Setting–up of GPS Reference Stations and Investigating the Effects of Antenna Radome

by

Godfrey Onyango Ogonda

A thesis submitted in partial fulfilment for the requirements
of admission into the Ph.D. studies in Navigation,
Institute of Navigation
University of Stuttgart

August, 2003

ABSTRACT

With the shutting down of Selective Availability (S/A) in year 2000 , accuracies as better as 5 to 9 metres in the horizontal and 8 to 9 metres in the vertical have been guaranteed in GPS positioning using code measurements in Single point Positioning (SPP) mode. Although the accuracies attainable through unassisted SPP are sufficient for most applications such as navigation, GIS and recreation, a whole range of experience has shown that millimetre accuracies can be attained through performance of GPS surveys using enhanced satellite systems, improved equipment and streamlined field procedures. Such concepts include the tendency to use reference stations (i.e. relative Positioning) to generate DGPS corrections and maintenance of reference frames.

The precisions and accuracies at which the reference stations are established and monitored are very high. All the possible sources of error to which the antennas and receivers at the site are susceptible to, must be identified and minimised or eliminated. This include Phase Centre Variation (PCV) and multipath. To protect the antennas from bad weather and vandalism, reference station antennas are usually covered. The PCV patterns are further complicated from the fact that addition of antenna covers (radomes) are known to have effects on the positions and the existence of several correction models.

In this study, two reference stations were established and an investigation on the effect of conical radome on one of the reference stations was carried out. A baseline of about 5 metres was set-up on top of the building housing the Institute of Navigation on *Breitscheid 2*. At one end of the baseline was station 1, mounted with a choke ring antenna, and the other end station 2, mounted with a compact L1/L2 antenna. Twenty four hour GPS observations at a data rate of 2 seconds were carried out in six consecutive days. The antenna setting for every two days was the same. Part of the data files collected on day 1 was used to fix the positions of the two reference stations with respect to the SAPOS network. A further analysis was done with the six day data files to determine the effect of the radome and the radome mount plate on station 1.

The solutions obtained show that the reference stations were successfully established and that the conical radome has a negligible effect of about 1.5 mm on the height component of station 1.

ZUSAMMENFASSUNG

Die Ausschaltung von *Selective Availability* (S/A) im Jahr 2000 ermöglicht bessere Genauigkeiten (5m bis 9m in der Horizontal und 8m bis 9m in der Vertikal) in einzelpunkten GPS-Positionierung mit Code Beobachtungen zu erreichen. Obwohl die Genauigkeiten erreicht, sind für meiste Anwendung des GPS zum Beispiel im GIS, Navigation und Freizeitgestaltungen hinlänglich, um mm-Genauigkeit zu bekommen, man muß GPS Positionierung mit weiterentwickelt Satellitensystem, aufgebessert Geräte und windschnittige (windschlüpfige) Beobachtungsverfahren machen. Beispiele Konzepte sind die Benutzung von Referenzstationen (bzw. Relative Positionierung) um DGPS Korrekturdaten zu generieren und die Erhaltung von Referenzsystemen.

Die Präzision und Genauigkeiten der Einrichtung von Referenzstationen sind hoch. Man muß alle möglichen Antennen- und Empfänger-fehlereinflüsse eliminieren. Die Phasen Zentrum Variationen (PCV) und Mehrwegeeffekt eingeschlossen. Um die Antennen von Unwetter und mutwillige Zerstörung zu schützen, sind sie manchmal bedeckt. Aber Einfügung von Antennenbedeckungen (Radome) macht die PCV-Schemata noch kompliziert. Wir Wissen schon daß die Einfügung der Radome verändert die PCV-Schemata und daß es verschiedene PCV-Korrekturmodellen gibt.

In dieser Arbeit sind die Einrichtung zweien GPS-Referenzstationen gemacht und der Einfluß eines Radoms untersucht. Auf dem Dach des Institutsgebäudes ist eine Basislinie circa 5m mit zwei Antennen, eine Choke-Ring und eine Compact L1/L2, ausgerüstet. Insgesamt sind sechs mal 24 Stunde GPS-Daten mit einer Datenrate von 2 Sekunden durchgeführt und aufgezeichnet. Der Aufbau der Antennen waren gleich für jeden zwei-täglich Datenblöcke. Die erste Teil der Aufgabe war die Bestimmung der Position zweier Referenzstationen bezüglich des SAPOS Netzes. Die zweite Teil war die Untersuchung zum Einfluß des Antennenradoms der Choke-Ring Antenne.

Die Auflösungen zeigt daß die Einrichtung zweier Referenzstationen erledigt ist und daß der Einfluß des Antennenradoms im Höhe etwa 1,5 mm ist und er geringfügig ist.

ACKNOWLEDGEMENTS

I would like to acknowledge the encouragement, support, suggestions and criticisms of all individuals and groups who directly and indirectly contributed to the completion of this study. My first sincere gratitude are to Prof. Dr.-Ing. A. Kleusberg for having accepted me as his student thereby giving me an opportunity to study at the Institute of Navigation, University of Stuttgart. His support, guidance, valuable suggestions and concern for my welfare were of immense importance to this research.

Special thanks to all the staff members of the Institute of Navigation, University of Stuttgart and more specifically to Dr. -Ing. K-H. Thiel for having facilitated the necessary setting-up of the project and to Dipl. –Ing. Alexandra Seifert who introduced me to the equipment and software used in the research.

I am also grateful to DAAD for having granted me a scholarship to pursue my studies at the University of Stuttgart. Your gracious financial support that enabled me to travel and stay in Stuttgart can never be forgotten.

Last but not least, I would like to extend my special thanks to my wife Carren, all my friends and Kenyan colleagues in Stuttgart Charles Wasomi, Kevin Nyabuto, Alex Khaemba and Stephen Arowo. Your company, friendship, support and encouragement in times of need was invaluable in my stay, study and research. May God bless you all.

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

CHAPTER ONE

1. INTRODUCTION

The technique of positioning using satellite-based radio-positioning and time transfer systems has the advantages of; being globally accessible, functioning independent of local weather conditions and being able to provide three-dimensional position, velocity and time in a common reference system anywhere on or near the surface of the earth, on a continuous basis.

Several satellite positioning systems or Global Navigation Satellite Systems (GNSS) as they are collectively known, have been in operation while more are still being developed. Examples of such systems include, the now obsolete Navy Navigation Satellite System (NNSS) and the widely used Navigation Satellite Timing and Ranging (NAVSTAR) Global Positioning System (GPS) developed and maintained by the US department of defence (Parkinson and Spilker, 1996). Others are, the GLObal NAvigation Satellite System (GLONASS) developed by the Russian Federation which further improved the situation by increasing the satellite availability, and GALILEO, being developed by the European Space Agency (ESA) in corporation with the European Union which is projected to start operating by the year 2008 and will also add more strength into the system. Although they are different, the basic principles of their design and operation are similar and consist of the space segments, the control segments and the user segments, details of which are covered by several authors (see e.g. Hofmann-Wellenhof et al., 2001; Teunissen and Kleusberg, 1998; Leick, 1995; Parkinson, 1994; Seeber, 1993).

1.1 Global Positioning System

This project is based only on the GPS technique which by far is the most popular GNSS in use currently. The GPS constellation consists of 24 satellites in 6 orbital planes with 4 satellites in each plane. The ascending node of each plane are separated by 60 degrees and the planes are inclined at 55 degrees in the case of block II satellites. The orbit of each GPS satellite is approximately circular and semi-synchronised (20200 Km above the earth’s surface). The orbits of the GPS satellite are available by broadcast (broadcast ephemerides)– superimposed on the GPS pseudorandom noise codes (PRN), or after processing (precise ephemerides), from organisations such as Jet Propulsion Lab (JPL) or the International GPS Service (IGS) among others. The GPS receiver convert the satellites signal into position, velocity and time estimates for navigation, positioning, time determination or geodesy.

1.1.1 GPS Positioning Services

GPS has two levels of positioning services; the Precise Positioning Service (PPS), which has so far remained a reserve to the U.S. and allied military forces and other U.S.A government agencies, and the Standard Positioning Service (SPS) accessed by users world-wide. The SPS determines positions by way of Coarse-Acquisition (C/A) 1023 MHz megachirp per second Pseudo-Random-Noise (PRN) codes on the GPS L1 frequency at 1575 MHz . SPS initially gave positions at an accuracy of 100m horizontally and at an accuracy of 156m vertically at 95% confidence level. The removal of selective availability (SA) on May 2, 2000 improved the accuracy to 5m horizontally and of 8 to 9m vertically at 95% confidence level thus almost approaching the accuracy of PPS.

1.1.2 GPS Positioning Modes

The two fundamental GPS measurements for position determination are pseudorange and carrier phase observations. The phase and pseudo range measurements can be written as follows;

$$P_r^s = \rho_r^s + d\rho^s + c(dt^s - dT_r) + d_{ion}^s + d_{trop}^s + \varepsilon(p_{rx}) + \varepsilon(p_{mult})_r^s \tag{1.1}$$

$$\Phi_r^s = \rho_r^s + d\rho^s + c(dt^s - dT_r) + \lambda N_r^s - d_{ion}^s + d_{trop}^s + \varepsilon(\Phi_{rx}) + \varepsilon(\Phi_{mult})_r^s \tag{1.2}$$

where

P_r^s	is the pseudorange measurement by the GPS receiver to the satellite (m)
ρ_r^s	is the true range or “geometric” range (m)
$d\rho^s$	is the orbit error term (m)
dt^s	is the satellite clock error (m)
dT_r	is the receiver clock error (m)
d_{ion}^s	is the ionospheric delay term (m)
d_{trop}^s	is the tropospheric delay term (m)
$\varepsilon(P_{rx})$	is the error in pseudorange measurement due to receiver noise (m)
$\varepsilon(P_{mult})_r^s$	is the error in pseudorange measurement due to multipath (m)
c	is the speed of light (ms^{-1})
Φ_r^s	is the carrier phase measurement by the GPS receiver to the satellite (m)
λN_r^s	is the carrier phase ambiguity between the GPS receiver and the satellite (cycles)

λ is the wavelength of the carrier phase (m)

$\varepsilon(\Phi_{rx})$ is the error in carrier phase measurement due to receiver noise (m)

$\varepsilon(\Phi_{mult})_r^s$ is the error in carrier phase measurement due to multipath (m)

The level of carrier phase measurement noise (at the mm level) is much lower than the level of pseudorange measurement noise (typically at the metre level) (Ogaja, 2002). There are numerous approaches to processing of carrier phase measurements; these include single, double, triple or undifferenced methods. The liability of the civilian users to access the P-code pseudorange measurements under the policy of Anti-spoofing (AS) reduces the accuracy of the GPS pseudorange positions and are only applied in areas requiring less accurate positioning. There are two methods by which a station position can be derived; Single Point Positioning (SPP) or Relative Positioning (RP).

1.1.2.1 Single Point Positioning (SPP)

When GPS observations made at only one particular station are used to independently derive the position coordinates of the point with respect to the reference frame WGS-84, the positioning technique is referred to as single point positioning. Data from a single station are processed to determine three dimensional coordinates (X,Y,Z) referenced to the WGS'84 Earth Centred reference frame (datum). SPP can further be classified as either Pseudorange-based point positioning and carrier-phase-based point positioning. With the presumption that the satellite position is known (as broadcast in the navigation message) then the antennas position can be computed from the resection using the pseudoranges. The accuracy of pseudo range based SPP depends on the ephemerides and period of observation and is currently about 5 metres in horizontal and 8 to 9 metres in vertical component (at 95% confidence level for civilian users. With the availability of precise GPS orbits and satellite clock corrections, precise carrier-based SPP has been proposed by Jet Propulsion Laboratory (Zumberge et al., 1997; Zumberge, 1999). This technique uses the carrier phase measurements from both frequencies (L1 and L2), with the post mission information in the estimation procedure, producing high precision positioning results. The method has the disadvantage that it requires large amount of data, and therefore instantaneous positioning is currently still not attainable.

1.1.2.2 Relative Positioning

Relative positioning also referred to as differential positioning involves the determination of position using two GPS receivers observing same satellites simultaneously. One receiver dubbed the reference receiver is set up on a reference station whose position is known. The other receiver, dubbed the “rover” is positioned based on the reference station. The main disadvantage of relative positioning is that the accuracy of the determined position is dependent on the distance between the two stations, with the residual error increasing with the distance and the quality of the reference station. When the position of one or more stations are known, the coordinates of the new station can be determined by adjusting for the systematic differences between the reference system for the GPS satellites and local geodetic control network. Relative positioning is further classified, depending on the status of the rover receiver and the period of observation as static, fast-static, kinematic or real-time kinematic.

1.1.3 Sources of Error

Major sources of error in GPS observations are satellite biases, receiver biases, signal propagation biases, poor satellite geometry and multipath.

1.1.3.1 Satellite Related Biases

These include satellite orbital and clock errors. The accuracy of the position being determined depend on how accurate the satellite position is known. The satellite orbit errors accrue as a result of imperfections in modelling of the satellite orbits causing differences between the predicted and the true satellite orbits. Since 1st January 1997, the International GPS Service (IGS) have been carrying out routine operations to generate precise post processed GPS orbits. The estimated quality of the IGS orbit products (IGS, 2003) as listed in Table (1.1) below:

Table 1.1: Quality of IGS Broadcast and Precise Ephemeris (IGS, 2003)

Orbit type	Accuracy	Latency	Updates
Broadcast Orbit	~ 260cm / ~7 ns	Real-time	--
Predicted Orbit	~ 25cm/ ~5 ns	Real-time	Twice Daily
Rapid Orbit	~ 5cm/ ~0.2 ns	After 17 hours	Daily
Final Orbit	< 5cm/ ~0.1 ns	After 13 days	Weekly

The difference between the clock time and the true GPS time is referred to as the satellite clock error. The behaviour of each satellite clock cannot be predicted (JPS, 1998) and this can, in SPP, result in a residual error after applying the broadcast clock error model. In relative positioning though, the satellite cock error is eliminated by differencing the measurements obtained from two receivers, since the error would be constant (same satellite at the same time).

1.1.3.2 Receiver Related Biases

The receiver related biases include receiver noise, receiver clock errors, inter-channel biases and antenna phase centre variations. Receiver clock error is the difference between receiver time and the true GPS time. In the case of SPP, receiver clock error can be eliminated by treating it as an additional unknown parameter in the estimation process. In the case of relative positioning, the receiver clock error is eliminated by differencing the measurements made at the same receiver.

The interchannel biases arise due to the fact that multichannel receivers takes the measurements to different satellites using different hardware tracking channels. However multiplexing and single channel receivers are generally free of interchannel biases (Seeber,1993). The interchannel biases can be calibrated at the submillimetre level or better (Hofmann-Wellenhof et al., 2001)

The measurements made by the receiver are usually referred to the distance between the electrical centre of the satellite transmitter and the electrical centre of the receiving antenna. The discrepancy between the antenna electrical centre and the physical centre is the phase centre offset. The electrical centre tend to vary with the direction and strength of the incoming signal. In addition, the phase centre variations for L1 and L2 carriers may have different properties (Leick,1995; Rothacher et al., 1990). For most antenna types, the phase centre (PC) is usually calibrated by the manufacturer. Phase centre variation models for various antenna models can be obtained from the National Geodetic Survey. For further discussion on the PCV, see Section (2.2.8). The models can subsequently be applied to mitigate the effect of antenna phase variations. For high precision applications, it is recommended not to mix antenna types or swap antennas and receivers between stations during Survey (Rizos, 1997).

The receiver noise is dependent on parameters such as the S/N ration and tracking bandwidth. As a rule of the thumb for classical receivers, the measurement noise is about 1% of the signal wavelength. That means the level of noise in pseudorange measurements is about 3m (~300m wavelength) for C/A code in the order of 0.3m (~30m wavelength) for P-code, while the noise in carrier-phase is a few millimetres for L1 (~19cm wavelength) and L2 (~24cm wavelength). Modern receiver technology tends to bring the internal phase noise below 1mm and to reduce the C/A code noise to the decimetre level. (JPS, 1998; Qiu, 1993; Seeber, 1993).

The effect of the geometry and number of the satellites on the position quality is called Goemetric Dilution of Precision (GDOP). The DOP values are often expressed in different terms relating to the propagation of the satellite configuration into the position fix in its different components e.g. Positional DOP, Time DOP etc. GPS receivers assign the satellite geometry a PDOP rating depending on the configurations of the satellites. The lower the value of PDOP, the more accurate the data is assumed to be. For precise single point positioning, PDOP values of less than 2 are recommended while in relative positioning, relative DOP (RDOP) values of 0.1 are considered acceptable. Pre-planning is useful in determining the time intervals to avoid (fewer satellites) prior to making any observation.

Geodetic receivers produces a degraded L2 phase observable under Anti-Spoofing (AS), which in theory should lead to degraded geodetic solutions. AS alters the GPS signal by changing the characteristics of the P-code by mixing it with the so-called W-code resulting in the Y-code. It is the latter that is modulated onto the carriers and is thus designated to prevent availability of the receiver to make P code measurements. Many receivers though have developed techniques through intensive tuning, for example cross correlation and squaring, to minimise the error. AS directly affects Kinematic, rapid static and other users employing short (<30 minutes) averaging time.

1.1.3.3 Signal Propagation Biases

On the assumption that the antenna site has been properly chosen and there are therefore no signal interferences/obstructions to limit the number of satellite signals available at the antenna, the satellite signals travel from the satellite to the antenna will possibly be affected by atmospheric delay and possible multipath. The two atmospheric layers, the ionosphere and the troposphere diffract the signal differently hence the ionospheric and tropospheric delays.

The ionospheric layer of the atmosphere span from about 50 Km to 1000 Km above the earth’s surface (Hofmann-Wellenhof et al., 2001; Seeber, 1993). Due to the presence of free electrons in this layer, the GPS signal does not travel at the speed of light as they transit this region (Parkinson and Spilker, 1996) and therefore result in longer measured pseudoranges and shorter measured phase range. The ionospheric delay is a function of Total Electronic Content (TEC) along the signal path and the frequency of the propagated signal (Lin, 1997). The locations with major influencing factors being the solar activity and the geomagnetic field (Klobucher, 1991; Leick, 1995; Seeber, 1993). In extreme cases, the ionospheric delay can range from about 50 m for signals at the zenith to as much as 150 m for measurements at the antennas horizon.

Since the ionospheric delays tend to be correlated up to a few tens of kilometres above the earths surface, their impact can be significantly reduced through differencing of measurements made at two stations over short baseline to the same satellites (Ogaja, 2002). Dual frequency receivers have the capability to eliminate ionospheric effects. The magnitude of the ionospheric effect is more during the day than at night. The magnitude also has a cyclical period of about 11 years that reaches a maximum and a minimum.

The tropospheric layer of the atmosphere, on the other hand, spans from the surface of the earth to about 50 km above the earths surface (Spilker, 1996). The tropospheric delay is a function of elevation and altitude of the antenna and depend on many factors such as the atmospheric pressure, temperature and water vapour content. The tropospheric delay ranges from about 20m for signals at an elevation angle of 10 degrees (Brunner & Welsch, 1993). Unlike the ionospheric delay, the tropospheric delay is not frequency dependent and cannot therefore be eliminated through linear combination of L1 and L2 observations.

Several standard tropospheric models exist and are be used to estimate the magnitude of the tropospheric delay (e.g Saastamoinen model, Hopfield model, Black model and many more). The tropospheric delay can be classified into two components; the dry component and the Wet component. Due to high variation in the wet component, it is difficult to predict or model. The standard models can therefore only account for about 90% of the total delay (the dry component). The tropospheric delay can also largely be eliminated by differencing of observations made at two stations over short baselines to the same satellites (Ogaja, 2002). For high precision static positioning, the tropospheric delay in the double-differenced observable may be treated as additional unknown parameters in the baseline estimation process (e.g. Rothacher et al., 1990).

In band interference and jamming of signals increase daily as new communication systems are put in place and the Radio Frequency (RF) spectrum become congested. The threat is not only from the interfering signals themselves but also from their harmonics that fall inside the GPS band.

1.1.3.4 Multipath

The GPS signal has the property of being reflected by objects such as trees, buildings, the ground, water surfaces, vehicles just to mention but a few. Due to the reflection property, the environment surrounding the antenna of a GPS receiver significantly affects the signal propagation by introducing noise into the measured pseudoranges and carrier phase observable. This error is referred to as multipath (see Figure 1.1). When the multipath averages at the GPS antenna, two problems occur;

- A multiple signal with amplitude and phase shifting

    If the multipath signal reverses the polarity, the direct and reflected signals may cancel each other at the receiving antenna. If the multipath signals converges at the antenna in phase, the direct and the reflected signal sum up together causing the received signal to significantly increase in amplitude.

- A multiple signal with differencing ranges

    Since the multipath signal travels a longer distance to arrive at the GPS antenna, the two C/A code correlations are displaced in time causing distortion in the correlation peak and subsequently errors in range measurements.

As a rule of the thumb, the maximum pseudorange multipath error is approximately one chip length of the code (that is, about 300m for the C/A code and approximately 30m for the P-code), while the maximum carrier phase multipath error is about a quarter of the wavelength (that is, about 5cm for the L1 carrier and 6cm for the L2 carrier) (Georgiadou & Kleusberg, 1988; Lachapelle, 1990; Wells et al., 1987). As high precision applications demand high accuracies, GPS carrier-phase multipath have assumed importance and is currently a research issue.

Most of the carrier phase measurement errors like atmospheric delay, orbital and clock errors are spatially correlated and can easily be eliminated through data differencing techniques. However due to the dependency of the multipath error on the antennas environment, it cannot be eliminated by the data differencing technique. Several suggestions have been made to reduce the effects of multipath or example by Rizos (1997);

- Care should be taken in selecting of the antenna sites (both reference and rover) so as to avoid reflective surfaces
- Use of multipath resistance quality antennas
- Use of receivers with capabilities of internally digitally filtering multipath disturbances

- Use of high elevation satellite signals which are less susceptible to multipath.

For successful isolation and mitigation of this error, there is importance in understanding the general characteristics of carrier phase multipath for example as presented by Georgiadou and Kleusberg (1988). Good efforts were made by scholars (e.g. Hagerman, 1973; Van Nee, 1995; Braasch, 1996) to characterise code multipath.

Multipath Modes

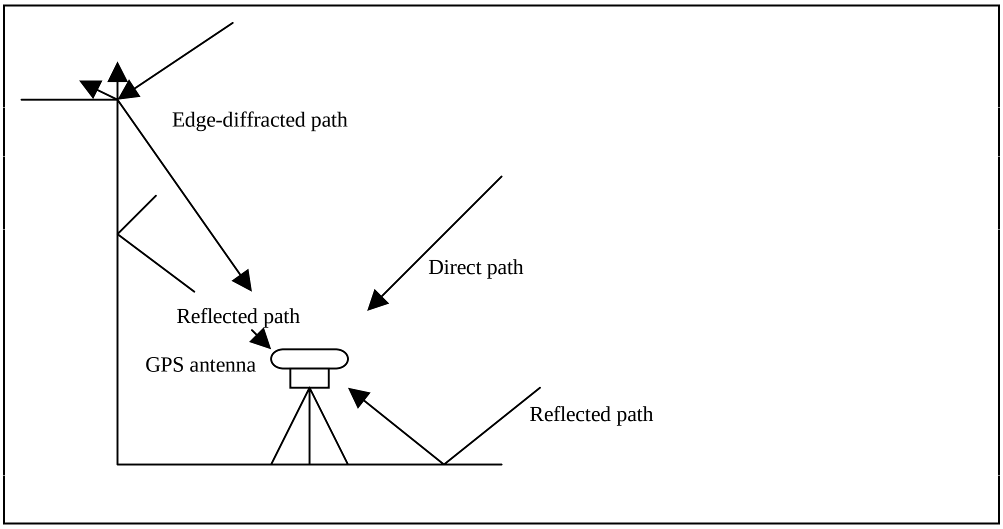


Fig. 1.1: The multipath environment around a GPS receiver (After Ogaja, 2000)

The multipath effects cannot be easily represented by means of mathematical expression due to the dependency of its phase and amplitude on the GPS satellite constellation geometry. The distributions caused by multipath in phase measurements are due to the interference of the direct and the reflected signals (Ogaja, 2002).

El-Mowafy (1994) classifies the effects into two major categories; *common mode multipath* and *differential mode multipath*. Common mode multipath occurs when the GPS antennas are very close to each other e.g. in the range of centimetres or a few metres. In this mode, the reflected signals producing multipath effects virtually take the same path to the antennas and thus the correlations between the effects at the two antennas is strong enough to be eliminated by differencing technique.

Depending on whether the antenna is stationary or in motion, the multipath effect can also be classified as *low frequency* and *high frequency* multipath. If the antenna is in motion, the signal diffraction due to the rapidly changing satellite-reflector-antenna geometry results in randomisation of the multipath error hence in high frequency multipath effect. The period of high frequency multipath effect is sub-minute to 2-3 minutes. If the antenna is stationary, on the other hand, the multipath effect will be characterised with a very low fluctuating period being dependent on the reflective surface in the vicinity e.g. 5-10 minutes due to specular reflection in the vicinity, or 50-60 for water surfaces (El-Mowafy, 1994).

Multipath Elimination Techniques

Several hardware and software multipath mitigation techniques have been developed but due to dependency of the multipath effects on local environment surrounding the antenna, they cannot be considered ideal. Proposals have subsequently been made on how to handle the multipath error.

Antenna Site Selection

A careful selection of the antenna site may significantly reduce multipath influence. Though highly ideal and unrealisable, the site should have no obstruction i.e. with a clear view of the sky from horizon to horizon at all bearings and elevation angle. Reflective surfaces should be avoided.

Repeatability of Satellite Geometry

Since the antennas in reference station establishment processes are semi- or permanently fixed, only the low frequency multipath phenomenon are expected with a sinusoidal oscillation periods of 6-10 minutes (0.001 – 0.003 Hz) (Qiu, 1993). Multipath effects repeat when the satellite geometry relative to the stationery GPS antenna repeats for example after one sidereal day. This results in 85% of the day-to-day correlation of the multipath effects which further depend on how static the environment remains. Thus, if the antenna is kept at one position and the surroundings remain unchanged, multipath can be estimated and eliminated due to its dependency on azimuth and elevation only (Radovanovic, 2001). This characteristic of multipath can be exploited to improve the positioning accuracies, by for example analysing series of baseline solutions over several days. The multipath error can be calculated at every epoch and subsequently subtracted from the data collected on the subsequent day(s). Repeatability of satellite geometry, and therefore of the satellite signals, after one side-real day is a property that is used as a concept to eliminate multipath in given GPS observation data. The range of repeatability of satellite geometry is not exactly 3 min 56 s (236s) but varies from 240s to 256s (Seeber et al., 1997)

Filtering and Fourier Transforms

Low frequency multipath can be removed through long term averaging while the noise like high frequency multipath can be minimised through filtering (El-Mowafy, 1994). Spectral techniques such as direct and inverse fourier transform (FFTs), where the collected data is transformed to frequency domain, have been suggested for multipath detection and removal (e.g. Schwarz et al., 1993). Likewise a Finite Impulse Response (FIR) filter or detection and removal of multipath by transforming the measured data into spectral domain have been proposed by Han and Rizos (1997b).

Special Antenna Design

Antennas are designed to have low gain at low elevations so as to reduce the influence of the ground reflected signals (Ding et al., 1999). Antennas with good low elevation signal rejection capabilities such as flat plate microstrip, patch and choke-ring antennas have been designed. The choke ring is fitted with concentric corrugations that reduce antenna sensitivity to ground reflected multipath effects. The disadvantage of this type of antennas is that the all in view requirement of satellite navigation is not possible while the satellite signals from low elevation satellites are rejected together with the multipath signals. The other disadvantage of the choke ring antennas is that they are typically designed for only one type of frequency (e.g. L1) and will therefore have no effect in the other frequencies. This reduces their effectiveness to eliminate multipath effects on both measured frequencies simultaneously.

A good antenna should also incorporate left hand circular polarisation (LHCP) rejection capability. The Antennas should be designed for RHCP so that multipath signals which tend to be LHCP most of the time can be rejected.

