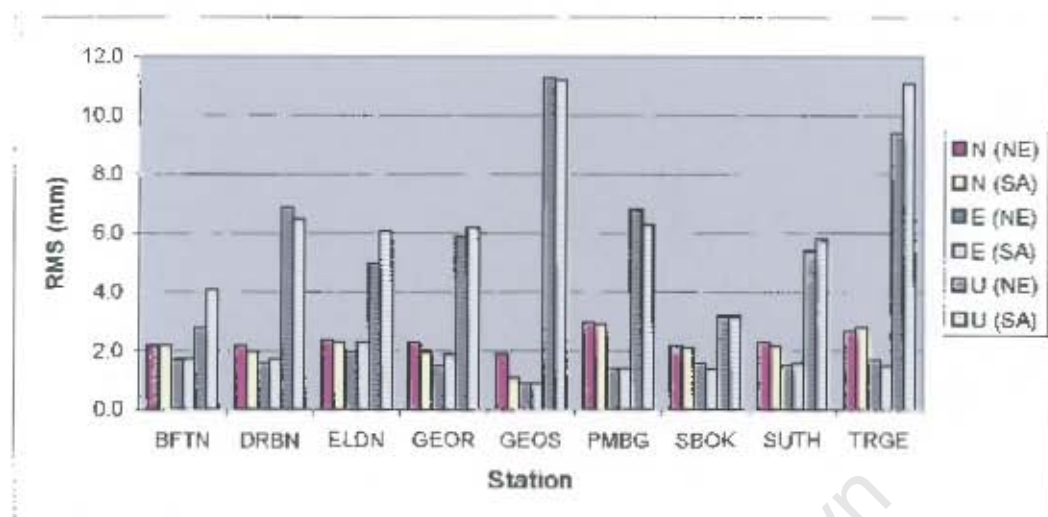


Figure 6.13 RMS^{1D} for the NENG10 and SANG10 strategies in January.

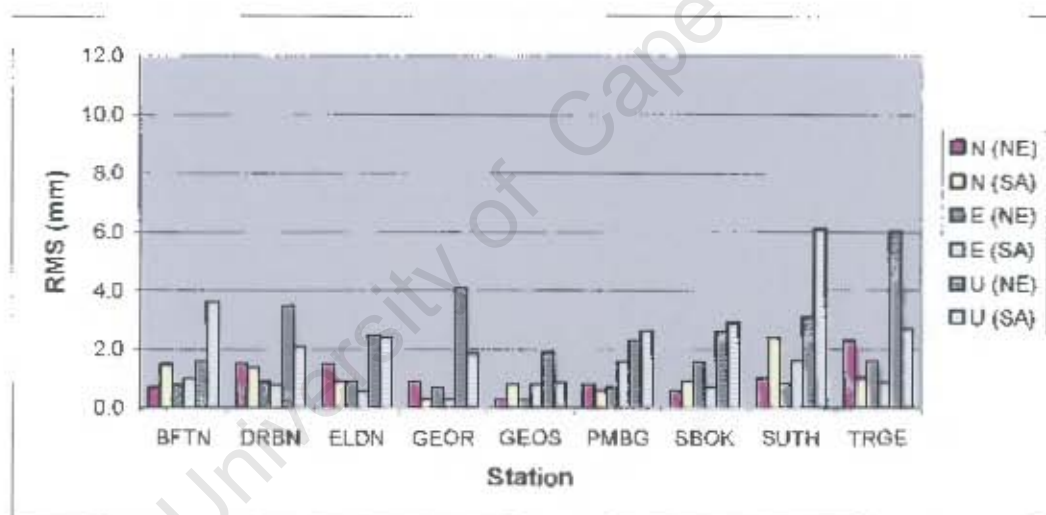


Figure 6.14 RMS^{1D} for the NENG10 and SANG10 strategies in June.

Figures 6.13 and 6.14 shows the repeatability of station coordinates (RMS^{1D}) for the NENG10 and SANG10 strategies during both campaigns. Even at the station level, there was no clear evidence (at 10°) to show that one strategy produces better results than the other does.

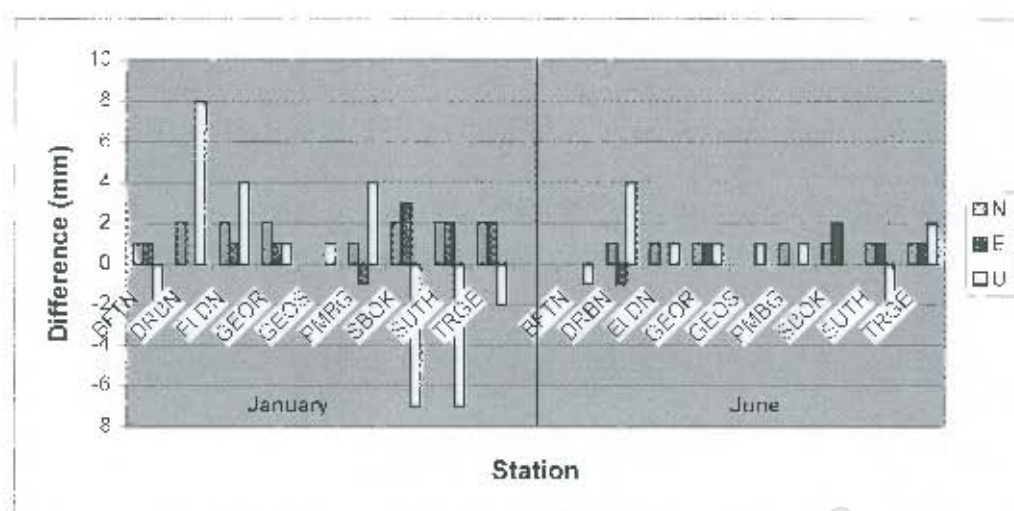


Figure 6.15 Coordinate differences between NENG10 and SANG strategies.

Figure 6.15 shows coordinate differences stemming from the NENG10 and SANG10 strategies for both campaigns. The station HRAO was omitted since it was constrained at all stages. The horizontal coordinates stemming from the two strategies differed very little, with a maximum of 3 mm (E) at SBOK in January. The horizontal coordinate differences were larger in January than in June. Since all non-troposphere related options were identical during processing, the Author can only conclude that these differences were caused by the scalar effect (see section 3.4) of the residual troposphere errors in either, or even both the estimation strategies.

Whereas the NENG10 horizontal (N, E) coordinates were slightly larger than the SANG10 coordinates in most cases, the differences in the Up components showed much more variability and were larger in magnitude. Again the differences peaked in January, with a maximum of +8 mm (U) at DRBN, followed by SBOK and SUTH, both with a -7 mm difference. In June, the station DRBN had the largest difference of +4 mm (U). The substantially less consistent TZD estimates (see section 6.5) from the two respective strategies in January (compared to June), is most likely the cause of the rather larger differences in January.

6.9 INTERNAL PRECISION OF ALL ESTIMATION STRATEGIES.

The output of the least squares adjustment of each daily session from all the strategies were analysed. Short solution statistics were extracted for each of the 108 session adjustments since the detailed outputs from the session adjustment program (*GPSEST*) generated reports of 35 pages each.

Estimation Strategy	January 2002						June 2002					
	1 13 th	2 14 th	3 15 th	4 16 th	5 17 th	6 18 th	1 24 th	2 25 th	3 26 th	4 27 th	5 28 th	6 29 th
	$\hat{\sigma}^2$ (in mm)											
SANG05	1.4	1.4	1.7	1.7	1.8	1.3	1.1	1.1	1.2	1.1	1.1	1.2
SANG10	1.2	1.2	1.5	1.5	1.6	1.1	1.0	0.9	1.1	0.9	0.9	1.0
SANG15	1.3	1.3	1.6	1.6	1.7	1.2	1.0	1.0	1.1	0.9	1.0	1.0
NENG05	1.5	1.6	1.9	1.9	2.0	1.5	1.3	1.3	1.4	1.3	1.3	1.3
NENG10	1.3	1.3	1.8	1.7	1.8	1.3	1.1	1.0	1.2	1.0	1.0	1.1
NENG15	1.5	1.5	1.8	1.8	1.9	1.5	1.3	1.3	1.4	1.3	1.3	1.3
NEWG05	1.5	1.5	1.9	1.8	2.0	1.5	1.3	1.2	1.4	1.3	1.3	1.3
NEWG10	1.5	1.5	1.9	1.8	1.9	1.5	1.3	1.3	1.4	1.3	1.3	1.3
NEWG15	1.5	1.5	1.9	1.9	1.9	1.5	1.3	1.3	1.4	1.3	1.3	1.3

Table 6.5 "A posteriori sigma of unit weight" after each session adjustment

Table 6.5 tabulates the "a posteriori sigma of unit weight", resulting from each session (daily adjustment) for each strategy. This quantity is an important indicator for the quality of the receivers used and for the quality of the solution. This value is furthermore used as the scaling factor for the estimated covariance matrix (Hugentobler, Schaer and Fridez, 2001). The SANG10 strategy consistently had the best a variance factors associated with all of the processing days when compared to any other strategy. Of the strategies using the NMF, the NENG10 strategy had the best variance factors. This is consistent with the findings thus far, and confirms that the SANG10 strategy produced better results (although marginally) than the NENG10 strategy.

6.10 COMPARISON OF BASELINE LENGTHS

The daily baseline lengths were compared with the average (of the campaign), and the RMS of the baseline lengths RMS^{bl} were calculated (using Equation 6.2) for the baselines defined in Table 5.3.

Campaign	Strategy		NENG10		SANG10		Baseline length difference (mm)
	From	To	Baseline length (m)	RMS^{bl} (mm)	Baseline length (m)	RMS^{bl} (mm)	
January 2002	GEOS	HRAO	62258.2418	0.3	62258.2407	0.9	1.1
	HRAO	BFTN	381657.5178	0.9	381657.5168	2.0	1.0
	BFTN	PMBG	400511.5014	1.3	400511.5016	1.0	-0.2
	PMBG	DRBN	67819.8338	0.8	67819.8347	2.1	-0.9
	DRBN	ELDN	451350.4691	2.5	451350.4741	1.4	-5.0
	ELDN	GEOR	516997.8832	0.9	516997.8822	1.8	1.0
	GEOR	SUTH	231961.7936	0.7	231961.7869	1.2	6.7
	SUTH	SBOK	410665.3238	0.9	410665.3257	0.7	-1.9
	SBOK	TRGE	279448.6220	1.8	279448.6209	2.8	1.1
June 2002	GEOS	HRAO	62258.2405	0.9	62258.2418	0.2	-1.3
	HRAO	BFTN	381657.5160	2.0	381657.5180	0.8	-2.0
	BFTN	PMBG	400511.5007	1.1	400511.5016	1.3	-0.9
	PMBG	DRBN	67819.8344	1.9	67819.8338	0.7	0.6
	DRBN	ELDN	451350.4726	1.4	451350.4695	2.4	3.1
	ELDN	GEOR	516997.8806	1.8	516997.8837	0.9	-3.1
	GEOR	SUTH	231961.7866	1.2	231961.7937	0.7	-7.1
	SUTH	SBOK	410665.3251	0.6	410665.3239	0.9	1.2
	SBOK	TRGE	279448.6204	2.8	279448.6222	1.9	-1.8

Table 6.6 Baseline statistics for the NENG10 and SANG10 strategies during both campaigns.

