AN INVESTIGATION OF THE APPLICATIONS AND LIMITATIONS OF UTILISING GLOBAL NAVIGATIONAL SATELLITE SYSTEMS (GNSS) APPLICATIONS IN THE SOUTH AFRICAN NATIONAL DEFENCE

Submitted in partial fulfilment of the requirements for the degree

Master of Science

in the

Department of Geography, Geoinformatics and Meteorology
Faculty of Natural and Agricultural Science of the
University of Pretoria
South Africa

Frankie van Niekerk
Student Number: 27469299

Supervised by:
Professor W.L. Combrinck

February 2011

Table of Contents

Chapter 1 : Introduction 1-1

Background Information 1-1

Assumptions/Exclusions 1-3

Research Question 1-3

Aim and Objectives 1-4

Significance of this Study....1-4

Brief Chapter Overview....1-4

Chapter 2 : Conceptual Framework and Methods 2-1

Background....2-1

Receivers, Software and Data 2-3

Chapter 3 : Common Frame of Reference 3-1

Reference Systems....3-1

Positional Accuracy Standards 3-18

Chapter 4 : GPS Fundamentals 4-1

Introduction 4-1

Operational Aspects....4-1

GPS Measurement: Errors and Biases....4-14

GPS Measurement Augmentation 4-23

Chapter 5 : GPS in the Field – Applications 5-1

Introduction 5-1

Measurements with Geodetic Type GPS Receivers 5-3

Measurements with Navigational type GPS Receivers 5-23

Increasing Baselines for Differential GPS Measurements....5-28

Precise Point Positioning Techniques 5-32

Field Measurements with Navigational GPS Receivers 5-34

Satellite Based Augmentation System Tested 5-50

Concluding Remarks....5-51

Selective Denial or Intentional Jamming....5-51

Unintentional Jamming 5-54

Chapter 6 : Summary of Conclusions 6-1

Appendix A: References 1

Appendix B: Datums used in Africa 1

Appendix C: Military Data Standards used in the SANDF 1

Multinational Geospatial Co-production ProgramME Standard 1

ICAO D9881 Standard 3

S-57 Data Standard 7

Appendix D: GPS Field Manual 1

Table of Figures

Figure 3-1: Maclear's Meridian Arc 3-2

Figure 3-2: WGS 84 Ellipsoid Values 3-3

Figure 3- 3: Ellipsoidal Coordinate System 3-4

Figure 3- 4: Geocentric Cartesian Coordinate System 3-5

Figure 3-5: ECEF Reference System 3-6

Figure 3-6: WGS84 Reference Stations 3-8

Figure 3-7: Selection of the best Ellipsoid 3-9

Figure 3-8: HRAO Velocities: 1996 to 2010 3-11

Figure 3-9: Orthometric Height (H) = h - N 3-13

Figure 3-10: IGS Reference Stations - Africa 3-14

Figure 3-11: UTM Zones of Africa 3-16

Figure 3-12: MGRS Blocks - South Africa 3-17

Figure 3-13: Accuracy and Precision 3-19

Figure 4-1: Generic Layout of a GPS Satellite's Subsystems 4-3

Figure 4-2: GPS Ground Control Stations 4-4

Figure 4-3: Generic Layout of a GPS Receiver 4-6

Figure 4-4: GPS Signal Structure 4-7

Figure 4-5: Synchronisation of Satellite and GPS Receiver Signals to Measure Time and Range 4-9

Figure 4-6: Satellite and Receiver Clock Offsets Calculated to Measure Time and Range 4-9

Figure 4-7: Ranging from four Satellites 4-11

Figure 4-8: Measuring Time and Range with Carrier Signals 4-13

Figure 4-9: Satellite Geometry - Dilution of Precision 4-16

Figure 4-10: Sunspot Activity since 1995 4-17

Figure 5-1: Location of GPS Station Positions in Local Network. 5-2

Figure 5-2: Distances between Stations (Global View - WGS 84, UTM Projection, Z35S 5-2

Figure 5-3: Distances between Stations (Focused View - WGS 84, UTM Projection, Z35S) 5-3

Figure 5-4: Station 1 - 2010_03_03 (1H) 5-4

Figure 5-5: Station 2 - 2010_03_03 (1H) 5-5

Figure 5-6: Station 3 - 2010_03_03 (1H) 5-5

Figure 5-7: Station 4 - 2010_03_03 (1H) 5-6

Figure 5-8: Station 5 - 2010_03_03 5-6

Figure 5-9: Satellites and PDOP Values 5-7

Figure 5-10: Electron Content: 100 km to 2 000 km 5-8

Figure 5-11: Electron Density: 09:00 - 23:00 5-9

Figure 5-12: Correlation between Electron Density and GPS Precision 5-10

Figure 5-13: Global Ionosphere Model 5-11

Figure 5-14: Station 1 - 2010_03_03 (2H) 5-12

Figure 5-15: Station 2 - 2010_03_03 (2H) 5-12

Figure 5-16: Station 4 - 2010_03_03 (H3) 5-13

Figure 5-17: Station 5 - 2010_03_03 (3H) 5-13

Figure 5-18: Station 1 - 2010_03_10 (1H) 5-14

Figure 5-19: Station 1 - 2010_03_10 (2H) 5-14

Figure 5-20: Station 1 - 2010_03_10 (3H) 5-15

Figure 5-21: Consecutive Measurements 5-15

Figure 5-22: Station3 - ProXH - 2010_03_24 5-19

Figure 5-23: Station 3 - ProXH - 2010_03_25 5-19

Figure 5-24: Station 3 - ProXH - 2010_03_26 5-20

Figure 5-25: Station 3 – ProXH - 2010_03_27 5-20

Figure 5-26: Station 3 - ProXH - 2010_03_24 (20 min intervals) 5-21

Figure 5-27: Station 3 - Consecutive Measurements - 2010_03_23 5-22

Figure 5-28: Station 3: Garmin GPSMap 60CSx - 2010_03_08 5-24

Figure 5-29: Station 3 - Garmin GPSMap 60CSx - 2010_03_09 5-25

Figure 5-30: Station 3: Garmin eTrex - 2010_03_12 5-25

Figure 5-31: Station 3 – Garmin eTrex - 2010_03_16 5-26

Figure 5-32: Geometry of Station 4 (Zwartkop) 5-35

Figure 5-33: Geometry of Station 5 (Schanskop) 5-36

Figure 5-34: Trimble ProXH Track - Valhalla 5-37

Figure 5-35: Trimble ProXH Track Valhalla (South) 5-37

Figure 5-36: Trimble ProXH Track Valhalla (North) 5-38

Figure 5-37: Garmin GPSMap 60CSx Track (in Pouch) - South 5-39

Figure 5-38: Garmin GPSMap 60CSx (in Pouch) - North 5-39

Figure 5-39: Garmin eTrex 1 (in Hand) South 5-40

Figure 5-40: Garmin eTrex 1 (in Hand) – North 5-40

Figure 5-41: Garmin eTrex (in Pouch) - South 5-41

Figure 5-42: Garmin eTrex 2 (in Pouch) - North 5-42

Figure 5-43: Trimble ProXH Track though Pretoria 5-43

Figure 5-44: ProXH Tracks - Intersection 5-44

Figure 5-45: ProXH Tracks - Highway 5-45

Figure 5-46: Garmin GPSMap 60CSx - Intersection 5-45

Figure 5-47: Garmin GPSMap 60CSx - Highway 5-46

Figure 5-48: Garmin GPSMap 60CSx Track - Fountains Valley Traffic Circle/Interchange 5-47

Figure 5-49: Garmin GPSMap 60CSx Track - Traffic Circle 5-47

Figure 5-50: ProXH and eTrex Tracks - Inner City (Sunnyside, Pretoria) 5-48

Figure 5-51: ProXH and eTrex Tracks - Tree Cover (Brooklyn – Pretoria) 5-49

Figure 5-52: Garmin eTrek Tracks with EGNOS Activated 5-50

Figure 5-53: Photo of Jammer Setup 5-52

Figure 5-54: Viewshed of GPS Jamming Tests 5-52

List of Tables

Table 3-1: Differences of TrigNet Stations' coordinates between HART94 and ITRF 2005 3-10

Table 4-1: Summary of GPS Signal Components 4-7

Table 4-2: Attainable Accuracies with Stand-alone and DGPS 4-25

Table 5-1: Topcon GB-1000 measurement values of Network - Precision 5-3

Table 5-2: Correlation between Electron Density and GPS Precision on 2010_03_03 5-10

Table 5-3: Correlation between Electron Density and GPS Precision on 2010_03_10 5-10

Table 5-4: Topcon GB-1000 measurements comparison with the HRAO receiver - Accuracy 5-17

Table 5-5: Trimble ProXH measurement values at Station 3 - Precision 5-18

Table 5-6: Trimble ProXH measurement values at Station 3 on 2010_03_24 (20 min intervals) 5-21

Table 5-7: Topcon GB-1000 UTM Coordinates at Station 3 5-23

Table 5-8: Trimble ProXH UTM Coordinates at Station 3 – Accuracy 5-23

Table 5-9: Garmin GPSMap 60CSx UTM Coordinates at Station 3 - Accuracy 5-27

Table 5-10: Garmin eTrex UTM Coordinates at Station 3: Accuracy 5-27

Table 5-11: Topcon GB-1000 GPS: Increasing Baselines - Precision 5-28

Table 5-12: Topcon GB-1000: Increasing Baselines - Accuracy 5-29

Table 5-13: Topcon GB-1000 GPS stand-alone measurements - Accuracy 5-30

Table 5-14: Trimble ProXH: Increasing Baselines - Precision 5-30

Table 5-15: Trimble ProXH: Increasing Baselines - Accuracy 5-31

Table 5-16: Trimble ProXH stand-alone measurements - Accuracy 5-31

Table 5-17: Topcon GB-1000 measurements with relative PPP (AUSPOS) - Precision 5-32