Antennas can also be fitted with ground-planes to reduce their sensitivity to multipath signals. The antenna ground plane creates a stabilsing artificial environment on which the antenna rests. The bigger the plane (relative to number of wavelengths at the operating frequency), the higher the stabilsing effect. The ground planes also shield the antenna against Radio frequency signal reflections below the antenna radiation pattern horizon. The disadvantage of "flat plate" ground plane is that it results in "two boundary conditions". One allows the electromagnetic wave to propagate along the ground plane (hard boundary condition) while the other (soft boundary condition) prevents the signal from propagating. The choke ring is designed based on the latter principle thereby creating a soft boundary condition.

Inbuilt Receiver Algorithms

The GPS receivers have also been loaded with algorithms to reduce multipath at the internal receiver signal processing stage for example the Multipath Estimation Delay-Lock-Loop (MEDLL) presented by Townsend et al. (2000). MEDLL mitigates the effect of multipath using the receiver tracking loops. The processing algorithms aim at both reducing the threshold for multipath detection and rejection and improve the measurement accuracy (e.g. Townsend and Fenton, 1994). This technique uses the concept of time delay difference between direct and reflected signals. The disadvantage is that this technique has no effect on carrier multipath. Advances in this area have been made in mitigation of code multipath but not much has been achieved in addressing the carrier phase multipath effects. Weill (1997) states that this is mainly due to the fact that maximum effect in carrier phase multipath occurs for very short signal paths (less than 1m) where mitigation is not possible.

Cut-Off Elevation Angle

Setting of the cut-off angle for signal reception at the data processing stage, so that the signals reflected from surfaces so and the low elevation satellites can be rejected. This technique is always not applicable in all cases for example setting of low using cut-off elevation angles may mask useful satellites in airborne applications. But for base stations, the technique is highly recommended. Also several works have shown that the errors related to interaction between the GPS antennas and surrounding environment are prevalent at low elevation angles and hence the need to observe GPS satellites at low elevation so as to estimate signal delays due to tropospheric water vapour.

Signal to Noise Ratio

Recent receiver technology resulted in mitigation of code multipath but carrier phase multipath continues to be a problem because it has effects for very short excess signal paths (<1m) where no mitigation is possible (Weill, 1997). Elimination is done by use of appropriate methods of processing the carrier phase data.

The carrier phase multipath error ε_m due to a single reflected component is a function of excess signal path (multipath delay), the ratio of direct signal amplitude to indirect signal amplitude damping factor and carrier wavelength and is given by Georgiadou and Kleusberg (1988) as:

$$\varepsilon_m = \frac{\lambda}{2\pi} \arctan \frac{\alpha \sin(\frac{d}{\lambda}.2\pi)}{1+\alpha \cos(\frac{d}{\lambda}.2\pi)} \qquad (1.3)$$

where α is damping factor ranging between 0 and 1

d is multipath delay in metres

λ is the carrier phase wavelength in metres

Access to the S/N values can provide valuable information for multipath detection and elimination (Axelrad et al., 1994)

Höper et al. (2001) state that pseudorange carrier phase single differences and signal-to noise ratio are best suited for the detection of multipath effects on the GPS signals by use of only one receiver. The measured signal propagation time $\tau_m(t)$ is the composition of true signal propagation time $\tau_o(t)$, the receiver's clock error $\tau_r(t)$, the satellite's clock error $\tau_s(t)$ and the signal propagation time error $\tau_f(t)$ and can be represented by equation (1.4) below;

$$\tau_m(t) = \tau_o(t) + \tau_r(t) + \tau_s(t) + \tau_f(t) \qquad (1.4)$$

Wanninger and May (2000) state that multipath is significantly reduced for commonly used linear combinations of the dual-frequency observations but not the original L1 and L2 observations themselves.

Table 1.2: Comparison of differencing equations (Jülg, 1997)

	Multipath Detection	Quantification of code phase error	Quantification of carrier phase error	Number of necessary receivers
satellite single differences	•	∘	∘	1
receiver single differences	•	•	•	1
epoch single differences	∘	∘	∘	1
Pseudorange-carrier phase single differences	• • •	• • •	∘	1
Receiver-satellite double differences	• •	• •	• •	2
Receiver-epoch double differences	∘	∘	∘	2
Pseudorange carrier phase-receiver double differences	•	•	•	2
Receiver-satellite-epoch triple differences	∘	∘	∘	2
Signal to noise ratio	• • •	∘	∘	1

Suitability: (• • •) very good (• •) good (•) little (∘) not at all

1.2 Statement of the Problem

Even though the satellite systems, more specifically the GPS, have revolutionised the art of positioning and navigation, there are still several setbacks to the accuracies that can be attained. This is mainly due to the intentional and unintentional sources of error to which the system and satellite signals are susceptible to and include for example anti-spoofing (AS), receiver clock errors, satellite clock errors, satellite orbit errors, satellite signal interference and multipath. The accuracy of the unassisted GPS single point positioning signal is adequate for most applications such as recreation, automobile navigation and fleet tracking, but many other applications still require greater accuracy. The use of GPS for geodetic survey applications has resulted in a critical need for development of acceptable accuracy standards and GPS survey specifications for control surveys performed by relative positioning techniques. Satellite positioning with an accuracy better than 5m obviously requires the use of a reference station. As Trimble editorial once put it, "*surveyors have been using GPS for precise surveys for years fixing points to an accuracy of millimetres. This requires the use of multiple receivers-so involved that only trained geodesists can do it*".

Precise positioning under SPS requires the use of GPS carrier phase observables under relative positioning. Carrier phase observables are susceptible to ambiguity and carrier phase multipath. For dual frequency receivers, ambiguity resolution is not much of a problem but the quality of the carrier phase multipath calibration depends on the ability to separate the multipath effects from other errors especially phase centre variation and ionospheric effects. For closely spaced antennas, the carrier phase is the dominant error source and the effects are highly correlated and can thus be estimated and eliminated (Brown and Wang, 1999; Ray, 1999)

Reference stations have the advantage of providing correction information which is useful to the Rover receivers in modelling remaining tropospheric, ionospheric and orbit biases. The antennas of GPS reference stations are often equipped with radomes (radar domes) as a protection against wear and soiling. However depending on their size, shape and material, these covers may affect the signal propagation and subsequently the estimated position in particular the vertical component (Kaniuth and Stuber, 1997).

In view of all these errors, the process of reference station establishment should therefore take into consideration all the possible sources of such errors and try to eliminate or reduce them.

When the antenna is covered by a radome, the effects of the radome on the PCV patterns should thoroughly be investigated.

1.3 Study Objectives

The need to have a reference station for the day to day GPS data processing at the Institute of Navigation, was the basis of the first main objective of this study i.e. to establishm two GPS reference stations on top of the building housing the institute on *Breitscheidstrasse 2*. One of the stations (dubbed station1) was mounted with a Choke ring antenna. But with the experience that the antenna corrodes after 2 to 5 years of operation, the choke ring antenna was therefore covered with a radome as a protective measure against bad weather conditions. With the knowledge that addition of radome over an antenna causes errors in the computed positions especially the height component, the second objective was to investigate the influence of the antenna radome on the reference station.

1.4 Organisation of the report

This report is organised in six chapters. Chapter One is an introduction and briefly introduces the concept of GPS positioning, discusses the various positioning techniques and lists some of the sources of error encountered in GPS measurements. The statement of the research problem and research objectives are also outlined in Chapter One. Chapter Two takes a look at the reference stations, the basic considerations in setting-up reference stations including antenna calibration and reference station networks. Antenna radomes are also discussed in Chapter Two. In Chapter Three, the test experiment including the equipment, software and GPS data collection is presented in details. Chapter Four outlines all the data processing carried out in the research and the solutions attained. In Chapter Five the comparisons and analysis carried out in this study are presented. The conclusions are drawn in Chapter Six and a few recommendations are made.

CHAPTER TWO

2. REFERENCE STATIONS

2.1 Introduction

Reference stations are mainly used in GPS positioning for the following three purposes;

- Harmonisation of the different geodetic reference systems around the world and more specifically, transforming the WGS84 reference system to user defined ellipsoid/datum, such as Clarke 1866 or Geodetic Reference System of 1980 (GRS80) on which ETRS89 is based.
- Detection of malfunctioning and failure of other reference stations
- Attenuation of the satellite, receiver and signal propagation biases.

Methods have been, and are still being, developed to reduce the effects of errors and enhance the accuracies attainable with GPS is currently in use world-wide. A concept commonly known as Differential GPS (DGPS) positioning. The differential mode eliminates most of the errors except multipath and some receiver errors which are local and usually depend on the environment surrounding the station(receiver). The main advantage of satellite positioning since its inception in the early 1980s is that it permits the determination of position of one receiver relative to another reference receiver without the requirement of station intervisibility unlike the earlier conventional techniques such as triangulation, trilateration and traversing using theodolites and electromagnetic distance measuring equipment. There are two types of differential mode GPS, real time and post-processed DGPS. Although the selective availability was turned off by the U.S.A government in May 2000, that did not obviate for DGPS although accuaracies as better as 5 to 7 metres in the horizontal and 8 to 9 metres in the vertical at 95% confidence have been guaranteed.

For the required accuracies to be achieved in the positioning, two main factors have to be taken into consideration

i) The position of the reference station should be determined at the highest accuracy possible by eliminating or reducing all the errors affecting the station position.

ii) The stations should be closely spaced since in relative/differential positioning, the same conditions are assumed to exist between the receivers at either ends of the baseline.

The corrections

- can be performed in real-time or in post processing

- may be obtained from one or more reference stations
- can be from a permanent service or service specific to the project

Satellite positioning users who need sub-metre accuracy have the following alternative forms of differential correction sources.

2.1.1 Sources of Differential Corrections

Differential corrections can be performed as either post-processed operation, or in real time while the user is receiving GPS signal/positions. The latter is important in navigation. A variety of differential corrections are available. These include:

- MSK beacons
- Satellite differential providers
- FM subscriber broadcasts
- Private reference stations

Most of these sources transit differential correction messages via radio frequencies to a radio link attached to the GPS receiver.

2.1.1.1 Minimum Shift Key Beacons (MSK)

The radio beacons are maintained by coast guards are a source of real time DGPS corrections. The main purpose of radio beacons or MSK beacons as they are commonly known, is to provide differential corrections to shipping along the coast, harbours and navigable waterways around the world. Since these corrections are several of kilometres; land based GPS applications such as mapping and GIS data collection can also use the corrections for their own purpose. Availability is usually restricted to countries with shipping industries for example U.S.A, Iceland, Canada, United Kingdom, Europe and Asia. Accuracy vary from sub-metre to 10 metres and are usually free of charge.

2.1.1.2 Satellite Differential Providers

Another alternative source of DGPS corrections is the subscription to a commercial satellite corrections service such as Omnistar and Landstar. Differential corrections from a series of ground based reference stations are sent to central control centre, which then transmits the corrections up to the satellites. The satellites can then transmit these corrections to an activated GPS receiver which interpolates a correction value based on its current location. This technique is referred to as Virtual Reference station (VRS/VBS) technology. Due to equatorial location of the satellites however, the signals become attenuated and eventually disappears in higher latitudes thereby limiting availability. Accuracy is in the range of sub-metre to 5 metres. Subscription and additional L-band receiver is required.

2.1.1.3 FM Sub-carrier Broadcasts

This technique was developed in Europe and transmits data over FM radio frequencies together with other programs. The Radio Data System (RDS) allows data to be transmitted along with regular programmes. Availability is limited to the ranges of existing FM frequencies mostly 70-100 kilometres from broadcast towers. Fees are charged based on services. The accuracies vary from sub-metre to 10 metres.

2.1.1.4 Wide Area Systems

Wide Area DGPS or Satellite-Based Augmentation Systems (SBAS) were originally designed for aviation, but the systems are also suitable for terrestrial and in-shore marine use and are available for anyone with a WADGPS enabled receiver. WAAS in North-America, European Geostationary Navigation Overlay System (EGNOS) in Europe and Multi-functional transport Satellite-based Augmentation System (SNAS) in China and Australian GRAS are some of the examples. In a WADGPS or SBAS, a network of reference receivers combine to create a model of best DGPS corrections for a wide area. Geostationary satellites then broadcast these corrections in the same band that regular GPS satellite use. The result is a DGPS correction that can be deciphered by any WAGPS enabled receiver for example Novatel WADGPS compatible receivers. No additional Antennas, receivers or subscription fees are required.

2.1.1.5 Private Reference Stations

The use of the above mentioned DGPS correction sources to support a range of high accuracy applications has been hampered by the need for the reference receiver to be within tens of meters or so of the survey area. The further away the base station is, the more the errors and therefore larger observation time for a baseline determination. The establishment of a network of GPS receivers at a density to support GPS surveys is hardly feasible. For example, in the case of Germany, the reference station network SAPOS consist of dual frequency receivers with station distances of about 50 km. Most of the DGPS sources charges a fee-for-service which can be costly for long period operations. The best option in overcoming this short fall therefore, is the establishment of a private reference station DGPS system, of course at an additional cost due extra equipment.

EUREF Permanent Network

One good example of private reference stations is the europeans permanent tracking stations in the EUREF Permanent Network (EPN) which is providing in near real time high quality GPS data to local and regional data centres. EUREF is the densification of IGS network with more than 100 stations around Europe. EPN analysis centres routinely analyse the data from this network and deliver to the GPS community precise co-ordinates for all in-stations involved in the network. EUREFs multi-year network submissions to the International Earth ration services assures the integration of EPN tracking stations in the successive realisation of ITRS which is the basis for European reference system. A reference station according to IGS and EUREF standards should produce compressed hourly and daily RINEX files which are sent to the regional data centres.

2.2 Basic Considerations in Setting-up Reference Stations

Reference stations are supposed to provide high accuracy and reliable data. For this to be achieved, the following technical basic considerations should highly be taken into account in the establishment process of a reference station, be it permanent or a temporary station. The difference between a conventional field reference station and a permanent reference station is that the latter requires an advanced, reliable and robust infrastructure so as to be able to run permanently providing data at certain epochs e.g. near real time daily or hourly. The basic considerations include accuracy specifications, network geometry, instrumentation and monumentation, calibration procedures, field procedures and office reduction procedures.

2.2.1 Accuracy Specifications

The accuracy standards for the horizontal coordinates are based on a distance accuracy standard “which is the ratio of the relative positional error of a pair of points to the horizontal separation of these points. This depends on the planning, observation strategy and procedures used in data processing software. Based on the purpose for which the reference station is being established, the accuracy should be specified in advance, proper planning and correct observation procedures applied, and appropriate processing software used to achieve the desired specification. Beutler et al. (1989) state that the baseline accuracy obtainable by GPS is reflected by the law

$$\frac{db}{b} = \sqrt{\frac{1}{2b}} \quad mm/km \tag{2.1}$$

Where b is the baseline length in km

db is the error in (one of) the baseline components in (mm)

2.2.2 Site Location and Monumentation: Locations with optimal conditions should be used so as to have clear sky view thus allowing reception of low elevation signals. Monumentation of the station should also be stable and highly durable.

2.2.3 Instrumentation and Equipment

Instrumentation for the reference stations consist of three major components; an antenna, a receiver or processor and recording unit. Weather measuring and remote control instruments for example Trimble survey controller are optional. The instruments used at a reference station are typically a PC connected to a GPS receiver with the capability of being used as a reference station, application software running on this PC to configure and control GPS operations and should perform all or part of the following tasks;

- Manage site parameters
- Sensor configuration, sensor operation control and monitor and display GPS sensor operation status.
- Enable/provide RTK/RTCM data transmission
- Run data logging and archiving
- Creation and archival of receiver network exchange (RINEX) observation files
- Support other external devices like meteos and tilt sensors
- Perform all operations automatically without the user interaction requirement

The receiver should have a survey grade antenna and be able to be used as a reference station. The receiver should be able to receive both L1 and L2 carrier frequencies transmitted by GPS satellites so as to correct for the effects of ionospheric refraction. In order to minimise any possible multipath degradation of the satellite signals, typically high precision choke ring antennas which comply with IGS standards are recommended, thus providing the best phase centre stability. Antenna protection covers or radar domes as they are commonly known are recommended to prevent long term antenna damage. The equipment should also be powered steadily with guarantee and sufficiency. The equipment should be protected from power failures and outrages, vandalism, theft and electronic surge.

2.2.4 Planning, Observation and Reference Data

The GPS observations should be carried out using suitable field procedures which take into account the accuracy requirements, satellite availability and project logistical considerations during observation. The precision of the GPS baseline results depend on the number of satellites visible simultaneously from each station during an observation session, their geometrical relationship, duration of the period when the desired number of satellites can be observed simultaneously, the uncorrected effects of atmospheric delays and the length of the baseline (FGCC, 1989).

The reference data must be accurate, precise and if possible known in local and global reference frames with known fixed transformation parameters between the two. Most popular global reference frame is the IERS Terrestrial Reference Frame (ITRF) which has been defined in different years and epochs (Bock, 1998)

2.2.5 Data Processing Software

Office reduction procedures can be done with either special processing software like Trimble Total Control (TTC) or through minimal constraint (free) adjustment using least squares. The later being important in measurements investigating crustal motion, subsidence monitoring and motion of structures. Software used to process the raw tracking data should handle either single or multiple baseline input. The software should also be able to perform; orbit refinement modelling, difference (single, double or triple) versus non-difference processing of carrier phase observations, carrier phase ambiguity and cycle-slips resolutions, atmospheric refraction modelling and produce relative position coordinates and corresponding variance-covariance statistics.

The criteria for processing of GPS relative positioning are; cut-off elevation angle for data points should be greater than 20^0, reference station coodinates should be held fixed and referenced to the satellite orbital coordinates (ephemerides) currently WGS'84 (DMA, 1987). The offset of antenna phase centre (horizontal and vertical) relative to station mark must be accounted for, the number of simultaneous phase observations rejected should be less than a given percentage depending on the accuracy required, number of observation, quality of data, reduction methods and baseline length. Standard deviation i.e. range of residuals should be minimal.

2.2.6 Accessibility: depending on the numbers of users, the reference station data accessibility can be remote to the PC or through the internet based on the File Transfer Protocol (FTP) data distribution.

2.2.7 External Devices: should be able to support other external devices like meteo and tilt sensors

2.2.8 Antenna Calibration

A typical antenna has band pass filter and amplifiers. The following errors are usually experienced by antennas:

i) GPS carrier-phase time-transfer performance depends on the stability of the delays of the receiving antenna, receivers, cables, amplifiers and other related electronics. GPS antenna system with its associated amplifiers and band filters is typically located outside in uncontrolled environment. Temperatures therefore affect narrow band pass filters to cause group delay.

ii) Phase Centre Variation: Phase centre is the point at which the GPS signals physically arrive in the antenna and is not homogenous. In base line solutions the assumption is that the measurements are made between the phase centres of the different antennas at either end of the baselines. Truly speaking, a real antenna has no precisely defined phase centre (PC) and instead the location of the PC is a function of the direction from which the antenna receives a signal. The PCV affects the antenna offset that is needed to connect the antenna phase centre to a reference monument. The effect can be considered in two parts, the horizontal effect and the vertical effect. The PCV of an antenna is inseparable from the offset of a given antenna since the PCV values are usually derived from averaged phase centre offsets. The phase centre can be determined in different ways:

<u>Pure offset:</u>

This is the most rudimentary method of PCV approximation. A 2-D or 3-D offset relative to an antenna reference point is determined. The offsets depend on elevation mask, multipath, constellation and location.

<u>Relative field calibration:</u>

GPS antenna calibration is a deliberate attempt to determine the antenna offset and antenna PCV and usually consist of two parts:

- Determination of an average phase centre offset with respect to a physical feature of the antenna
- Determination the phase centre variation with elevation and possibly azimuth

Relative field calibration involves determination of the Phase centre location of an antenna relative to a reference antenna using GPS observations gathered on very short and accurately known baselines.

Absolute field calibration:

Note that only phase centre variations may be derived from GPS observations unless the antenna is rotated and tilted with the help of a high precision robot during data collection. Only then can the estimation of absolute antenna patterns from the GPS data be possible (Rothacher, 2001). Absolute antenna calibration can be achieved in two ways. Antenna is precisely moved within an anechoic chamber and an artificial signal used. This is referred to as *Absolute chamber calibration.* This is difficult to achieve due to the limited number of observations. Alternatively, an actual field observation is made with technical instruments through rotation, tilting and elimination of multipath at the antenna resulting in absolute and non site PCV values. This is called *Absolute field calibration*. Azimuthal PCV resolved to elevation zero can be determined (Menge et al., 1999). The PCV is inseparable from the PC offset hence the need to use PCV and offsets which were determined at the same time and point.

"Nullantenna"

The nullantenna has an absolute and isotropic characteristics. Hence the nullantenna has no PCV since the PCV are reduced to the antenna reference point (ARP) in order to avoid problems arising from mean phase centre (i.e. for dual frequency antennas). Some differential correction providers have started to correct their broadcasted reference station data for absolute antenna correction values.

Two problems usually arise; finding the mean centre or the so called nominal phase centre for dual frequency antennas and secondly, the various correction models from different sources which make the use of such models complicated.

The average phase centre location is a weighted average of all individual phase centres for each of the measurements included in the solution. For identical antennas at the end of very short baselines, the variations cancel out and the effect is not noticed. In GPS observations where different antenna models have been used, it is important to apply phase centre corrections since each antenna has a different phase centre pattern and do not cancel out during data differencing. The stations are more likely to be occupied by different antenna models, hence the phase centre offsets and PCV values with respect to a station reference point must be accurately determined. In precise Geodetic GPS surveying, antenna calibration is an essential process.

Almost all antennas have an averaged phase centre offset and a PCV with respect to an antenna reference point stipulated by the manufacturer. Since in most cases, it is not possible to carry out an antenna calibration for every site occupied by the antennas, it is essential to know the predetermined PCV values (mostly supplied by antenna manufacturers), so that they can be used during data post processing.

Antenna phase centre problems are usually avoided by ensuring that identical antenna models are used throughout the survey. But with the increase in the use of reference station networks established around the world such as SAPOS, there is more likelihood of ending up in a situation where different types of antenna occupy both ends of a baseline, hence the need to solve for the PCV. Recognising this problem, the International GPS Service (IGS) released phase centre models for many commonly used antennas in June 1996 (Rothacher and Mader, 1996).

The NGS calibration uses field measurements to determine the relative phase centre position and phase centre variation with respect to a reference antenna. Mader (1996) stipulates that there is no practical difference between using relative or absolute antenna calibrations unless the base line exceeds about 1000 kilometres in length. As the baseline increases, the curvature of the earths surface causes the satellite to appear at increasingly different elevations at both ends of the baseline. For almost all other situations short of a global network, relative antenna calibrations should be satisfactory.

Most GPS antennas currently in use are azimuthaly symmetric. The dominant phase variation therefore occurs with respect to elevation (Mader, 1996). It is important to note that the variations in local environment around the antenna can introduce both azimuthal and elevation dependent variations different from the modelled phase patterns.

Elevation-dependent PCV can also affect baseline solution in which tropospheric scale factor is being adjusted. In the GPS data processing, an estimate of the phase delay as the signal travels through the troposphere to each antenna is usually estimated. The computation models assume that the phase delays contained in the GPS data are solely due to tropospheric effects. This means therefore, that any additional phase delay caused by the antenna and superimposed on the GPS data will still be treated as being due to tropospheric effect alone. This result in incorrect tropospheric scale factor adjustment and consequently error in the estimated baseline components.

2.3 Reference Station Networks

Application of GPS surveys over larger areas, may require the establishment of several reference stations. In that case there would be need to link the reference stations together though simple network solution to complex real-time network systems.

A whole range of experience has been gained in performing GPS survey with an enhanced satellite system, improved GPS survey equipment and streamlined field procedures. One such field procedure is the tendency to use permanent GPS arrays for a wide variety of applications including generating DGPS corrections and maintenance of reference frames. This is made possible due to technological advances in global data transmission infrastructure. Data from reference stations are sent to a central site for further processing, storage and distribution by means of internet. GPS data from the global network of the international GPS service (IGS), the European tracking network EUREF and a number of other permanent networks are freely available. Currently the Scripts Orbits and Permanent Array Centre (SOPAC) provides data in receiver independent exchange (RINEX) format (Gurther, 1993) of about 20 permanent arrays or 800 stations.

Attempts are being made to make the real time data distribution a reality through the following concepts.

- The internet has been used for real time data distribution provided data latency can be kept within bounds e.g. fleet management systems based on GPS, wireless network and the internet .
- Internet based WADGPS- accuracy within several decimetres

Some of the reference station schemes are listed below.

2.3.1 Single Site System

A single receiver is set up with a PC at the site. All data is stored and managed locally at the specific site. A radio or GSM may be connected to provide RTK/DGPS data to other roaming receivers. A serial link provides communication between PC and sensor. Several such single sites may be interconnected to one control site for remote control and data access using computer network or telephone modems. It is the simples of the reference schemes.

2.3.2 Multi-Site Central System

In the multi-sensor central system; only GPS hardware are installed at the site and the raw data is logged inside the sensors internal memory. A radio or GSM link is then established to provide RTK/DGPS data to a PC at a central site. This provides a central reference station management and data archive. It is also a relatively simple system.

2.3.3 Networked System

The reference station is permanently connected to the GPS sensors receiving continuous raw data stream. All sensor control and data archiving is performed at the central location. The RTK/DGPS data is also managed centrally and can be distributed via the network to other end users. It is the most complex in terms of configuration, engineering, communication infrastructure, maintenance and cost.

2.4 Antenna Radomes

Antennas of permanent GPS reference stations are increasingly being equipped with radar domes or radomes (Raydomes) as they are commonly known as a protection against wear (soiling), vandalism from animals and snow accumulation. Several manufacturers, including Ashtech and Trimble now sell covers for their antennas. For example, the choke ring antenna has been found to corrode in 2-5 years of operation in the field as well as the “chalking” of the fibreglass dome that houses the Dorne-Margolin antenna element (USGS, 1998). However, because radomes cause additional delays to the GPS signals, they can alter the antenna phase pattern and subsequently the average phase centre. Several principle investigators for example University NAVSTAR Consortium (UNAVCO), have carried out tests aimed at determining the effects the covers have on baseline solutions. An experiment conducted in 1995 at UNAVCO ARI receiver and antenna tests with raydomes mounted on only one of the antennas resulted in 15 mm biases in the vertical baseline component as verified by UNAVCO. Braun et al. (1994) also showed that of the semispherical and conical radomes tested, the conical shaped radome had the largest effect. Depending on the cover type (shape, size and material), antenna type and cut-off elevation angle used in processing of the data, these covers may affect the signal propagation and thus the estimated position particularly the vertical component (Kaniuth and Stuber, 2002).

Ashtech and Trimble both offer conical radomes made of different materials, different thickness and do not mount over antenna in the same way.

Schmitz and Wübbena (2001) also observed that there is a large change in elevation dependency at high elevations and that changes in the height component must be expected from adding a radome to any antenna. This effect can additionally be magnified by the location of the station on the so called "Nothern-Hole". The radomes are usually made of resin so as to be transparent to the GPS signal and painted white to minimise sunlight absorption. Water droplets on the domes from condensation could certainly affect propagation of the GPS signal as would the accumulation of dust.

Kaniuth and Stuber (2002) concluded that antenna radomes affect height estimates as soon as local troposphere parameters are to be estimated and that the errors caused by spherical radomes will not exceed a few centimetres. Depending on the size of the radome, the antenna itself and the cut-off elevation angle, conical radomes may affect the height estimates by up to 5 cm.

2.4.1 Types of Antenna Radomes

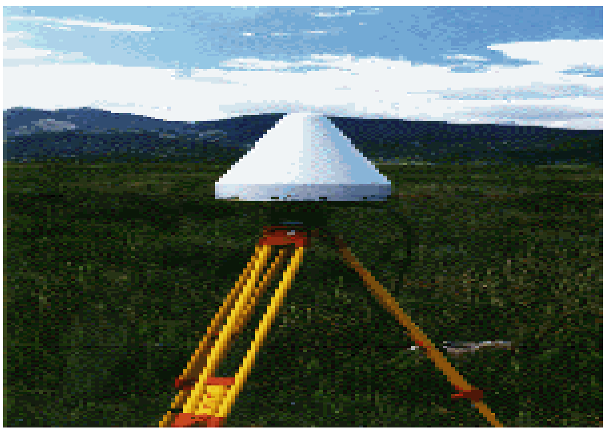


Figure 2.1: Ashtech Conical Radome

Figure 2.1 shows an Ashtech conical radome. The cover is conically shaped and is mounted on the antenna using a set of plastic (non-conducting) screws. There are no metallic or conducting surfaces.