The NENG10 and SANG10 strategies produced results with baseline lengths consistent to ± 5 mm, and baseline length repeatability. The maximum RMS^{bl} for both strategies were 2.8 mm. This confirms that the daily baseline length varied very little, regardless of strategy or campaign. The January and June campaigns produced baseline length repeatability (precision) of similar magnitude, for both NENG10 and SANG10 strategies.

The RMS^{bl} for the SANG10 strategy ranged from 2-31 parts per billion (ppb) in January and 2-11 ppb in June. The repeatability for the NENG10 strategy were very

similar, ranging from 3-28 ppb in January and 2-11 ppb in June. In all cases, the baseline PMBG-DRBN had the largest “ppb”. This is attributable to the short distance between the two stations.

When comparing baseline lengths stemming from the two strategies, the maximum difference was 6.7 mm (GEOR↔SUTH) in January and -7.1 mm (GEOR↔SUTH) in June. Table 6.6 shows that the actual baseline lengths were similarly consistent between the two strategies in June. There was no clear trend in the sign of the baseline differences, indicating that there was no evident scale factor.

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6.11 VALIDATION

During the first phase of processing, only the coordinates of HRAO (CODE submission to IGS; see section 5.6) were constrained when the normal equations were combined. This yielded a coordinate for SUTH for each strategy that could be compared to the IGS00 value (CODE submission) for validation. During the second phase of processing, which followed the identification of the optimal (best performing) estimation strategy, both HRAO and SUTH were constrained to the IGS00 value (see Table 6.7 below for CODE values used).

EPOCH: 2002-01-15 11:59:45						
	X	Y	Z	Latitude	Longitude	Height
HRAO	5085352.4675	2668395.7481	-2768731.5755	25 53 24.37938	-27 41 13.1271	1414.1390
SUTH	5041274.8246	1916054.0756	-3397075.9826	32 22 48.75986	-20 48 37.6630	1799.7449
EPOCH: 2002-06-26 11:59:45						
HRAO	5085352.4768	2668395.7672	-2768731.5984	25 53 24.37981	-27 41 13.1275	1414.1644
SUTH	5041274.8482	1916054.0913	-3397076.0123	32 22 48.76019	-20 48 37.6632	1799.7841

Table 6.7 CODE IGS weekly coordinate solutions

Of the three validation procedures identified in section 5.5, the Auto-Gipsy (AG) data submission was the most tedious and time consuming. Tabulating the results from the AUSPOS service was a much easier task. Both the AG and AUSPOS daily individual station solutions were first collated into daily files. These daily files were used for repeatability analysis. The RMS^{1D} of the AG and AUSPOS stations were computed using the Bernese *COMPAR* programme, in the same way as for all other strategies tested.

6.11.1 Estimation of the Sutherland Coordinates.

The Figure 6.16 below shows the coordinate differences of the combined six-day solutions stemming from the all the strategies tested and the IGS (CODE) estimate of SUTH.

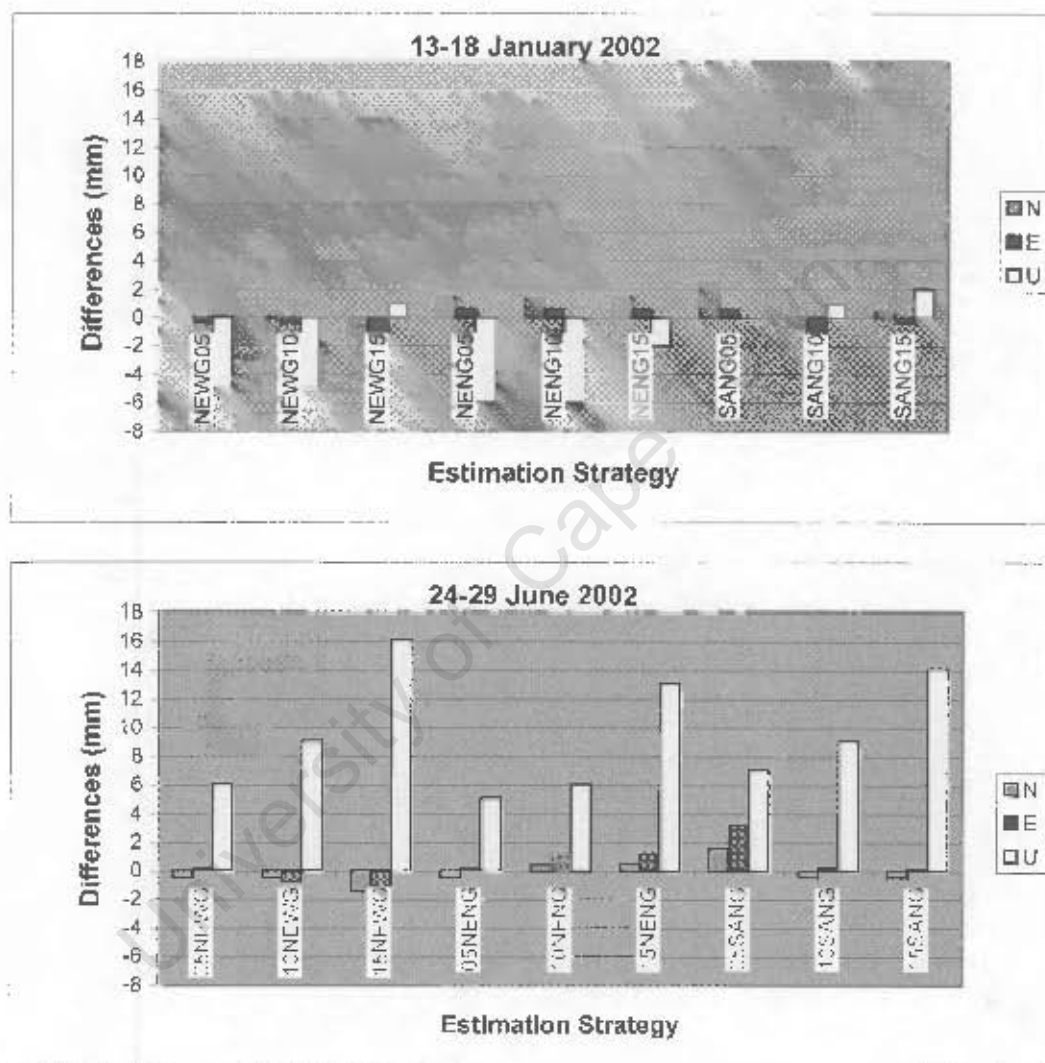


Figure 6.16 Coordinate differences between SUTH IGS values and those derived from the various estimation strategies.

In January, the maximum difference in the horizontal components (N, E) between the SUTH CODE values and the estimates from the various strategies was -3.4 mm ("E" component, of the NENG15 strategy). This shows that the strategies tested had very little influence (at least cause very little variation) on horizontal component. All

the strategies seemed to have resulted in very accurate determination of the horizontal component. The maximum difference in January on the Up component was -6mm.

The SUTH coordinate stemming from the SANG10 (Jan) strategy differed by only 1.6 mm, 1.4 mm and 1.0 mm in the North, East and Up (N,E,U) components respectively. This coordinate estimate was the closest to the CODE value. However, the RMS^{ID} of the SUTH coordinate components for the SANG10 strategy were 2.2 mm, 1.6 mm and 5.8 mm (N,E,U). Therefore, the 1.0 mm difference in the U component must be seen as a co-incidence, and not a real measure of accuracy.

In **June**, the comparison of the coordinate of SUTH obtained using the nine different strategies and the coordinate of the CODE weekly solution yielded unexpected results. The maximum difference in the horizontal components of SUTH coordinate of all the various strategies from the CODE values was 3.2mm. The same conclusion can be made here that all strategies yielded very accurate determinations of the horizontal component of SUTH. However, all the strategies displayed a rather significant deviation in the Up component from the CODE value. The SUTH coordinate stemming from the SANG10 (June) strategy differed by 0.2 mm, -0.5 mm and 9.0 mm (N,E,U). Here, the RMS^{ID} of the SUTH coordinate components for the SANG10 strategy were 0.9 mm, 0.7 mm and 2.9 mm (N,E,U). This large discrepancy in heights stemming from all strategies in June was very peculiar, as this was expected for January instead. The RMS^{ID} of the U component of SUTH (all strategies) were significantly less in June than January. No correlation could be found between the RMS of coordinate comparison, (see Figure 6.14) of the strategy and the deviation from the SUTH IGS (CODE) coordinates.

Since the CODE AC used data down to 5°, and a different troposphere estimation (see section 7) strategy, it is possible that the solutions generated here has some systematic bias relative to the CODE solution.