Table 5-18: Topcon GB-1000 measurements with relative PPP (AUSPOS) - Accuracy 5-33

Table 5-19: Topcon GB-1000 measurements with absolute PPP (CSRS) – Precision 5-33

Table 5-20: Topcon GB-1000 measurements with absolute PPP (CSRS) - Accuracy 5-33

Table 5-21: Trimble ProXH measurements with absolute PPP (CSRS) - Precision 5-34

Table 5-22: Trimble ProXH measurements with absolute PPP (CSRS) - Accuracy 5-34

Table 5-23: GPS Receiver Jamming Resistance (P = Position, NP = No position) 5-53

ACRONYMS

AFREF:	African Reference Frame
AUSPOS:	Australian Positioning Service
C/A-code:	Coarse Acquisition Code
CDNGI:	Chief Directorate National Geospatial Information, formally CDSM
CDSM:	Chief Directorate Surveys and Mapping, now CDNGI
CEP:	Circular Error Probability
CORS:	Continuously Operating GPS Reference Stations
CSRS:	Canadian Spatial Reference System
DGPS:	Differential GPS
DOP:	Dilution of Precision
DSSS:	Direct Sequence Spread Spectrum
ECEF:	Earth-centred Earth-fixed
ECI:	Earth-centred Inertial
EGM 96	Earth Gravitational Model 1996
EGM 2008:	Earth Gravitational Model 2008
EGNOS:	European Geostationary Navigation Overlay System
GALILEO:	European Union’s GNSS
GBAS:	Ground Based Augmentation Systems
GCP:	Ground Control Point
GIS:	Geographical Information System
GLONASS:	The Russian GNSS
GNSS:	Global Navigational Satellite Systems
GPRS:	General Packet Radio Service
GPS:	Global Positioning System
GRS80:	Geodetic Reference System 1980
HART94:	Hartebeesthoek Datum 1994
HartROA:	Hartebeesthoek Radio Astronomy Observatory near Pretoria, South Africa
HDOP:	Horizontal Dilution of Precision

HRAO:	IGS reference station at HartRAO
ICAO:	International Civil Aviation Organisation
IGS:	International GNSS Service
IHO:	International Hydrographical Office
ITRF:	International Terrestrial Reference Frame
JPL:	Jet Propulsion Laboratory of NASA
LLR:	Lunar Laser Ranging
MGCP:	Multinational Geospatial Co-production Programme
MGRS:	Military Grid Reference System
MSL:	Mean Sea Level
NASA**:**	National Aeronautics and Space Administration of the USA
NAVSTAR:	Navigation System with Timing and Ranging
NGA:	National Geospatial-intelligence Agency
NTRIP:	Network Transport of RTCM via Internet Protocol
P-code:	Precise Code
PDOP:	Positional Dilution of Precision
PPP:	Precise Point Positioning
PPS:	Precise Positioning Service
PRN:	Pseudorandom Noise
RINEX:	Receiver Independent Exchange Format
RTCM:	Radio Technical Commission for Maritime Services
SAC:	Satellite Application Centre
SANDF:	South African National Defence Force
SBAS:	Satellite Based Augmentation System
SLR:	Satellite Laser Ranging
SPS:	Standard Positioning Service
SUTH	IGS reference station at Sutherland, South Africa
SVN:	Space Vehicle Number
TDOP:	Time Dilution of Precision

TEC:	Total Electron Content
UERE:	User Equivalent Range Error
UTC:	Coordinated Universal Time
UTM:	Universal Transverse Mercator Coordinate System
UVM:	Urban Vector Map Standard of the NGA
VDOP:	Vertical Dilution of Precision
VLBI:	Very Long Baseline Interferometry
WAAS:	Wide Area Augmentation System
WGS84:	World Geodetic System 1984

GLOBAL NAVIGATIONAL SATELLITE SYSTEMS (GNSS) APPLICATIONS FOR THE SOUTH AFRICAN NATIONAL DEFENCE FORCE

ABSTRACT

Global Navigational Satellite Systems (GNNS,) of which the Global Positioning System (GPS) of the United States is the most widely used, is increasingly being used by the South African National Defence Force (SANDF) for navigation and positional data. However, the SANDF can only use civilian type GPS receivers, which make use of the Standard Positioning Serves (SPS) and not the encrypted Precise Positioning Service (PPS), which is only available to the United States military forces and its allies. The aim of this work is to understand the influences that impact on the use of a GPS and specifically the capabilities of civilian type GPS receivers. The first objective will be to propose and motivate the use of a standardised reference frame that can be used by the SANDF for positional data in general and for GPS measurements specifically. In this regard it is proposed that the SANDF standardises on the World Geodetic System 1984 (WGS 84) as the standard ellipsoid and also use it as a universal horizontal datum for mapping projects. For survey tasks WGS 84 can be used in combination with a selected International Terrestrial Reference Frame (ITRF) epoch for reference stations. The International GNNS Service (IGS) stations can be used as such reference stations; the geometric distribution can be improved as the African Reference Frame (AFREF) add more stations to the existing IGS network. In the absence of a common vertical datum it is suggested that the Earth Gravitational Model 2008 (EGM 2008) be used. Secondly, the use of GPS for positional data should be aligned with the required positional accuracy requirements and standards of the SANDF. In this regard it is suggested that international positional accuracy standards are accepted and implemented to ensure interoperability. The third objective is to describe and understand how to mitigate influences that impact on the reliability of GPS. This is specifically important with the use of low accuracy civilian type GPS receivers for navigation and the collection of ground control for mapping projects. The fourth objective will be to establish with practical field trials the effect of these influences on GPS measurements and device appropriate data collection strategies. One serious impact is the susceptibility of civilian GPS receivers to jamming. This is addressed but not sufficiently to formulate policy and would require further investigation. There is a worldwide drive to make GPS reliable for safety of life applications such as air and rail transport which also benefits its use for military applications. It is therefore important for the SANDF users to know and understand these influences on GPS in order to optimise its use for operations.

Acknowledgments

I would like to express my gratitude to the following individuals and institutions whose support made this research possible:

Professor Ludwig Combrinck, the Associate Director of HartRAO who aided me throughout this research. His practical and innovative approach is commendable.

The Director Geospatial Information, Brigadier General Pieter Thirion who created the opportunity and environment to conduct the research.

The young people of Directorate Geospatial Information for assisting in obtaining GNSS measurements over extended periods.

The Training Staff of SA Army Combat Training Centre at Lohatla.

Special Forces Headquarters' Staff.

The Commander and Staff of the Mobile Deployment Wing and the Reutech personnel for assisting with jamming tests with RADAR.

Dr Adriaan Combrink of CK Surveying for giving advice and assistance on various aspects of this research.

Mr Fritz van der Merwe of the Geography Department of the University of Pretoria for giving advice on statistical analysis.

Mr Richard Wonnacott of the Chief Directorate National Geospatial Information for giving advice on content and reference systems.

CHAPTER 1: INTRODUCTION

BACKGROUND INFORMATION

1. The South African National Defence Force (SANDF) requires positional data for various applications, including situational awareness, navigation and surveying. Positional data are also required for the accurate delivery of munitions, logistics supply, delivery of medical health services, administrative and construction activities. Two broad approaches are used to provide positional data that relate to the chicken and egg situation, for instance, maps and charts are used for positional data but positional data are required to create maps and charts. Firstly, the more traditional approach is to use hard copy maps and charts that are updated manually from various sources, such as reconnaissance reports. Secondly, an approach is used which involves the use of a digital map by means of a Geographical Information System (GIS) to which deployed sensors report automatically via connected communication systems to update the digital map. A variation on this approach is to use an operator to update the digital map manually.

2. Almost all digital map data are created from satellite imagery and aerial photography. In order to extract features that meet the required positional accuracy, these images need to be geometrically rectified based on accurate positional data. The SANDF is deployed on the African continent in places such as the Democratic Republic of the Congo (DRC) and Sudan, where the collection of positional data is difficult and risky. It should also be noted that a general lack of reference points and minimal infrastructure in rural areas poses significant challenges for acquiring positional data. Built-up areas and densely populated areas pose different challenges. Thus, different approaches need to be developed to collect positional data in rural and urban areas.

3. With the advent of Global Navigation Satellite Systems (GNSS), of which the Global Positioning System (GPS) of the United States Air Force is the most widely used, a new opportunity for acquiring positional data is available. Other satellite navigational systems, which include the Russian GNSS (GLONASS) and the proposed European GALILEO system can and will render positional data. However, as early as the 1980s the South African Defence Force started to use Navigation System with Timing and Ranging (NAVSTAR) GPS to acquire positional data to confirm positions in the field. The GPS receiver was never used as the only source of positional data, but merely to confirm positions that were derived from conventional navigational techniques.

4. The GPS is a space based navigational system. At least twenty-four satellites orbiting the earth at a mean distance of 26 600 km in space are transmitting radio signals that

propagate through the atmosphere at the approximate speed of light. These signals are used by a GPS receiver to determine a position on Earth by converting the known positions of the satellites to a single position on earth. This is made possible by using the known speed of these signals from each satellite multiplied by the time it took to reach the receiver. The intersection of these signal vectors allows the receiver to determine a position on a reference ellipsoid that is a close representation of the earth's shape. Software conversion packages are used to convert this position on the ellipsoid to a three dimensional position on Earth that may have an error in the range from 10 m to sub-centimetre. This is a hugely oversimplified version of reality, but may suffice to create an understanding of the basic concepts involved. Aspects of how GPS functions and the influences on accurate measurements will be discussed in more detail in Chapter 3.