Trimble conical cover is shown in Figure 2.2 The cover is mounted on a metallic plate under the antenna. Figure 2.3 below shows the one-eighth inch spherical cover from UNAVCO.

Figure 2.2: Trimble Conical Radome

Figure 2.3: UNAVCO Spherical Radome

CHAPTER THREE

3. THE TEST EXPERIMENT

3.1 Introduction

As already mentioned in chapter 1, the main objectives of this project were to establish two reference stations and to investigate the effect of radome on one of the antennas. To achieve these goals, two antenna mounting piers were fixed on top of the building housing the Institute of Navigation on *Breitscheidstrasse 2*. The piers were fixed so as to define a baseline of about 5m between the two stations and were adapted so that they can be mounted with several antenna models. For this experiment, one of the piers, dubbed station 1, was mounted with a Trimble L1/L2 choke ring antenna and the other, dubbed station 2, was mounted with a Trimble compact geodetic L1/L2 antenna with ground plane. (See Figure 3.1 below). The site location is relatively high enough in relation to the surrounding environment and has a good view of the sky except for the south western sky which has a slight obstruction at lower elevation due to one tall building.

The station markings are steel pipes with circular centred screws for fastening the antennas.

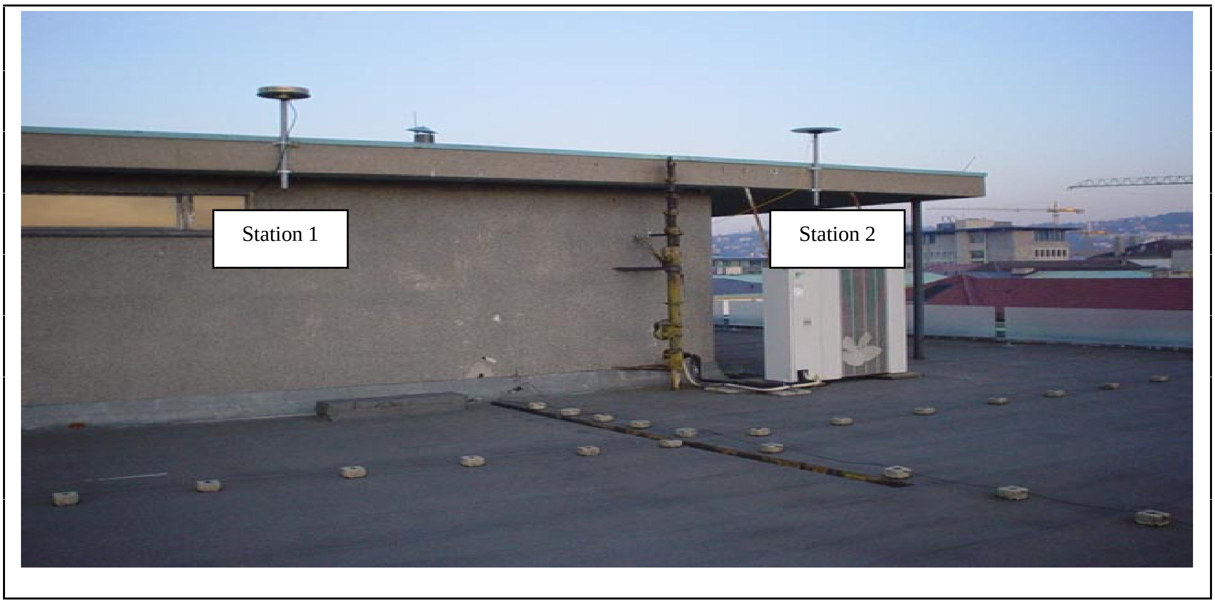


Figure 3.1: Antennas on Station 1 and 2 Piers

3.2 Hardware and Software Specifications

The hardware for a GPS survey basically include the GPS receiver, antenna, PC running data logging software and power supply.

The Trimble choke ring antenna mounted on Station 1 was connected to a Trimble 4700 receiver and a (Satellite 4100XCDT) laptop running a Trimble Reference Station (TRS) version 1.0 software (see Figure 3.2). The software was used to control the receiver and to log the GPS raw data in the Laptop. The compact geodetic L1/L2 antenna on Station 2 was also connected to a Trimble 4700 receiver and a Total Survey Controller (TSC) version 7 part number 32969-20-ENG (see Figure 3.2). The TSC was used to operate the receiver and GPS raw data was logged in the PC card. The GPS receivers were powered by two adapters connected to the main power supply. Stand-by batteries were also connected to act as backup power supply incase of power failure at the mains. The TSC was powered through one of the receivers.

3.2.1 Receiver Specifications

The choice of the receiver depends on some or all of these factors; the accuracy achievable, the receiver probability, reliability and power requirement, the receiver flexibility to field operations and ease of use, storage capacity and cost. There exist varieties of GPS receivers generally classified based on the types of observable and use (e.g. civilian, navigation and geodetic receivers).

(i) Civilian receivers tracking C/A code on L1 frequency.

(ii) Military receivers tracking P(Y) code on both L1 and L2 frequencies.

(iii) Single frequency (L1) carrier phase tracking receivers.

(iv) Dual frequency (L1 and L2) carrier phase tracking receivers.

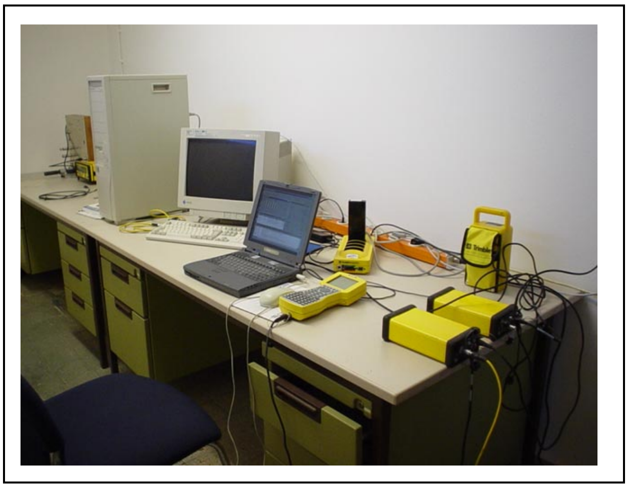


Figure 3.2: Data Logging Hardware Setup

The receiver used in this project (Trimble 4700) is a modular, real-time kinematics (RTK) survey system for fast accurate survey of all types (e.g. topographic, stake-out boundary, seismic and geodetic control). The receiver has 9 channels, dual-frequency with an integrated radio modem for RTCM SC-104 input/output and NMEA-0183 output. The receiver is designed to used 10.5 to 24 VDC power supply.

3.2.2 Antenna Specifications

The role of the antenna is to filter, amplify and down-convert the incoming GPS signals so that they can be processed by the receiver electronics. The main components of an antenna are the antenna element (e.g. monopole, quadrifilar and spherical helices, microstrip), preamplifier and a ground plane (not always available).

Antennas should be calibrated so that the antenna offsets and PCV parameters are known. This is usually done by the antenna manufacturers or research and government institutions through field calibration (see section 2.2.8).

The Trimble choke ring antenna

Station 1 was fitted with the Trimble L1/L2 choke ring antenna. The antenna was designed in 1996 to be used in land surveying and GIS data collection, and has a noise figure of 2.1 (dB) and uses between 7 to 12V DC power and can operate at upto 40°C. The choke ring antenna is designed to consist of deep concentric wells in the ground plane, typically of a depth equal to ¼ wavelength of the signal to which the antenna is tuned. The ¼ -wave wells act to trap signals reflected from objects near the ground.

Figure 3.3: Trimble Choke-Ring Antenna

The antenna is very effective for single frequency but suffers inherent weakness with dual frequency GPS receivers;

- The ¼-wave wells can only be effective for one frequency and not both since they are functions of the wavelength.
- The line-of-sight of signals from low elevation satellites are attenuated along with the offending multipath signals thus reducing low elevation tracking which is of importance in certain aerial applications.

The Compact L1/L2 Geodetic Antenna

Figure 3.4: Compact L1/L2 Antenna

Compact L1/L2 geodetic antenna was designed in 1997 and can be used in several applications including vehicle tracking. The antenna has a lower noise figure of about 1.8 (dB) compared to choke-ring. The antenna has a direction indicator which must be oriented in the north direction to ensure that the antenna phase centre offsets propagate in a systematic manner.

The centering of the antennas was not a problem since the mounting piers have antenna mounting screws at the centre. The antenna height was set to 1.000m during observation but this was later changed to 0m in the data processing stage. The antenna reference points (ARP) are the top of the mounting piers (see Appendices **A2** and **A3**).

3.2.3 Software Specifications

A GPS survey software should enable pre-survey planning, data logging and downloading, data editing and processing, quality control and representation modules (e.g. output, graphics etc.) . There are basically three types of GPS data processing software;

- The so called commercial-off-the-shelf (COTs) software developed by GPS receiver manufacturers
- The specialist software are intended for specific applications for example GIS data capture, airborne and marine operations, altitude determination, GPS and other sensor integration etc.
- The specific software are mainly designed by research institutes, governments or universities for specific research purposes and are usually more accurate.

Trimble Total Control (TTC)

Trimble Total Control (TTC) software is an example of the COTS software developed by receiver manufacturer (Trimble Navigation Limited). TTC is a powerful, advanced survey and analysis package for GPS, total station and digital leveling data, and supports most raw data formats therefore accommodating mixed-brand receiver surveys. Importation of control/raw observation data into TTC project is fast, convenient and accurate. The software generates ephemeride files and reports the processed project results/output in HTML format.

Trimble Reference Station (TRS)

Trimble Reference Station (TRS^{TM}) base station software is also a product of Trimble navigation limited and is developed to record raw GPS data, including pseudoranges, carrier phases and ephemeris information. It is capable of performing real-time differential and RTK corrections over a communication link. The software also records measurements in DAT, SSF and RINEX file formats. TRS also allows scheduling of the data logging using weekly calendar.

Applanix POSGPS

This is an example of a specialist GPS data processing software intended for the integration of GPS and inertial navigation systems (INS). The software allows for quick processing of multiple static baseline through batch processing method and outputs results in different formats one of which is tailored towards integration with INS.

3.3 GPS Data Observations

GPS raw data was logged continuously for 24 hours on 6 consecutive days (064, 065, 066, 067, 068 and 069) within the GPS weeks 1208 and 1209. The GPS receiver connected to Station 1 antenna was operated using the TRS software and the data was logged directly in the laptop. The GPS receiver connected to station 2 antenna was operated using the Trimble Survey Control (TSC) and the data was logged on the PC card held within the TSC with a capacity of 30 MB. For every two days, the antenna setting was similar as shown in Figures 3.5, 3.6, and 3.7 below. A summary of the observations made and antenna settings is also given in Table 3.1.

Note that the GPS data logging was initially planned to last for 24 hours, 6 days and logged at a data rate of 1 second. The 6 data blocks were to be observed on consecutive days and each pair of data block was supposed to start and end at the same time of the day. But due to technicalities in data saving capacities and alteration of the antenna settings, only 22 hours data common for the 6 days was captured as described below. Each receiver was synchronised to start logging at the same time and at the same data rate. The field log sheets for the field observations are contained in Appendices **B1** through **B6**.

3.3.1 Day 1 and 2

On the first (Julian day 064) and second (Julian day 065) days, the choke ring antenna was not covered with radome nor was the radome mounting plate used. A base plate of equal thickness as the radome mounting plate was although placed underneath the antenna (see Figure 3.5). The compact L1/L2 antenna on station 2 was mounted directly onto the pier. For Julian day 064, the data logging started at 1243 hours UTC time and ended at 1245 hour UTC time the following day. The data logging at station 1 was done directly in the laptop while that at station 2 was done on the PC card inside the TSC and later transferred to the laptop. The second day data logging started at 1255 hours UTC time and ended at 1257 hours the following day. The data was logged as in Julian day 064, in the laptop and PC card (see Table 3.1 below).

3.3.2 Day 3 and 4

For the third and fourth days (Julian Days 066 and 067), the base plate underneath the station 1 antenna was replaced with the radome mounting plate (see Figure 3.6). The antenna setting on station 2 was unaffected. For Julian day 066, the data logging started at 1313 hours UTC time and ended at 1315 hours UTC time the following day. The data logging at station 1 was done directly in the laptop while that at station 2 was done on the PC card inside the TSC and later transferred to the laptop. The fourth day data logging started at 1320 hours UTC time and ended at 1322 hours the following day. The data was logged as in Julian day 066, in the laptop and PC card (see Table 3.1).

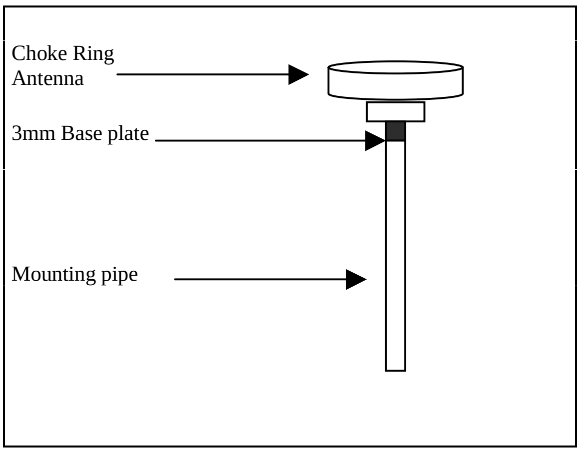


Figure 3.5: Antenna Setting Day 1 and Day 2

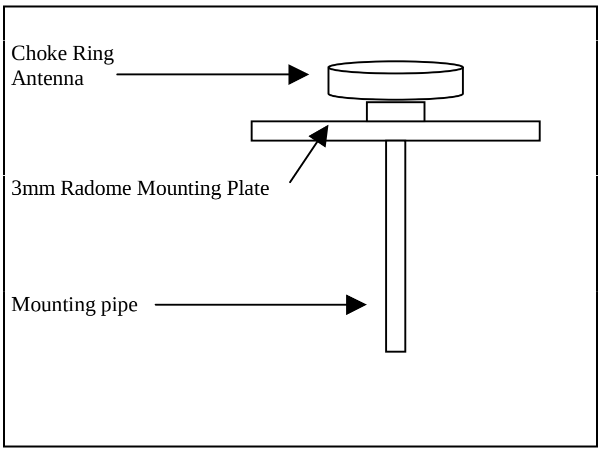
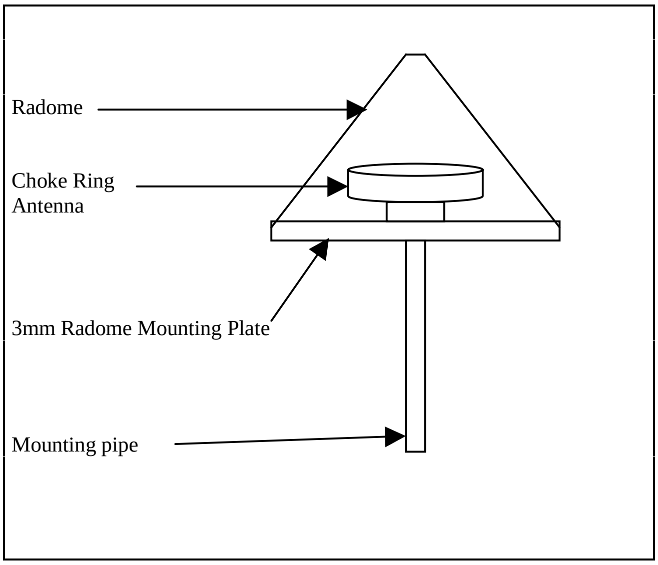


Figure 3.6: Antenna Setting Day 3 and Day 4

3.3.3 Day 5 and 6

For the last two data blocks (Julian Days 068 and 069), the antenna on station 1 was covered by a conical radome (see Figure 3.7). The antenna setting on station 2 remained unaffected. For Julian day 068, the data logging started at 1347 hours UTC time and ended at 1349 hours UTC time the following day. The data logging at station 1 was done directly in the laptop while that at station 2 was done on the PC card inside the TSC and later transferred to the laptop. The sixth day data logging started at 1358 hours UTC time and ended at 1400 hours the following day. The data was logged as in day Julian 068, in the laptop and PC card (see Table 3.1).



Fi*gure 3.7: Antenna Setting Day 5 and Day* 6

Table 3.1: Summary of GPS Observations

Date	GPS day	Station Name	Start Time (UTC)	End Time (UTC)	Data Rate	Antenna Type	Antenna Height (m)	Antenna Orient	Remarks on antenna settings
05-03-2003	064	Station 1 Station 2 384	1243 1243 1400	1245 1245 1900	2 sec 2 sec 2 sec	Choke Ring Compact L1/L2 wGP Permanent L1/L2	1.000 1.000 0.073	None North North	With base plate Without Radome Reference GPS Data
06-03-2003	065	Station 1 Station 2	1255 1255	1257 1257	2 sec 2 sec	Choke Ring Compact L1/L2 wGP	1.000 1.000	None North	With base plate Without Radome
07-03-2003	066	Station 1 Station 2	1313 1313	1315 1315	2 sec 2 sec	Choke Ring Compact L1/L2 wGP	1.000 1.000	None North	With Mounting Plate Without Radome
08-03-2003	067	Station 1 Station 2	1320 1320	1322 1322	2 sec 2 sec	Choke Ring Compact L1/L2 wGP	1.000 1.000	None North	With Mounting Plate Without Radome
09-03-2003	068	Station 1 Station 2	1347 1347	1349 1349	2 sec 2 sec	Choke Ring with Radome Compact L1/L2 wGP	1.000 1.000	None North	With Radome Without Radome
10-03-2003	069	Station 1 Station 2	1358 1358	1400 1400	2 sec 2 sec	Choke Ring with Radome Compact L1/L2 wGP	1.000 1.000	None North	With Radome Without Radome

3.3.4 SAPOS Reference Station Data

Part of the data collected on the first day (Julian day 064) were used to fix the positions of the Reference stations 1 and 2 with respect to the SAPOS (*Satelittenpositionierungsdienst*) reference station network. For this purpose, 5 hours GPS data in RINEX format was obtained from the *Landes Vermessungamt Baden-Württemberg* at a data rate of 2 seconds logged from 1400 to 1900 hours UTC time (see Table 3.1).

The SAPOS Network consists of dual-frequency receivers with station distances of about 50 kilometres and is a project of *the Vermessungsverwaltugen der Länder der Bundesrepublik Deutschland* (AdV). The system makes available to anyone the position data in the official 3-D reference system anytime anywhere in Germany. SAPOS in Baden-Württemberg offers 4 types of services:

- SAPOS EPS Real Positioning Service with an accuracy of ±1-3 m
- SAPOS HEPS High Precision Real Positioning Service with an accuracy of ±1-5 cm
- SAPOS GPPS Geodetic Precision Positioning Service with an accuracy of ±1 cm
- SAPOS GHPS Geodetic High Precision Positioning Service with an accuracy of ±5-10 mm

The stations are equipped with geodetic type receivers and the GPS data are available in RINEX format with delays ranging from a few minutes to 24 hours. No signal to Noise values are given with the data. The reference station (384) used in this project was built in 1995 and is located in Stuttgart on *Büchenstrasse 54.* The station is fitted with a permanent L1/L2 antenna and a Trimble 4000SSi receiver. The reference system is based on the European Terrestrial Reference System 1989 (ETRS89) and the reference ellipsoid is GRS80. The GPS receiver and antenna are calibrated as per the International GPS Service (IGS) conventions. The reference station position details are shown in Appendix **A1**.

4. DATA PROCESSING AND RESULTS

A variety of software packages developed by either universities, government departments or GPS receiver manufacturers are available for GPS data processing. The main components of the processing software include pre-survey planning (for decision making and reconnaissance), support of field operations (e.g. real-time kinematic, data logging and data downloading), baseline processing, network adjustment and quality control.

4.1 Pre-processing

Pre-processing involves the following tasks:

- Data transfer and decoding
- Data screening and editing
- Data reporting and database creation/entry
- Ephemeris generation

Data collected in GPS survey sessions are usually evaluated to establish their authenticity in a specified project. It's only after the pre-processing that the possibility of repeating the observation at a site is determined. The Trimble Total Control and Applanix (POSGPS) software used in this project have several features for the pre-analysis of the observation data.

Trimble Total Control (TTC) offers three areas of checking the quality, data, network and processor. In the data quality check, the *antenna eccentricity test* and *observation file integrity* were carried out. The antenna eccentricity test showed no significant variations and the integrity tests indicated no error in the observed data files. In the network quality checks, *single observation points test* and the *network connectivity test* were carried out. Both tests were passed as okay for all the six days data blocks. The processor check is in two parts*; the loop closure test* which examines all possible combinations of baselines for closed loops with a pre-set length in parts per million and the repeatability test which checks if the duplicate baselines were within a given range (significance). Both this test also passed with a significance of *5mm+1ppm*. The TTC software performs automatic detection and repair of cycle slip and outputs results.

The data was then edited to create 5 hour and hourly sessions through splitting and renaming of the 24 hours GPS data files logged on day 1 (Julian day 064). The RINEX data logged at the SAPOS reference station on *Büchsenstrasse* obtained from the *Landesvermessungsamt-*

Baden-Württemberg (LV-BW) was also edited and station coordinates and antenna offsets confirmed as per the internet website site detail information (see Appendix **A**).

4.2 Phase One Data Processing

Processing of the observed GPS data files was carried out in two phases. Phase one as described in section 1.3 had the overall goal of establishing the positions of the two reference stations, referred to as station1 and station 2 in the project, with respect to the *SAPOS* network. The data processing to obtain position values for station 1 was carried out as depicted by the flow diagram in Figure 4.1 while the flow diagram in Figure 4.2 depicts the data processing for station 2. These involved processing of five hour and hourly data files logged at station 1 and station 2 using TTC and POSGPS software. The five hour data file collected at the SAPOS station on *Büchenstrasse* was used as the fixed control station data.

The results obtained through processing of the data files using precise ephemeris from IGS (2003) were found to be exactly the same as the results obtained using broadcast ephemeris hence only the latter are tabulated for further analysis and comparison. The TTC software automatically generates results for single, double and triple differences for both the float and fixed baseline components. All the results generated are contained in the CDs appended at the end of this report. Only the double differenced fixed baseline results are tabulated below for purposes of analysis. All the coordinates are referred to the European Terrestrial Reference System 1989 (ETRS89) as per the reference station data.

4.2.1 Station 1 Data Processing (TTC Software and Trimble PCV Parameters)

After assessment and editing of the data, as outlined in section 4.1 above, the elevation cut-off angle of 10^0 and the phase centre variation (PCV) parameters supplied by Trimble were set in the TTC software. The dual frequency data logged at station1 was then processed and the Earth-Centred Earth Fixed coordinates (X, Y, Z) and ellipsoidal height (h) obtained as indicated in Table 4.1 below. The antenna heights were set to zero meaning all the positions computed are referred to the antenna phase centres. The 5 hours data file was again processed but with the cut-off elevation angle varied to 05^0,15^0, 20^0, 25^0 and 30^0.

4.2.2 Station 1 Data Processing (TTC Software and NGS PCV Parameters)

After the assessment and editing of the data files, as outlined in section 4.1 above, the elevation cut-off angle of 10^0 and the phase centre variation (PCV) parameters as determined by NGS were set in the TTC software. The station 1 data was again processed and the Earth-Centred Earth Fixed coordinates (X, Y, Z) and ellipsoidal height (h) obtained as indicated in Table 4.2 below. The 5 hours data file was again processed but with the cut-off elevation angle varied to 05^0,15^0, 20^0, 25^0 and 30^0 and the PCV parameters as obtained by NGS used.

Table 4.1: TTC Station 1 results (Trimble PCV Parameters)

Observation Period (hour : min)		Cut-off Elevation Angle	Coordinates (Metre)			Elipsoidal height (Metre)	Remarks
Start	End		X	Y	Z	h	
14:00	15:00	10^0	4157189.0189	671201.9091	4774768.6179	325.9688	Computed to Phase centre
15:00	16:00	10^0	4157189.0190	671201.9099	4774768.6169	325.9682	Computed to Phase centre
16:00	17:00	10^0	4157189.0211	671201.9098	4774768.6196	325.9715	Computed to Phase centre
17:00	18:00	10^0	4157189.0197	671201.9106	4774768.6180	325.9696	Computed to Phase centre
18:00	19:00	10^0	4157189.0218	671201.9096	4774768.6176	325.9705	Computed to Phase centre
14:00	19:00	05^0	4157189.0200	671201.9098	4774768.6179	325.9696	Computed to Phase centre
14:00	19:00	10^0	4157189.0199	671201.9098	4774768.6178	325.9697	Computed to Phase centre
14:00	19:00	15^0	4157189.0205	671201.9099	4774768.6184	325.9704	Computed to Phase centre
14:00	19:00	20^0	4157189.0203	671201.9099	4774768.6183	325.9701	Computed to Phase centre
14:00	19:00	25^0	4157189.0216	671201.9100	4774768.6190	325.9715	Computed to Phase centre
14:00	19:00	30^0	4157189.0214	671201.9102	4774768.6188	325.9712	Computed to Phase centre

4.2.3 Station 2 Data Processing (TTC Software and Trimble PCV Parameters)

After the assessment and editing of the data, as outlined in section 4.1 above, the elevation cut-off angle of 10^0 and the phase centre variation (PCV) parameters supplied by Trimble were set in the TTC software. The data logged at station 2 was then processed and the Earth-Centred Earth Fixed coordinates (X, Y, Z) and ellipsoidal height (h) obtained as indicated in Table 4.3 below. The 5 hours data file was again processed but with the cut-off elevation angle varied to 05^0,15^0, 20^0, 25^0 and 30^0 (see Figure 4.2) .

Table 4.2: TTC Station 1 results (NGS PCV Parameters)

Observation Period (hour : min)		Cut-off Elevation Angle	Coordinates (Metre)			Elipsoidal height (Metre)	Remarks
Start	End		X	Y	Z	h	
14:00	15:00	10^0	4157189.0206	671201.9110	4774768.6182	325.9704	Computed to Phase centre
15:00	16:00	10^0	4157189.0209	671201.9119	4774768.6174	325.9700	Computed to Phase centre
16:00	17:00	10^0	4157189.0227	671201.9117	4774768.6198	325.9730	Computed to Phase centre
17:00	18:00	10^0	4157189.0214	671201.9125	4774768.6183	325.9711	Computed to Phase centre
18:00	19:00	10^0	4157189.0233	671201.9117	4774768.6177	325.9718	Computed to Phase centre
14:00	19:00	05^0	4157189.0216	671201.9118	4774768.6180	325.9709	Computed to Phase centre
14:00	19:00	10^0	4157189.0217	671201.9119	4774768.6183	325.9712	Computed to Phase centre
14:00	19:00	15^0	4157189.0221	671201.9119	4774768.6185	325.9716	Computed to Phase centre
14:00	19:00	20^0	4157189.0217	671201.9118	4774768.6183	325.9712	Computed to Phase centre
14:00	19:00	25^0	4157189.0230	671201.9119	4774768.6189	325.9726	Computed to Phase centre
14:00	19:00	30^0	4157189.0229	671201.9121	4774768.6188	325.9724	Computed to Phase centre

Table 4.3: TTC Station 2 results (Trimble PCV Parameters)

Observation Period (hour : min)		Cut-off Elevation Angle	Coordinates (Metre)			Elipsoidal height (Metre)	Remarks
Start	End		X	Y	Z	h	
14:00	15:00	10^0	4157191.9828	671204.6094	4774765.6198	325.9254	Computed to Phase centre
15:00	16:00	10^0	4157191.9846	671204.6129	4774765.6211	325.9279	Computed to Phase centre
16:00	17:00	10^0	4157191.9839	671204.6125	4774765.6215	325.9276	Computed to Phase centre
17:00	18:00	10^0	4157191.9831	671204.6142	4774765.6209	325.9269	Computed to Phase centre
18:00	19:00	10^0	4157191.9816	671204.6138	4774765.6180	325.9237	Computed to Phase centre
14:00	19:00	05^0	4157191.9830	671204.6130	4774765.6201	325.9262	Computed to Phase centre
14:00	19:00	10^0	4157191.9829	671204.6133	4774765.6202	325.9263	Computed to Phase centre
14:00	19:00	15^0	4157191.9832	671204.6132	4774765.6204	325.9266	Computed to Phase centre
14:00	19:00	20^0	4157191.9829	671204.6128	4774765.6204	325.9264	Computed to Phase centre
14:00	19:00	25^0	4157191.9835	671204.6129	4774765.6205	325.9268	Computed to Phase centre
14:00	19:00	30^0	4157191.9843	671204.6128	4774765.6212	325.9279	Computed to Phase centre

4.2.4 Station 1 Data Processing (TTC Software and NGS PCV Parameters)

After the data assessment and editing was done as outlined in section 4.1 above, the elevation cut-off angle of 10^0 and the phase centre variation (PCV) parameters as determined by NGS were set in the TTC software. The station 2 data was again processed and the Earth-Centred Earth Fixed coordinates (X, Y, Z) and ellipsoidal height (h) obtained as indicated in Table 4.3

below. The 5 hours data file was again processed but with the cut-off elevation angle varied to 05^0,15^0, 20^0, 25^0 and 30^0 and the PCV parameters as obtained by NGS used (see Figure 4.2).