6.11.2 Comparison of Precision Derived with Bernese, AUSPOS and AG

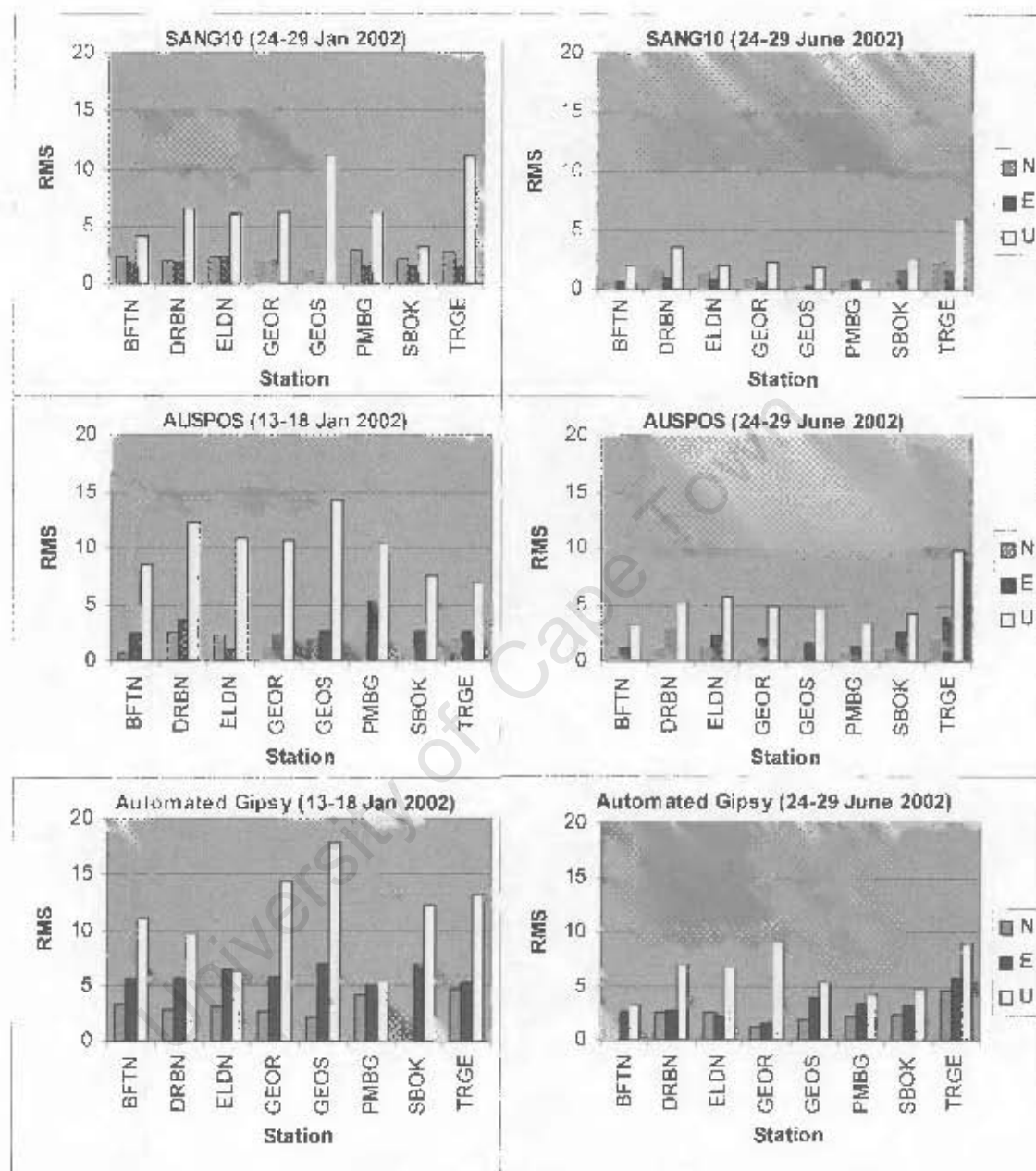


Figure 6.17 Comparisons between RMS^{1D} (in mm) achieved with the Bernese, AUSPOS and AG.

Figure 6.17 shows a high correlation in the scatter (RMS^{1D}) derived from the SANG10 strategy and the AUSPOS and AG results. A visual inspection shows that, with all three processing suites, the relative performances of stations are very similar. The stations GEOS and TRGE, for example, consistently showed relatively high scatter during both January and June (regardless of software used). The stations

BFTN, on the other hand, exhibited far less scatter. The correlation coefficients of RMS^{1D} values of SANG10 strategy and AUSPOS are 0.80 in January and 0.89 in June. The correlation is less between SANG10 strategy and AG with coefficients of 0.76 and 0.80 for January and June respectively.

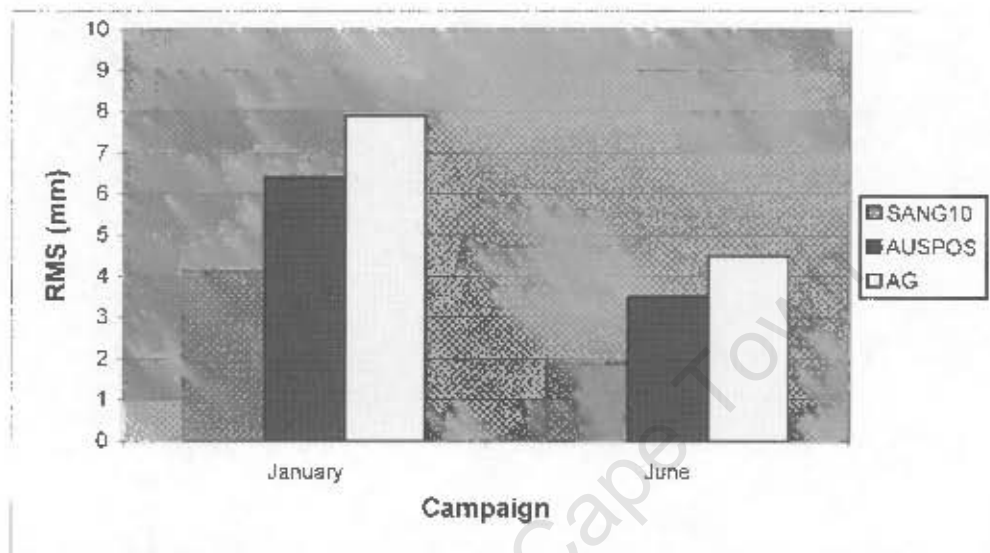


Figure 6.18 RMS^{3D} of SANG10, AUSPOS and AG final coordinates.

What is interesting is that the RMS^{3D} values were almost 50% lower in June, regardless of processing suite. This supports the argument that the primary cause of the substantial improvement in precision in June was the better quality data and resultant improved ambiguity resolution.

The AUSPOS service returned results that were less precise (see Figure 6.18) than that obtained with the Bernese. The AUSPOS derived RMS^{1D} values were larger than that obtained by the Bernese (at 10°) for all stations. Using the station GEOS (Up component, which had the most scatter in January) as an example, the range (max-min) was 33.1 mm and the maximum deviation from the unweighted mean was 19.5mm. For the same station, the AUSPOS results showed a 41.0 mm range and maximum deviation of -23.2mm. The AG results have a range of 46.9 mm and a maximum deviation of 35.7mm.

6.11.3 Comparison of Coordinates derived with the Bernese, AUSPOS and AG

The Bernese coordinates that are being compared here are from the chosen SANG10 strategy, where the IGS00 (CODE submission) coordinates of HRAO and SUTH were used to constrain the final adjustment. Similarly, the AUSPOS service constrained the IGS station coordinates (IIRB, IIRAO, SUTH) to the weekly solutions from the Australian AC. Although the AG service uses a precise point-positioning algorithm, the precise orbits, clocks and ERPs used are all defined in the reference frame of the JPL weekly solution (Zumberge et al., 1997). Since none of the solutions used the IGS final combined product, the coordinates were expected to differ.

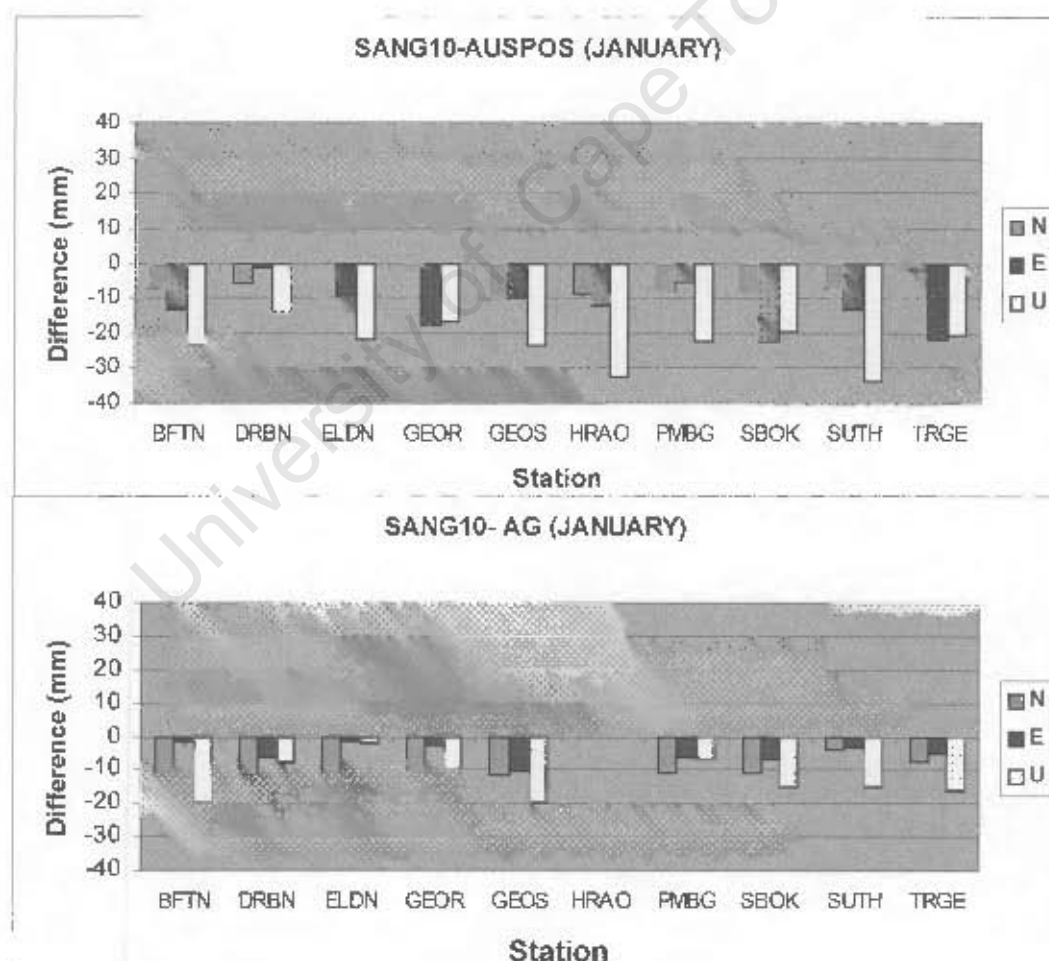


Figure 6.19 Differences between SANG10 and AUSPOS /AG derived coordinates for the January campaign.

Figures 6.19 and 6.20 show the differences in station coordinates derived by subtracting the coordinates of AUSPOS/AG from the Bernese (SANG10 strategy, with HRAO and SUTH fixed) values for the January and June campaigns respectively. It is useful to first note the differences at HRAO and SUTH, since these coordinates were obtained from the respective ACs weekly SINEX files, and was not subject to processing error by the Author. Ideally, all the TrigNet stations coordinates should differ by roughly the same magnitude as the HRAO and SUTH differences.