5. The GPS satellite signal structure is of paramount importance for positioning. Each satellite is transmitting two signals, namely the L1 at 1 575.42 MHz and L2 at 1 227.6 MHz, also referred to as the carrier signals. Two other signals that are used for determining range are modulated on these carrier signals. On L1 a Coarse Acquisition code (C/A-code) and a Precise code (P-code) are modulated whereas on L2 only the P-code is modulated. The GPS navigation message containing information about the status of satellite orbits and clocks is also modulated on both carrier signals. Most civilian navigational type GPS receivers use only the C/A-code to determine position. More expensive survey type receivers are also able to use the carrier signals to determine position. However, the encrypted P-code code is only available to the United States military forces and its allies. Two additional satellite signals, the L2C and the L5, are planned for the modernisation and improvement of GPS and will most probably be available from 2013. The signal structure and its implications for positioning will be discussed in Chapter 4.

6. The accuracy of the measurement with a GPS receiver is dependent on various environmental factors, satellite deficiencies and quality of the receiver. Environmental aspects include refraction of the GPS satellite signal travelling through the atmosphere, reflection of signals from surfaces close to the receiver that creates bogus signals and objects obscuring the signal from reaching the receiver. Satellite deficiencies include orbit and clock errors as well as sub-optimal positioning of the satellites in the sky at the time of measurement, for instance being clustered in one segment or too low on the horizon. The quality of the receiver relates to the number of satellites that can be tracked, the quality of the receiver clock and the capability to receive and process positions from both code and carrier signals. All these aspects and ways to mitigate accuracy limiting factors will be discussed in more detail in Chapter 4.

7. One way of improving the accuracy of GPS measurements is to use a known position as a reference point. By deploying a GPS receiver at this known point or base station of which the position has been measured accurately before, any deviation in the measurements caused by environmental influences or satellite deficiencies can be measured relative to the known point. These deviations can then be used to correct any measurement taken with another GPS receiver in the vicinity of the base station. This concept is known as the differential correction of GPS measurements and can be conducted on the fly or afterwards during post-processing. This concept will be discussed in more detail in Chapter 4 as it plays an important role in taking accurate measurements for mapping and surveying purposes.

8. The SANDF is making use of civilian type receivers for positional data. Directorate Geospatial Information, the SA Army Engineer Formation, the SA Navy Hydrographer and Directorate Aviation Safety all use GPS receivers that are capable of using both carrier and code signals for mapping and surveying. Naval vessels and aircraft use embedded GPS receivers and integrate their measurements with other onboard inertial navigational systems to render an integrated positional solution. The rest of the SANDF, including infantry soldiers and peace observers, uses navigation type receivers that utilise the C/A-code for determining position. It can be assumed that a large number of SANDF members also use privately owned GPS receivers in this category.

ASSUMPTIONS/EXCLUSIONS

9. This study focuses on the use of civilian type GPS receivers and its application in the SANDF. Munitions guidance and GPS solutions as applied to weapon systems will not be discussed. Neither will survey applications be discussed, although the principles outlined in this study may be of great value to both weapon system developers and military surveyors.

10. Other GNSS solutions such as the Russian GLONASS and the European planned GALILEO system will not be discussed.

RESEARCH QUESTION

11. There is a requirement to identify suitable approaches to using civilian GNSS to acquire accurate positional data for diverse applications in the SANDF. The limits and capabilities of GNSS as applied in the SANDF need to be identified and evaluated to ensure correct use. Currently there is no official policy or guidelines on the use of GNSS in the SANDF.

AIM AND OBJECTIVES

12. The aim of this study is to discuss the different positional data requirements in the SANDF and create a theoretical and tested approach for collection of these data using GNSS. This will be done by

a. discussing a proposed common frame of reference for positional data that can be used by the SANDF;

b. discussing an attainable positional accuracy standard for use in the SANDF;

c. discussing the functioning of GPS in general, including GPS errors and its effect on measurements;

d. completing an empirical study of how to overcome some of these errors and to create a repeatable and reliable approach for GPS use in the field; and

e. presenting a field manual that can be used by the SANDF for GPS data collection.

SIGNIFICANCE OF THIS STUDY

13. This study will establish a firm base for policy guidelines for using civilian type GPS receivers under different circumstances, including restrictive influences. The SANDF will most probably remain dependent on civilian type GPS receivers and will therefore need to develop knowledge and skills to use this type of receiver.

BRIEF CHAPTER OVERVIEW

14. After an appropriate introduction (Chapter 1) and (Chapter 2) sketching a conceptual framework, this study will establish a theoretical approach for a common frame of reference for positional data on the African continent in Chapter 3. Aspects such as different coordinate systems, ellipsoids, horizontal and vertical datums are discussed. This is followed by a discussion of positional accuracy requirements with proposed accuracy standards to be adopted in the SANDF.

15. Chapter 4 contains a discussion of the theoretical aspects of GPS and the capabilities and limitations of the different types of receivers. It includes the environmental effects, satellite health and receiver quality that impact on the accuracy and reliability of measurements. This chapter also includes selective denial or jamming of GPS signals and concludes with augmentation techniques to improve the accuracy of measurements. The

focus remains on applications on the African continent and concludes the bulk of the literature study.

16. Chapter 5 encapsulates testing of the theoretical approach established in the preceding chapters through the introduction of measurements taken with different types of receivers under different conditions. An approach for using the different types of receivers in the field is developed. Conclusions of this study are summarised in Chapter 6.

17. Appendix D provides a practical hands-on field manual for GPS users in the SANDF.

CHAPTER 2: CONCEPTUAL FRAMEWORK AND METHODS

BACKGROUND

1. Establishing a Departure Point. This study would like to establish a theoretical and tested approach for the collection of positional data for use in the SANDF by making use of civilian type GPS receivers. Although the focus will be on the collection of positional data, the requirements for navigation by means of GPS are equally important and will be addressed by implication. The departure point for positional data is a common reference frame. A theoretical approach will be followed to discuss trends globally and on the African continent to establish an approach for such a common reference frame. The objective is to suggest an approach that can be used by the SANDF. This will be followed by a discussion of the theoretical requirements for positional data by the various services in the SANDF. In the absence of existing policy, applicable international policy guidelines will be suggested as the way to be followed. Some of these international trends are followed in practice, but are not taken up in SANDF policy.

2. Discussing GPS Fundamentals. The objective will be to explain the basic functions of GPS to provide a theoretical framework that can be used to understand the capabilities of different GPS receivers, including its limitations. Causes of less than optimal measurements and the augmentation of GPS measurements for the improvement of accuracy will be discussed as an integral part of collecting positional data and navigation. This approach will build on the previous discussion by explaining how the common reference frame is used by GPS to provide positional data and lay the foundation for the discussion of practical field measurements.

3. Field Measurements. The theoretical approach of the previous sections will be verified by the analysis of field data. The approach will be to determine a reference network that can be used to test the precision and accuracy of other receivers. The following process will be followed:

   a. Reference Network with Geodetic Receivers. A reference network with geodetic type GPS receivers will be established that could be used to evaluate and calibrate other receivers. The precision, accuracy and repeatability of measurements with these receivers in the network will be analyzed and discussed. This will require measurements longer than eight hours throughout the network to render sufficient data for this analysis. To ensure that measurements are not influenced by controllable systematic errors, the following precautionary steps are implemented. The positions of the stations in the network are to be selected to ensure that the influence of the ionosphere would be the same throughout the network. This requires baselines shorter than 15 km according to Combrinck (personal communication, 2010). Stations will be selected which are stable where foreseen or predictable movements of the receiver antennas will not occur. It should also be both accessible and out of reach of the general public to prevent tampering with the receivers or the antennas while measurements are taken. Station positions in the network will be selected to prevent multipathing and/or shadowing. The influences that impact on the accuracy of measurements as well as the augmentation of GPS measurements discussed in the theoretical discussions will be analysed in practice, including exploring the extension of baselines to a distance that would be more suitable for stand-alone GPS receivers instead. The challenge of insufficient base stations on the Continent and the inherent risks involved in setting up own base stations highlight the importance of this analysis.

b. Mapping GPS Receivers. The next process will be to establish the precision and accuracy levels attainable with typical mapping GPS receivers that are used in the SANDF. These receivers are used for mapping projects and are used for the collection of ground control data. These receivers will be deployed at the same stations as the reference network to evaluate the levels of precision and accuracy attainable with mapping receivers. These mapping receivers will also be used for the evaluation of extended baselines.

c. Navigational Receiver. Typical navigational receivers that are used in the SANDF will be used to establish attainable precision and accuracy levels at the same network stations. Although navigational receivers are not the primary instruments for collecting ground control data, the number of these receivers in the field and the high costs associated with deploying mapping receivers impel the use of navigational receivers for this purpose. It is therefore important to understand the levels of precision and accuracy attainable with these receivers.

d. Collection of Positional Data. Positional data are collected by means of GPS receivers in the field. This takes place by means of handheld GPS receivers used on patrols on foot and vehicles or imbedded GPS receivers on board vehicles or craft. Whatever the application, the precision and accuracy of data collected by these means need to be established to provide useful and reliable positional data.

4. Reliability. The reliability of the GPS receivers for navigation and collection of data is of paramount importance in the military. It is therefore important to explore and understand accuracy, precision and reliability of different civilian type GPS receivers. Susceptibility of these GPS receivers to jamming will also be discussed and tested in field trials. However, it will not be possible to explore the topic sufficiently to provide thorough policy guidelines. The possible tactics applied in the jamming and prevention of jamming of GPS receivers may be sensitive. The objective therefore will only be to demonstrate the vulnerability of civilian type GPS receivers to jamming.