Table 4.4: TTC Station 2 results (NGS PCV Parameters)

Observation Period (hour : min)		Cut-off Elevation Angle	Coordinates (Metre)			Elipsoidal height (Metre)	Remarks
Start	End		X	Y	Z	h	
14:00	15:00	10^0	4157191.9825	671204.6106	4774765.6217	325.9267	Computed to Phase centre
15:00	16:00	10^0	4157191.9842	671204.6143	4774765.6232	325.9293	Computed to Phase centre
16:00	17:00	10^0	4157191.9836	671204.6140	4774765.6235	325.9291	Computed to Phase centre
17:00	18:00	10^0	4157191.9829	671204.6155	4774765.6233	325.9286	Computed to Phase centre
18:00	19:00	10^0	4157191.9809	671204.6150	4774765.6200	325.9249	Computed to Phase centre
14:00	19:00	05^0	4157191.9826	671204.6144	4774765.6223	325.9278	Computed to Phase centre
14:00	19:00	10^0	4157191.9825	671204.6146	4774765.6223	325.9277	Computed to Phase centre
14:00	19:00	15^0	4157191.9827	671204.6145	4774765.6223	325.9278	Computed to Phase centre
14:00	19:00	20^0	4157191.9821	671204.6141	4774765.6221	325.9273	Computed to Phase centre
14:00	19:00	25^0	4157191.9825	671204.6141	4774765.6221	325.9275	Computed to Phase centre
14:00	19:00	30^0	4157191.9832	671204.6140	4774765.6227	325.9284	Computed to Phase centre

4.2.5 Station 1 and 2 Data Processing (Applanix POSGPS)

As a check the 5 hour data files logged at both stations 1 and 2 were processed using POGPS software. The cut-off elevation angle was set to 10^0 and the software only uses NGS PCV parameters. The results obtained are indicated in the Table 4.5 below.

Table 4.5: Station 1 and 2 results (Applanix POSGPS)

Observation Period (hour : min)		Cut-off Elevation Angle	Coordinates (Metre)			Elipsoidal height (Metre)	Remarks
Start	End		X	Y	Z	h	
14:00	19:00	10^0	4157189.0247	671201.9134	4774768.6190	325.9740	Station 1 position computed to Phase Centre
14:00	19:00	10^0	4157191.9845	671204.6143	4774765.6209	325.9279	Station 2 position Computed to phase centre

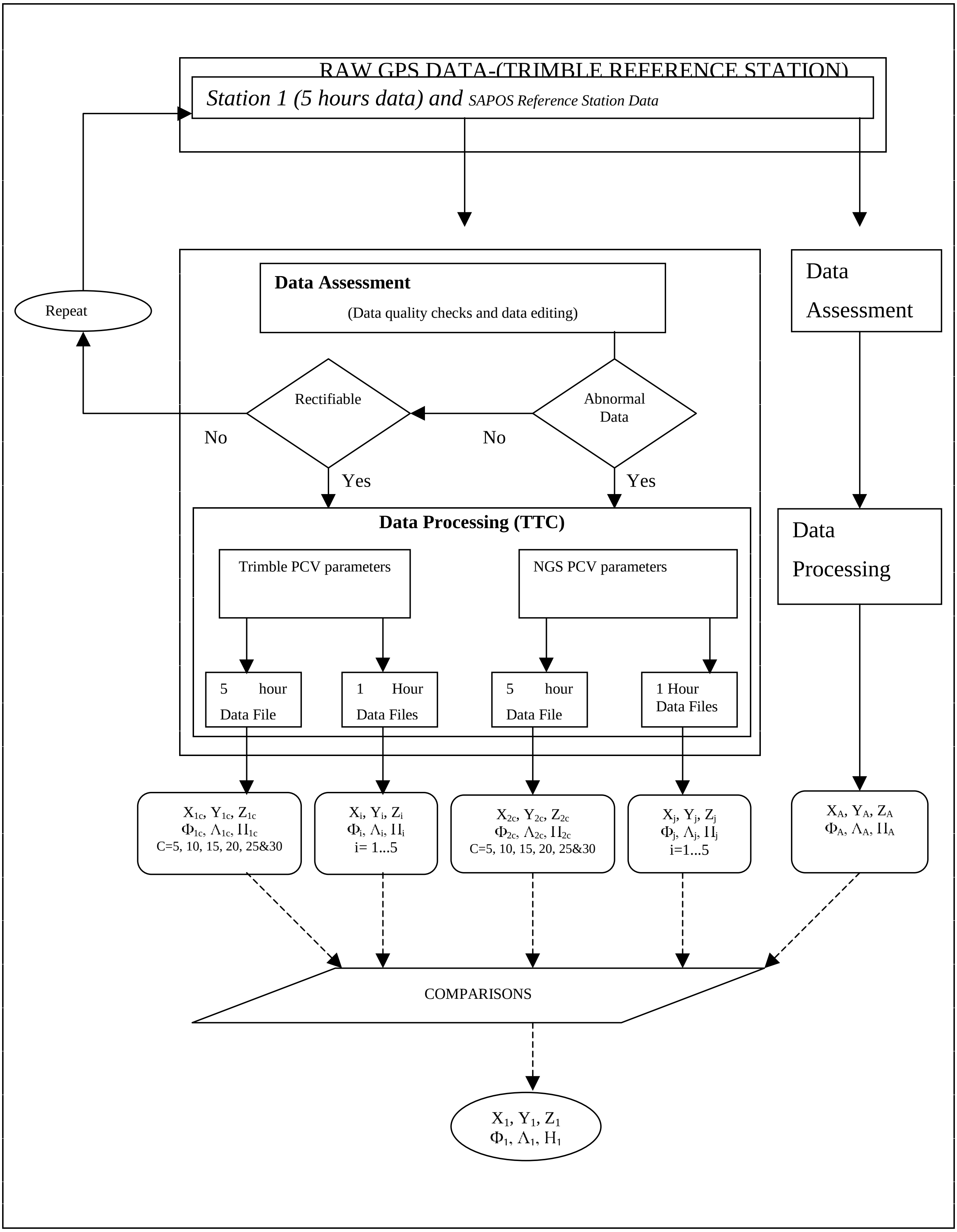


Figure 4.1: Station 1 data processing

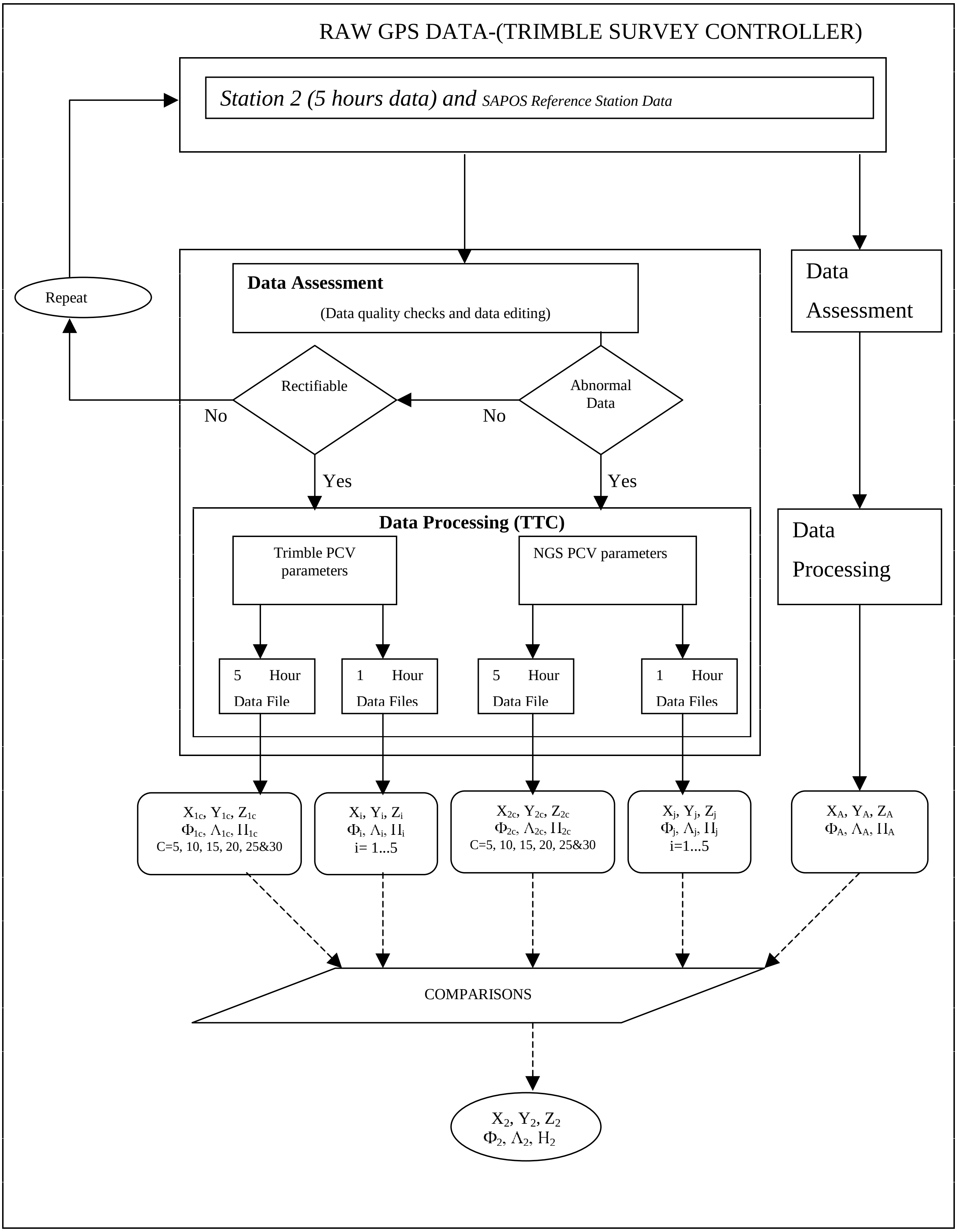


Figure 4.2: Station 2 data processing

4.3 Phase Two Data Processing

Phase two data processing as outlined in section 1.3 had the objective of investigating the effect of the antenna radome fixed on station1 on the fifth and sixth days (Julian days 068 and 069) of observation. The data processing to obtain position values for station 1 was in this case carried out as depicted by the flow diagram in Figure 4.3. This involved processing of the whole 22 hours data files and then the hourly data files logged at station 1 using TTC software and Trimble PCV parameters. The 22 hours data files observed at station 2 was used as fixed control station data.

The results of the data processing using precise ephemeris from IGS (2003) were found to be exactly the same as the results obtained using broadcast ephemeris hence only the latter are tabulated for further analysis and comparison. The single, double and triple differences for both the float and fixed baseline components generated during data processing are contained in the CDs appended at the end of this report. Only the double differenced fixed baseline results are tabulated below for purposes of analysis. All the coordinates are referred to the European Terrestrial Reference System 1989 (ETRS89) as per the reference station data. As in the phase one data processing all the antenna heights were set to 0 which means all the results are referred to the antenna phase centre. Even though the raw data observations on the six consecutive days were each logged for a duration of 24 hours, as already mentioned in section 3.3, only 22 hours of the raw data were common for all the six days. This was due to the necessity to interrupt the data logging between days 2 and 3 (to replace the underlying base plate with a radome mounting plate) and between day 4 and 5 (to mount the radome on the antenna). The results of the data processing for each of the six days (Julian days 064, 065, 066, 067, 068 and 069) using Trimble PCV parameters are tabulated in Tables 4.6, 4.7, 4.8, 4.9, 4.10 and 4.11 below respectively. The standard cut-off elevation angle for all the data processing was set to 10^0. But for the purposes of comparison, only the 22 hours data files logged on each of the six days were processed using TTC software with the PCV parameters set to those determined by NGS. The results of the data processing using the NGS PCV parameters are contained in Table 4.12 below.

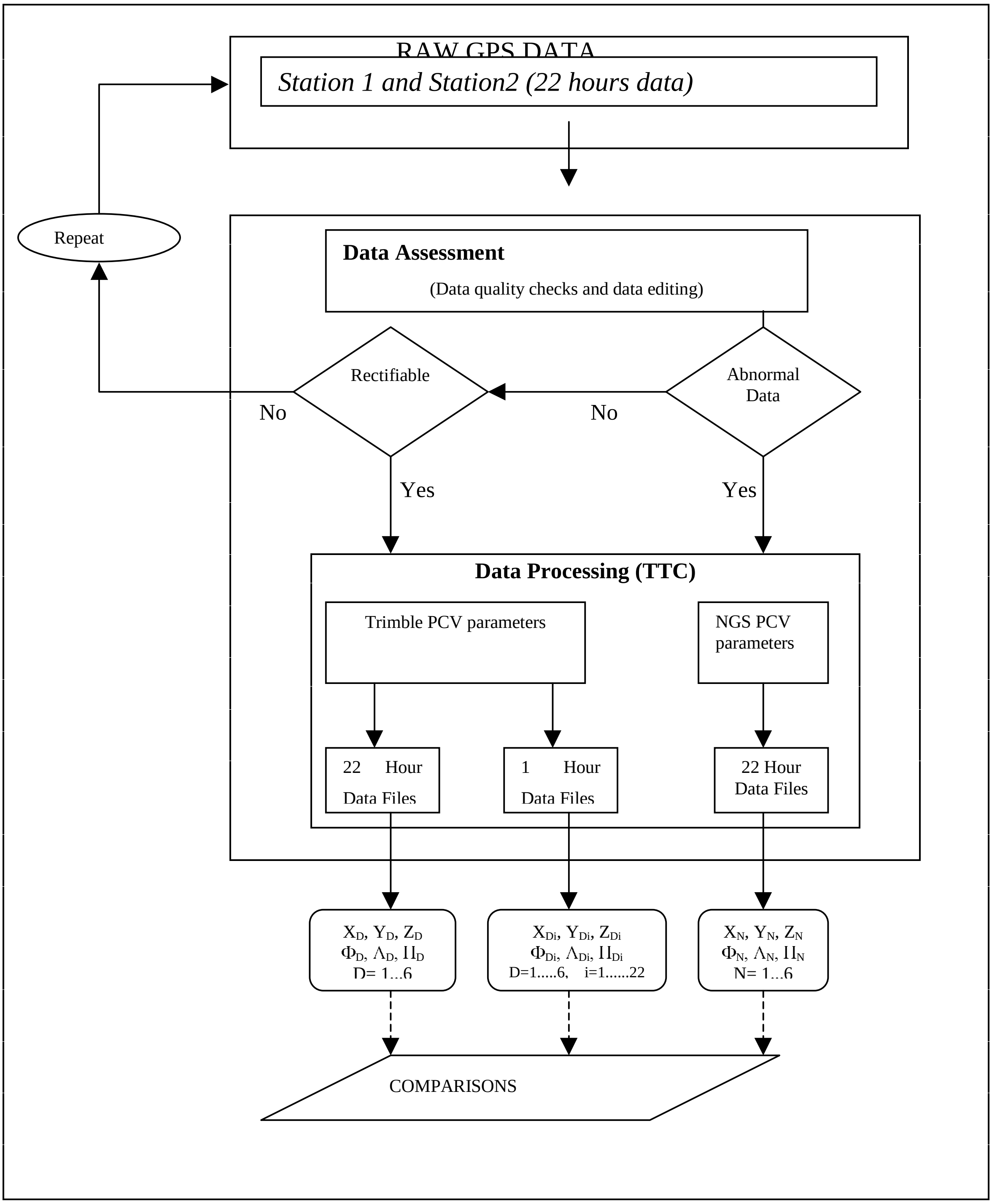


Figure 4.3: Phase Two data processing

Table 4.6: TTC Station 1 results for Day 1 (Julian Day 064)

Observation Period (hour : min)		Cut-off Elevation Angle	Coordinates (Metre)			Elipsoidal height (Metre)	Remarks
Start Time	End Time		X	Y	Z	h	
14:00	15:00	10^0	4157189.0186	671201.9142	4774768.6181	325.9693	Computed to Phase centre
15:00	16:00	10^0	4157189.0172	671201.9110	4774768.6157	325.9662	Computed to Phase centre
16:00	17:00	10^0	4157189.0199	671201.9112	4774768.6180	325.9697	Computed to Phase centre
17:00	18:00	10^0	4157189.0193	671201.9104	4774768.6169	325.9685	Computed to Phase centre
18:00	19:00	10^0	4157189.0229	671201.9098	4774768.6194	325.9726	Computed to Phase centre
19:00	20:00	10^0	4157189.0195	671201.9105	4774768.6178	325.9693	Computed to Phase centre
20:00	21:00	10^0	4157189.0178	671201.9107	4774768.6164	325.9671	Computed to Phase centre
21:00	22:00	10^0	4157189.0212	671201.9108	4774768.6188	325.9712	Computed to Phase centre
22:00	23:00	10^0	4157189.0192	671201.9100	4774768.6183	325.9694	Computed to Phase centre
23:00	00:00	10^0	4157189.0181	671201.9112	4774768.6184	325.9690	Computed to Phase centre
00:00	01:00	10^0	4157189.0198	671201.9112	4774768.6176	325.9694	Computed to Phase centre
01:00	02:00	10^0	4157189.0197	671201.9100	4774768.6187	325.9700	Computed to Phase centre
02:00	03:00	10^0	4157189.0199	671201.9103	4774768.6179	325.9696	Computed to Phase centre
03:00	04:00	10^0	4157189.0191	671201.9109	4774768.6166	325.9681	Computed to Phase centre
04:00	05:00	10^0	4157189.0211	671201.9117	4774768.6188	325.9711	Computed to Phase centre
05:00	06:00	10^0	4157189.0193	671201.9140	4774768.6193	325.9706	Computed to Phase centre
06:00	07:00	10^0	4157189.0206	671201.9111	4774768.6190	325.9710	Computed to Phase centre
07:00	08:00	10^0	4157189.0185	671201.9104	4774768.6174	325.9683	Computed to Phase centre
08:00	09:00	10^0	4157189.0202	671201.9112	4774768.6183	325.9701	Computed to Phase centre
09:00	10:00	10^0	4157189.0217	671201.9103	4774768.6180	325.9708	Computed to Phase centre
10:00	11:00	10^0	4157189.0194	671201.9110	4774768.6172	325.9688	Computed to Phase centre
11:00	12:00	10^0	4157189.0188	671201.9116	4774768.6182	325.9692	Computed to Phase centre
14:00	12:00	10^0	4157189.0196	671201.9108	4774768.6178	325.9697	Computed to Phase centre

Table 4.7: TTC Station 1 results for Day 2 (Julian Day 065)

Observation Period (hour : min)		Cut-off Elevation Angle	Coordinates (Metre)			Elipsoidal height (Metre)	Remarks
Start Time	End Time		X	Y	Z	h	
14:00	15:00	10^0	4157189.0187	671201.9145	4774768.6182	325.9693	Computed to Phase centre
15:00	16:00	10^0	4157189.0180	671201.9107	4774768.6138	325.9654	Computed to Phase centre
16:00	17:00	10^0	4157189.0216	671201.9116	4774768.6189	325.9715	Computed to Phase centre
17:00	18:00	10^0	4157189.0189	671201.9160	4774768.6167	325.9686	Computed to Phase centre
18:00	19:00	10^0	4157189.0229	671201.9098	4774768.6194	325.9726	Computed to Phase centre
19:00	20:00	10^0	4157189.0195	671201.9105	4774768.6178	325.9693	Computed to Phase centre
20:00	21:00	10^0	4157189.0191	671201.9213	4774768.6145	325.9677	Computed to Phase centre
21:00	22:00	10^0	4157189.0172	671201.9137	4774768.6176	325.9680	Computed to Phase centre
22:00	23:00	10^0	4157189.0200	671201.9104	4774768.6186	325.9702	Computed to Phase centre
23:00	00:00	10^0	4157189.0175	671201.9122	4774768.6177	325.9681	Computed to Phase centre
00:00	01:00	10^0	4157189.0202	671201.9115	4774768.6186	325.9704	Computed to Phase centre
01:00	02:00	10^0	4157189.0214	671201.9097	4774768.6201	325.9722	Computed to Phase centre
02:00	03:00	10^0	4157189.0206	671201.9097	4774768.6190	325.9707	Computed to Phase centre
03:00	04:00	10^0	4157189.0181	671201.9109	4774768.6109	325.9632	Computed to Phase centre
04:00	05:00	10^0	4157189.0186	671201.9121	4774768.6172	325.9684	Computed to Phase centre
05:00	06:00	10^0	4157189.0276	671201.9147	4774768.6266	325.9816	Computed to Phase centre
06:00	07:00	10^0	4157189.0209	671201.9118	4774768.6199	325.9719	Computed to Phase centre
07:00	08:00	10^0	4157189.0199	671201.9105	4774768.6192	325.9705	Computed to Phase centre
08:00	09:00	10^0	4157189.0189	671201.9107	4774768.6176	325.9687	Computed to Phase centre
09:00	10:00	10^0	4157189.0224	671201.9103	4774768.6188	325.9719	Computed to Phase centre
10:00	11:00	10^0	4157189.0196	671201.9112	4774768.6168	325.9686	Computed to Phase centre
11:00	12:00	10^0	4157189.0188	671201.9118	4774768.6181	325.9692	Computed to Phase centre
14:00	12:00	10^0	4157189.0203	671201.9110	4774768.6183	325.9704	Computed to Phase centre

Table 4.8: TTC Station 1 results for Day 3 (Julian Day 066)

Observation Period (hour : min)		Cut-off Elevation Angle	Coordinates (Metre)			Elipsoidal height (Metre)	Remarks
Start Time	End Time		X	Y	Z	h	
14:00	15:00	10^0	4157189.0181	671201.9147	4774768.6185	325.9693	Computed to Phase centre
15:00	16:00	10^0	4157189.0183	671201.9117	4774768.6192	325.9696	Computed to Phase centre
16:00	17:00	10^0	4157189.0204	671201.9123	4774768.6192	325.9711	Computed to Phase centre
17:00	18:00	10^0	4157189.0199	671201.9106	4774768.6179	325.9696	Computed to Phase centre
18:00	19:00	10^0	4157189.0239	671201.9098	4774768.6213	325.9747	Computed to Phase centre
19:00	20:00	10^0	4157189.0204	671201.9109	4774768.6194	325.9711	Computed to Phase centre
20:00	21:00	10^0	4157189.0178	671201.9115	4774768.6184	325.9687	Computed to Phase centre
21:00	22:00	10^0	4157189.0198	671201.9105	4774768.6196	325.9708	Computed to Phase centre
22:00	23:00	10^0	4157189.0197	671201.9100	4774768.6203	325.9713	Computed to Phase centre
23:00	00:00	10^0	4157189.0182	671201.9116	4774768.6202	325.9703	Computed to Phase centre
00:00	01:00	10^0	4157189.0201	671201.9116	4774768.6191	325.9707	Computed to Phase centre
01:00	02:00	10^0	4157189.0214	671201.9096	4774768.6201	325.9722	Computed to Phase centre
02:00	03:00	10^0	4157189.0191	671201.9112	4774768.6190	325.9699	Computed to Phase centre
03:00	04:00	10^0	4157189.0209	671201.9110	4774768.6192	325.9713	Computed to Phase centre
04:00	05:00	10^0	4157189.0212	671201.9119	4774768.6207	325.9727	Computed to Phase centre
05:00	06:00	10^0	4157189.0186	671201.9142	4774768.6210	325.9715	Computed to Phase centre
06:00	07:00	10^0	4157189.0208	671201.9118	4774768.6198	325.9717	Computed to Phase centre
07:00	08:00	10^0	4157189.0185	671201.9114	4774768.6187	325.9694	Computed to Phase centre
08:00	09:00	10^0	4157189.0211	671201.9105	4774768.6189	325.9711	Computed to Phase centre
09:00	10:00	10^0	4157189.0224	671201.9105	4774768.6206	325.9732	Computed to Phase centre
10:00	11:00	10^0	4157189.0196	671201.9114	4774768.6187	325.9701	Computed to Phase centre
11:00	12:00	10^0	4157189.0188	671201.9118	4774768.6189	325.9698	Computed to Phase centre
14:00	12:00	10^0	4157189.0199	671201.9112	4774768.6193	325.9709	Computed to Phase centre

Table 4.9: TTC Station 1 results for Day 4 (Julian Day 067)

Observation Period (hour : min)		Cut-off Elevation Angle	Coordinates (Metre)			Elipsoidal height (Metre)	Remarks
Start Time	End Time		X	Y	Z	h	
14:00	15:00	10^0	4157189.0184	671201.9145	4774768.6179	325.9690	Computed to Phase centre
15:00	16:00	10^0	4157189.0178	671201.9117	4774768.6187	325.9690	Computed to Phase centre
16:00	17:00	10^0	4157189.0207	671201.9126	4774768.6197	325.9717	Computed to Phase centre
17:00	18:00	10^0	4157189.0200	671201.9105	4774768.6182	325.9699	Computed to Phase centre
18:00	19:00	10^0	4157189.0237	671201.9101	4774768.6217	325.9749	Computed to Phase centre
19:00	20:00	10^0	4157189.0203	671201.9107	4774768.6196	325.9711	Computed to Phase centre
20:00	21:00	10^0	4157189.0188	671201.9112	4774768.6192	325.9699	Computed to Phase centre
21:00	22:00	10^0	4157189.0201	671201.9102	4774768.6196	325.9710	Computed to Phase centre
22:00	23:00	10^0	4157189.0194	671201.9104	4774768.6198	325.9707	Computed to Phase centre
23:00	00:00	10^0	4157189.0188	671201.9117	4774768.6203	325.9709	Computed to Phase centre
00:00	01:00	10^0	4157189.0208	671201.9114	4774768.6195	325.9715	Computed to Phase centre
01:00	02:00	10^0	4157189.0218	671201.9095	4774768.6204	325.9727	Computed to Phase centre
02:00	03:00	10^0	4157189.0191	671201.9115	4774768.6184	325.9696	Computed to Phase centre
03:00	04:00	10^0	4157189.0210	671201.9118	4774768.6205	325.9725	Computed to Phase centre
04:00	05:00	10^0	4157189.0195	671201.9127	4774768.6202	325.9713	Computed to Phase centre
05:00	06:00	10^0	4157189.0192	671201.9111	4774768.6201	325.9709	Computed to Phase centre
06:00	07:00	10^0	4157189.0204	671201.9116	4774768.6201	325.9717	Computed to Phase centre
07:00	08:00	10^0	4157189.0186	671201.9114	4774768.6194	325.9700	Computed to Phase centre
08:00	09:00	10^0	4157189.0220	671201.9103	4774768.6193	325.9720	Computed to Phase centre
09:00	10:00	10^0	4157189.0229	671201.9110	4774768.6202	325.9733	Computed to Phase centre
10:00	11:00	10^0	4157189.0199	671201.9114	4774768.6187	325.9703	Computed to Phase centre
11:00	12:00	10^0	4157189.0194	671201.9118	4774768.6195	325.9706	Computed to Phase centre
14:00	12:00	10^0	4157189.0205	671201.9112	4774768.6200	325.9716	Computed to Phase centre

Table 4.10: TTC Station 1 results for Day 5 (Julian Day 068)