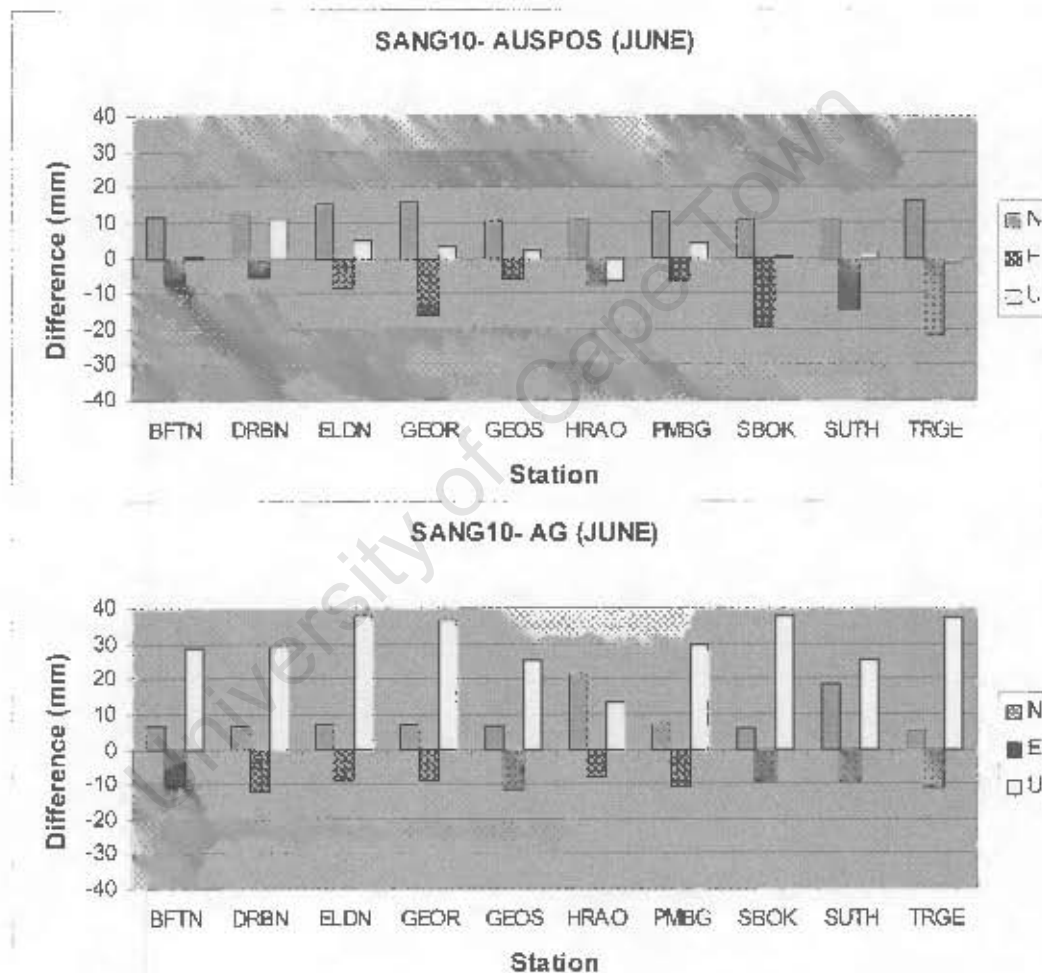


Figure 6.20 Differences between SANG10 and AUSPOS /AG derived coordinates for the June campaign.

	JANUARY		JUNE	
	SANG10-AUSPOS (mm)	SANG10 – AG (mm)	SANG10-AUSPOS (mm)	SANG10 – AG (mm)
N	-6.1 ± 3.5	-10.0 ± 2.6	12.7 ± 2.3	9.2 ± 5.6
E	-12.8 ± 6.7	-4.9 ± 2.9	-11.4 ± 6.1	-10.0 ± 1.3
U	-22.8 ± 6.2	-12.5 ± 6.2	1.9 ± 4.6	30.1 ± 7.7

Table 6.8 SANG10 (final) coordinate differences with AUSPOS and AG solutions.

Table 6.8 lists the mean coordinate differences (all stations, and the standard deviation, at 1 sigma) between SANG10 strategy and AUSPOS and AG. In **January**, the coordinate differences with AUSPOS solutions were negative in all components for all stations. Interestingly, the AUSPOS East components showed the greatest variability relative to the Bernese results. The differences with AG were also all negative in January, but the Up component showed the most variability.

In **June**, the coordinate differences with AUSPOS were not all of the same sign. Again the AUSPOS East components showed the greatest variability relative to the Bernese results. The differences with AG were also all negative in January, but the Up component showed the most variability.

The lack of a clear trend and consistency in coordinate differences could be a result of differences in elevation masks used, ambiguity resolution algorithms, and data screening processes and ionosphere and troposphere estimation models used.

6.12 RELATIVE MOTION BETWEEN CAMPAIGNS

All geodetic datums are 4 dimensional by definition. In instances of minimal relative motion over time between points that defines the datum, it becomes convenient to base the coordinates of a National Control Survey network on a reference epoch on which all subsequent surveys can be based. This assumption is held in South Africa for the Hartebeesthoek94 datum. In the South Pacific region for example, this is far more complicated, where the New Zealand geodetic datum has been subjected to earth deformation of between 2 and 3 metres since the first geodetic observations were performed. This forced the consideration of a “dynamic” datum, that would include a velocity model along with periodic readjustments (Grant and Pearse, 1995). Knowledge of any relative movement of stations, whether abrupt or slow and imperceptible, is of great importance to PGA operators. Since TrigNet is designed to serve as a fiducial network, the accuracy achieved must be of the highest order, and all sources of error must be minimised and communicated to clients and users where necessary.

The final coordinates from the SANG10 strategy of the two campaigns were compared by computing Helmert parameters (combinations of translations, rotations and scale) between both coordinate systems.

Option	Parameters Computed	No of Parameters	RMS ^t of Transformation (mm)
A	- Translations in X, Y and Z	3	5.0
B	- Translations in X, Y and Z - Scale Factor	4	4.9
C	- Translations in X, Y, and Z - Rotations around Y and Z axes only - Scale Factor	6	4.2
D	- Translations in X, Y, and Z - Rotations around X axis only - Scale Factor	5	2.8
E	- Translations in X, Y, and Z - Rotations around X, Y and Z axes - Scale Factor	7	2.7

Table 6.9 RMS^t between January and June campaigns.

Table 6.9 lists the RMS^t between the January and June campaigns (using the chosen SANG10 strategy) for various combinations of parameters computed. When only translation parameters were computed (dX, dY, dZ; also referred to as a Moledensky parameters), the RMS^t was 5.0mm. The RMS^t decreased insignificantly (by 0.1 mm to 4.9mm) when a scale factor (± 3 ppb) was computed in addition to the translations. This indicates that the scale of the network was almost identical between the campaigns.

The RMS^t, when excluding rotation around the X- axis (see option C in Table 6.6) was 4.2mm. When the rotations around X-axis were computed and around the Y and Z-axes were omitted (option D), the RMS^t reduced significantly to 2.8mm. This indicates that the most significant rotation occurred around the X-axis (in South Africa, this roughly equates to a change in longitude). The optimal transformation result was obtained by computing all seven parameters (option E), where an RMS^t of 2.7 mm was achieved. This indicates that the relative geometry between the stations processed had not changed significantly and that the two networks are consistent to the millimetre level (see Appendix D for detailed outputs of options A-E).

Table 6.10 lists the Helmert transformation parameters between the January and June campaigns (using the chosen SANG10 strategy). The standard deviation of the residuals of the seven-parameter transformation was 2.1 mm, 2.4 mm and 2.9 mm (N,E,U).

As expected, the Up component had the largest residuals. This can be attributed to the less precise determination of this component (Santerre, 1991). The station SUTH had the largest residuals (-1.7 mm, 4.5 mm and -4.1 mm in the North, East and Up components respectively). However, this station was held fixed during the final adjustment. The Author could not find a plausible explanation for this (large residuals).

NUM	NAME	FLG	RESIDUALS IN MILLIMETERS		
			North	East	Up
1	BLOEMFONTEIN	M M	-0.5	-0.7	-2.1
2	DURBAN	M M	2.3	3.0	-2.6
3	EASTLONDON	M M	-1.6	-2.1	-0.1
4	GEORGE	M M	0.8	-3.1	1.7
5	GEOSCIENCE	M M	-2.0	0.1	3.6
6	HRAO 30302M004	F F	-0.8	-0.6	-3.1
7	PIETERMARITZBURG	M M	2.1	1.6	4.0
8	SPRINGBOK	M M	-2.5	-1.9	1.3
9	SUTH 30314M002	F F	-1.7	4.5	-4.1
10	TRGEMOWBRAY	M M	3.8	-0.8	1.5
RMS / COMPONENT			2.1	2.4	2.9
NUMBER OF PARAMETERS : 7 NUMBER OF COORDINATES : 30 RMS OF TRANSFORMATION : 2.7 MM PARAMETERS: TRANSLATION IN X : 13.3 +- 0.8 MM TRANSLATION IN Y : -10.6 +- 0.8 MM TRANSLATION IN Z : -28.5 +- 0.8 MM ROTATION AROUND X-AXIS: - 0 0 0.0027 +- 0.0005 " ROTATION AROUND Y-AXIS: 0 0 0.0010 +- 0.0006 " ROTATION AROUND Z-AXIS: 0 0 0.0005 +- 0.0003 " SCALE FACTOR : -0.0036 +- 0.0016 MM/KM NUMBER OF ITERATIONS : 2					

Table 6.10 Helmert transformation parameters between January and June campaigns.

It is important to remember that not all the residuals should be interpreted as movement/motion. The results stemming from both campaigns still have some residual error that was either not modelled or incorrectly modelled.

Chapter VII

7. Conclusions and Recommendations

7.1 SUMMARY AND CONCLUSIONS

In order for the TrigNet PGA to serve its purpose as a fiducial network for horizontal and vertical control, it has to be monitored for motion/movement and coordinated within the global ITRF. To achieve the precision and accuracy required of a fiducial network such as TrigNet, data stemming from high quality receivers needs to be processed with software that meet the highest accuracy requirements. The Bernese has proved to be an ideal tool.

The modelling and estimation of tropospheric parameters remain as the primary accuracy limiting factors, especially the vertical component. Unlike ionosphere estimation algorithms and techniques, which seem to have matured over the last couple of years, there is still a considerable amount of research to be done relating to troposphere modelling and parameter estimation.