RECEIVERS, SOFTWARE AND DATA

5. Geodetic Type GPS Receivers. Topcon GB-1000 receivers and associated antennas provided by Professor W.L. Combrinck of the Hartebeesthoek Radio Astronomy Observatory (HartRAO) will be used as geodetic receivers. These 40 channel receivers are capable of collecting data from both the GPS and GLONASS satellites, although only GPS data will be processed. These receivers can collect positional data with the C/A-code, L1 and L2 satellite signals.[1]

6. Mapping Type GPS Receivers. Trimble ProXH receivers and associated Zephyr antennas provided by the SANDF will be used as mapping receivers. These 12 channel receivers are capable of collecting positional data with the C/A-code, L1 and L2 carrier signals[2].

7. Navigational Receivers. Garmin GPSMap 60CSx and eTrex Legind HCx receivers with internal antennas provided by the SANDF will be used as navigational type receivers[3]. Data will be collected with 30 second intervals (static) and one second intervals (mobile), exported with the propriety Garmin software into .gpx format. These .gpx exported files can be imported into Microsoft Office Excel 2003 where it can be analysed.

8. Reference Data. Precise ephemeris data, which includes accurate satellite clock and orbit data will be accessed from the International GNSS Service (IGS) website and will be used throughout this study where measurements are post-processed differentially. These

---

[1] More technical detail of these receivers can be accessed at http://www.topconpositioning.com.

[2] More technical detail of these receivers can be accessed at http://www.trimble.com.

[3] Technical detail about these receivers can be accessed at http://www.garmin.co.za.

data are only available approximately two weeks after measurement. Epoch data (station coordinates) will be accessed from the International Terrestrial Reference Frame (ITRF) website. The IGS station at Hartebeesthoek (HRAO) will be used as base stations for post-processing, while the Australian Positioning Service (AUSPOS) and the Canadian Spatial Reference System (CSRS) will be used for Precise Point Positioning (PPP). The TrigNet stations of Chief Director National Geospatial Information (CDNGI) will also be used for assessing increasing baselines. WGS84 will be used as the reference ellipsoid and EGM2008 as geoid model. Base stations will be fixed to the published ITRF 2005, 2008_01_09 epoch values to create a single reference epoch for all differential processing. Ellipsoidal height values will be used throughout this study.

9. Data Analysis.

a. Survey and Mapping Receivers. Static measurements with survey and mapping receivers used in this study will be collected during periods extending over eight hours. Data will be collected at 30 second intervals, exported in Receiver Independent Exchange Format (RINEX) format and post-processed with Topcon Tools Version 7.3. using precise ephemeris data, base stations and station coordinates as indicated in paragraph 8. The Topcon Tools software will be used to export processed data in ellipsoidal coordinates, including the precision of these measurements in metre values. A special software package TEQC[4] will be used to decimate measurements into shorter time periods to establish the repeatability of sessions. Take note that after processing with the Topcon Tools software, which includes adjustments, the standard deviations on the measurements values throughout the 5 station network will be the same for all stations. The accuracy of measurements will be determined by comparing it with measurements with a receiver with a known higher accuracy capability. For accuracy comparisons measurement values will be converted to Universal Transverse Mercator Projection (UTM) plane coordinates in metre values which is a typical military map projection that can be used across the African continent. Height values will be in ellipsoidal values. A software package XForm version 4.3 and 4.4 acquired from Professor C.L. Merry will be used for these conversions.

---

[4] Teqc can be downloaded from http://facility.unavco.org/software/teqc

b. Navigational Receivers. Static measurements with navigational type receivers will be exported in .gpx format to Microsoft Excel. The precision of measurements will be determined by calculating averages and standard deviations over the complete collection period as well as in one hour segments. The accuracy of measurements with these receivers will be conducted similar to survey and mapping receivers.

c. Mobile Measurements. Mobile measurements will be collected by means of practical field trials with navigational and mapping GPS receivers that are used in the SANDF, this will be conducted to establish attainable levels of accuracy and to provide advice on how to improve measurements with these types of receivers. To provide sufficient data for reliable analysis, these trials will be conducted over and over and with different operators. Most of these trials will exceed thirty incidences to provide for a reliable statistical analysis. Data for the analysis of mobile solutions will be collected at one second intervals. Points and tracks collected with survey and mapping receivers will be used to indicate the accuracy of tracks collected with navigational receivers. Measurements with mapping receives in the mobile role will be processed with the Timble Pathfinder Office version 4.10 software. The TrigNet station of CDNGI in Silverton will be used as a base station for this processing. Background images will be used to create a visual orientation of these mobile measurements.

10. Background Data. Results of the analysis of GPS receiver capabilities will be presented in table and line graph formats. However, where navigational and mapping GPS receivers are used in the field the results will be displayed in a GIS product. ArcGIS Version 9.3.1 provided by the SANDF will be used for these analyses and background data for these products were provided as follows:

a. High Resolution Aerial Photography. The Satellite Application Centre (SAC) of the CSIR at Hartebeesthoek supplied the 10 cm resolution photography of the Tshwane Metropolitan Area. Date (probably 2007) and the sensor is unknown.

b. High Resolution Satellite Imagery. In addition, SAC also supplied the 5 m Spot (2009) imagery of the General Piet Joubert Training Area.

c. High Resolution Digital Elevation Model (DEM). The 20 m resolution DEM that will be used to conduct the analysis of the jamming of GPS signals was supplied by CDNGI.

d. Google Earth Imagery. Google Earth imagery will be used to demonstrate the effect of EGNOS on measurements with a navigational GPS receiver.

CHAPTER 3: COMMON FRAME OF REFERENCE

REFERENCE SYSTEMS

1. Introduction. A geographic position or location of a feature is expressed relative to something else, e.g. the coffee shop is on the northern side of the mall opposite parking area five, or if you are using your GPS, at 25° 51' 25.2"S, 28° 11' 10.0"E (relative to 0° latitude and 0° longitude). The GPS derived position can be expressed in latitude and longitude. This reference system (lines of latitude and longitude) is internationally accepted and was developed over hundreds of years; it is strongly tied to celestial observations. Originally man observed celestial objects to determine position as well as the shape and size of the earth. Important contributions by Eratosthenes, Posidonius, Thales and Ptolemy played a significant role in this regard. The first of such observations in South Africa started in 1751 by Abbe de la Caille. His work was improved by Sir Thomas Maclear in the 1840s with measurements from the Cape towards Namaqualand creating a meridian arc depicted in Figure 3-1. Triangulation and traversing in combination with celestial observations for control, were used to determine fixed points that could serve as reference points. Many followed Maclear and today a network of ~29 000 passive trigonometric beacons, commonly referred to as Trig Beacons, augmented with town markers, serve as reference points for mapping and surveying tasks in South Africa. Celestial observations, triangulation and traversing are dependent on line of sight optical measurements. Trig Beacons are therefore generally located at high points (mountain tops, towers or high buildings). A limitation of this type of observation therefore, is the inability to link measurements of landmasses that are separated by over the horizon water masses (Bolstad: 67 – 70, Hofmann-Wellenhof *et al.*, 2001: 1 – 2; Leick, 2004: 11 – 12; Varner, 2000: 1 – 2).

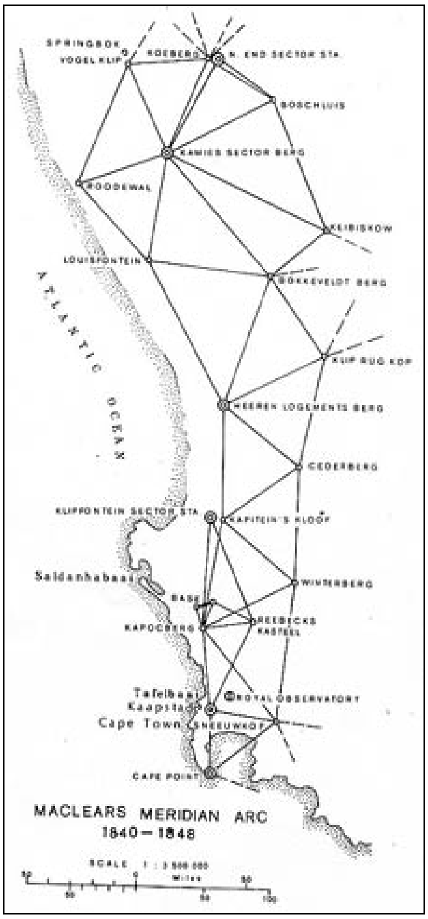

Figure 3-1: Maclear's Meridian Arc[1]

2. <u>The Shape and Size of the Earth – The Geoid</u>. The irregular surface of the earth inhibits coordinate computations. A surface close to mean sea level referred to as the geoid can be used as an approximation of the shape of the earth. This surface is everywhere perpendicular to the direction and force of gravity that is influenced by the density of the earth's crust. This three-dimensional equipotential surface is determined by means of gravity observations and represents a surface with equal or constant gravitation value or potential. It changes slowly over wavelengths of tens of kilometres and globally deviates approximately one metre from measured mean sea level. Global measurements to determine the geoid were not possible until recently. The National Geospatial Intelligence Agency (NGA) of the United States used satellite observations to compute a global geoid model. The first widely used global geoid model, Earth Gravitational Model 1996 (EGM96), has been replaced with a more detailed and accurate model (EGM2008) that was released in April 2008. Knowledge of the geoid is also important for height measurements for mapping projects that will be discussed further in paragraph 6 under Vertical Datums (Iliffe & Lott, 2008: 8).