Observation Period (hour : min)		Cut-off Elevation Angle	Coordinates (Metre)			Elipsoidal height (Metre)	Remarks
Start Time	End Time		X	Y	Z	h	
14:00	15:00	10^0	4157189.0182	671201.9143	4774768.6176	325.9686	Computed to Phase centre
15:00	16:00	10^0	4157189.0184	671201.9126	4774768.6200	325.9705	Computed to Phase centre
16:00	17:00	10^0	4157189.0213	671201.9131	4774768.6196	325.9720	Computed to Phase centre
17:00	18:00	10^0	4157189.0181	671201.9131	4774768.6170	325.9680	Computed to Phase centre
18:00	19:00	10^0	4157189.0238	671201.9104	4774768.6216	325.9749	Computed to Phase centre
19:00	20:00	10^0	4157189.0206	671201.9108	4774768.6198	325.9715	Computed to Phase centre
20:00	21:00	10^0	4157189.0194	671201.9115	4774768.6201	325.9711	Computed to Phase centre
21:00	22:00	10^0	4157189.0203	671201.9102	4774768.6197	325.9712	Computed to Phase centre
22:00	23:00	10^0	4157189.0189	671201.9103	4774768.6202	325.9707	Computed to Phase centre
23:00	00:00	10^0	4157189.0196	671201.9121	4774768.6208	325.9718	Computed to Phase centre
00:00	01:00	10^0	4157189.0208	671201.9115	4774768.6190	325.9711	Computed to Phase centre
01:00	02:00	10^0	4157189.0215	671201.9097	4774768.6202	325.9724	Computed to Phase centre
02:00	03:00	10^0	4157189.0188	671201.9113	4774768.6187	325.9695	Computed to Phase centre
03:00	04:00	10^0	4157189.0214	671201.9121	4774768.6210	325.9731	Computed to Phase centre
04:00	05:00	10^0	4157189.0200	671201.9128	4774768.6203	325.9717	Computed to Phase centre
05:00	06:00	10^0	4157189.0198	671201.9111	4774768.6199	325.9711	Computed to Phase centre
06:00	07:00	10^0	4157189.0216	671201.9116	4774768.6194	325.9720	Computed to Phase centre
07:00	08:00	10^0	4157189.0189	671201.9118	4774768.6196	325.9704	Computed to Phase centre
08:00	09:00	10^0	4157189.0221	671201.9098	4774768.6189	325.9717	Computed to Phase centre
09:00	10:00	10^0	4157189.0237	671201.9113	4774768.6207	325.9742	Computed to Phase centre
10:00	11:00	10^0	4157189.0204	671201.9118	4774768.6194	325.9712	Computed to Phase centre
11:00	12:00	10^0	4157189.0184	671201.9115	4774768.6180	325.9688	Computed to Phase centre
14:00	12:00	10^0	4157189.0203	671201.9114	4774768.6195	325.9713	Computed to Phase centre

Table 4.11: TTC Station 1 results for Day 6 (Julian Day 069)

Observation Period (hour : min)		Cut-off Elevation Angle	Coordinates (Metre)			Elipsoidal height (Metre)	Remarks
Start	End		X	Y	Z	h	
14:00	15:00	10^0	4157189.0180	671201.9140	4774768.6169	325.9680	Computed to Phase centre
15:00	16:00	10^0	4157189.0181	671201.9126	4774768.6195	325.9699	Computed to Phase centre
16:00	17:00	10^0	4157189.0218	671201.9126	4774768.6195	325.9722	Computed to Phase centre
17:00	18:00	10^0	4157189.0203	671201.9105	4774768.6181	325.9700	Computed to Phase centre
18:00	19:00	10^0	4157189.0230	671201.9106	4774768.6211	325.9749	Computed to Phase centre
19:00	20:00	10^0	4157189.0204	671201.9106	4774768.6195	325.9711	Computed to Phase centre
20:00	21:00	10^0	4157189.0205	671201.9118	4774768.6200	325.9717	Computed to Phase centre
21:00	22:00	10^0	4157189.0203	671201.9106	4774768.6191	325.9708	Computed to Phase centre
22:00	23:00	10^0	4157189.0188	671201.9108	4774768.6210	325.9713	Computed to Phase centre
23:00	00:00	10^0	4157189.0185	671201.9124	4774768.6205	325.9709	Computed to Phase centre
00:00	01:00	10^0	4157189.0207	671201.9117	4774768.6192	325.9712	Computed to Phase centre
01:00	02:00	10^0	4157189.0205	671201.9098	4774768.6200	325.9715	Computed to Phase centre
02:00	03:00	10^0	4157189.0189	671201.9115	4774768.6188	325.9698	Computed to Phase centre
03:00	04:00	10^0	4157189.0210	671201.9124	4774768.6209	325.9728	Computed to Phase centre
04:00	05:00	10^0	4157189.0193	671201.9131	4774768.6201	325.9711	Computed to Phase centre
05:00	06:00	10^0	4157189.0202	671201.9111	4774768.6198	325.9713	Computed to Phase centre
06:00	07:00	10^0	4157189.0210	671201.9115	4774768.6192	325.9714	Computed to Phase centre
07:00	08:00	10^0	4157189.0188	671201.9120	4774768.6201	325.9707	Computed to Phase centre
08:00	09:00	10^0	4157189.0222	671201.9098	4774768.6189	325.9717	Computed to Phase centre
09:00	10:00	10^0	4157189.0235	671201.9110	4774768.6212	325.9745	Computed to Phase centre
10:00	11:00	10^0	4157189.0205	671201.9116	4774768.6201	325.9718	Computed to Phase centre
11:00	12:00	10^0	4157189.0189	671201.9113	4774768.6184	325.9695	Computed to Phase centre
14:00	12:00	10^0	4157189.0202	671201.9090	4774768.6196	325.9711	Computed to Phase centre

Table 4.12: TTC Station 1 results (NGS PCV Parameters))

Observation Period (hour : min)		Cut-off Elevation Angle	Coordinates (Metre)			Elipsoidal height (Metre)	Remarks
Start	End		X	Y	Z	h	
14:00	12:00	10^0	4157189.0217	671201.9116	4774768.6161	325.9697	Day 1 (without Radome)
14:00	12:00	10^0	4157189.0223	671201.9117	4774768.6162	325.9702	Day 2 (without Radome)
14:00	12:00	10^0	4157189.0220	671201.9120	4774768.6175	325.9710	Day 3 (with Mount plate)
14:00	12:00	10^0	4157189.0224	671201.9121	4774768.6179	325.9715	Day 4 (with Mount plate)
14:00	12:00	10^0	4157189.0224	671201.9122	4774768.6178	325.9715	Day 5 (with Radome)
14:00	12:00	10^0	4157189.0223	671201.9122	4774768.6179	325.9715	Day 6 (with Radome)

CHAPTER FIVE

5. DATA ANALYSIS

5.1 Phase one

The estimated relative baseline components in phase one of the project have in average 2 to 3 mm root mean square scatter. Analysis of the processed solutions at station 1 showed that the X-Y-Z coordinates and height component generated from the 1 hour data files varied by between –1.5 to 1.9 mm (in the case of Trimble PCV parameters) and by between –1.2 to 1.8 mm (in the case of NGS PCV parameters) from the X-Y-Z coordinates and height component generated from the 5 hour data files (see Figures 5.1 and 5.2). The comparison of Figures 5.1 and 5.2 indicated similarity in the variation patterns between the solutions obtained using the two types of PCV parameters.

Similar analysis of the GPS data processing at station 2 showed that the X-Y-Z coordinates and height component generated from the 1 hour data files vary by between –3.9 to 1.7 mm (in the case of Trimble PCV parameters) and by between –4.0 to 1.7 mm (in the case of NGS PCV parameters) from the X-Y-Z coordinates and height generated from the 5 hour data files (see Figures 5.3 and 5.4).). In this case also, the comparison of Figures 5.3 and 5.4 indicate similarity in the variation patterns between the solutions obtained using the two types of PCV parameters with a mean swing of –3.9 to 1.7 mm.

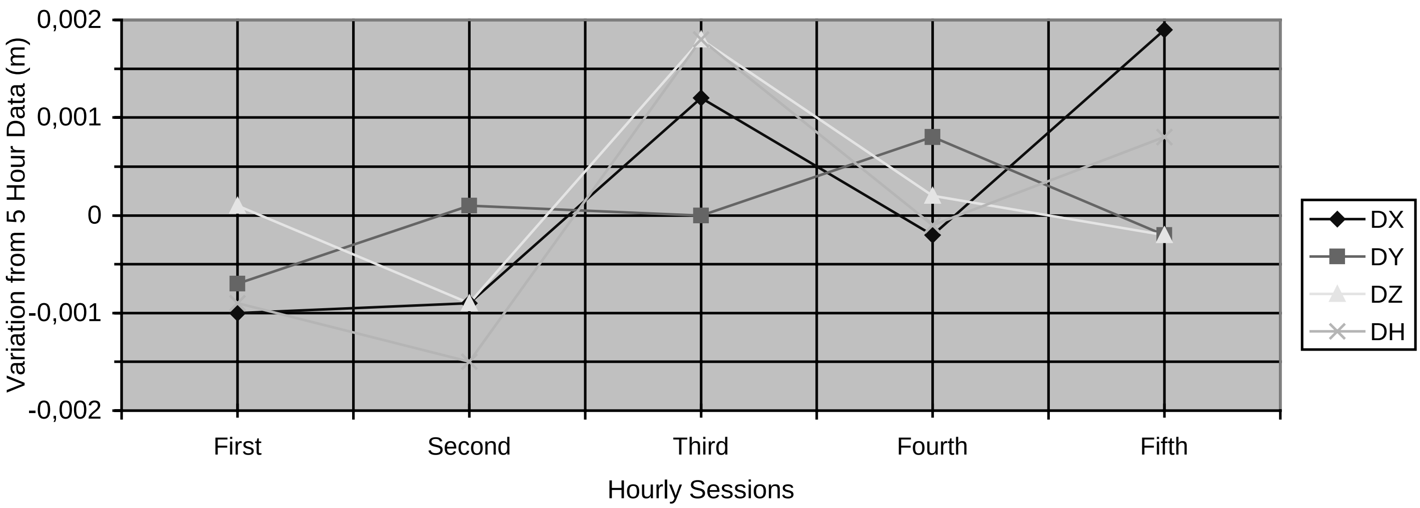


Fig. 5.1: Station 1 Coordinates and Height Comparison (TRIMBLE PCV Parameters)

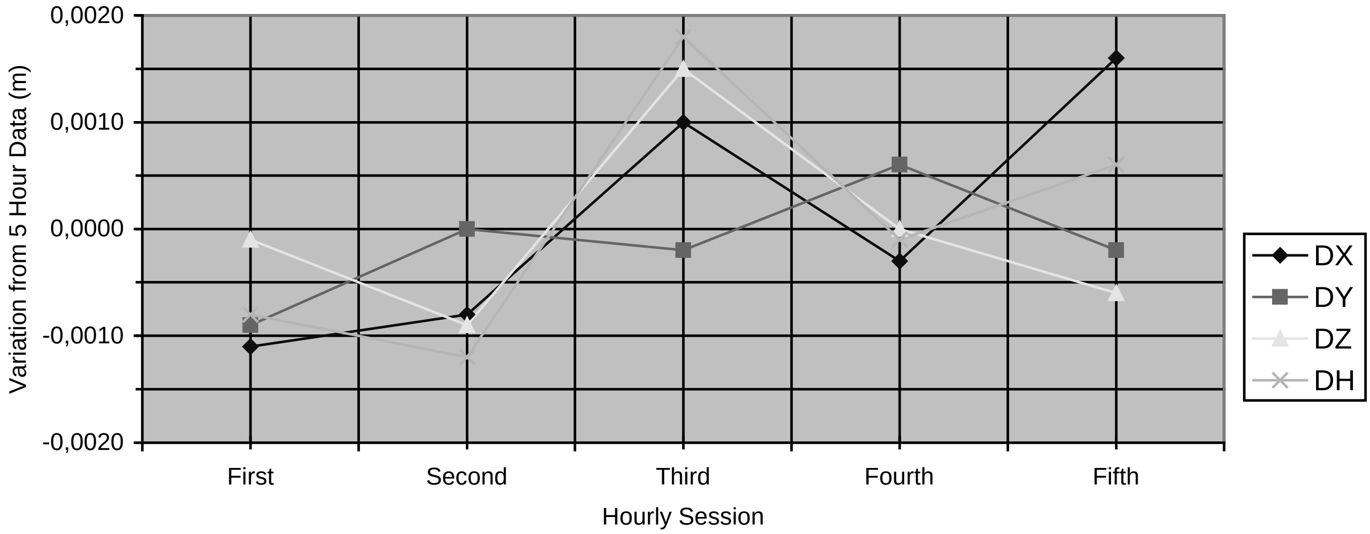


Fig. 5.2: Station 1 Coordinates and Height Comparison (NGS PCV Values)

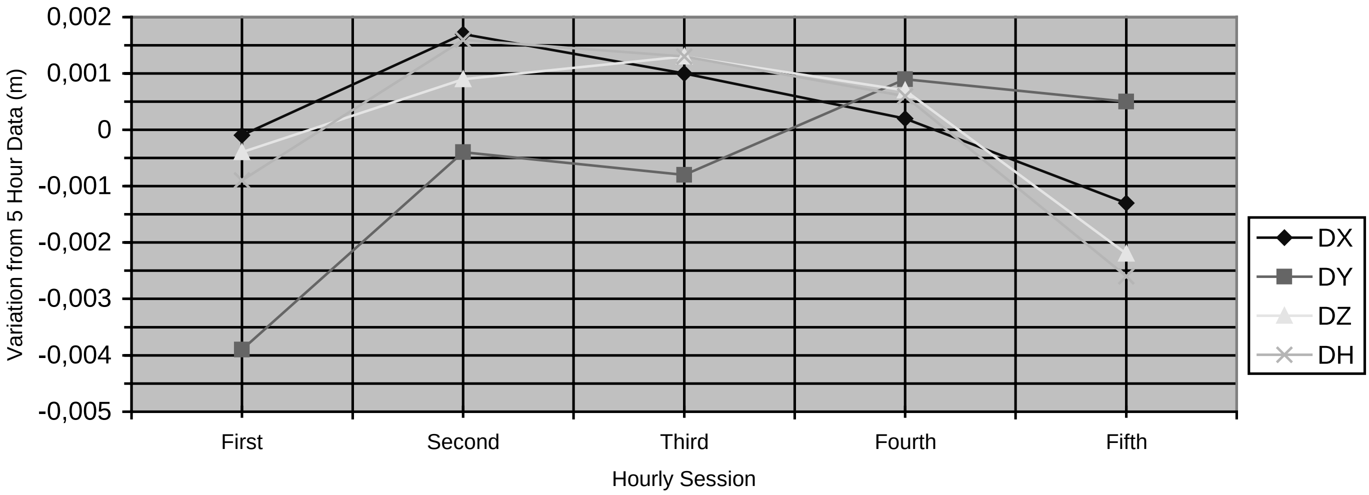


Fig. 5.3: Station 2 Coordinates and Height Comparison (TRIMBLE PVC Parameters)

Another comparison carried out was with respect to the cut-off elevation angles. Analysis of the position solutions obtained for station 1 showed that the X-Y-Z coordinates and height component generated by setting of elevation cut-off angles to 5^0, 15^0, 20^0, 25^0 and 30^0 varied by between –0.3 to 1.4 mm (in the case of Trimble PCV parameters) and by between –1.2 to 1.9 mm (in the case of NGS PCV parameters) from the X-Y-Z coordinates and height generated by setting of an elevation cut-off angle of 10^0 i.e. using the solutions obtained from 10^0 cut-off elevation angle as standard. (see Figures 5.5 and 5.6). It is also noticeable that the variations at station 1 increases with the increase in cut-off elevation angle as depicted in Figures 5.5 and 5.6. This applies to both cases of Trimble and NGS PCV parameters.

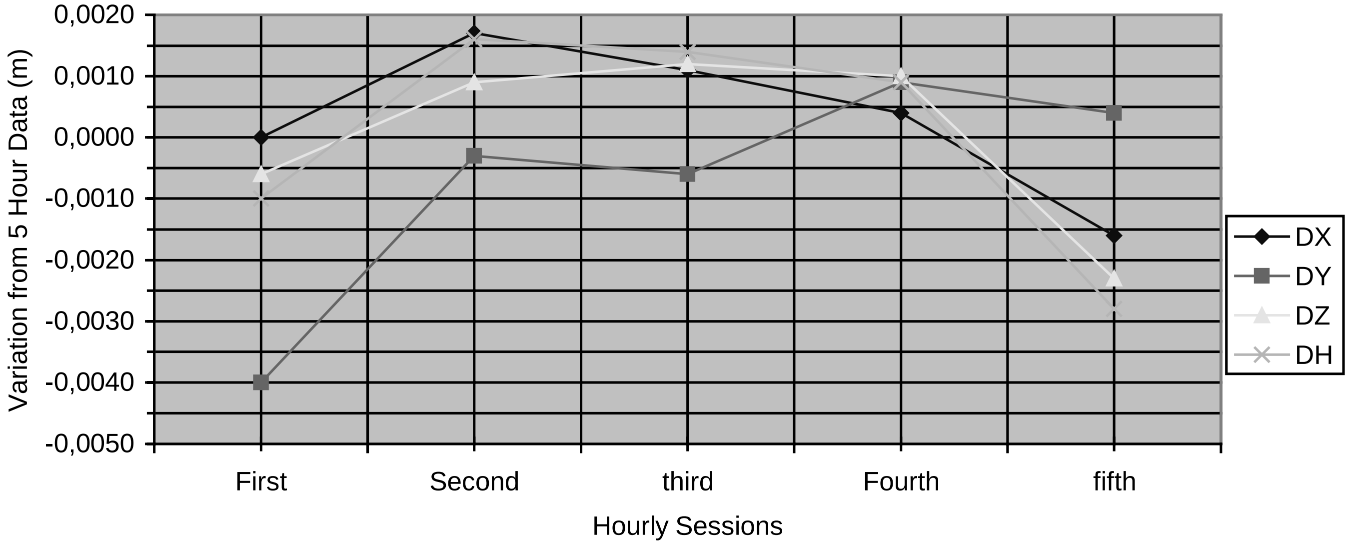


Fig. 5.4: Station 2 Coordinates and Height Comparison (NGS PCV Parameters)

Similar analysis of the GPS processed data at station 2 showed that the X-Y-Z coordinates and height component generated by setting of elevation cut-off angle to 5^0, 15^0, 20^0, 25^0 and 30^0 varied by between –0.5 to 1.5 mm (in the case of Trimble PCV parameters) and by between –0.6 to 0.7 mm (in the case of NGS PCV parameters) from the X-Y-Z coordinates and height generated by setting of an elevation cut-off angle of 10^0 (see Figures 5.7 and 5.8).

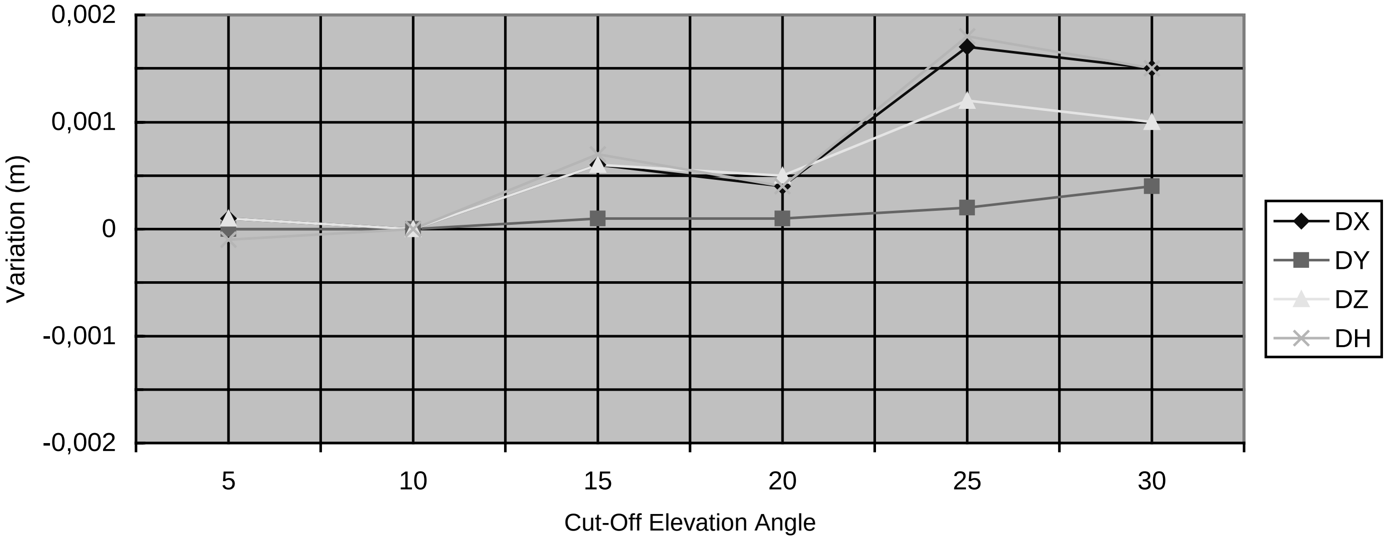


Fig. 5.5: Station 1 Coordinates and Height Comparison (TRIMBLE PCV Parameters)

It is again noticeable that the variations at station 2 increases with the increase in cut-off elevation angle as depicted in Figures 5.7 and 5.8. This applies to both cases of Trimble and NGS PCV parameters.

A comparison of the stations 1 and 2 X-Y-Z coordinates generated using Trimble PCV parameters and those generated using NGS PCV parameters showed a discrepancy of about 2 mm in average (see Tables 5.1 and 5.2 and Figures 5.9 and 5.10 below).

Fig. 5.6: Station 1 Coordinates and Height Comparison (NGS PCV Parameters)

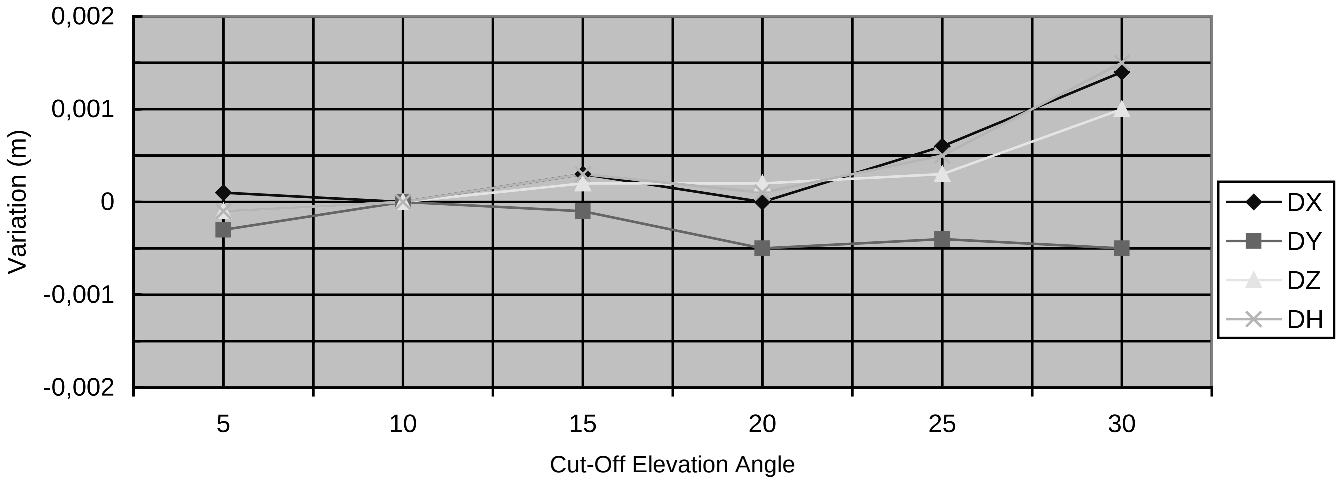


Fig. 5.7: Station 2 Coordinates and Height Comparison (TRIMBLE PCV Parameters)

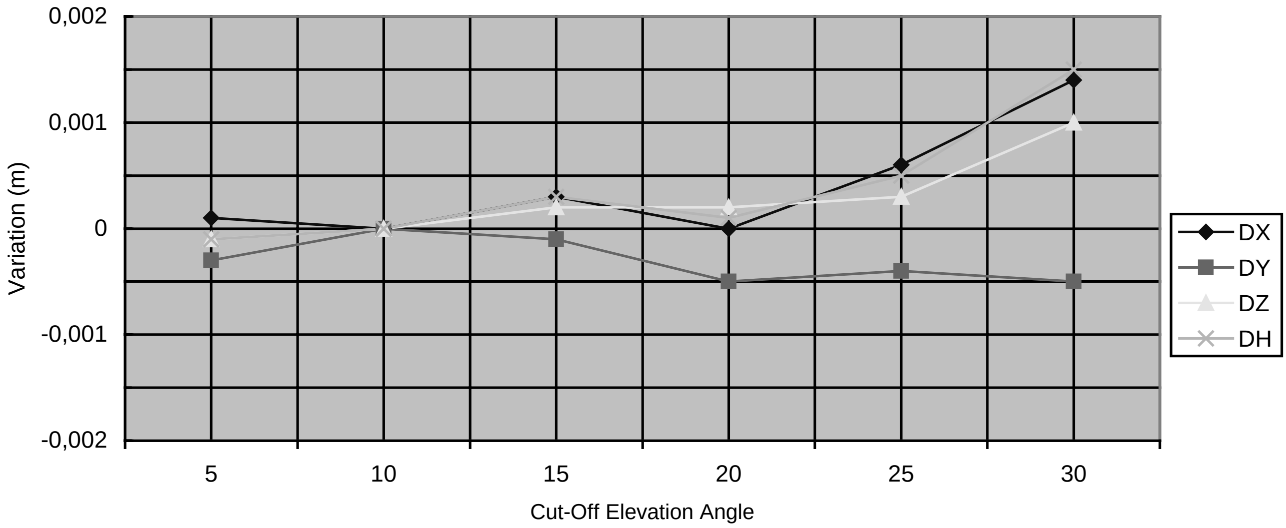


Fig. 5.8: Station 2 Coordinates and Height Comparison (NGS PCV Parameters)

Table 5.1: Differences in Station 1 Results due to Trimble and NGS PCV parameters

Data File Type	Data Size	Difference			
		ΔX	ΔY	ΔZ	ΔH
5 hour data file	5	0.0018	0.0021	0.0005	0.0015
First hour	1	0.0017	0.0019	0.0003	0.0016
Second Hour	1	0.0019	0.0020	0.0005	0.0018
Third Hour	1	0.0016	0.0019	0.0002	0.0015
Fourth Hour	1	0.0017	0.0019	0.0003	0.0015
Fifth Hour	1	00015	0.0021	0.0001	0.0013
Mean Difference		**0.0017**	**0.0020**	**0.0003**	**0.0015**

Table 5.2: Differences in Station 2 Results due to Trimble and NGS PCV parameters

Data File Type	Data Size	Difference (m)			
		ΔX	ΔY	ΔZ	ΔH
5 hour data file	5	-0.0004	0.0013	0.0021	0.0014
First hour	1	-0.0003	0.0012	0.0019	0.0013
Second Hour	1	-0.0004	0.0014	0.0021	0.0014
Third Hour	1	-0.0003	0.0015	0.0020	0.0015
Fourth Hour	1	-0.0002	0.0013	0.0024	0.0017
Fifth Hour	1	-00007	0.0012	0.0020	0.0012
Mean Difference		**-0.0004**	**0.0013**	**0.0021**	**0.0014**

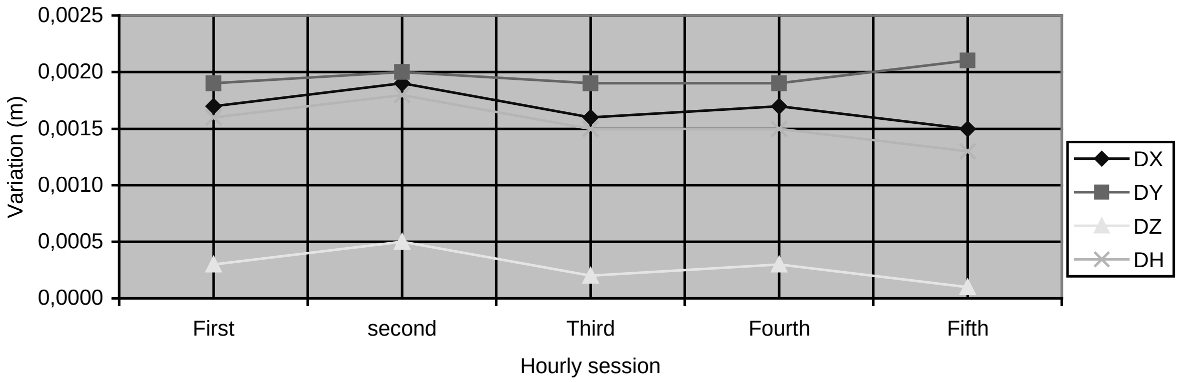


Fig. 5.9: Variation of Station 1 Results with respect to PCV Parameters

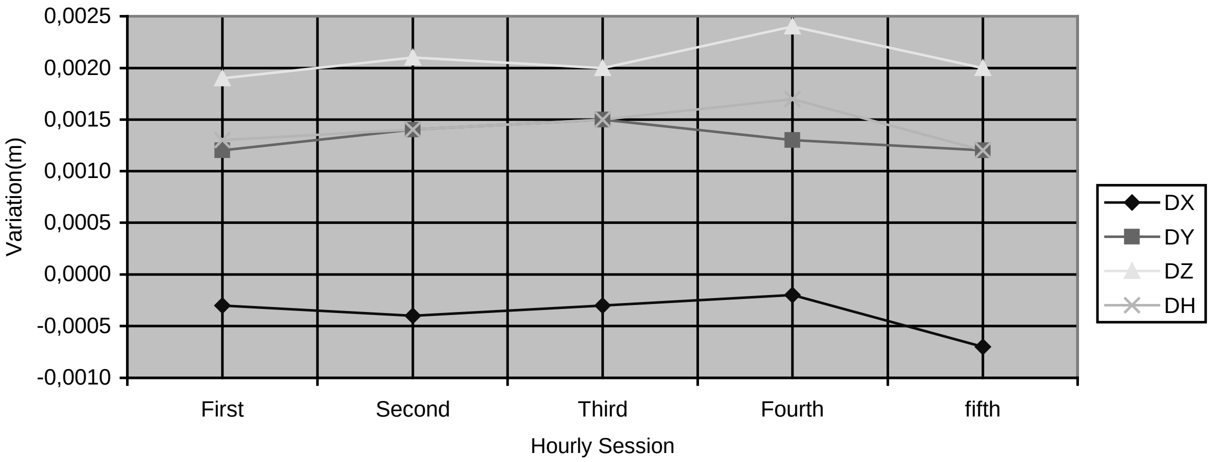


Fig. 5.10: Variation of Station 2 Results with respect to PCV Parameters

Examination of the residuals generated during the processing of the two baselines (see Figures 5.11 through 5.14) indicate a variation within the range of ±5mm with the exception of a few excursions, for the fixed L1 solutions and ±1cm for the L2 solutions.