There is a global trend to include **low elevation data**, even down to 3° to decorrelate the vertical component and the troposphere parameter. There is no doubt that the inclusion of data at low elevation not only decreases the daily scatter (and hence the precision) of the station height estimation, but also improves accuracy of the estimation. This should of course be done with an elevation dependent weighting model. However, no increase in precision was achieved with data lower than 10° during this research. This is probably owing to the fact that TrigNet data is characterised by relatively high multipath at elevations lower than 10° .

The estimation of tropospheric **gradients** did not yield any improvements in precision. The results of strategies that did not estimate gradients were consistently better than the strategies where gradients were estimated. This can also be attributed to the low quality data at elevations lower than 10° .

Once data lower than 15 degree are included, the choice of **mapping function** becomes increasingly important. Currently, the NMF is the favoured mapping function by Global Analysis Centres. The strategies employing the NMF have performed differently during the Southern Hemisphere summer and winter months when compared to non-NMF based strategies. However, The campaigns were very short (6 days), and one needs more data to make better conclusions using the processing strategies. Although not conclusive, the possibility of a seasonal bias in southern Africa during Northern Hemisphere winter, as suggested by Rocken et al. (2001), cannot be ruled out.

Surprisingly, the use of the Saastamoinen a priori model, together with the simple $1/\sin(E)$ MF yielded marginally better results than the strategies where the entire delay was estimated with the more modern (considered as state of the art) NMF. Since the initiation of this research, the CODE analysis centre has advised that instead of mapping the total tropospheric delay with the NMF (dry), they now consider a Saastamoinen-based a priori model (using NMF (dry)), and solve for the wet component using the NMF (wet).

Although this proposed combination was not tested in this research, the very good results obtained with the SANG strategy, and the generally good results obtained using the NENG10 strategy confirm the Authors findings that there is merit in using elements of both to have an even better troposphere estimation strategy. This will hopefully reduce the scatter evident especially in the vertical component.

7.2 RECOMMENDATIONS

Since this research was limited in scope and time, some recommendations for further work are:

- Only IGS (combined) final products be used for all processing, instead of products from one of the analysis centre (such as CODE in the case of this research).
- Weekly processing be done, after the IGS final orbits have been released.
- All future data be processed using observation data down to 10° with an elevation dependent weighting model.
- The two campaigns (January and June 2002) be reprocessed using the Saastamoinen / Niell (wet) mapping function combination at 10° to see if any improvements can be achieved.
- The effect and the magnitude of the seasonal bias of the NMF be investigated.
- The effect, and the feasibility, of introducing the IGS tropospheric parameters as known parameters, be investigated.
- Once the optimal a priori model/ mapping function combination is identified, data stemming from all TrigNet stations be processed with the Bernese on a daily basis by automating the procedures and options identified in this research.

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9. APPENDICES

Appendix A Summary of Data Retrieved

Table A.1	Summary of data retrieved for processing of January 2002 campaign.....	149
Table A.2	Summary of data retrieved for processing of January 2002 campaign.....	150

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APPENDIX A.1

CAMPAIGN INFORMATION							
Year/ Campaign : 2002							
Month : January							
Day of the Month	13	14	15	16	17	18	
Day of the Week	Sun/0	Mon/1	Tue/2	Wed/3	Thu/4	Fri/5	
Julian Day	013	014	015	016	017	018	
GPS Week	1149	1149	1149	1149	1149	1149	
DATA /PRODUCT TYPE	FILE NAMES						DATA SOURCE(ftp://)
Earth Rotation Parameters	cod11497.erp						ftp.unibe.ch/auib/CODE/CODwww7.
Zenith Delays							cddisa.gsfc.nasa.gov/...
Hart Rao (HRAO)	hrao1149.zpd						pub/gps/products/www/trop/sssswww
Sutherland (SUTH)	suth1149.zpd						
Orbits	cod11490.eph	cod11491.eph	cod11492.eph	cod11493.eph	cod11494.eph	cod11495.eph	ftp.unibe.ch/auib/CODE/CODwwwwd.
IONO TEC Maps	cod11490.ion	cod11491.ion	cod11492.ion	cod11493.ion	cod11494.ion	cod11495.ion	ftp.unibe.ch/auib/CODE/CODwwwwd.
Antenna Phase Centre Maps	phasc igs.01						ftp.unibe.ch/auib/BWUSER/GEN/phas
Ocean Loading Coefficients	TrigNet OL.blq						
Station Coordinates	cod11497.cdr						ftp.unibe.ch/auib/BWUSER/STA/COD
Observation Files							DATA SOURCE(ftp://)
Bloemfontein (BFJN)	bftn0130.02o	bftn0140.02o	bftn0150.02o	bftn0160.02o	bftn0170.02o	bftn0180.02o	TrigNet/%Station/%year/%month/
Durban (DRBN)	drbn0130.02o	drbn0140.02o	drbn0150.02o	drbn0160.02o	drbn0170.02o	drbn0180.02o	TrigNet/%Station/%year/%month/
East London (ELDN)	eldn0130.02o	eldn0140.02o	eldn0150.02o	eldn0160.02o	eldn0170.02o	eldn0180.02o	TrigNet/%Station/%year/%month/
George (GEOR)	geor0130.02o	geor0140.02o	geor0150.02o	geor0160.02o	geor0170.02o	geor0180.02o	TrigNet/%Station/%year/%month/
Hart Rao (HRAO)	hrao0130.02o	hrao0140.02o	hrao0150.02o	hrao0160.02o	hrao0170.02o	hrao0180.02o	cddisa.gsfc.nasa.gov/pub/gps/gpsdata/y
Pietermaritzburg (PMBG)	pmbg0013.02o	pmbg0014.02o	pmbg0015.02o	pmbg0016.02o	pmbg0017.02o	pmbg0018.02o	TrigNet/%Station/%year/%month/
Pretoria (GEOS)	geos0130.02o	geos0140.02o	geos0150.02o	geos0160.02o	geos0170.02o	geos0180.02o	TrigNet/%Station/%year/%month/
Springbok (SBOK)	sbok0130.02o	sbok0140.02o	sbok0150.02o	sbok0160.02o	sbok0170.02o	sbok0180.02o	TrigNet/%Station/%year/%month/
Sutherland (SUTH)	suth0130.02o	suth0140.02o	suth0150.02o	suth0160.02o	suth0170.02o	suth0180.02o	cddisa.gsfc.nasa.gov/pub/gps/gpsdata/
TricMowhray (TRGE)	trge0130.02o	trge0140.02o	trge0150.02o	trge0160.02o	trge0170.02o	trge0180.02o	TrigNet/%Station/%year/%month/

APPENDIX A.1

CAMPAIGN INFORMATION							
Year/ Campaign : 2002							
Month : July							
Day of the Month	24	25	26	27	28	29	
Day of the Week	Sun	Mon	Tue	Wed	Thu	Fri	
Julian Day	189	190	191	192	193	194	
GPS Week	1122						
DATA /PRODUCT TYPE	FILE NAMES						DATA SOURCE(ftp://)
Earth Rotation Parameters	COD11227.crp						ftp.unibe.ch/auib/CODE/CODwww7.
Zenith Delays							cdlisa.gsfc.nasa.gov/....
Hart Rao (HRAO)	hrai1122.zpd						pub/gps/products/www/trop/ssssww
Sutherland (SUTH)	suth1122.zpd						
Orbits	COD11220.eph	COD11221.eph	COD11222.eph	COD11223.eph	COD11223.eph	COD11224.eph	ftp.unibe.ch/auib/CODE/CODwww7d.
IONO TEC Maps	COD11220.eph	COD11221.eph	COD11222.eph	COD11223.eph	COD11223.eph	COD11224.eph	ftp.unibe.ch/auib/CODE/CODwww7d.
Antenna Phase Centre Maps	phas.igs.01						ftp.unibe.ch/auib/BWUSER/GEN/phas
Ocean Loading Coefficients	TrigNet_OL.b1q						
Station Coordinates	COD11227.crd						ftp.unibe.ch/auib/BWUSER/STA/COD
Observation Files							DATA SOURCE(ftp://)
Bloemfontein (BFTN)	bftn1890.01o	bftn1900.01o	bftn1910.01o	bftn1920.01o	bftn1930.01o	bftn1940.01o	TrigNet/%Station/%year/%month/
Durban (DRBN)	drbn1890.01o	drbn1900.01o	drbn1910.01o	drbn1920.01o	drbn1930.01o	drbn1940.01o	TrigNet/%Station/%year/%month/
East London (ELDN)	eldn1890.01o	eldn1900.01o	eldn1910.01o	eldn1920.01o	eldn1930.01o	eldn1940.01o	TrigNet/%Station/%year/%month/
George (GEOR)	geor1890.01o	geor1900.01o	geor1910.01o	geor1920.01o	geor1930.01o	geor1940.01o	TrigNet/%Station/%year/%month/
Hart Rao (HRAO)	hrai1890.01o	hrai1900.01o	hrai1910.01o	hrai1920.01o	hrai1930.01o	hrai1940.01o	cdlisa.gsfc.nasa.gov/pub/gps/gpsdata/y
Pietermaritzburg (PMBG)	pmbg1890.01o	pmbg1900.01o	pmbg1910.01o	pmbg1920.01o	pmbg1930.01o	pmbg1940.01o	TrigNet/%Station/%year/%month/
Pretoria (GEOS)	geos1890.01o	geos1900.01o	geos1910.01o	geos1920.01o	geos1930.01o	geos1940.01o	TrigNet/%Station/%year/%month/
Springbok (SBOK)	sbok1890.01o	sbok1900.01o	sbok1910.01o	sbok1920.01o	sbok1930.01o	sbok1940.01o	TrigNet/%Station/%year/%month/
Sutherland (SUTH)	suth1890.01o	suth1900.01o	suth1910.01o	suth1920.01o	suth1930.01o	suth1940.01o	cdlisa.gsfc.nasa.gov/pub/gps/gpsdata/
Trengwathley (TRGE)	trge1890.01o	trge1900.01o	trge1910.01o	trge1920.01o	trge1930.01o	trge1940.01o	TrigNet/%Station/%year/%month/