---

[1] Source: Chief Director: National Geospatial Information accessed during April 2009 at http://w3sli.wcape.gov.za

3. Shape and Size of the Earth - Ellipsoid. The measured geoid provides a shape of the earth that can be approximated with a mathematical model that simplifies coordinate computations. The earth is not perfectly spherical but flattened at the poles or ellipsoidal. An ellipsoid model of Earth is defined by its rotation about its semi-minor axis that relates to the polar axis, its semi-major axis that relates to the equator and its flattening factor. The difference between the two is approximately 21 km; hardly visible on a global scale. Over the years as technology has improved a number of different ellipsoid models of the earth were defined by different countries. The latest measurement techniques include using Satellite Laser Ranging (SLR), Lunar Laser Ranging (LLR), Very Long Baseline Interferometry (VBLI) and GPS. These improvements in measurement technology resulted in the definition of international or global ellipsoid models. The NGA defined such an ellipsoid, which is known as the World Geodetic System 1984 (WGS84) and is widely used as a reference ellipsoid and is also the ellipsoid used by GPS. The WGS84 ellipsoid is described by its semi-minor axis (a), semi-major axis (b) and flattening factor (f), values are indicated in Figure 3-3. The use of WGS84 will be discussed further in paragraph 5 (Iliffe & Lott, 2008: 9, USDOD, 2000: 2-1 – 2-6).

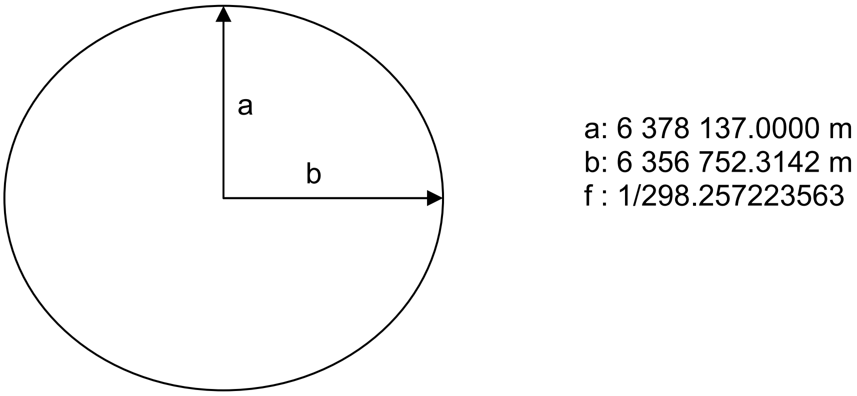

Figure 3-2: WGS 84 Ellipsoid Values

4. Coordinate Systems. A coordinate system is defined by its origin, the name of the axes, the sequence of the axes, the units of measurement and the direction in which the coordinates increment.

a. Ellipsoidal Coordinates. Ellipsoidal coordinates, which are also referred to as geodetic or geographic coordinates have their origin at the centre of a selected ellipsoid. The centre of the ellipsoid does not necessarily coincide with the centre of mass of the earth. The poles are defined by the rotational axis of the ellipsoid and the equator is the circle that bisects it in a northern and southern hemisphere, while the prime meridian is selected. The coordinates are defined as latitude (φ), longitude (λ) and height (h) in this sequence. Ellipsoidal coordinates can be two-dimensional (latitude and longitude) or three-dimensional (latitude, longitude and ellipsoidal height). Latitude is the angle formed by the ellipsoidal normal north (+) or south (-) from the equatorial plane. Longitude is the angle east (+) and west (-) from the prime meridian. Latitude and longitude are expressed in degrees or hours, where one hour equals 15 degrees, and height in metres above the surface of the ellipsoid. The equator is designated 0º. All other circles that run parallel to the equator are termed latitudes and their values are designated by their magnitude of direction of the ellipsoidal normal to a maximum value of 90º towards the poles. Lines of constant longitude are termed meridians or longitudes. In 1884 it was generally agreed that the longitude running through the Royal Greenwich Observatory in England will be designated 0º and is known as the Greenwich or Prime Meridian. Longitudes west of Greenwich are negative, while eastern longitudes are positive to the magnitude of its direction with the maximum value of 180º. Selecting and realising a geodetic datum constitutes ellipsoidal coordinates as a coordinate system which is the basis for mapping projects and will be discussed further under Horizontal Datum. Computations in ellipsoidal coordinates are complex (Iliffe & Lott, 2008: 8 – 14, Bolstad, 2006: 75 – 77).

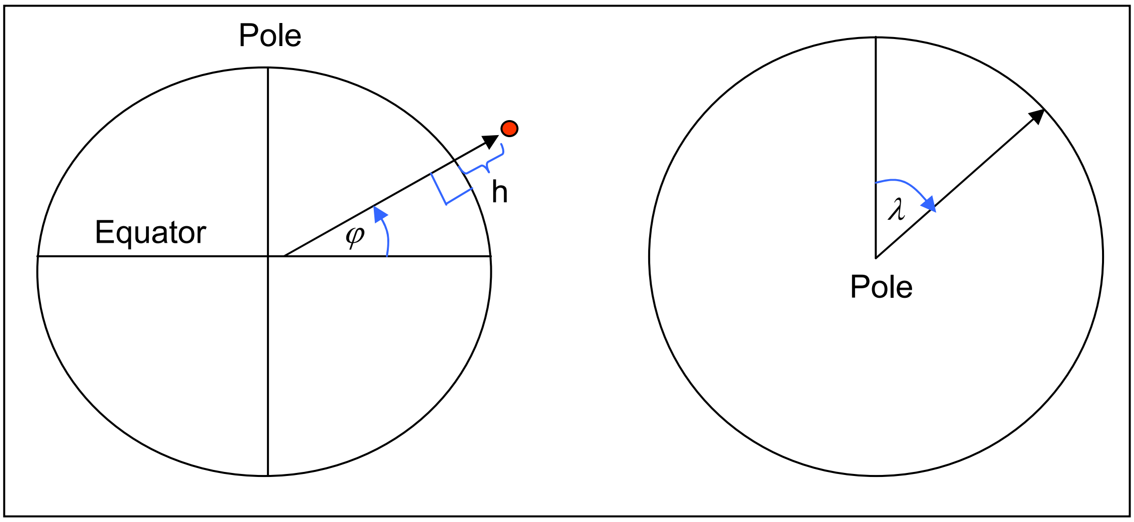

Figure 3- 3: Ellipsoidal Coordinate System

b. Geocentric Cartesian Coordinates. Geocentric Cartesian coordinates have their origin at the centre of a selected ellipsoid which is aligned with the centre of mass of the earth. It is three dimensional with the axes denoted as x, y and z. Units of measurement are normally metres but for space applications kilometres can be used. The z-axis is aligned with the polar axis of the ellipsoid, while the x-axis is in the equatorial plane and points to the prime meridian. The y-axis completes a right handed coordinate system. Cartesian coordinates can be converted to ellipsoidal coordinates and *vica versa*. (Iliffe & Lott, 2008: 8 – 15, Hofmann-Wellenhof *et al.*, 2001: 279 - 282).

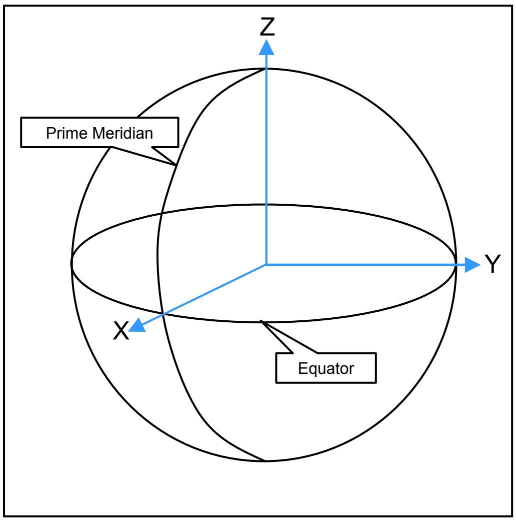

Figure 3- 4: Geocentric Cartesian Coordinate System

c. Earth-Centred Inertial (ECI) Coordinate System. The Cartesian coordinate system is also used to provide coordinates of celestial bodies which are referred to as its *ephemeris*. To determine the ephemeris of celestial objects relative to an imaginary celestial sphere an ECI coordinate system is used. The origin of this system is the centre of mass of the earth or geo-centre. The xy-plane of the ECI coordinate system coincides with the earth's equatorial plane, with the x-axis permanently fixed in the direction of the vernal equinox. The z-axis is orthogonal to the xy-plane, and coincides with the earth's rotational vector in the direction of the North Pole. The +y-axis forms the right-handed coordinate system. However, various forces, including gravitational forces of the sun and moon cause irregularities in the earth's movement relative towards the celestial sphere. This movement, also known as precession and notation, causes the ECI coordinate system to be near-inertial. To overcome this, the axis is defined at a particular moment in time or *epoch*. Such an epoch was defined on 1 January 2000 at 12:00 Coordinated Universal Time (UTC) denoted as J2000 according to the Julian calendar. It should be noted that the fixing of the ECI coordinate system is based on celestial observations of over 500 quasars and galactic nuclei. Although these celestial radio sources move through space at different velocities, the distances to these bodies are so large that they can be considered as fixed points in space. The ECI coordinate system is used to determine GPS satellite positions and orbits (Hofmann-Wellenhof *et al.*, 2001: 25 – 28; Leick, 2004: 11 – 28; Kaplan & Hegarty, 2006: 27 – 28).

d. Earth-Centred Earth-Fixed (ECEF) Coordinate System. To determine positions on earth, it is more appropriate to use a coordinate system that rotates with the earth, known as an earth-centred earth-fixed (ECEF) system. It is similar to the geocentric Cartesian coordinate system described above and is also referred to as the Conventional Terrestrial Reference System. GPS receivers compute coordinates in the ECEF coordinate system and converts positions to ellipsoidal coordinates. (Leick, 2004: 19; Kaplan & Hegarty, 2006: 28).