A comparison of the X-Y-Z coordinates and height component generated from 5 hours data file using POSGPS software with the X-Y-Z coordinates and height component generated from 5 hours data file using TTC software indicate a variation of about 4mm and 2mm in the height components of stations 1 and 2 respectively (see Table 5.3 below).

Table 5.3: Variation of Station 1 and 2 Results (Applanix POSGPS Solutions)

Station Name	Cut-off-Elev. Angle	Data File Size	ΔX (m)	ΔY (m)	ΔZ (m)	ΔH (m)
Station 1	10^0	5 hours	0.0048	0.0036	0.0012	0.0043
Station 2	10^0	5 hours	0.0016	0.0010	0.0007	0.0016

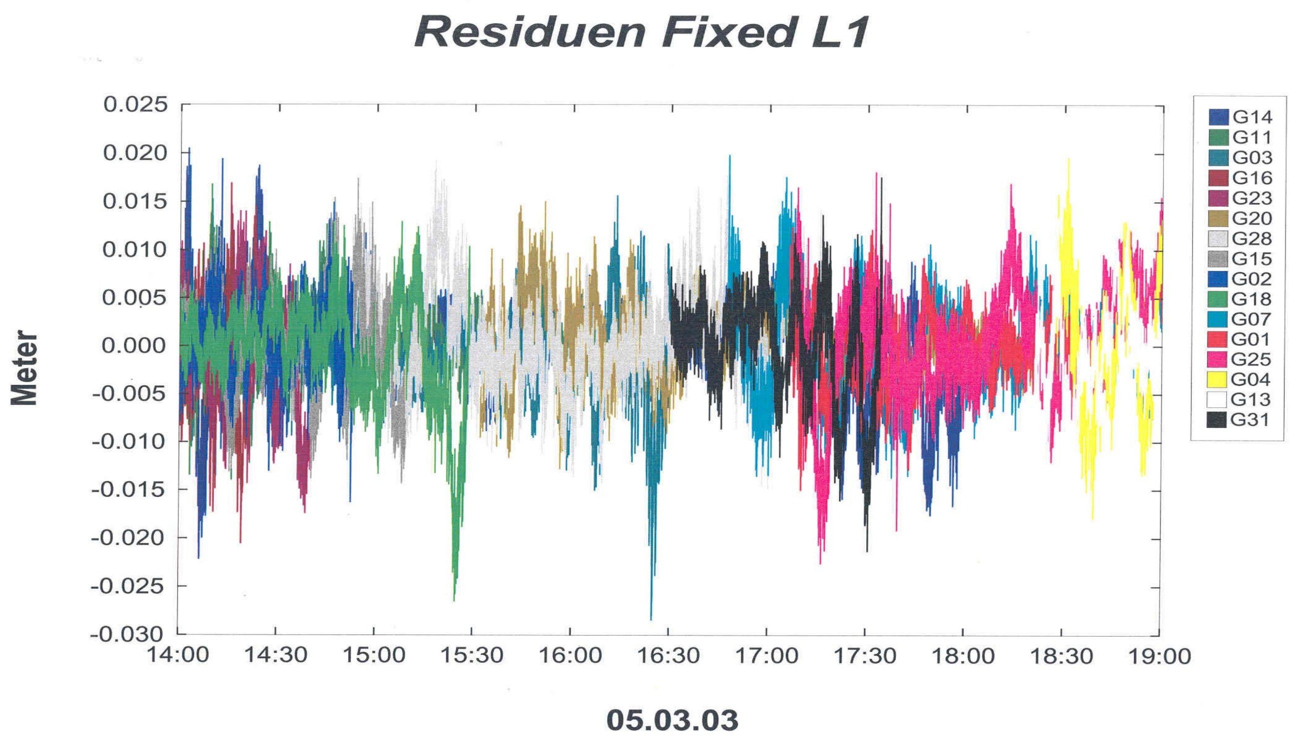


Figure 5.11: Baseline 1-Fixed L1 Residuals

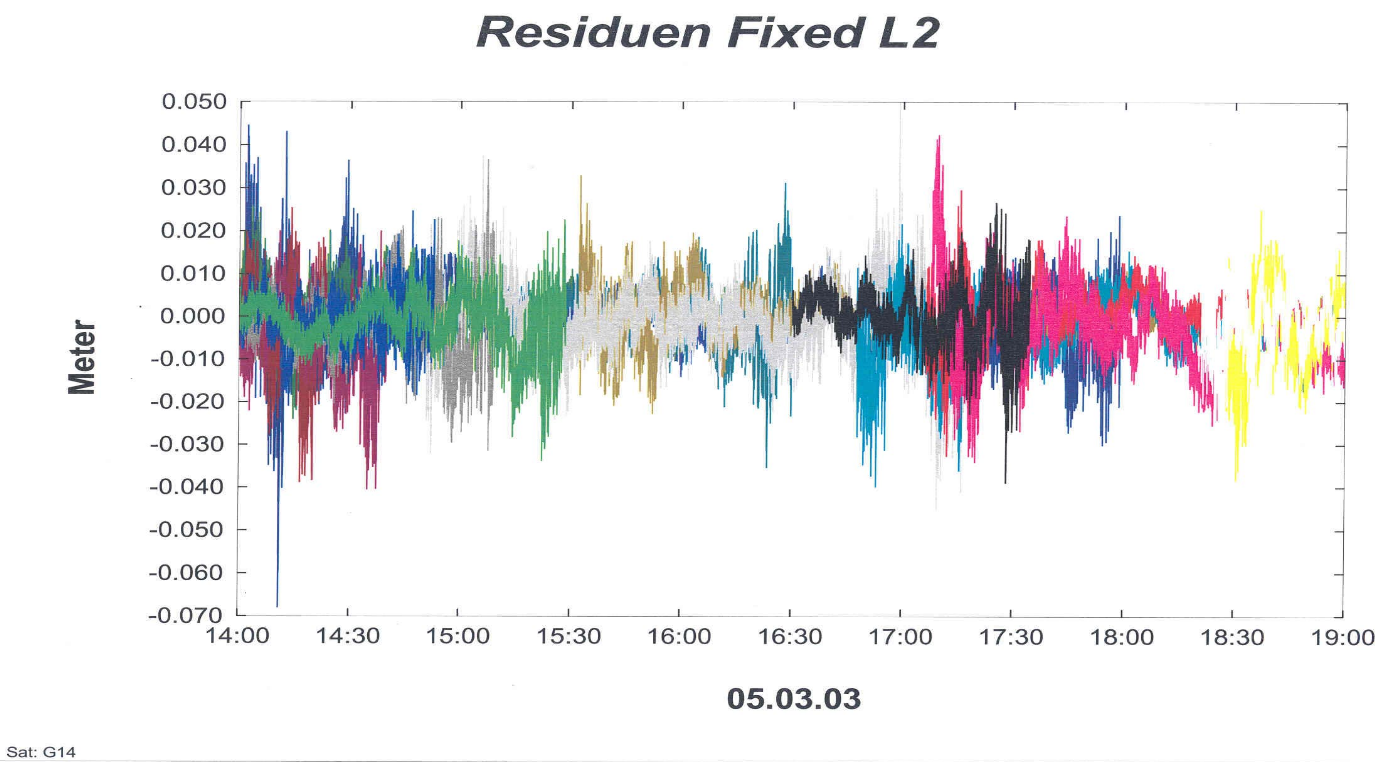


Figure 5.12: Baseline 1-Fixed L2 Residuals

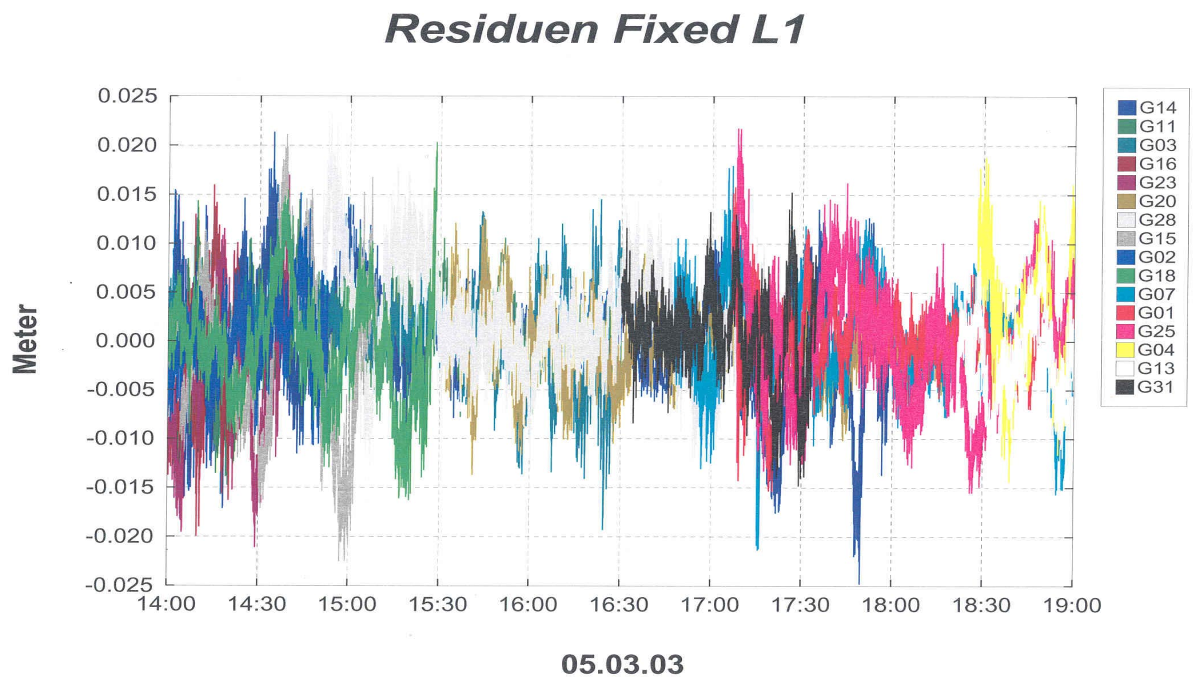


Figure 5.13: Baseline 2-Fixed L1 Residuals

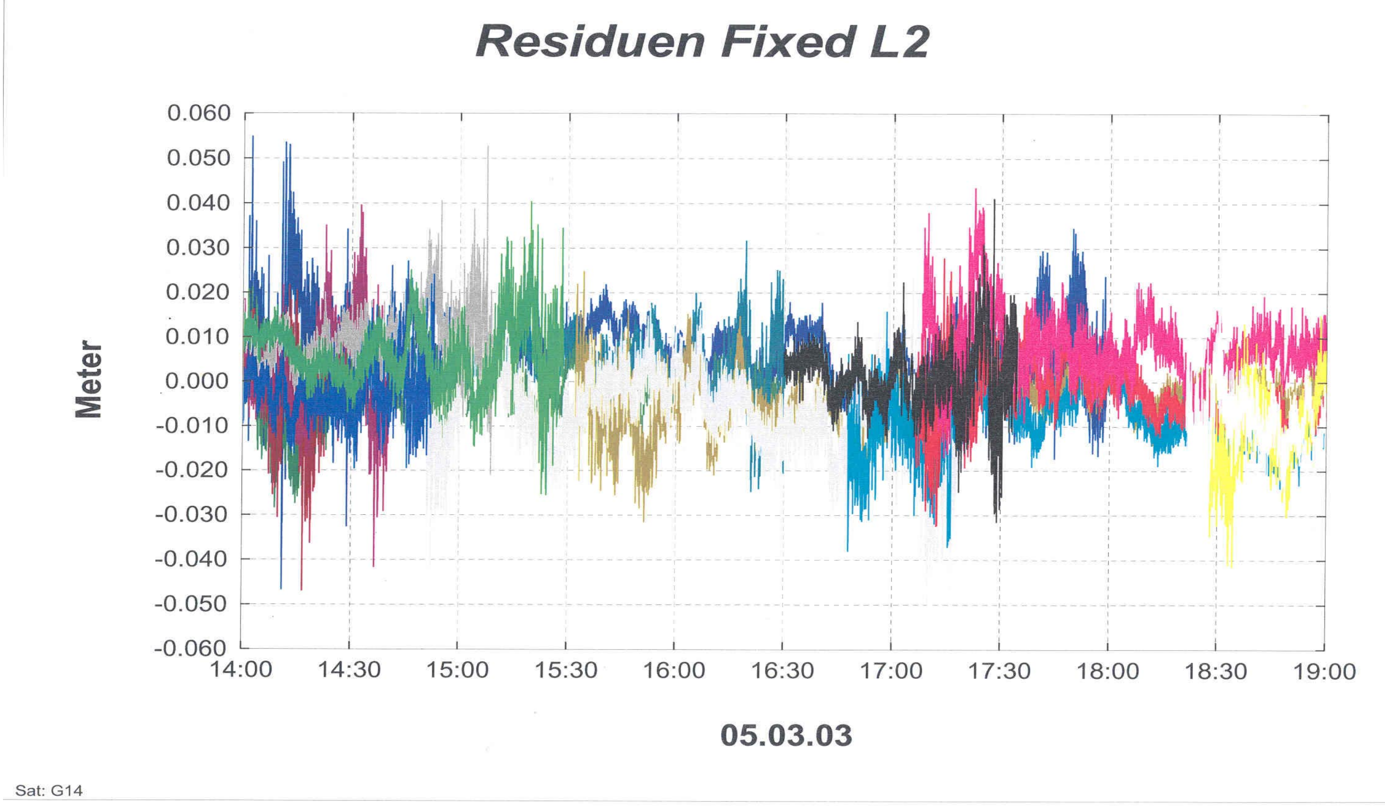


Figure 5.14: Baseline 2-Fixed L2 Residuals

5.2 Phase Two

Results of phase two of the project showed that when an antenna radome is used on one of the antennas, the height component is certainly affected as expected. This is shown in Figures 5.15 and 5.16 in which the mount plate and the radome produced a vertical shift of about 1.5 mm in the height component with the Trimble PCV values and about 2mm with the NGS PCV values. The variations of the Station 1 X-Y-Z coordinates and height generated using the 22 hour data files from the Station 1 X-Y-Z coordinates and height generated from the 5 hours data file using 10^0 cut-off elevation angle and TTC PCV parameters in phase one of the project are indicated in Table 5.4 and 5.5.

Table 5.4: Station 1 Coordinates and Height Variations (Trimble PCV Parameters)

Day of Observation	Data File Type	Coordinates			Height
		ΔX	ΔY	ΔZ	ΔH
Day 1	22 Hours	-0.0003	0.0010	0.0000	0.0000
Day 2	22 Hours	0.0004	0.0012	0.0005	0.0007
Day 3	22 Hours	0.0000	0.0014	0.0015	0.0012
Day 4	22 Hours	0.0006	0.0014	0.0022	0.0019
Day 5	22 Hours	0.0004	0.0016	0.0017	0.0016
Day 6	22 Hours	0.0003	-0.0008	0.0018	0.0014

Table 5.5: Station 1 Coordinates and Height Variations (NGS PCV Parameters)

Day of Observation	Data File Type	Coordinates			Height
		ΔX	ΔY	ΔZ	ΔH
Day 1	22 Hours	0.0018	0.0018	-0.0017	0.0000
Day 2	22 Hours	0.0024	0.0019	-0.0016	0.0005
Day 3	22 Hours	0.0021	0.0022	-0.0003	0.0013
Day 4	22 Hours	0.0025	0.0023	0.0001	0.0018
Day 5	22 Hours	0.0025	0.0024	0.0000	0.0018
Day 6	22 Hours	0.0024	0.0024	0.0001	0.0018

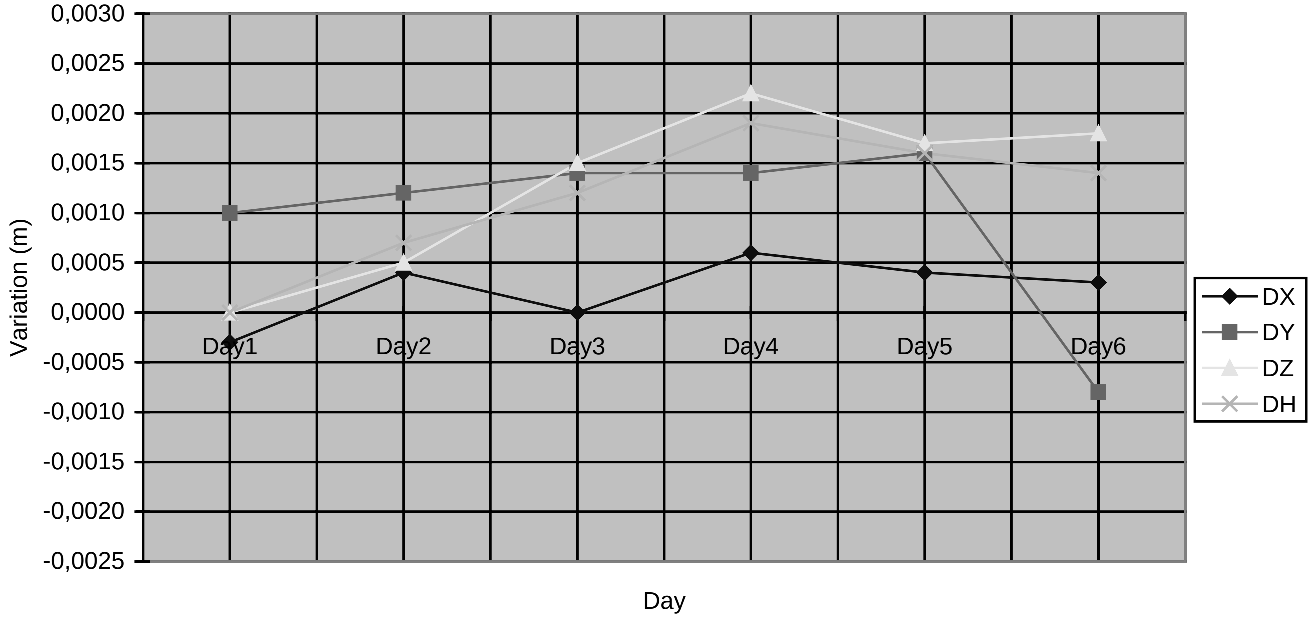


Fig. 5.15: Station 1 Coordinates and Height Variations (Trimble PCV Parameters)

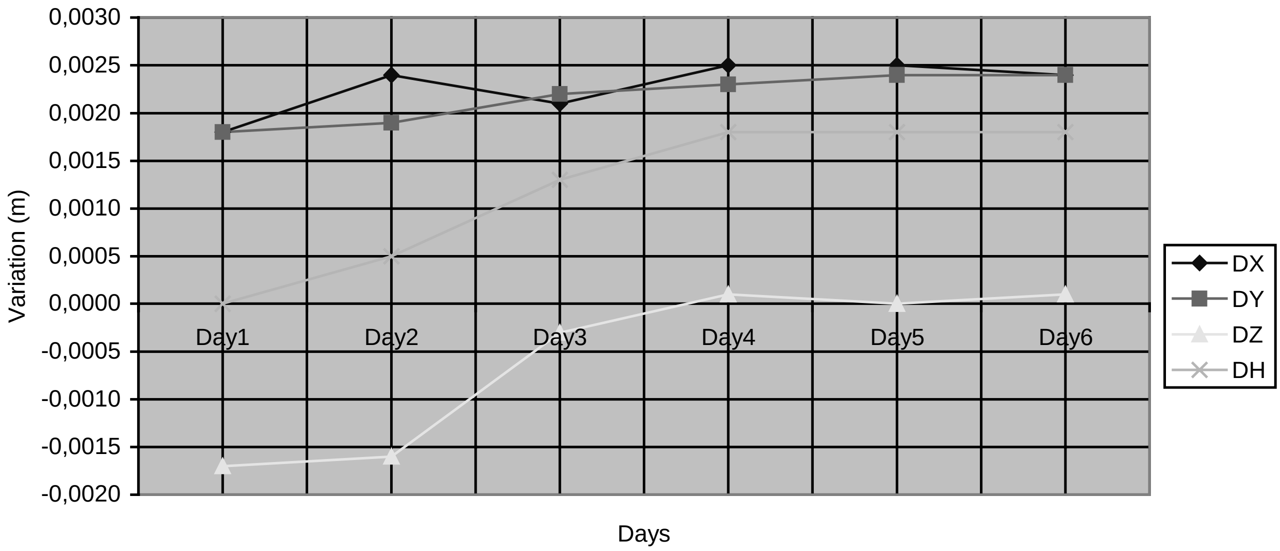


Fig. 5.16: Station 1 Coordinates and Height Variations (NGS PCV Parameters)

This test shows that the metallic radome mounting plate plays a roll since there is a contribution of about 1.5 mm on the height component on the third and fourth days when it was introduced. The variations of the Station 1 X-Y-Z coordinates and height generated using the hourly data files from the Station 1 X-Y-Z coordinates and height generated from the 5 hours data file using 10^0 cut-off elevation angle and Trimble PCV parameters in phase one of the project for each of the six days is indicated in Figures 5.17 through 5.22. An examination at this Figures indicate similarity in the variation patterns for the consecutive days except for the second day (see Figure 5.18) which shows relatively high variations in the 4th, 7th, 14th and 16th hours of the observations. The cause for these unique variations cannot be clearly explained but might have been due to some temporary interference, say for example a bird patching on the station 1 antenna, during the observation time resulting in poor quality data and subsequently large variations in the position coordinates.

The separation between the two stations is small enough (about 5m) to allow for the same conditions to exist at both ends of the baseline. Several errors such as ionospheric and tropospheric delays, orbit prediction biases etc. were eliminated through double differencing of the observations. The assumption is therefore that the variations were dominantly due to effects of the radome, carrier phase multipath effects and incorrectly estimated PCV patterns which are site dependent. In an attempt to characterise the multipath effects and random errors, further analysis was carried out on the variations as follows. The mean variation values were subtracted from the respective hourly variations shown in Figures 5.17 through 5.22 and the resulting variations re-plotted as shown in Figures 5.23 through 5.27. The second day observations have been ignored in this analysis due to the unexplained large variations. The subtraction of the mean variations from the hourly variations is assumed to eliminate PCV, multipath and radome effects and that the remaining variations can only be attributed to noise like random errors. There are similarities in the variation patterns in the result as shown in Figures 5.23 through 5.27 with the swing lying within ±2mm.