Appendix B : Sample Troposphere Parameter Output Files

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APPENDIX B1

AMBIGUITY FREE SOLUTION 1172_1 24 JUNE 2002

01-AUG-02 20:30

A PRIORI MODEL:		0	MAPPING FUNCTION:		3	GRADIENT MODEL:		1	MIN. ELEVATION:		5				
STATION NAME	FLG	YYYY MM DD HH MM SS	YYYY MM DD HH MM SS	MOD_U	CORR_U	SIGMA_U	TOTAL_U	CORR_N	SIGMA_N	CORR_E	SIGMA_E				
BLOEMFONTEIN	F	2002 06 23 23 59 56	2002 06 24 01 00 00	0.0000	2.03132	0.00098	2.03132	-0.00022	0.00004	-0.00076	0.00004				
BLOEMFONTEIN	F	2002 06 24 01 00 00	2002 06 24 02 00 00	0.0000	2.03295	0.00084	2.03295	-0.00022	0.00004	-0.00076	0.00004				
BLOEMFONTEIN	F	2002 06 24 02 00 00	2002 06 24 03 00 00	0.0000	2.03561	0.00070	2.03561	-0.00022	0.00004	-0.00076	0.00004				
BLOEMFONTEIN	F	2002 06 24 03 00 00	2002 06 24 04 00 00	0.0000	2.03717	0.00077	2.03717	-0.00022	0.00004	-0.00076	0.00004				
BLOEMFONTEIN	F	2002 06 24 04 00 00	2002 06 24 05 00 00	0.0000	2.04716	0.00084	2.04716	-0.00022	0.00004	-0.00076	0.00004				
BLOEMFONTEIN	F	2002 06 24 05 00 00	2002 06 24 06 00 00	0.0000	2.04527	0.00090	2.04527	-0.00022	0.00004	-0.00076	0.00004				
BLOEMFONTEIN	F	2002 06 24 06 00 00	2002 06 24 07 00 00	0.0000	2.04246	0.00076	2.04246	-0.00022	0.00004	-0.00076	0.00004				
BLOEMFONTEIN	F	2002 06 24 07 00 00	2002 06 24 08 00 00	0.0000	2.04704	0.00078	2.04704	-0.00022	0.00004	-0.00076	0.00004				
BLOEMFONTEIN	F	2002 06 24 08 00 00	2002 06 24 09 00 00	0.0000	2.04767	0.00076	2.04767	-0.00022	0.00004	-0.00076	0.00004				
BLOEMFONTEIN	F	2002 06 24 09 00 00	2002 06 24 10 00 00	0.0000	2.04422	0.00078	2.04422	-0.00022	0.00004	-0.00076	0.00004				
BLOEMFONTEIN	F	2002 06 24 10 00 00	2002 06 24 11 00 00	0.0000	2.04308	0.00081	2.04308	-0.00022	0.00004	-0.00076	0.00004				
BLOEMFONTEIN	F	2002 06 24 11 00 00	2002 06 24 12 00 00	0.0000	2.04211	0.00083	2.04211	-0.00022	0.00004	-0.00076	0.00004				
BLOEMFONTEIN	F	2002 06 24 12 00 00	2002 06 24 12 59 59	0.0000	2.03750	0.00070	2.03750	-0.00022	0.00004	-0.00076	0.00004				
BLOEMFONTEIN	F	2002 06 24 12 59 59	2002 06 24 13 59 59	0.0000	2.03710	0.00067	2.03710	-0.00022	0.00004	-0.00076	0.00004				
BLOEMFONTEIN	F	2002 06 24 13 59 59	2002 06 24 14 59 59	0.0000	2.04057	0.00082	2.04057	-0.00022	0.00004	-0.00076	0.00004				
BLOEMFONTEIN	F	2002 06 24 14 59 59	2002 06 24 15 59 59	0.0000	2.03232	0.00078	2.03232	-0.00022	0.00004	-0.00076	0.00004				
BLOEMFONTEIN	F	2002 06 24 15 59 59	2002 06 24 16 59 59	0.0000	2.03051	0.00081	2.03051	-0.00022	0.00004	-0.00076	0.00004				
BLOEMFONTEIN	F	2002 06 24 16 59 59	2002 06 24 17 59 59	0.0000	2.02921	0.00073	2.02921	-0.00022	0.00004	-0.00076	0.00004				
BLOEMFONTEIN	F	2002 06 24 17 59 59	2002 06 24 18 59 59	0.0000	2.02838	0.00074	2.02838	-0.00022	0.00004	-0.00076	0.00004				
BLOEMFONTEIN	F	2002 06 24 18 59 59	2002 06 24 19 59 59	0.0000	2.03309	0.00085	2.03309	-0.00022	0.00004	-0.00076	0.00004				
BLOEMFONTEIN	F	2002 06 24 19 59 59	2002 06 24 20 59 59	0.0000	2.03541	0.00074	2.03541	-0.00022	0.00004	-0.00076	0.00004				
BLOEMFONTEIN	F	2002 06 24 20 59 59	2002 06 24 21 59 59	0.0000	2.03049	0.00072	2.03049	-0.00022	0.00004	-0.00076	0.00004				
BLOEMFONTEIN	F	2002 06 24 21 59 59	2002 06 24 22 59 59	0.0000	2.03356	0.00080	2.03356	-0.00022	0.00004	-0.00076	0.00004				
BLOEMFONTEIN	F	2002 06 24 22 59 59	2002 06 25 00 00 03	0.0000	2.02892	0.00082	2.02892	-0.00022	0.00004	-0.00076	0.00004				

APPENDIX B2

AMBIGUITY FREE SOLUTION 1172_1 24 JUNE 2002

01-AUG-02 21:53

A PRIORI MODEL: 0 MAPPING FUNCTION: 3 GRADIENT MODEL: 0 MIN. ELEVATION: 5

STATION NAME	FLG	YYYY MM DD HH MM SS	YYYY MM DD HH MM SS	MOD_U	CORR_U	SIGMA_U	TOTAL_U	CORR_N	SIGMA_N	CORR_E	SIGMA_E
BLOEMFONTEIN	F	2002 06 23 23 59 56	2002 06 24 01 00 00	0.0000	2.03266	0.00087	2.03266				
BLOEMFONTEIN	F	2002 06 24 01 00 00	2002 06 24 02 00 00	0.0000	2.03185	0.00068	2.03185				
BLOEMFONTEIN	F	2002 06 24 02 00 00	2002 06 24 03 00 00	0.0000	2.03599	0.00051	2.03599				
BLOEMFONTEIN	F	2002 06 24 03 00 00	2002 06 24 04 00 00	0.0000	2.03707	0.00060	2.03707				
BLOEMFONTEIN	F	2002 06 24 04 00 00	2002 06 24 05 00 00	0.0000	2.04841	0.00068	2.04841				
BLOEMFONTEIN	F	2002 06 24 05 00 00	2002 06 24 06 00 00	0.0000	2.04556	0.00074	2.04556				
BLOEMFONTEIN	F	2002 06 24 06 00 00	2002 06 24 07 00 00	0.0000	2.04421	0.00056	2.04421				
BLOEMFONTEIN	F	2002 06 24 07 00 00	2002 06 24 08 00 00	0.0000	2.04889	0.00060	2.04889				
BLOEMFONTEIN	F	2002 06 24 08 00 00	2002 06 24 09 00 00	0.0000	2.04970	0.00058	2.04970				
BLOEMFONTEIN	F	2002 06 24 09 00 00	2002 06 24 10 00 00	0.0000	2.04642	0.00063	2.04642				
BLOEMFONTEIN	F	2002 06 24 10 00 00	2002 06 24 11 00 00	0.0000	2.04456	0.00065	2.04456				
BLOEMFONTEIN	F	2002 06 24 11 00 00	2002 06 24 12 00 00	0.0000	2.04356	0.00068	2.04356				
BLOEMFONTEIN	F	2002 06 24 12 00 00	2002 06 24 12 59 59	0.0000	2.03908	0.00051	2.03908				
BLOEMFONTEIN	F	2002 06 24 12 59 59	2002 06 24 13 59 59	0.0000	2.03592	0.00047	2.03592				
BLOEMFONTEIN	F	2002 06 24 13 59 59	2002 06 24 14 59 59	0.0000	2.04124	0.00068	2.04124				
BLOEMFONTEIN	F	2002 06 24 14 59 59	2002 06 24 15 59 59	0.0000	2.03327	0.00061	2.03327				
BLOEMFONTEIN	F	2002 06 24 15 59 59	2002 06 24 16 59 59	0.0000	2.03076	0.00064	2.03076				
BLOEMFONTEIN	F	2002 06 24 16 59 59	2002 06 24 17 59 59	0.0000	2.02824	0.00056	2.02824				
BLOEMFONTEIN	F	2002 06 24 17 59 59	2002 06 24 18 59 59	0.0000	2.03024	0.00053	2.03024				
BLOEMFONTEIN	F	2002 06 24 18 59 59	2002 06 24 19 59 59	0.0000	2.03484	0.00066	2.03484				
BLOEMFONTEIN	F	2002 06 24 19 59 59	2002 06 24 20 59 59	0.0000	2.03696	0.00053	2.03696				
BLOEMFONTEIN	F	2002 06 24 20 59 59	2002 06 24 21 59 59	0.0000	2.03198	0.00054	2.03198				
BLOEMFONTEIN	F	2002 06 24 21 59 59	2002 06 24 22 59 59	0.0000	2.03381	0.00064	2.03381				
BLOEMFONTEIN	F	2002 06 24 22 59 59	2002 06 25 00 00 03	0.0000	2.03034	0.00065	2.03034				