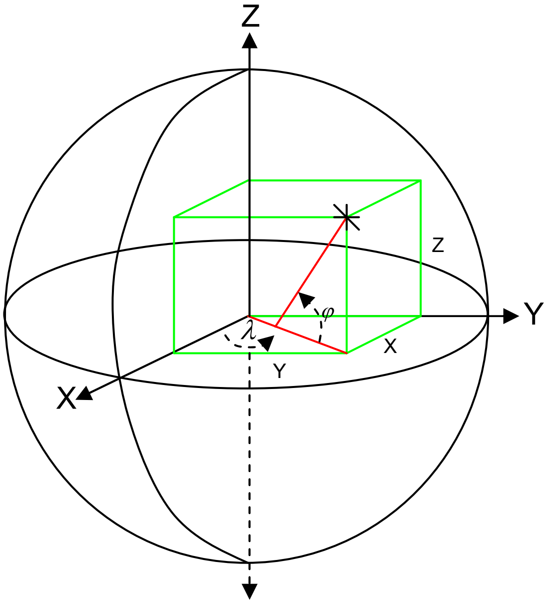

Figure 3-5: ECEF Reference System

e. Plane Coordinates. Two-dimensional Cartesian coordinates are used for plane coordinates. Mathematical transformations are developed for mapping ellipsoidal coordinates to plane coordinates. This cannot be accomplished without distortions and will be discussed further under Map Projections.

Suffice to indicate that there are a number of plane coordinate systems that denote axes such as X and Y, y and x or eastings (E) and northings (N). Measurement value is in metre such as in the UTM projection (Iliffe & Lott, 2008: 16, Merry, 2006: 9 – 11).

5. WGS 84. The coordinate system of the WGS84 ellipsoid is the same as the ECEF system. That is, the origin is the geocentre, the z-axis coincides with the mean rotation axis of the earth and the x-axis points to the Greenwich meridian. A GPS receiver by default computes coordinates referenced to the WGS84 ellipsoid. However, the shape of the earth is not static and is changing due to various forces imparted by changes in the rotation rate and orientation of the earth around its own axis, gravitational forces (mainly the sun and moon) and plate tectonic movement. The flattening of the earth is also affected by global mass movement which changes the oblateness of the earth. These factors cause small positional deviations that are monitored by reference stations of the IGS around the globe and need to be included during data processing. Final global positions are published in the International Terrestrial Reference Frame (ITRF) that can be accessed at www.itrf.ensg.ing.fr. The ITRF is realised through the different space geodetic techniques (VLBI, SLR, GNSS, Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS)), with the large number of globally distributed GNSS stations providing densification. The Hartebeesthoek Radio Astronomy Observatory's 26 m VLBI antenna at Hartebeesthoek west of Pretoria serves as such a reference point. The third and most current version of WGS84 that is used as a GPS reference frame is WGS84 (G1150) and is based on ITRF2000 coordinates[2]. Figure 3-4 indicates the WGS84 reference stations. It should be mentioned that the mean difference between the current and previous version of WGS84 is 5 cm globally (Bolstad, 2006: 70 – 82; Merry, 2006: 5 – 15, Wells, 1987: 3.0 – 3.14).

---

[2] More detail about WGS84 (G1150) can be accessed at www1.nga.mil and www.nga.noaa.gov

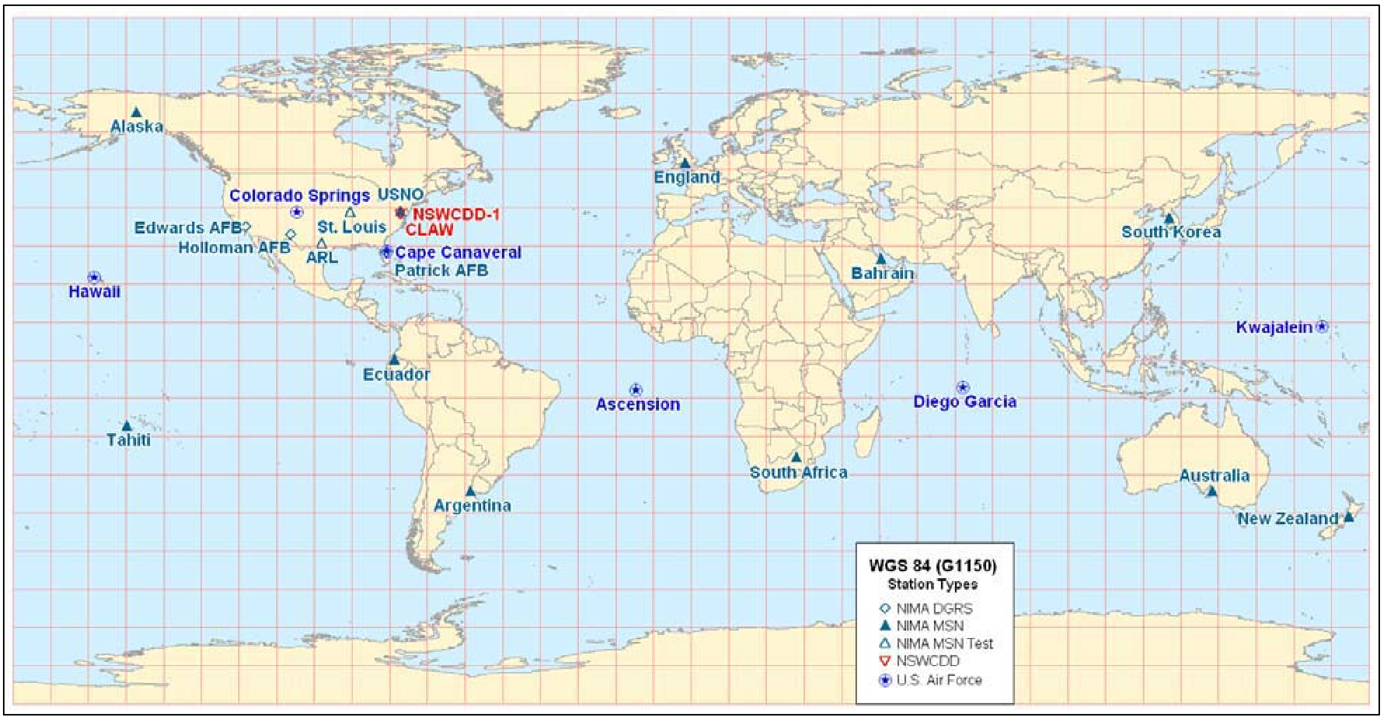

Figure 3-6: WGS84 Reference Stations[3]

6. Horizontal Datum. WGS84 (G1150) is a best-fit ellipsoid globally. However, because of variations in the shape of the earth, local ellipsoids are used that have a better fit to the shape of the earth for that geographical location. A number of countries are using these best-fit ellipsoids. Determining a horizontal datum involves selecting an ellipsoid that fits the geoid the best for that location and determining the initial point where the ellipsoid coincides with the geoid. The rotational axis of the ellipsoid is aligned with the rotational axis of the earth. Selecting a local best-fit ellipsoid implies that the centre of the ellipsoid does not necessarily coincides with the centre of mass of the earth. The demarcation of the initial point to define the horizontal datum for that country is depicted in Figure 3-5 by means of the blue and red circles respectively.

---

[3] Source: www1.nga.mil, accessed October 2010

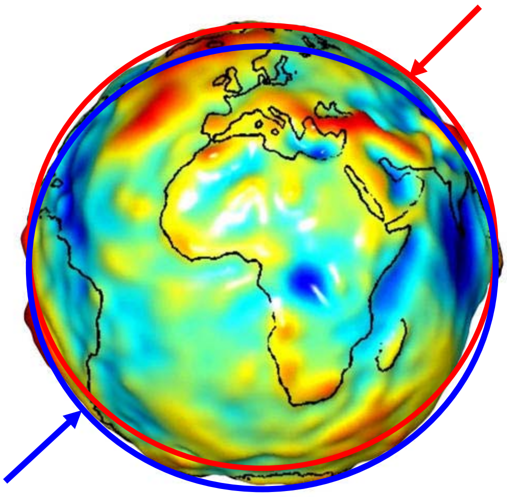

Figure 3-7: Selection of the best Ellipsoid[4]

In South Africa the Cape Datum was initially used and was based on the Clark 1880 ellipsoid. The values for the Clark 1880 ellipsoid are:

a: 6 378 294.1454 m
b: 6 356 514.9667 m
f: 1/293.5

The initial point is demarcated as the Trig Beacon at Buffelsfontein just west of Port Elizabeth. This is significant because some older maps in use in the RSA are still based on the Cape Datum. However, on 1 January 1999 South Africa started to use the Hartebeesthoek Datum 1994 (HART94). This datum was based on ITRF91 (epoch 1994.0) and WGS84 was used as the reference ellipsoid. The coordinates of the initial point were based on VLBI measurements at the radio astronomy telescope (antenna) at Hartebeesthoek. The coordinates of the initial point (intersection of the perpendicular projection of the declination axis onto the polar axis of the 26 m radio telescope) of HART94 were extrapolated to the existing network of passive Trigonometric Beacons, commonly referred to as Trig Beacons. This constituted a datum shift that caused the plane coordinates of these Trig Beacons to change by approximately 300 metres. These values of the Trig Beacons are fixed and will most probably remain unchanged for purposes of consistency. Plate tectonic motion will cause all GPS measurements based on WGS84 to vary slightly from these values. Coordinates published by CDNGI of its active TrigNet stations were converted to UTM values. (The TrigNet will be discussed in Chapter 4,

---

[4] Source: www.csr.utexas.edu/grace, accessed during September 2010.