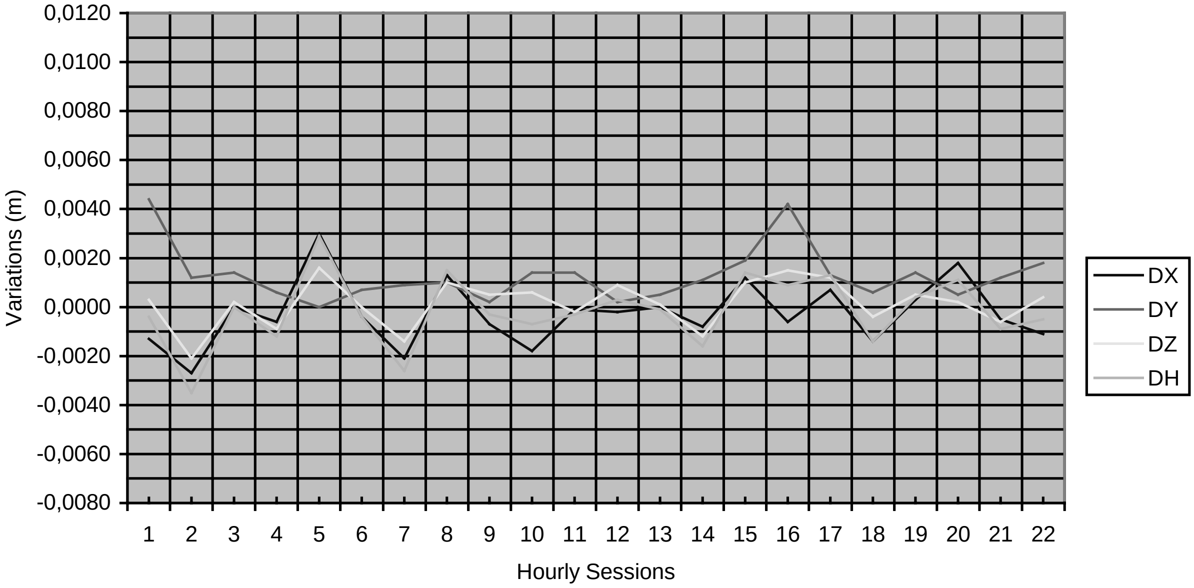


Figure 5.17: Station 1 Coordinates and Height Variations (Julian Day 064)

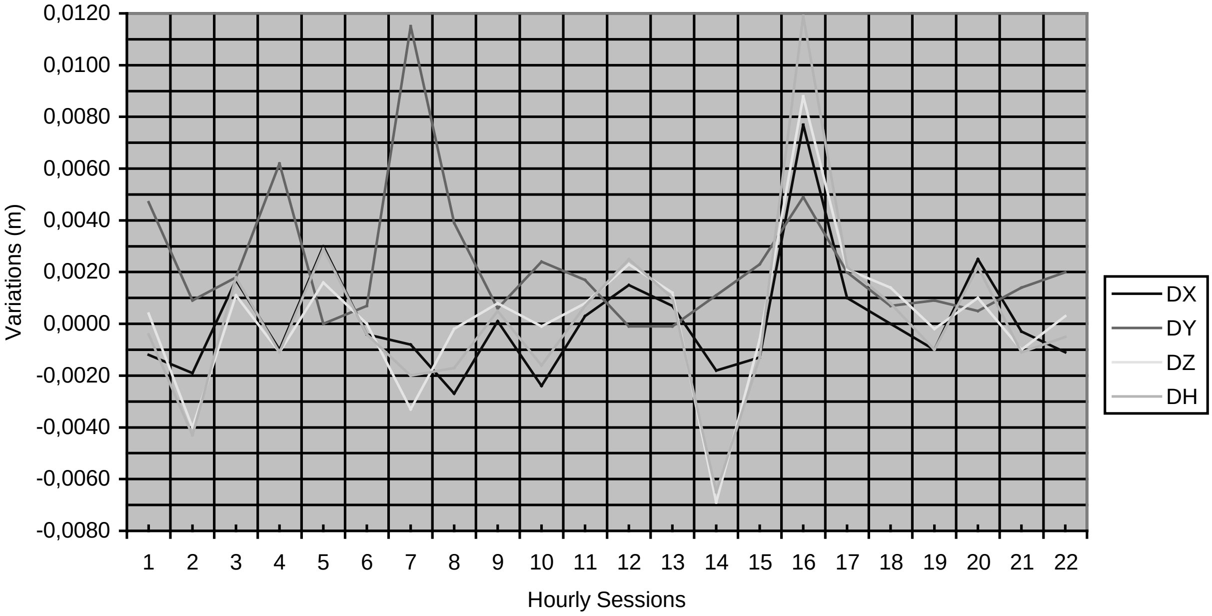


Figure 5.18: Station 1 Coordinates and Height Variations (Julian Day 065)

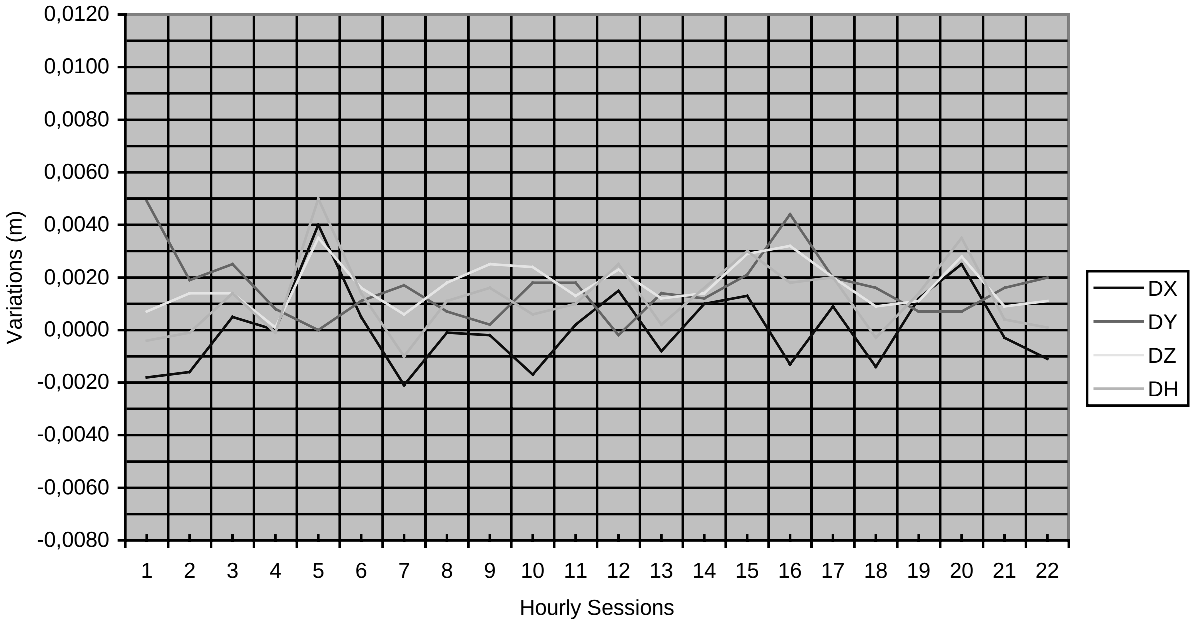


Figure 5.19: Coordinates and Height Variations (Julian Day 066)

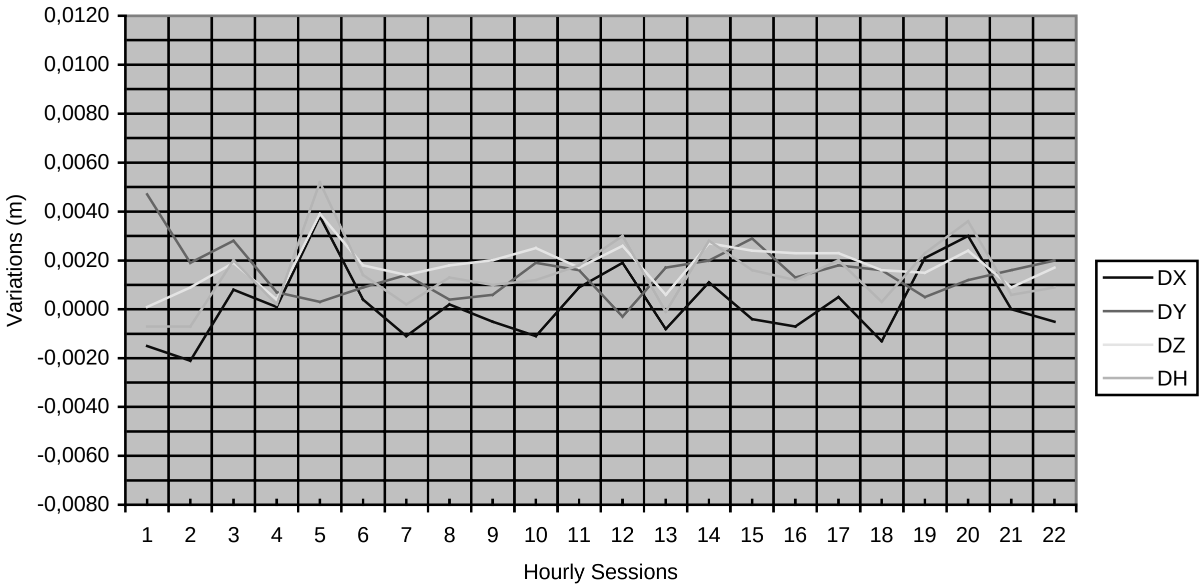


Figure 5.20: Coordinates and Height Variations (Julian Day 067)

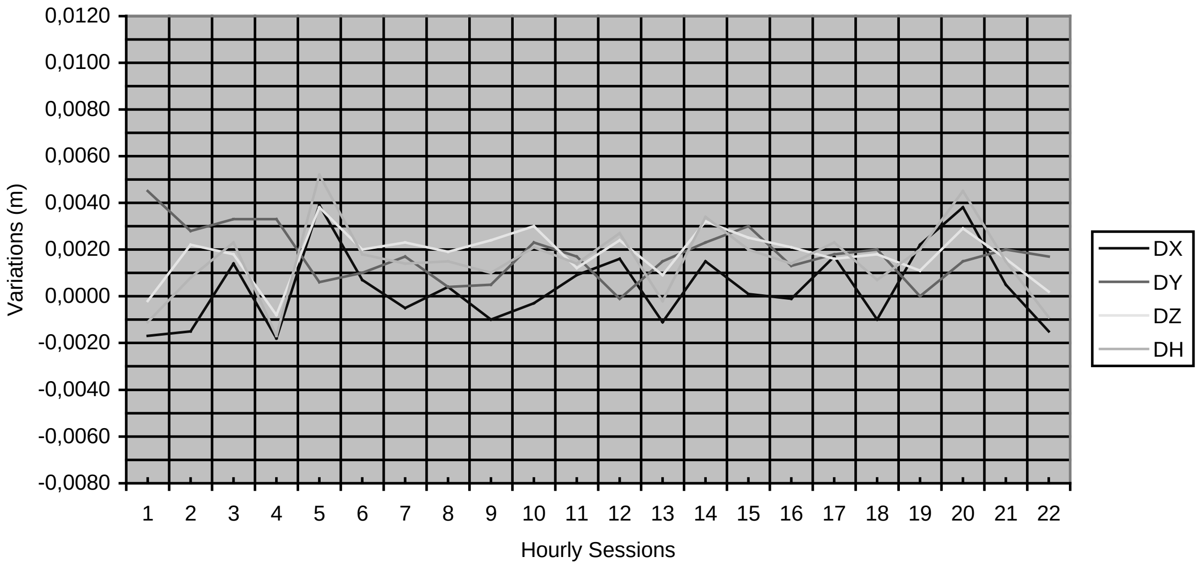


Figure 5.21: Coordinates and Height Variations (Julian Day 068)

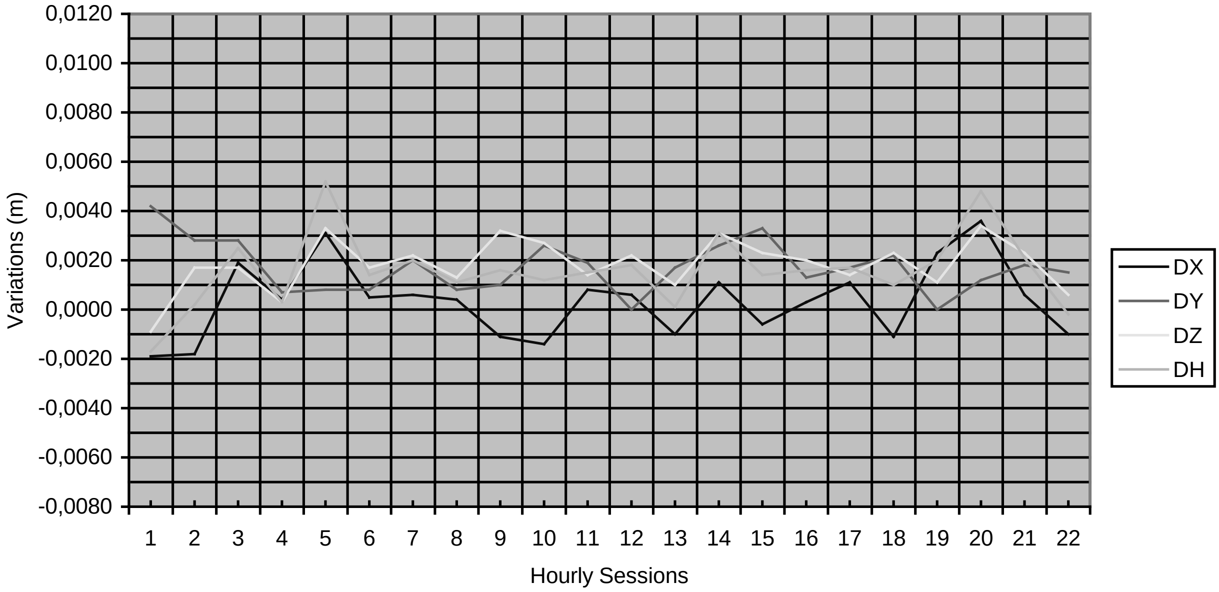


Figure 5.22: Coordinates and Height Variations (Julian Day 069)

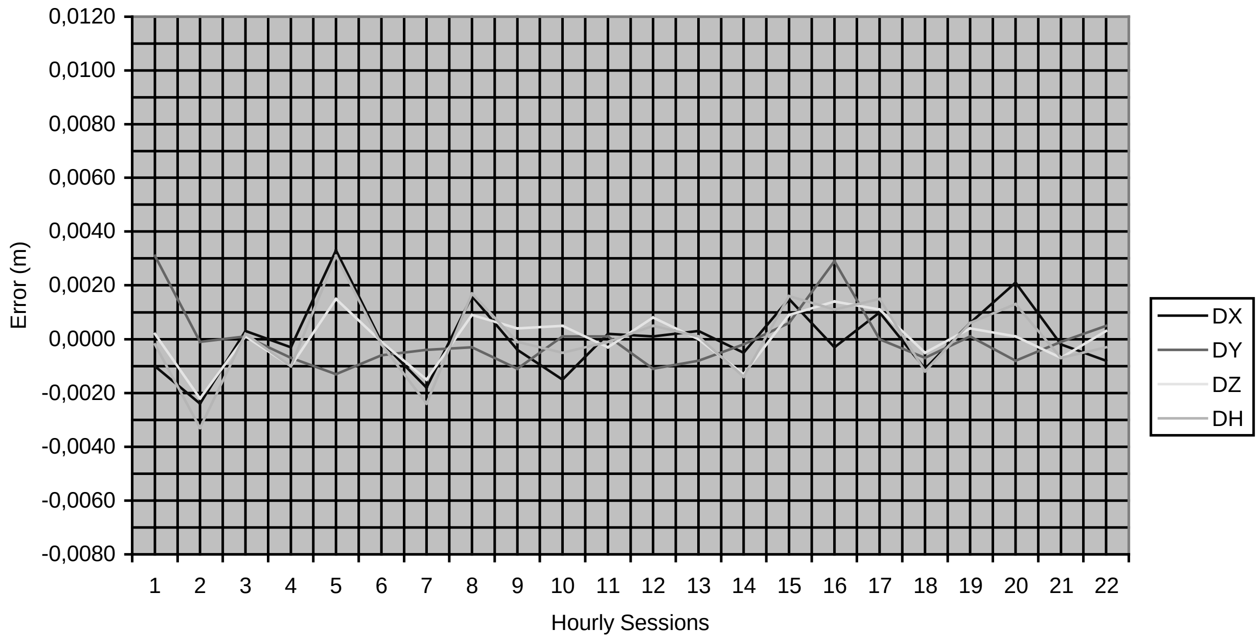


Figure 5.23: Station1 Random Errors (Day 064)

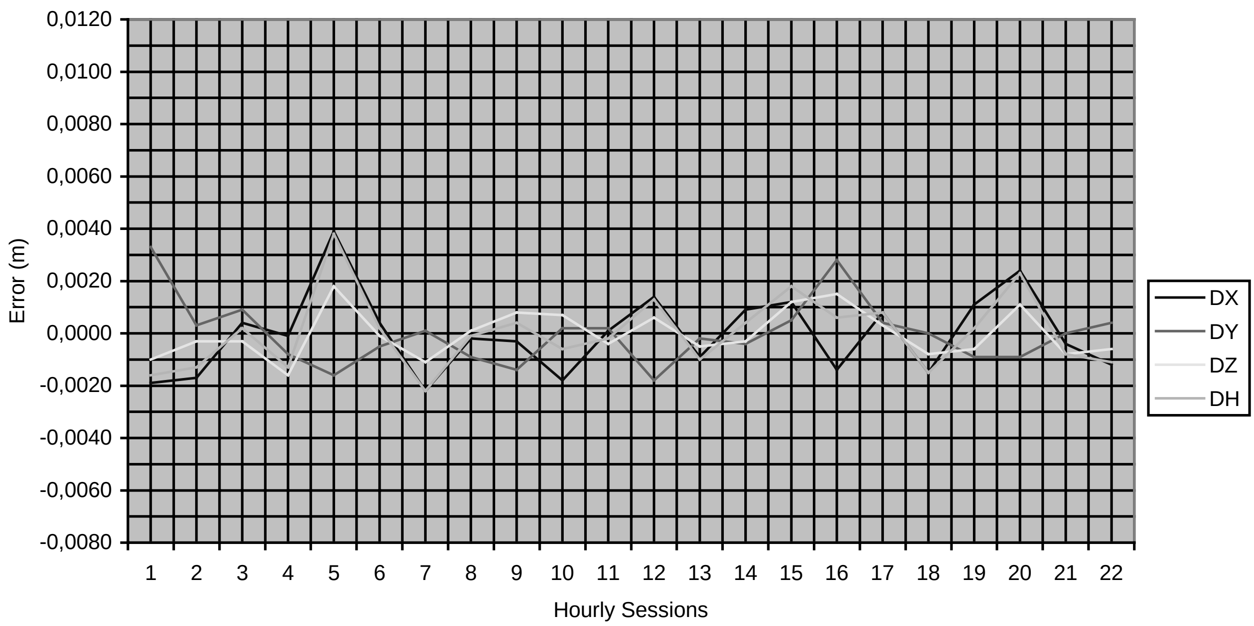


Figure 5.24: Station 1 Random Errors (Day 066)

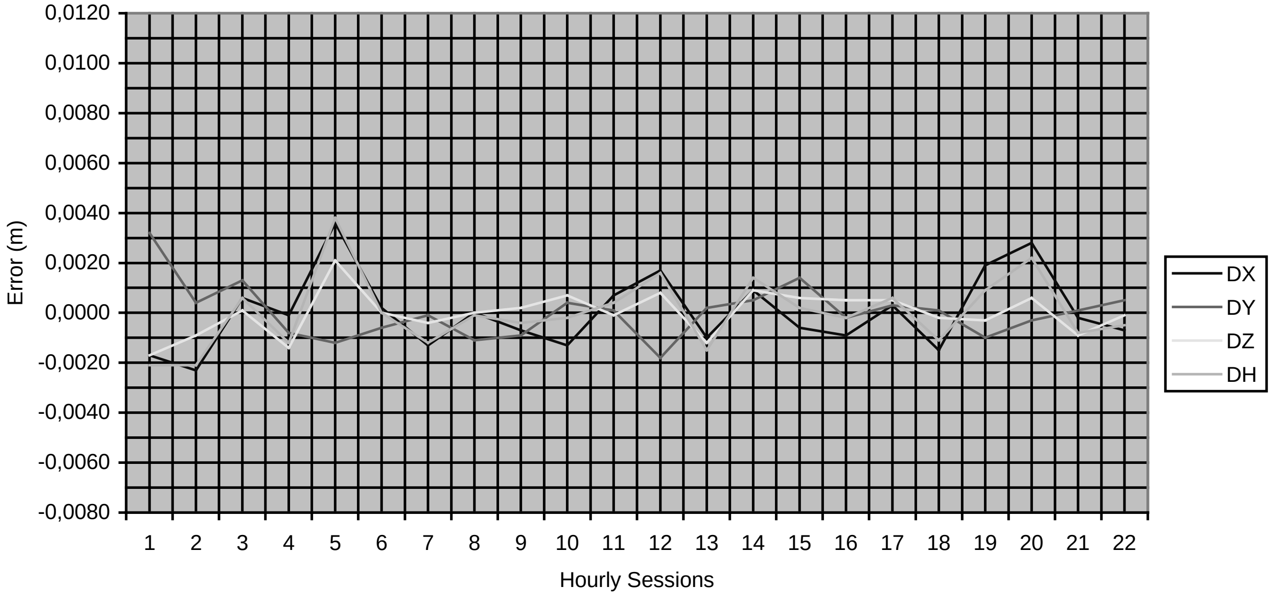


Figure 5.25: Station 1 Random Errors (Day 067)

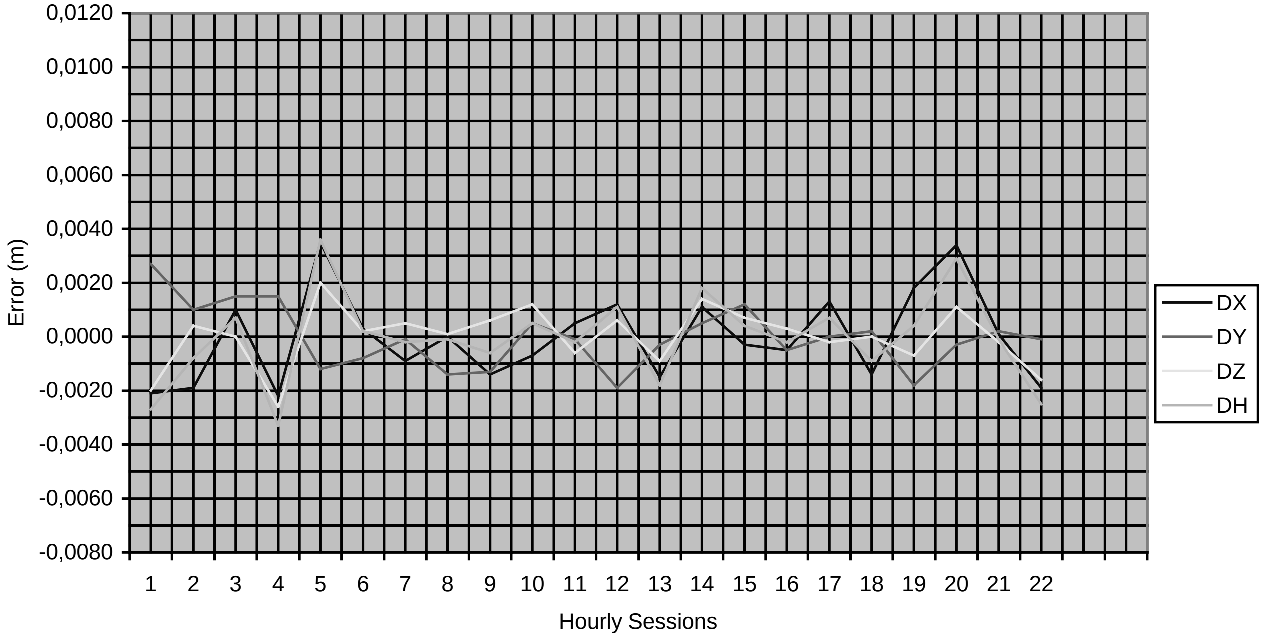


Figure 5.26: Station 1 Random Errors (Day 068)

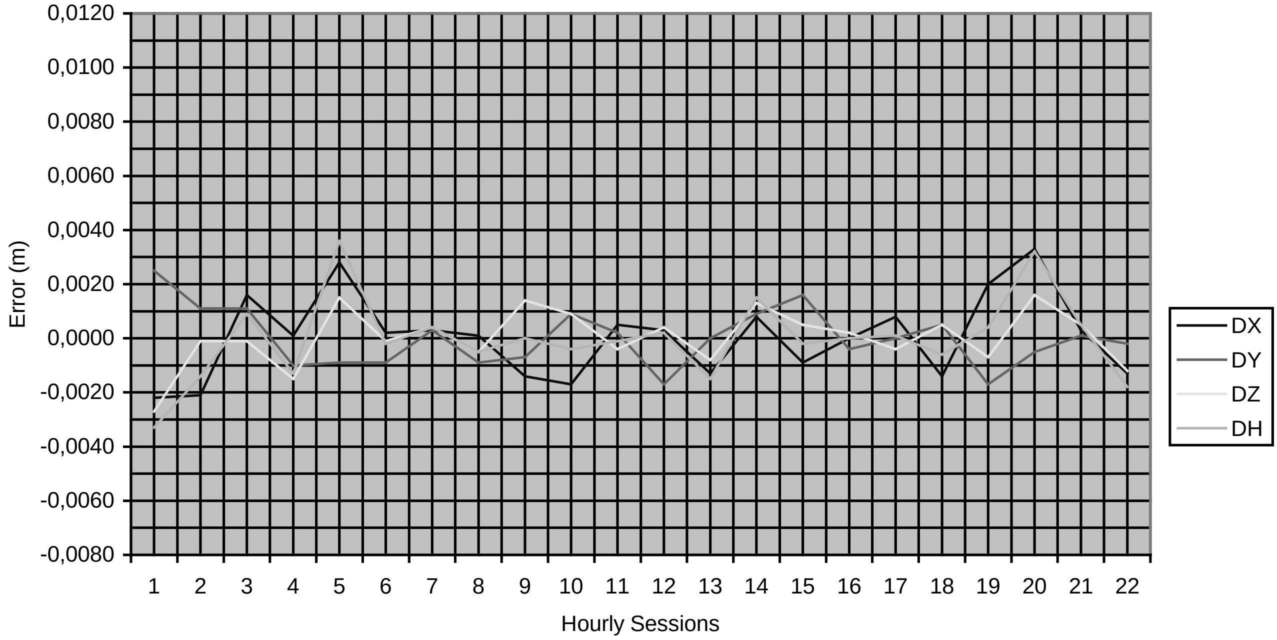


Figure 5.27: Station 1 Random Errors (Day 069)

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary

In the establishment of GPS reference stations, the raw data being collected are subject to many errors as listed in section 1.1.3, but with the current improved technologies in GPS antenna and receiver designs coupled with sophisticated data processing algorithms, most of these errors are usually eliminated or attenuated. Two types of error though, that is multipath and antenna PCV, are currently of the main concern in relative GPS positioning and are heavily being researched on. The accuracy of a new station being set-up depends on the following factor;

- How well the multipath error at the specific new location of the antenna is modelled out of the raw GPS data.
- How accurate is the reference station from which the position is being transferred to the new station. Any error in the reference station will of course be propagate into the new station.
- The calibration done at the site to determine the antenna offsets and PCV values used in the analysis of the raw GPS data (absolute and relative calibration)
- And last but not least, the capabilities of the receiver, antenna and software used in the project.

With the need to protect the antennas from bad weather conditions and vandalism, attempts are usually made to cover the antennas with radomes. But the addition of radome has effects on the antenna PCV patterns thus every such setting should be investigated to determine the significance of these effects.

In this project, GPS observations were carried out in six consecutive days. On first and second days, the choke ring antenna on station 1 was neither covered with a radome nor was the radome mount plate used. An underlying base plate was though used to compensate for the height difference as a result of the radome mounting plate (see Figure 3.5). On the third and fourth days the underlying plate was replaced with the radome mount plate but without the radome. And on fifth and sixth days, the antenna was covered with the radome.

Part of the GPS data observed on the first day (5 hour data file) was used in phase one of the project to fix the reference stations 1 and 2 with respect to the SAPOS network. In phase two of the project, the GPS data collected in six days were processed using TTC and POSGPS software and each pair of data block compared and analysed. Station 2 was used in this case as the reference station and the analysis was made on station 1 to determine the effects of the radome and the radome mounting plate on the station position.

An analysis of the solutions obtained indicate that the objectives set were attained and conclusions were drawn as below.

6.2 Conclusions

For the day-to-day GPS data processing at the institute, there was need to establish a reference station to avoid dependency on other sources of reference station data and cut down the extra costs due to acquiring such reference station data. The first objective of setting-up of the reference stations has been achieved with the establishment of reference stations dubbed herein as Station 1 and Station 2. For the final position coordinates and other details please see Appendix **A2** and **A3**. Please note that the Antenna Reference Point (ARP) for both stations is at the top of the mounting piers.

With the knowledge that addition of radome over antennas causes an error in height component, the antenna covers should be avoided if possible. But with the need to protect the antennas, especially the reference station antennas which are more likely to be fixed permanently, this is not possible. The second objective of the project was therefore, to investigate if the conical radome causes vertical height bias. The radome has effects on the station 1 position values but is very minimal in this case and can therefore be neglected. The effects of the metallic radome mount plate is also negligible.

A comparison of the X-Y-Z coordinates and height components of station 1 generated using Trimble PCV parameters and NGS PCV parameters clearly demonstrate that the two phase centre variation patterns have a systematic difference of about 2 mm as shown in the solutions obtained from the GPS data processing using TTC software.

6.3 Recommendations

A thorough investigation of the multipath effects at the antenna sites is necessary to characterise the effects and subsequently the error caused on the position.

Since the antennas used in the investigation of the effects of the radome were not identical, some error due to the use of different antenna models may be present in the observations. A repeat of the same investigation but with a similar choke ring antenna used as a reference station is therefore recommended.

For the purposes of integrity of the reference station solutions obtained, further observations should be independently carried out, at least once or twice, and the results compared.

REFERENCES

Axelrad, P., C. Comp and P. MacDoran (1994). Use of Signal-to-Noise Ratio for Multipath Error Correction in GPS Differential Phase Measurements: Methodology and Experimental Results, Proceedings of ION GPS-94, Salt Lake City, UT, 655-666.

Beutler, G., I. Bauersima, S. Botton, W. Gurther, M. Rothacher & T. Schildknecht (1989). Accuracy and biases in geodetic application of the Global Positioning System, Manuscripta Geodaetica, 14, 28 – 35.

Bock, Y. (1998). Reference Systems, in GPS for Geodesy, Edited by P.J.G. Teunissen and A. Kleusberg, 2nd Edition, Chap. 1., pp. 1-41, Springer, Berlin.

Braasch, M. S. (1996). Multipath Effects, Global Positioning Systems: Theory and Applications, American Institute of Aeronautics and Astronautics, Vol. 1., Chapter 14, pp. 547-568.

Braun, J., C. Rocken and J. Johnson (1994). Consistency of High Precision GPS Antenna. UNAVCO/UCAR Technical Report, July.