APPENDIX B3

AMBIGUITY FREE SOLUTION

06-AUG-02 20:50

A PRIORI MODEL: -1 MAPPING FUNCTION: 1 GRADIENT MODEL: 0 MIN. ELEVATION: 5

STATION NAME	FLG	YYYY MM DD HH MM SS	YYYY MM DD HH MM SS	MOD_U	CORR_U	SIGMA_U	TOTAL_U	CORR_N	SIGMA_N	CORR_E	SIGMA_E
BLOEMFONTEIN	F	2002 06 23 23 59 56	2002 06 24 01 00 00	1.9789	0.06511	0.00072	2.04402				
BLOEMFONTEIN	F	2002 06 24 01 00 00	2002 06 24 02 00 00	1.9789	0.07062	0.00055	2.04953				
BLOEMFONTEIN	F	2002 06 24 02 00 00	2002 06 24 03 00 00	1.9789	0.06031	0.00042	2.03922				
BLOEMFONTEIN	F	2002 06 24 03 00 00	2002 06 24 04 00 00	1.9789	0.06291	0.00049	2.04182				
BLOEMFONTEIN	F	2002 06 24 04 00 00	2002 06 24 05 00 00	1.9789	0.07427	0.00056	2.05318				
BLOEMFONTEIN	F	2002 06 24 05 00 00	2002 06 24 06 00 00	1.9789	0.07212	0.00061	2.05103				
BLOEMFONTEIN	F	2002 06 24 06 00 00	2002 06 24 07 00 00	1.9789	0.07189	0.00046	2.05080				
BLOEMFONTEIN	F	2002 06 24 07 00 00	2002 06 24 08 00 00	1.9789	0.07778	0.00049	2.05669				
BLOEMFONTEIN	F	2002 06 24 08 00 00	2002 06 24 09 00 00	1.9789	0.07643	0.00048	2.05534				
BLOEMFONTEIN	F	2002 06 24 09 00 00	2002 06 24 10 00 00	1.9789	0.07632	0.00051	2.05523				
BLOEMFONTEIN	F	2002 06 24 10 00 00	2002 06 24 11 00 00	1.9789	0.07031	0.00054	2.04922				
BLOEMFONTEIN	F	2002 06 24 11 00 00	2002 06 24 12 00 00	1.9789	0.07073	0.00056	2.04964				
BLOEMFONTEIN	F	2002 06 24 12 00 00	2002 06 24 12 59 59	1.9789	0.06596	0.00042	2.04487				
BLOEMFONTEIN	F	2002 06 24 12 59 59	2002 06 24 13 59 59	1.9789	0.06781	0.00038	2.04672				
BLOEMFONTEIN	F	2002 06 24 13 59 59	2002 06 24 14 59 59	1.9789	0.06791	0.00056	2.04682				
BLOEMFONTEIN	F	2002 06 24 14 59 59	2002 06 24 15 59 59	1.9789	0.06081	0.00050	2.03972				
BLOEMFONTEIN	F	2002 06 24 15 59 59	2002 06 24 16 59 59	1.9789	0.06690	0.00052	2.04581				
BLOEMFONTEIN	F	2002 06 24 16 59 59	2002 06 24 17 59 59	1.9789	0.06028	0.00045	2.03919				
BLOEMFONTEIN	F	2002 06 24 17 59 59	2002 06 24 18 59 59	1.9789	0.06176	0.00043	2.04067				
BLOEMFONTEIN	F	2002 06 24 18 59 59	2002 06 24 19 59 59	1.9789	0.07349	0.00054	2.05240				
BLOEMFONTEIN	F	2002 06 24 19 59 59	2002 06 24 20 59 59	1.9789	0.06783	0.00043	2.04674				
BLOEMFONTEIN	F	2002 06 24 20 59 59	2002 06 24 21 59 59	1.9789	0.06428	0.00044	2.04319				
BLOEMFONTEIN	F	2002 06 24 21 59 59	2002 06 24 22 59 59	1.9789	0.06989	0.00052	2.04880				
BLOEMFONTEIN	F	2002 06 24 22 59 59	2002 06 25 00 00 03	1.9789	0.06659	0.00052	2.04550				

Appendix C : Final coordinates

Table C.1	Final weighted coordinates from the SANG10 strategy,.....	156
Table C.2	Final weighted coordinates from of AUSPOS and AG,.....	157

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APPENDIX C1

SANG10 (FINAL COORDINATES) EPOCH: 2002-01-13 11:59:45

*RMS :are formal RMS values from the combined normal equations

	X RMS	Y RMS	Z RMS	Latitude RMS	Longitude RMS	Height RMS
BFTN	5001111.7949	2471465.7658	-3084618.5030	29 06 13.25175	26 17 52.12294	1380.6153
	0.0003	0.0001	0.0002	0.0001	0.0001	0.0004
DREN	4742985.5542	2843868.5022	-3167037.3655	29 57 54.04068	30 56 48.02664	46.3781
	0.0003	0.0002	0.0002	0.0001	0.0001	0.0004
ELDN	4733299.6790	2498614.5724	-3457594.0007	33 02 17.27098	27 49 43.24903	164.1225
	0.0003	0.0001	0.0002	0.0001	0.0001	0.0004
GEOR	4894604.9265	2015576.0506	-3546707.4893	34 00 05.09970	22 22 53.90868	233.6481
	0.0003	0.0001	0.0002	0.0001	0.0001	0.0004
GEOS	5064032.2356	2724720.7686	-2752950.9428	25 43 55.30055	28 16 57.47906	1387.3044
	0.0003	0.0002	0.0002	0.0001	0.0001	0.0004
HRAO	5085352.4675	2668395.7481	-2768731.5755	25 53 24.37938	27 41 13.12708	1414.1390
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
PMBG	4788546.6585	2807544.1247	-3132334.9825	29 36 02.61765	30 22 59.76164	743.9770
	0.0003	0.0002	0.0002	0.0001	0.0001	0.0004
SBOK	5279491.9778	1703114.1305	-3139093.0806	29 40 09.57369	17 52 45.15501	1043.0484
	0.0004	0.0002	0.0002	0.0001	0.0001	0.0005
SUTH	5041274.8246	1916054.0756	-3397075.9826	32 22 48.75986	20 48 37.66297	1799.7449
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TRGE	5023564.6212	1677795.0933	-3542026.1044	33 57 05.16772	18 28 06.76136	83.6821
	0.0004	0.0002	0.0003	0.0001	0.0001	0.0005

SANG10 (FINAL COORDINATES) EPOCH: 2002-06-26 11:59:45

	X RMS	Y RMS	Z RMS	Latitude RMS	Longitude RMS	Height RMS
BFTN	5001111.8050	2471465.7841	-3084618.5274	29 06 13.25218	26 17 52.1234	1380.6422
	0.0002	0.0001	0.0001	0.0001	0.0001	0.0002
DREN	4742985.5555	2843868.5126	-3167037.3883	29 57 54.04122	30 56 48.0270	46.3951
	0.0002	0.0001	0.0001	0.0001	0.0001	0.0002
ELDN	4733299.6859	2498614.5896	-3457594.0236	33 02 17.27137	27 49 43.2495	164.1468
	0.0002	0.0001	0.0001	0.0001	0.0001	0.0002
GEOR	4894604.9370	2015576.0689	-3546707.5161	34 00 05.10013	22 22 53.9092	233.6769
	0.0002	0.0001	0.0001	0.0001	0.0001	0.0003
GEOS	5064032.2375	2724720.7833	-2752950.9597	25 43 55.30092	28 16 57.4795	1387.3196
	0.0002	0.0001	0.0001	0.0001	0.0001	0.0003
HRAO	5085352.4768	2668395.7672	-2768731.5984	25 53 24.37981	27 41 13.1275	1414.1644
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
PMBG	4788546.6571	2807544.1356	-3132335.0035	29 36 02.61817	30 22 59.7620	743.9911
	0.0002	0.0001	0.0001	0.0001	0.0001	0.0002
SBOK	5279491.9957	1703114.1505	-3139093.1054	29 40 09.57402	17 52 45.1555	1043.0808
	0.0002	0.0001	0.0001	0.0001	0.0001	0.0003
SUTH	5041274.8482	1916054.0913	-3397076.0123	32 22 48.76019	20 48 37.6632	1799.7841
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
TRGE	5023564.6354	1677795.1096	-3542026.1352	33 57 05.16822	18 28 06.7618	83.7147
	0.0002	0.0001	0.0001	0.0001	0.0001	0.0002

APPENDIX C2

AUSPOS Results, EPOCH: 2002-01-13 11:59:45

	X	Y	Z	Latitude	Longitude	Height
BFTN	5001111.8040	2471465.7850	-3084618.5210	29 06 13.2520	26 17 52.1234	1380.6386
DREN	4742985.5610	2843868.5080	-3167037.3780	29 57 54.0409	30 56 48.0267	46.3920
ELDN	4733299.6910	2498614.5890	-3457594.0130	33 02 17.2710	27 49 43.2494	164.1446
GEOR	4894604.9320	2015576.0710	-3546707.5000	34 00 05.0998	22 22 53.9093	233.6648
GEOS	5064032.2450	2724720.7850	-2752950.9630	25 43 55.3009	28 16 57.4794	1387.3277
HRAO	5085352.4840	2668395.7710	-2768731.5980	25 53 24.3797	27 41 13.1275	1414.1715
PMBG	4788546.6690	2807544.1370	-3132335.0010	29 36 02.6179	30 22 59.7618	743.9994
SBOK	5279491.9830	1703114.1550	-3139093.0980	29 40 09.5740	17 52 45.1558	1043.0678
SUTH	5041274.8430	1916054.0960	-3397076.0070	32 22 48.7601	20 48 37.6635	1799.7786
TRGE	5023564.6300	1677795.1180	-3542026.1180	33 57 05.1678	18 28 06.7622	83.7030

AG Results , EPOCH: 2002-01-13 11:59:45

BFTN	5001111.8048	2471465.7721	-3084618.5229	29 06 13.2521	26 17 52.1230	1380.6352
DREN	4742985.5516	2843868.5078	-3167037.3800	29 57 54.0411	30 56 48.0269	46.3859
ELDN	4733299.6742	2498614.5717	-3457594.0117	33 02 17.2714	27 49 43.2491	164.1246
GEOR	4894604.9273	2015576.0539	-3546707.5038	34 00 05.1001	22 22 53.9088	233.6579
GEOS	5064032.2419	2724720.7838	-2752950.9622	25 43 55.3009	28 16 57.4794	1387.3243
HRAO						
PMBG	4788546.6554	2807544.1300	-3132334.9960	29 36 02.6180	30 22 59.7619	743.9836
SBOK	5279491.9828	1703114.1389	-3139093.0981	29 40 09.5741	17 52 45.1552	1043.0634
SUTH	5041274.8330	1916054.0824	-3397075.9941	32 22 48.7600	20 48 37.6631	1799.7600
TRGE	5023564.6284	1677795.1006	-3542026.1201	33 57 05.1680	18 28 06.7615	83.6984

AUSPOS Results, Epoch: 2002-06-26 11:59:45

BFTN	5001111.8070	2471465.7930	-3084618.5170	29 06 13.2518	26 17 52.1236	1380.6421
DREN	4742985.5500	2843868.5160	-3167037.3710	29 57 54.0408	30 56 48.0272	46.3838
ELDN	4733299.6860	2498614.5990	-3457594.0080	33 02 17.2709	27 49 43.2498	164.1421
GEOR	4894604.9370	2015576.0850	-3546707.5010	34 00 05.0996	22 22 53.9098	233.6736
GEOS	5064032.2370	2724720.7900	-2752950.9490	25 43 55.3006	28 16 57.4797	1387.3174
HRAO	5085352.4830	2668395.7790	-2768731.5910	25 53 24.3794	27 41 13.1278	1414.1710
PMBG	4788546.6560	2807544.1430	-3132334.9900	29 36 02.6177	30 22 59.7623	743.9868
SBOK	5279491.9950	1703114.1700	-3139093.0960	29 40 09.5737	17 52 45.1562	1043.0808
SUTH	5041274.8480	1916054.1060	-3397076.0020	32 22 48.7598	20 48 37.6637	1799.7829
TRGE	5023564.6390	1677795.1320	-3542026.1220	33 57 05.1677	18 28 06.7626	83.7160

AG Results , Epoch: 2002-06-26 11:59:45

BFTN	5001111.7809	2471465.7836	-3084618.5073	29 06 13.2519	26 17 52.1238	1380.6134
DREN	4742985.5307	2843868.5118	-3167037.3678	29 57 54.0410	30 56 48.0274	46.3661
ELDN	4733299.6575	2498614.5842	-3457593.9971	33 02 17.2711	27 49 43.2498	164.1092
GEOR	4894604.9094	2015576.0666	-3546707.4899	34 00 05.0999	22 22 53.9095	233.6404
GEOS	5064032.2144	2724720.7842	-2752950.9427	25 43 55.3007	28 16 57.4799	1387.2943
HRAO	5085352.4707	2668395.7735	-2768731.5725	25 53 24.3791	27 41 13.1278	1414.1510
PMBG	4788546.6324	2807544.1338	-3132334.9826	29 36 02.6179	30 22 59.7624	743.9614
SBOK	5279491.9649	1703114.1495	-3139093.0811	29 40 09.5738	17 52 45.1558	1043.0431
SUTH	5041274.8347	1916054.0955	-3397075.9825	32 22 48.7596	20 48 37.6636	1799.7590
TRGE	5023564.6058	1677795.1104	-3542026.1098	33 57 05.1680	18 28 06.7622	83.6774

APPENDIX D: Datum Transformation Parameters (between SANG10 Jan and June).