Measurement Augmentation.) The difference in metres between coordinate values of some of these stations in the HART94 and ITRF 2005 (epoch 2008_01_09) are as follows:

Table 3-1: Differences of TrigNet Stations' coordinates between HART94 and ITRF 2005[5]

TrigNet Station	∆E (m)	∆N (m)
Springbok	0.234	0.298
Beaufort Wes	0.122	0.427
Cape Town	0.224	0.424
Sutherland	0.142	0.415
Aliwal North	0.054	0.397
De Aar	0.123	0.385
Grahamstown	0.061	0.495
Port Elizabeth	0.103	0.548
Pretoria	0.207	0.355
Durban	0.219	0.367
Thohoyandou	0.120	0.421

Plate tectonic movement measured at the HRAO station generally correlates with the values of Table 3-1. See Figure 3-6 for detail of the HRAO station velocities. Movement in both the latitude and longitude is positive which causes movement in a north-easterly direction of approximately 2 cm per annum.

---

[5] Source: www.Trignet.co.za accessed during November 2010.

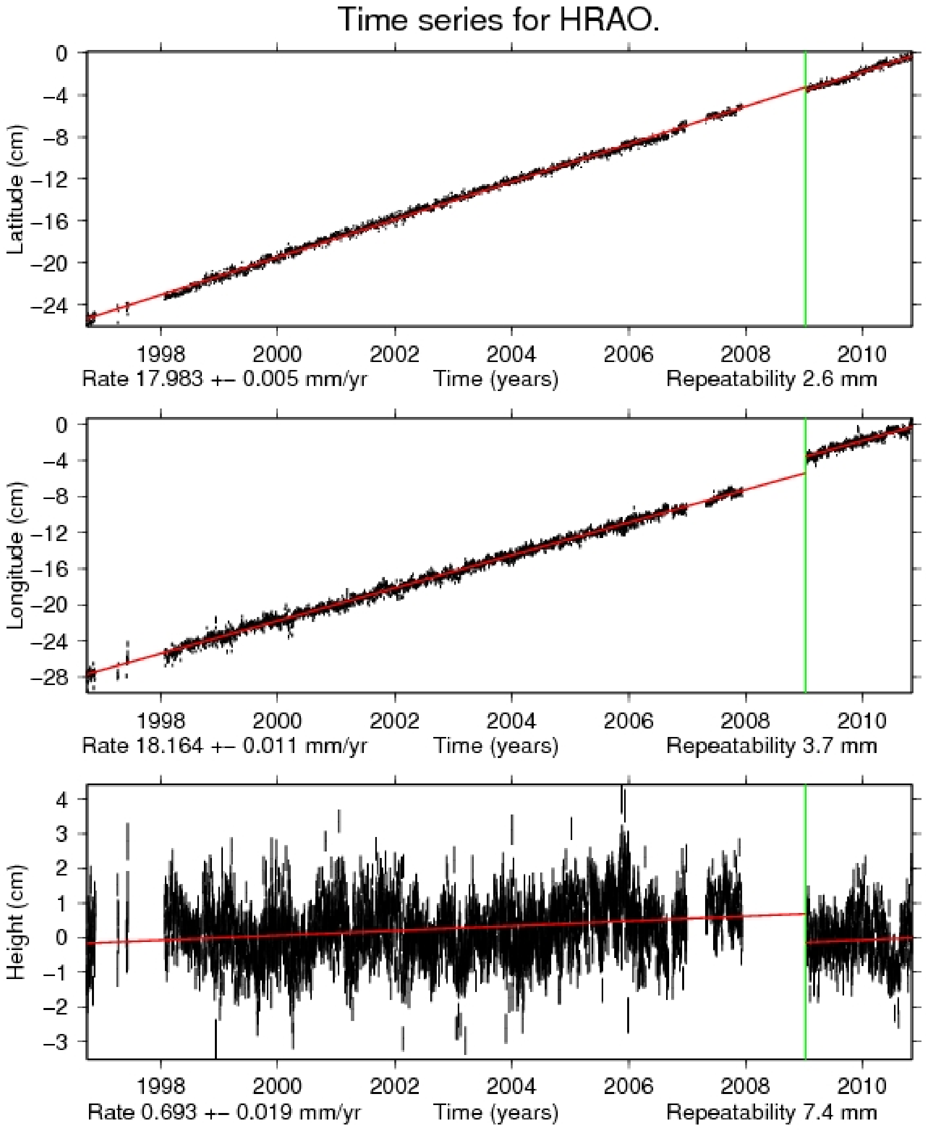

Figure 3-8: HRAO Velocities: 1996 to 2010[6]

These differences are insignificantly small and it should have no impact on navigation or mapping projects in the SANDF. (Bolstad, 2006: 82; Merry, 2006: 14 – 17)

7. Other Regional Horizontal Datums. Botswana, Lesotho and Swaziland use the original Cape Datum based on the Clark 1880 ellipsoid and is included in the network of observations that constitutes the Cape Datum. Zimbabwe uses an adjusted Cape Datum, while Namibia's datum is based on the Bessel ellipsoid with the initial point at Schwarzek,

---

[6] Source: http://sideshow.jpl.nasa.gov/mbh/series.html accessed in January 2011

east of Windhoek. Mozambique uses the Clark 1866 ellipsoid and used three different initial points that constitute three different datums. The datum of Angola is also based on the Clark 1866 ellipsoid. The Arc Datum which is used in some parts of Southern- and East Africa is based on the Clark 1880 ellipsoid. It consists of a single chain of triangulations along the 30th meridian starting from Buffelsfontein stretching up to the Uganda-Sudan border. It differs from the Cape Datum as it consists of a single chain of observations, while the Cape Datum is a network of observations. Coordinates of the Arc Datum were calculated twice, in 1950 and in 1960 resulting in two versions, Arc 1950 and Arc 1960. Some Southern African countries may have started to use the WGS 84 ellipsoid. See Appendix B for a NGA list of datums used in Africa. Datums used in the region are highlighted in yellow. Observe that South Africa is indicated as using the Cape Datum. Thus, there may be more errors on the list (Merry, 2006: 16 - 17).

8. Vertical Datums. Whereas the horizontal datum is used to define the latitude and longitude coordinates of a network of reference points, the heights of these points are defined differently. Traditionally heights are defined above mean sea level (MSL) and are established by measurements with tidal meters. However, until recently it was not possible to determine this type of height for all places on earth with a reasonable level of accuracy. Gravitational forces of the earth cause mean sea levels to vary over the surface of the earth. The average ocean surface level at Iceland is more than 150 m higher than the average ocean surface at north eastern Jamaica. As indicated in paragraph 2, the geoid is a close representation of mean sea level and can be used for height measurements. Test measurements in some places in South Africa rendered accuracies of 15 cm for EGM2008. Accuracies elsewhere on the African continent are unknown. A limitation of the model is that although satellite technology was used to determine the equipotential surface or geoid, the model is dependent on measurements on the earth's surface to improve and confirm its accuracy. Gravitational measurements on the African continent is lacking for large areas. However, using any other vertical references, such as a locally derived MSL, values may provide more problems than solutions. Challenges are the absence of tide gauges, errors in tide measurements and the systematic rise of MSL. Heights along the South Africa - Zimbabwe border differ with 2.5 m because heights in Zimbabwe were determined from MSL at Beira. Currently, CDNGI is confirming the vertical coordinates of Trig Beacons that has resulted in a project to augment EGM2008 with GPS measurements that provide a South African Geoid Model 2010[7]. With extensive validation it was found that this model can

---

[7] More detail as well as the geoid model can be downloaded from www.trignet.co.za at Raw Data Download, Station Information, SA Geoid.

render vertical accuracies of 7 cm. According to Merry (2003) a similar process was followed in the UK, USA and Australia and will have to be developed for mapping projects on the African continent (Bolstad, 2006: 72 – 75; Merry, 2003: 12 – 14; Merry, 2008: 23, Chandler and Merry 2010: 29 - 33; Iliffe & Lott, 2008: 30 – 35; personal communication R Wonnacott of CDNGI during the first quarter of 2009).

9. <u>Ellipsoidal, Geoidal and Orthometric Heights</u>. From the previous discussions one can deduce that a number of height measurements are possible from these reference surfaces as indicated in Figure 3-7. The first is the ellipsoidal height (h) which defines the height above the ellipsoid. A GPS receiver, by default, measures heights above the ellipsoid (WGS84). Geoidal height (N) is the difference between the ellipsoid and the geoid or the *geoidal undulation* and varies globally between + 85 m and -150 m. However, the height that is generally used in mapping projects is orthometric height (H) or height above MSL. This height is to a large extent similar to the height above the geoid. Advanced GPS software can convert ellipsoidal height measurements to orthometric or MSL measurements using Earth Gravitational Model 2008 (EGM 2008) (Bolstad, 2006: 73; Iliffe & Lot, 2008: 32; Kaplan & Hegarty, 2006: 32 – 34; Merry, 2006: 13).