Brown, A. and J. Wang (1999). High Accuracy Kinematic GPS Performance Using a Digital Beam-Steering Array, Proceedings of ION GPS-99, Nashville, Tennessee, September.

Brunner, F. K. and W. M. Welsch (1993). Effects of Troposphere on GPS Measurements, GPS World, 4(1), 42-51.

Ding, X., Y. Chen, J. Zhu and D. Huang (1999). Surface Deformation Detection Using Multipath Signals, 12th Int. Technical Meeting of GPS Division of the U.S. Institute of Navigation, Nashville, Tennessee, 14-17 September, 53-62.

DMA, 1987. Department of Defense World Geodetic System 1984: Its Definition and Relationships with Local Geodetic Systems, Technical Report No. 8350.2, Defense Mapping Agency, Washington, pp. 121.

El-Mowafy, A. (1994). Kinematic Attitude Determination from GPS, UCGE Report Number 20074, The University of Calgary, 215pp.

Federal Geodetic Control Committee (FGCC), (1989). Geometric Geodetic Accuracy Standards and Specifications for using GPS Relative Positioning Techniques. Version 5.0, U. S. Department of Commerce, May 11 1988, Reprinted with corrections, August 1, 1989.

Georgiadou, Y. and A. Kleusberg, (1988). On Carrier Signals Multipath Effects in Relative GPS Positioning, Manuscripta Geodaetica, 13, 172-179.

Gurtner, W. (1993). RINEX: The Receiver Independent Exchange Format. Version 2, Revision April 1993, Astronomical Institute, University of Berne.

Hagerman, L. L. (1973). Effects of Multipath on Coherent and Non-coherent PRN Ranging Receivers, Aerospace Report No. TOR-0073 (3020-03)-3, Development planning Division, The Aerospace Coorporation, 39pp.

Han, S. and C. Rizos (1997b). Multipath Effects on GPS in Mine Environments, Xth Int. Congress on the International Society for Mine Surveying, Fremantle, Austria, 2-6 November, 447-457.

Hofmann-Wellenhof, B., H. Lichtenegger, and J. Collins (2001). Global Positioning System: Theory and Practice, 5th edition, Springer-Verlag, Berlin Heidelberg New York, ISBN 3211835342, 382pp.

IGS (2003). International Global Positioning System (GPS) Service website, Http://igscb.jpl.nasa.gov/components/prods.html

JPS (1998). A GPS Tutorial: Basics of High Precision Global Positioning Systems, Javad Positioning Systems, inc., Http://www.topconps.com/gpstutorial/.

Jülg, T. (1997). Einfluß der Mehrwegeausbreitung auf die Laufzeit- und Phasenmessungen beim Globalen Navigationssystem (GPS). Dissertation, Technische Hochschule Darmstadt, Fachbereich Elektrotechnik und Informationstechnik.

Kaniuth, K. and K. Stuber (1997). Einfluß von Antennen-Radomen auf die GPS-Höhenbestimmung. Allg. Vermessungs-Nachrichten, 106, 234-238.

Kaniuth, K. and K. Stuber (2002). The Impact of Antenna Radomes on Height Estimmates in regional GPS networks. IAG Symposia, 101-106, Springer Verlag.

Klobucher, J. A. (1991). Ionospheric Effects on GPS, GPS World, 2(4), 48-51.

Lachapelle, G. (1990). GPS Observables and Error Sources for Kinematic Positioning, IAG International Symposium No. 107 on Kinematic Systems in Geodesy, Surveying and Remote Sensing, Springer-Verlag, New York, 10-13 September, !7-26.

Leick, A. (1995). GPS Satellite Surveying, 2nd Edition, John Wiley & Sons, Inc., New York, ISBN 047 81990-5, 560pp.

Lin, L. S. (1997). Real Time Estimation of Ionospheric Delay Using GPS Measurements, Ph.D. Thesis, School of Geomatic Engineering, The University of New South Wales, Sydney, Australia, 198pp.

Mader, G. (2000). A Comparison of Absolute and Relative Phase Centre Variations. IGS Analysis Workshop 2000, Proceedings Preprints, IGS Electronic Mail 20 November, Message No. 3107. Also Submitted to GPS Solutions No. 4, 2001.

Mader, G. (1996). GPS Antenna Calibration at the National Geodetic Survey. National Geodetic Survey, NOAA Silver Spring, MD. URL: http://www.ngs.noaa.gov/ANTCAL

Menge, F., V. Böder, G. Seeber, G. Wübbena and M. Schmitz (1999). Variability of GPS errors on-site-investigations of Antenna PCV and Multipath towards a Station calibration. International Union of Geodesy and Geophysics, IUGG99, July 19-30, Birmingham, UK.

NGS (2003). National Geodectic Survey Website: http://www.ngs.noaa.gov/ANTCAL/.

Ogaja, C. (2002). A Framework in Support of Structural Monitoring by Real Time Kinematic GPS and Multisensor Data, Dissertation, The University of New South Wales, School of Geomatic Engineering, UNISURV S-71, 555pp.

Parkinson, B. W. and J. J. Spilker Jr. (eds) (1996). Global Positioning System: Theory and Applications (Vol. 1.), American Institute of Aeronautics and Astronautics, Inc., Washington D. C., ISBN 1-56347-106-X, 793pp.

Parkinson, B. W. (1994). GPS Eyewitness: The early years, GPS World, 5(9), 32-45.

Qiu, W. (1993). An Analysis of some Critical Error Sources in Static GPS Surveying, UCGE Report Number 20054, The University of Calgary, 102pp.

Radovanovic, R. S. (2001). High Accuracy Deformation Monitoring via Multipath Mitigation by day-to-day Correlation Analysis, 13th Int. Technical Meeting of the Satellite Division of the U.S. Institute of Navigation, Salt Lake City, Utah, 19-22 September, 35-44.

Ray, J. K. (999). Use of Multiple Antennas to Mitigate Carrier Phase Multipath in Reference Stations, 12th international Technical Meeting of Satellite Division of the U.S. Institute of Navigation, Nashville, Tennessee, 15-18 September, 1025-1034.

Rizos, C. (1997). Principles and Practice of GPS Surveying, Monograph 17, School of Geomatic Engineering, The University of New South Wales, ISBN 0 85839 071, 555pp.

Rothacher, M. (2001). Kombination Absoluter und Relativer Antennenkalibrierungen. 3. GPS-Antennen-Workshop 2001, Geodätisches Institut der Rheinischen Friedrich-Wilhehms-Universität Bonn, Mai 11.

Rothacher, M. and G. Mader (1996). Combination of Antenna Phase Centre offsets and variations. Antenna calibration set: IGS_01. International GPS Service for Geodynamics, central Bureaux (http://igscb.jpl.nasa.gov).

Rothacher, M., G. Beutler, W. Gurtner, D. Schneider, A. Wiget, A. Geiger & H. G. Kahle (1990). The Role of Atmosphere in small GPS Networks, 2nd Int. Symposium on Precise Positioning with the Global Positioning System, Ottawa, Ontario, 3-7 September, 581-598.

Schmitz, M. and G. Wübbena (2001). Remarks on Effects of SCIS Radome on Phase Centre Variation. Web Publication, http://rincon.gps.caltech.edu/SCIGN/radomes/ , April.

Schwarz, K. P., Z. Li & A. El-Mowafy (1993). GPS Multipath Detection and Reduction using Spectral Technique, IAG General Meeting, Beijing, China, 9-13 August.

Seeber, G. (1996). GPS Satellite Surveying. John Wiley & Sons, New York/ Chichester/ Brisbane/ Toronto, ISBN 0-471-30626-6.

Seeber, G., F. Menge, C. Völksen, G. Wübbena, M. Schmitz (1997): Precise GPS Positioning Improvements by Reducing Antenna and Site Dependent Effects, Scientific Assembly of the International Association of Geodesy IAG97, Rio de Janeiro, September 3-9, 1997, In: International Association of Geodesy Symposia, Vol.118, F.K. Brunner (Ed.), Advances in Positioning and Reference Frames, 237-244, Springer.

Spilker, Jr., J. J. (1996). Trospheric Effects on GPS, In: Parkinson, B. W. et. al. (eds.), Global Positioning System: Theory and Applications, Progress in Astronautics & Astronautics, ISBN 1-56347-106-X, 163, 517-546.

Townsend, B. R., J. Wiebe and A. Jakab, (2000). Results and Analysis of Using the MEDLL Receiver as a Multipath Meter, Proceedings of the ION, National Technical Meeting, Anaheim, CA, U.S.A.

Townsend, B. and R. Fenton (1994). A Practical Approach to the Reduction of pseudorange Multipath Errors in an L1 GPS receiver, 6th Int. Tech. Meeting of the Satellite Division of the U.S. Institute of Navigation, Salt Lake City, Utah, 22-24 September, 1049-1057.

USGS (1999). United States Geological Survey website Report on the SCIGN Radome Project. http://pasadena.wr.usgu.gov/scign/group/dome.

Van Nee, R. (1995). Multipath and multi-transmitter interference in spread-spectrum communication and navigation systems. PhD Thesis, Delft University of Technology, Delft, The Netherlands.

Wanniger, L. and M. May (2000). Carrier Phase Multipath Calibration of GPS Reference Stations, Proceedings of the ION GPS-2000, Salt Lake City, UT, September.

Weill, L. R. (1997). Conquering Multipath: The GPS Accuracy Battle, GPS World, April, 59-66.

Wells, D. E., N. Beck, D. Delikaraohlou, A. Kleusberg, E. J. Krakiwsky, G. Lachapelle, R. B. Langley, M. Nakiboglu, K. P. Schwarz, J. M. Tranquilla & P. Vanicek (1987). Guide to GPS Positioning, 2nd Edition, Canadian GPS Associates, Fredericton, New Brunswick, Canada, ISBN 0920114733, 503pp.

Zumberge, J. F. (1999). Automated GPS Data Analysis Service, GPS Solutions, 2(3), 76-78.

Zumberge, J. F., M. B. Heflin, D. C. Jefferson, M. M. Watkins & F. H. Webb (1997). Precise Point Positioning for the Efficient and Robust Analysis of GPS Data from large Networks, Journal of Geophysical Research, 102(B3), 5005-5017.

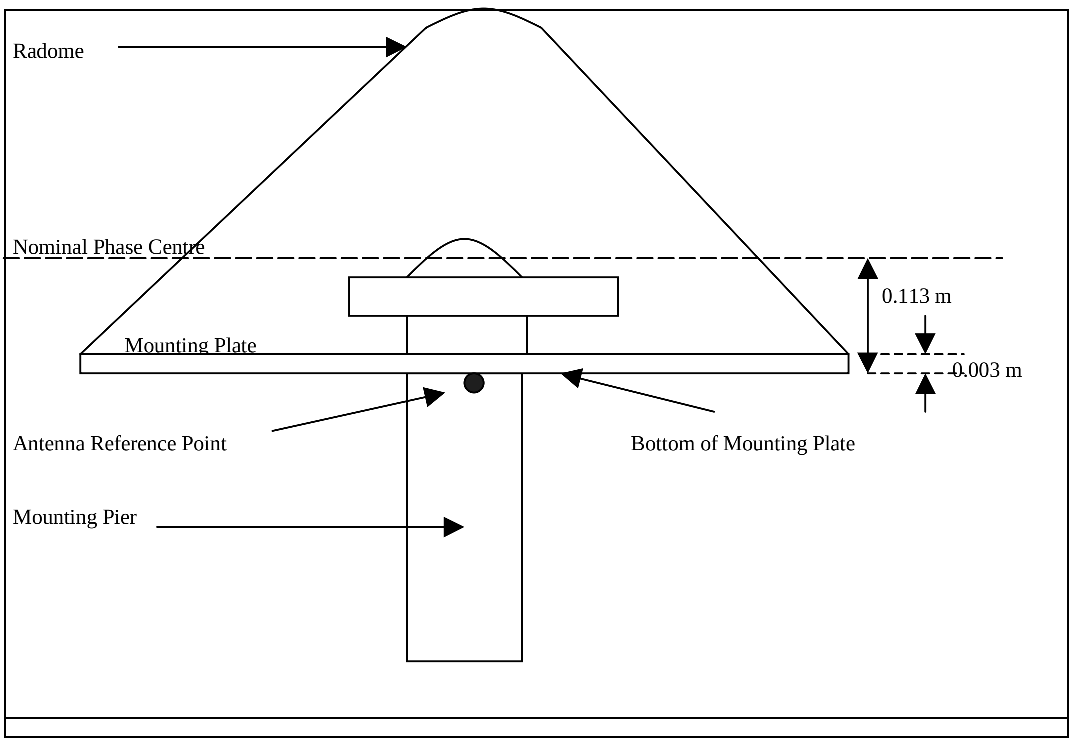
APPENDIX A1: SAPOS REFERENCE STATION

<table>
<tr><td colspan="8">SAPOS®-Referenzstationen Baden-Württemberg</td></tr>
<tr><td>Stationsname</td><td colspan="3">Stuttgart</td><td colspan="2">Kennung</td><td colspan="2">384</td></tr>
<tr><td colspan="8">Allgemeine Angaben</td></tr>
<tr><td>Ort</td><td colspan="3">Landesvermessungsamt,
Büchsenstrasse 54</td><td colspan="2">Aufbaudatum</td><td colspan="2">1995</td></tr>
<tr><td>Punktvermarkung</td><td colspan="7">GPS-Antennenträger - Stahlrohr mit kreisförmiger Grundplatte und zentrischer Schraube</td></tr>
<tr><td colspan="4">Anmeldung HEPS und GPPS</td><td colspan="4">E-Mail: sapos@vermbw.bwl.de</td></tr>
<tr><td colspan="4"></td><td colspan="4">Tel.: 0721/9185-345, -346, -348, -349</td></tr>
<tr><td colspan="8">GPS-Empfänger- und Antennenangaben</td></tr>
<tr><td>GPS-Empfänger</td><td colspan="3">Trimble 4000SSi</td><td colspan="2">GPS-Antenne</td><td colspan="2">TRM23903.00</td></tr>
<tr><td>ARP</td><td colspan="3">UK Antennenvorverstärker</td><td colspan="2">Abstand Marker-ARP</td><td colspan="2">0.073 m</td></tr>
<tr><td>Kalibrierung</td><td colspan="3"><u>Daten</u></td><td colspan="4"><u>Verwendung der Antenne</u></td></tr>
<tr><td colspan="8">Daten des HEPS</td></tr>
<tr><td colspan="4">Korrekturdaten</td><td colspan="4">Telefon-Nr</td></tr>
<tr><td colspan="4">RTCM 2.1(20,21)</td><td colspan="4">0173/3270428</td></tr>
<tr><td colspan="4">RTCM 2.1(20,21) FKP/VRS</td><td colspan="4">bei Bedarf einrichtbar</td></tr>
<tr><td colspan="8">Koordinaten</td></tr>
<tr><td colspan="4">Bezugspunkt</td><td colspan="4">Marker</td></tr>
<tr><td>Bezugssystem</td><td colspan="5">ETRS89</td><td>Ellipsoid</td><td>GRS 80</td></tr>
<tr><td colspan="8">Geozentrisch</td></tr>
<tr><td colspan="2">X</td><td colspan="4">Y</td><td colspan="2">Z</td></tr>
<tr><td colspan="2">4157307.424 m</td><td colspan="4">671171.686 m</td><td colspan="2">4774690.464 m</td></tr>
<tr><td colspan="8">Ellipsoidisch</td></tr>
<tr><td colspan="2">B</td><td colspan="4">L</td><td colspan="2">h</td></tr>
<tr><td colspan="2">48°46'46.11025"</td><td colspan="4">9°10'15.31154"</td><td colspan="2">341.034 m</td></tr>
<tr><td colspan="8">UTM</td></tr>
<tr><td colspan="4">Ost</td><td colspan="4">Nord</td></tr>
<tr><td colspan="4">32 512556.607 m</td><td colspan="4">5402955.630 m</td></tr>
<tr><td>Bezugssystem</td><td colspan="5">DHDN</td><td>Ellipsoid</td><td>Bessel</td></tr>
<tr><td colspan="8">Gauß-Krüger-Koordinaten / NN-Höhen</td></tr>
<tr><td colspan="2">Rechts</td><td colspan="4">Hoch</td><td colspan="2">H (NN)</td></tr>
<tr><td colspan="2">3512637.02 m</td><td colspan="4">5404678.06 m</td><td colspan="2">292.83 m</td></tr>
</table>

Hinweis: Der RINEX-Header (GPPS) enthält immer die aktuellen Koordinaten und Exzentrizitäten. Es empfiehlt sich nur diese Angaben für Post Processing Anwendungen zu verwenden.

APPENDIX A2: REFERENCE STATION 1

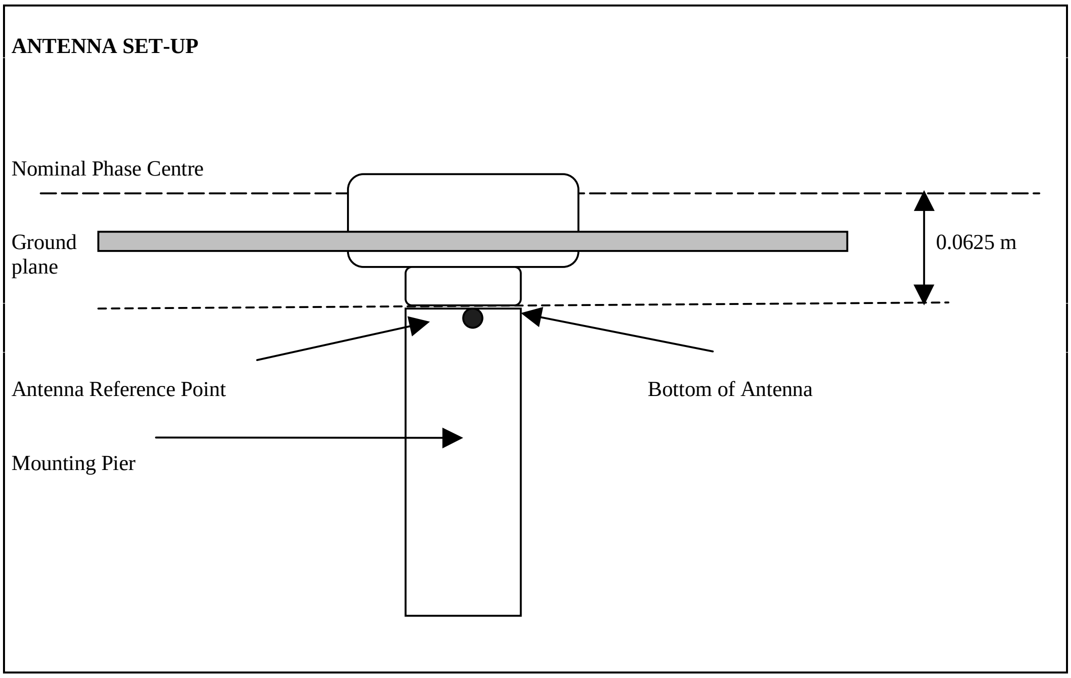
Station Name	Station 1		**Code**	ANT1	
General Details					
Place	Institute of Navigation Bereitscheidstrasse 2		**Date of Establishment**	February 2003	
Point Marking	GPS-Antenna Mounting Piers (Pipe with centre screw)				
Further Information			E-Mail: ins@nav.uni-stuttgart.de		
Institute of Navigation D-70174 Stuttgart			Tel.: 0711/121-3401		
GPS-Receiver and Antenna Details					
GPS-Receiver	Trimble 4700		**GPS-Antenna**	TRM29659.00 RPTR	
ARP	Top of Antenna mounting pier (Bottom of mounting plate)		**Distance (Mark-ARP)**	0.000m	
Calibration	None				
COORDINATES					
Reference Point					
Coordinate System	ETRS89		**Ellipsoid**	GRS 80	
Geocentric					
X		**Y**		**Z**	
4157188.946 m		671201.897 m		4774768.535 m	
Ellipsoidal					
Φ		**Λ**		**h**	
48° 46' 50.50625"		9° 10' 17.69735"		325.858 m	



APPENDIX A3: REFERENCE STATION 2

Station Name	Station 2	**Code**	ANT2
General Details			
Place	Institute of Navigation Bereitscheidstrasse 2	**Date of Establishment**	February 2003
Point Marking	GPS-Antenna Mounting Piers (Pipe with centre screw)		
Further Information	E-Mail: ins@nav.uni-stuttgart.de		
Institute of Navigation D-70174 Stuttgart	Tel.: 0711/121-3401		
GPS-Receiver and Antenna Details			
GPS-Receiver	Trimble 4700	**GPS-Antenna**	TRM22020.00+GP
ARP	Top of Antenna mounting pier (Bottom of Antenna)	**Distance (Mark-ARP)**	0.000m
Calibration	None		
COORDINATES			
Reference Point			
Coordinate System	ETRS89	**Ellipsoid**	GRS 80

Geocentric		
X	**Y**	**Z**
4157191.942 m	671204.606 m	4774765.573 m
Ellipsoidal		
Φ	**Λ**	**h**
48° 46' 50.36053"	9° 10' 17.80498"	325.864 m



APPENDIX B1: GPS FIELD LOG SHEET (DAY 1)

GPS Field Log Sheet

Project Name: DETERMINATION OF REFERENCE STATIONS

Date: 05-03-2003 Time: 13:00hr Observed By: OGONDA G.

Start of obs: 13:43 hrs End of Obs: 13:45hrs

Station

Station name: ANT 1 DAY 1 Station No. 1 Station Code: DAY 1

Session No. 1

Receiver

Type: TRIMBLE 4700 Serial No.:

Recording Rate: 2 seconds Type of Observation: STATIC

Elevation cut-off angle: 0°

Antenna

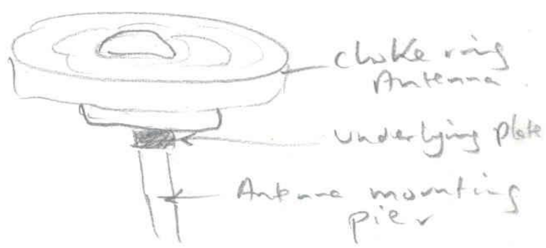
Type: TRIMBLE CHOKE RING Serial No.:

antenna Height: 1.00 m

Weather: CHILLY AND CLOUDY, NO SUNSHINE

Sketch and Remarks:

Day 1 observations done with no Radome on the Antenna but with an underlying plate under the Antenna (See sketch). About 12 Satellites are visible at the start of the observation



APPENDIX B2: GPS FIELD LOG SHEET (DAY 2)

GPS Field Log Sheet

Project Name: DETERMINATION OF REFERENCE STATIONS

Date: 06-05-2003 Time: 13:50 Observed By: OGONDA G.

Start of obs: 13:55 hrs End of Obs: 13:57 hrs

Station

Station name: ANT1DAY2 Station No. 1 Station Code: DAY2

Session No. 1

Receiver

Type: TRIMBLE 4700 Serial No.:

Recording Rate: 2 seconds Type of Observation: STATIC

Elevation cut-off angle: 0°

Antenna

Type: TRIMBLE CHOKE RING Serial No.:

antenna Height: 1.00 m

Weather: CLOUDY

Sketch and Remarks:

Same antenna setting as in day 1.

APPENDIX B3: GPS FIELD LOG SHEET (DAY 3)

GPS Field Log Sheet

Project Name: DETERMINATION OF REFERENCE STATIONS

Date: 07-03-2003 Time: 14:20hr Observed By: OLONDA G.

Start of obs: 14:13 hrs End of Obs: 14:15 hrs

Station

Station name: ANT1DAY3 Station No. 1 Station Code: DAY3

Session No. 1

Receiver

Type: TRIMBLE 4700 Serial No.:

Recording Rate: 2 Seconds Type of Observation: STATIC

Elevation cut-off angle: 0°

Antenna

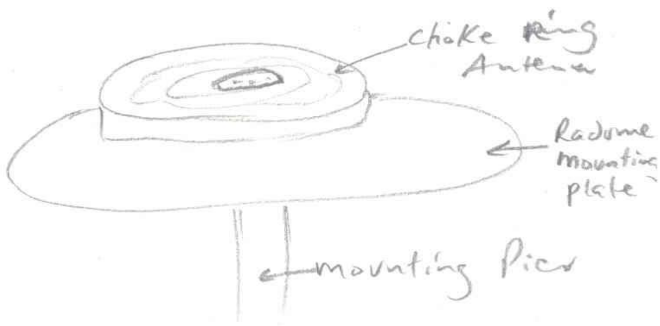
Type: TRIMBLE CHOKE RING Serial No.:

antenna Height: 1.00 m

Weather: CLOUDY

Sketch and Remarks:

On this day of the GPS observation, the underlying plate was replaced with a Radome mounting plate.



APPENDIX B4: GPS FIELD LOG SHEET (DAY 4)

GPS Field Log Sheet

Project Name: DETERMINATION OF REFERENCE STATIONS

Date: 08-03-2003 Time: 14^{00} hr Observed By: OGONDA G.

Start of obs: 14:20 hrs End of Obs: 14:22 hrs

Station

Station name: ANT1DAY4 Station No. 1 Station Code: DAY4

Session No. 1

Receiver

Type: TRIMBLE 4700 Serial No.:

Recording Rate: 2 seconds Type of Observation: STATIC

Elevation cut-off angle: 0°

Antenna

Type: TRIMBLE CHOKE RING Serial No.:

antenna Height: 1.00 m

Weather: CLOUDY AND VERY COLD

Sketch and Remarks:

Same antenna setting as in day 3.

APPENDIX B5: GPS FIELD LOG SHEET (DAY 5)

GPS Field Log Sheet

Project Name: DETERMINATION OF REFERENCE STATIONS

Date: 09-03-2003 Time: 14^{50} hr Observed By: OGUNDA G.

Start of obs: 14:47 Hrs End of Obs: 14:49 Hrs

Station

Station name: ANT1 DAY5 Station No. 1 Station Code: DAY5

Session No. 1

Receiver

Type: TRIMBLE 4700 Serial No.:

Recording Rate: 2 Seconds Type of Observation: STATIC

Elevation cut-off angle: 0°

Antenna

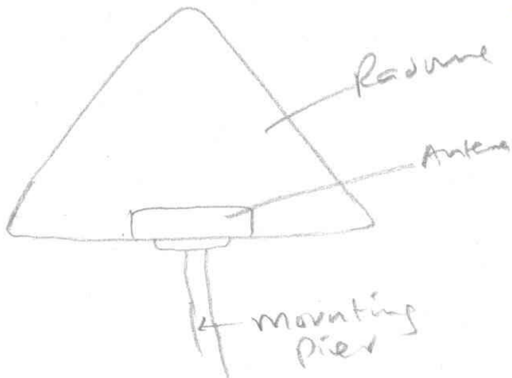
Type: TRIMBLE CHOKE RING Serial No.:

antenna Height: 1.00m

Weather: CLOUDY

Sketch and Remarks:

On the fifth day the Radome was placed on the choke Ring Antenna.



APPENDIX B6: GPS FIELD LOG SHEET (DAY 6)

GPS Field Log Sheet

Project Name: DETERMINATION OF REFERENCE STATIONS

Date: 10-03-2003 Time: 15:00hr Observed By: OGONDA G.O

Start of obs: 15:00 Hrs End of Obs: 15:02 Hrs

Station

Station name: ANT1 DAY6 Station No. 1 Station Code: DAY 6

Session No. 1

Receiver

Type: TRIMBLE 4700 Serial No.:

Recording Rate: 2 Seconds Type of Observation: STATIC

Elevation cut-off angle: 0°

Antenna

Type: TRIMBLE CHOKE RING Serial No.:

antenna Height: 1.00 m

Weather: CLOUDY

Sketch and Remarks:

Same antenna setting as on day 5.

DATA FILES IN CDs

1. Raw GPS Data-Day 1 **-Station 1**
-Station 2
-Reference Station
-Day 2 -Station 1
-Station 2
-Day 3 -Station 1
-Station 2
-Day 4 -Station 1
-Station 2
-Day 5 -Station 1
-Station 2
-Day 6 -Station 1
-Station 2

2. Processed GPS Data **Part 1** -Station 1
-Station 2
-Applanix Solutions
Part 2 -Day 1
-Day 2
-Day 3
-Day 4
-Day 5
-Day 6

3. Final Report – Word Document