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APPENDIX D1

HELMERT TRANSFORMATION

FILE 1: COMBINED SOL. FOR 13-18 JAN 2002 SANG10 AD 2 FIX

FILE 2: COMBINED SOL. FOR 24-29 JUN 2002 SANG10 AD 2 FIX

LOCAL GEODETIC DATUM: WGS - 84

RESIDUALS IN LOCAL SYSTEM (NORTH, EAST, UP)

NUM	NAME	FLG	RESIDUALS IN MILLIMETERS		
1	BLOEMFONTEIN	M M	-0.9	-1.8	0.0
6	HRAO 30302M004	F F	-1.9	-2.7	2.7
7	PIETERMARITZBURG	M M	3.1	-0.5	11.1
2	DURBAN	M M	3.6	0.9	5.0
3	EASTLONDON	M M	0.0	-2.4	1.7
4	GEORGE	M M	1.6	-1.2	-3.7
9	SUTH 30314M002	F F	-1.9	6.4	-10.7
5	GEOSCIENCE	M M	-3.1	-2.2	10.3
8	SPRINGBOK	M M	-4.4	0.7	-7.7
10	TRGEMOWBRAY	M M	3.8	2.7	-8.6
RMS / COMPONENT			2.9	2.8	7.6

NUMBER OF PARAMETERS : 3

NUMBER OF COORDINATES : 30

RMS OF TRANSFORMATION : 5.0 MM

PARAMETERS:

TRANSLATION IN X : 13.3 +- 1.6 MM
 TRANSLATION IN Y : -10.6 +- 1.6 MM
 TRANSLATION IN Z : -28.5 +- 1.6 MM

NUMBER OF ITERATIONS : 2

APPENDIX D2

HELMERT TRANSFORMATION

FILE 1: COMBINED SOL. FOR 13-18 JAN 2002 SANG10 AD 2 FIX
 FILE 2: COMBINED SOL. FOR 24-29 JUN 2002 SANG10 AD 2 FIX

LOCAL GEODETIC DATUM: WGS - 84
 RESIDUALS IN LOCAL SYSTEM (NORTH, EAST, UP)

NUM	NAME	FLG	RESIDUALS IN MILLIMETERS		
1	BLOEMFONTEIN	M M	-0.3	-1.4	0.1
6	HRAO 30302M004	F F	-0.1	-1.8	2.7
7	PIETERMARITZBURG	M M	3.4	1.4	11.1
2	DURBAN	M M	3.7	2.9	5.0
3	EASTLONDON	M M	-1.0	-1.5	1.8
4	GEORGE	M M	0.2	-2.1	-3.7
9	SUTH 30314M002	F F	-2.7	5.0	-10.7
5	GEOSCIENCE	M M	-1.2	-1.1	10.3
8	SPRINGBOK	M M	-4.2	-1.8	-7.7
10	TRGEMOWBRAY	M M	2.3	0.5	-8.7
RMS / COMPONENT			2.5	2.4	7.6

NUMBER OF PARAMETERS : 4
 NUMBER OF COORDINATES : 30
 RMS OF TRANSFORMATION : 4.9 MM

PARAMETERS:

TRANSLATION IN X : 13.3 +- 1.6 MM
 TRANSLATION IN Y : -10.6 +- 1.6 MM
 TRANSLATION IN Z : -28.5 +- 1.6 MM
 SCALE FACTOR : -0.0036 +- 0.0029 MM/KM

NUMBER OF ITERATIONS : 2

APPENDIX D3

HELMERT TRANSFORMATION

FILE 1: COMBINED SOL. FOR 13-18 JAN 2002 SANG10 AD 2 FIX
 FILE 2: COMBINED SOL. FOR 24-29 JUN 2002 SANG10 AD 2 FIX

LOCAL GEODETIC DATUM: WGS - 84
 RESIDUALS IN LOCAL SYSTEM (NORTH, EAST, UP)

NUM	NAME	FLG	RESIDUALS IN MILLIMETERS		
1	BLOEMFONTEIN	M M	-0.3	-1.0	-2.0
6	HRAO 30302M004	F F	-0.8	-0.5	-4.3
7	PIETERMARITZBURG	M M	2.1	1.6	10.0
2	DURBAN	M M	2.2	3.0	4.5
3	EASTLONDON	M M	-1.5	-2.2	5.9
4	GEORGE	M M	0.9	-3.2	1.9
9	SUTH 30314M002	F F	-1.6	4.4	-7.5
5	GEOSCIENCE	M M	-2.1	0.2	3.0
8	SPRINGBOK	M M	-2.6	-1.7	-8.6
10	TRGEMOWBRAY	M M	3.6	-0.6	-3.0
RMS / COMPONENT			2.1	2.4	6.0

NUMBER OF PARAMETERS : 6
 NUMBER OF COORDINATES : 30
 RMS OF TRANSFORMATION : 4.2 MM

PARAMETERS:

TRANSLATION IN X : 13.3 +- 1.3 MM
 TRANSLATION IN Y : -10.6 +- 1.3 MM
 TRANSLATION IN Z : -28.5 +- 1.3 MM
 ROTATION AROUND Y-AXIS: 0 0 0.0029 +- 0.0009 "
 ROTATION AROUND Z-AXIS: 0 0 0.0005 +- 0.0005 "
 SCALE FACTOR : -0.0036 +- 0.0024 MM/KM

NUMBER OF ITERATIONS : 2

APPENDIX D4

HELMERT TRANSFORMATION

FILE 1: COMBINED SOL. FOR 13-18 JAN 2002 SANG10 AD 2 FIX
 FILE 2: COMBINED SOL. FOR 24-29 JUN 2002 SANG10 AD 2 FIX

LOCAL GEODETIC DATUM: WGS - 84
 RESIDUALS IN LOCAL SYSTEM (NORTH, EAST, UP)

NUM	NAME	FLG	RESIDUALS IN MILLIMETERS		
1	BLOEMFONTEIN	M M	-0.3	-1.1	-1.6
6	HRAO 30302M004	F F	-0.1	-1.8	-1.1
7	PIETERMARITZBURG	M M	3.4	1.4	3.5
2	DURBAN	M M	3.7	2.9	-3.4
3	EASTLONDON	M M	-1.0	-1.3	-2.0
4	GEORGE	M M	0.2	-2.1	0.2
9	SUTH 30314M002	F F	-2.7	5.1	-4.5
5	GEOSCIENCE	M M	-1.2	-1.2	5.5
8	SPRINGBOK	M M	-4.2	-2.0	2.9
10	TRGEMOWBRAY	M M	2.3	0.1	0.6
RMS / COMPONENT			2.5	2.4	3.2

NUMBER OF PARAMETERS : 5
 NUMBER OF COORDINATES : 30
 RMS OF TRANSFORMATION : 2.8 MM

PARAMETERS:

TRANSLATION IN X : 13.3 +- 0.9 MM
 TRANSLATION IN Y : -10.6 +- 0.9 MM
 TRANSLATION IN Z : -28.5 +- 0.9 MM
 ROTATION AROUND X-AXIS: - 0 0 0.0031 +- 0.0004 "
 SCALE FACTOR : -0.0036 +- 0.0017 MM/KM

NUMBER OF ITERATIONS : 2

APPENDIX D5

HELMERT TRANSFORMATION

FILE 1: COMBINED SOL. FOR 13-18 JAN 2002 SANG10 AD 2 FIX

FILE 2: COMBINED SOL. FOR 24-29 JUN 2002 SANG10 AD 2 FIX

LOCAL GEODETIC DATUM: WGS - 84

RESIDUALS IN LOCAL SYSTEM (NORTH, EAST, UP)

NUM	NAME	FLG	RESIDUALS IN MILLIMETERS		
1	BLOEMFONTEIN	M M	-0.5	-0.7	-2.1
6	HRAO 30302M004	F F	-0.8	-0.6	-3.1
7	PIETERMARITZBURG	M M	2.1	1.6	4.0
2	DURBAN	M M	2.3	3.0	-2.6
3	EASTLONDON	M M	-1.6	-2.1	-0.1
4	GEORGE	M M	0.8	-3.1	1.7
9	SUTH 30314M002	F F	-1.7	4.5	-4.1
5	GEOSCIENCE	M M	-2.0	0.1	3.6
8	SPRINGBOK	M M	-2.5	-1.9	1.3
10	TRGEMOWBRAY	M M	3.8	-0.8	1.5
RMS / COMPONENT			2.1	2.4	2.9

NUMBER OF PARAMETERS : 7

NUMBER OF COORDINATES : 30

RMS OF TRANSFORMATION : 2.7 MM

PARAMETERS:

TRANSLATION IN X : 13.3 +- 0.8 MM
 TRANSLATION IN Y : -10.6 +- 0.8 MM
 TRANSLATION IN Z : -28.5 +- 0.8 MM
 ROTATION AROUND X-AXIS: - 0 0 0.0027 +- 0.0005 "
 ROTATION AROUND Y-AXIS: 0 0 0.0010 +- 0.0006 "
 ROTATION AROUND Z-AXIS: 0 0 0.0005 +- 0.0003 "
 SCALE FACTOR : -0.0036 +- 0.0016 MM/KM

NUMBER OF ITERATIONS : 2