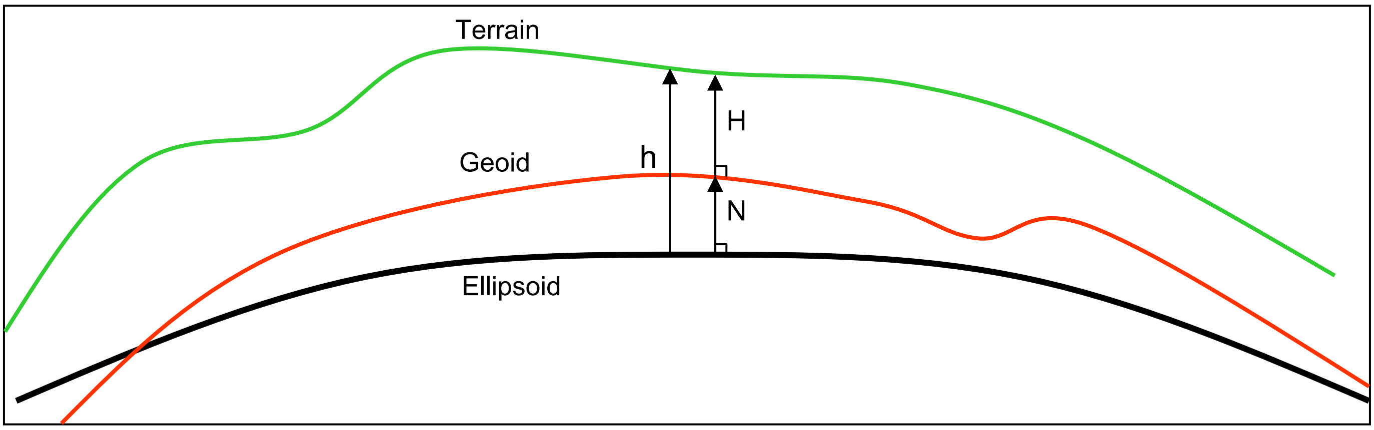

Figure 3-9: Orthometric Height (H) = h - N

10. <u>African Geodetic Reference Frame (AFREF)</u>. This reference frame is an initiative of some African countries and the international community to establish a common geodetic reference frame for Africa. This reference frame will be realised by a network of Continuously Operating GPS Reference Stations (CORS) operated by national mapping agencies and other institutions within the framework of the IGS. The solution will be linked to a particular epoch of the ITRF. The objective is to establish a network of reference points that can replace old datums and serve as a continental horizontal and vertical datum. It is planned that CORS stations will not be further than 1 000 km apart and will provide a trans-border reference. This network of reference stations can then be densified to serve specific national requirements. Progress with this initiative is limited and lacks regional and

continental cooperation. Several IGS reference stations on or close to the African continent can serve as a starting point for such a reference frame. It can also serve as reference stations for GPS measurements for mapping projects which will be discussed in Chapter 5 as part of GPS in the Field – Increasing Baselines. The 1 000 km buffers indicate a possible coverage of these IGS base stations on the Continent. See Figure 3-8 for IGS stations that may serve as reference points on the African continent (Merry, 2003; Wonnacott, 2005; Wonnacott, 2008).

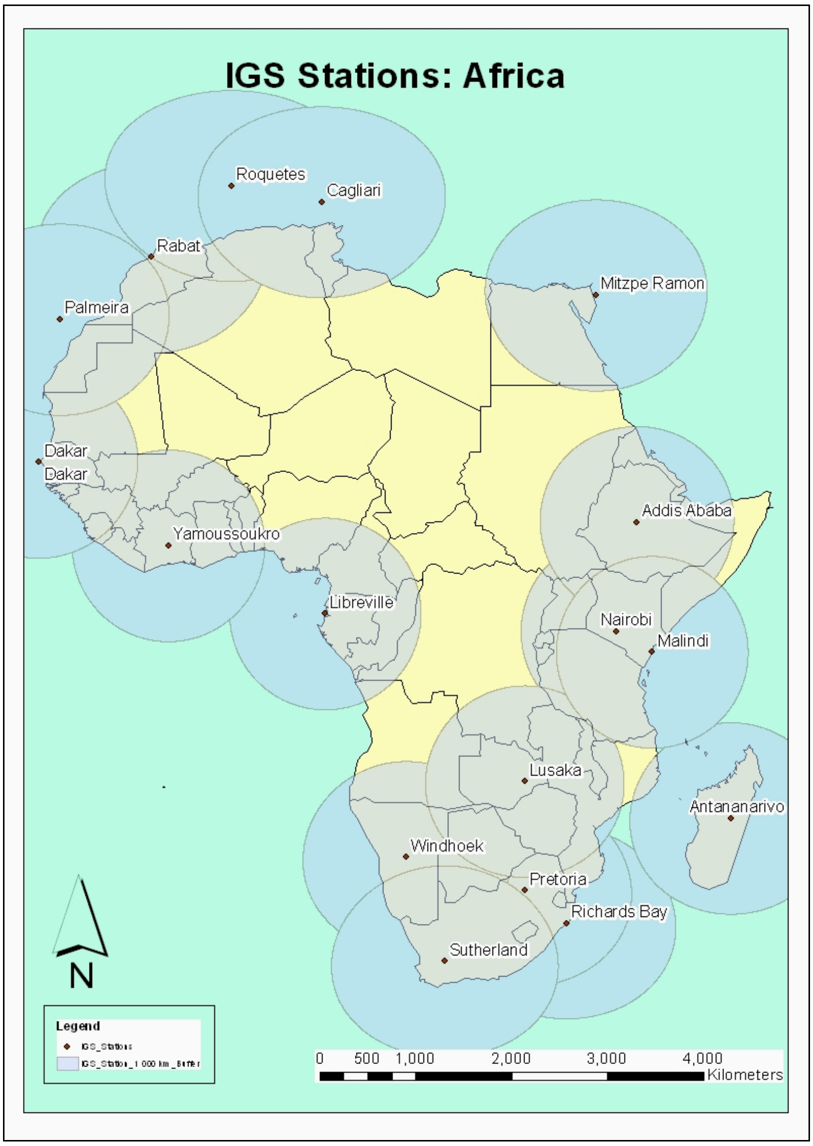

Figure 3-10: IGS Reference Stations - Africa[8]

11. Map Projections. Horizontal datums define the geographical coordinates of reference points (Trig Beacons) on the ellipsoid. However, these points and all other points referring to

---

[8] Stations extracted from the IGS website at http://igscb.jpl.nasa.gov accessed November 2010 and augmented with Lusaka and Malindi in July 2011.

them need to be represented on a flat surface such as a map to be useful for positional data in for example a command and control system. Map projections are the systematic rendering of positions from the curved surface of the ellipsoid to a flat surface. This cannot be accomplished without distortions in shape, area, distance or direction. Projections are classified in terms of the particular properties they were designed to preserve and no projection can solve more than two distortions. Projections are based on a developable surface like a cylinder, cone or plane with a projection centre defined as orthographic (at infinity), stereographic (at the antipode) or gnomonic (at ellipsoid centre). Map projections can also be a mathematical method to project points from the ellipsoid onto a flat surface (Bolstad, 2006: 88 – 94; Iliffe & Lot, 2008: 42 - 44).

12. Military Map Projections. In the military, conformal projections, such as the Mercator projection, are used. The Mercator projection is a cylindrical projection where the cylinder is tangent along the Equator. Along the Equator there will be no distortion. Each parallel is as long as the Equator and distortion is therefore towards the poles. In the Transverse Mercator projection the cylinder is rotated 90° and tangent with a chosen meridian, called the central meridian. Along the central meridian distances will be true and distances within 3° from the central meridian will be fairly accurate. Thus, by selecting a new central meridian for projection at every 6° and merging these projections, a fairly accurate global projection can be created, also referred to as the Universal Transverse Mercator Projection (UTM), which is used in the SANDF. A scale factor of 0.9996 is applied across the projection zone. The projection zones are limited to between 84° north and 80° south. The projection zones of the UTM are numbered from 1 to 60 in an easterly direction with zone one starting at the 180° West (International Datum Line). Thus, the central meridian for Zone 1 is 177° west and for Zone 2 it is 171° west and so on. South Africa lies between zones 33 and 36. Where operations are conducted within the borders of South Africa the maps of CDNGI are used. These maps are based on the Gauss Conform projection that is a variant of the Transverse Mercator projection that uses 2° zones centred on an uneven longitude starting at the 0° meridian, for example 19°, 21°, 23°, etc. Both the orientation and the labels of the axes are reversed to render a positive y value directed west and a positive x value is directed south. The Mercator projection is used for maritime charts, while the Polar Stereographic projection is used for the areas north of 84° north and south of 80° south (CDSM, 2010; Iliffe & Lot, 2008: 40 – 62; USDMA Technical Manual, 1996: 2-5 – 2-14).

13. Universal Transverse Mercator Grid System (UTM). The UTM was developed by the NGA for the military as a universal metre coordinate system. In the UTM the globe is divided in 60 zones, each 6° wide and is limited to an area between 84° North and 80° South that

correlates with the Transverse Mercator projection. Numbering of the zones starts at 180º and proceed eastwards. Each zone has a central meridian. Thus, Zone 1 central meridian is at 177º west, Zone 2 central meridian is at 171º west, and so on. The UTM is based on 120 Transverse Mercator projections; two for each UTM zone, one for the northern and one for the southern hemisphere. The x-value is called Easting and the central meridian of each zone has a value of 500 000 m. The y-value is called Northing and the equator has a value of 0 m for the northern hemisphere and 10 000 000 m for the southern hemisphere to avoid negative northings. The coordinates of the flagpole in front of the Union Buildings is 28º 12' 42.4'' E, 25º 44' 27.9" S in degrees, minutes and seconds. The UTM reference for this flagpole reads 35 J 0621542, 7152431. See Figure 3-10 for the UTM zones of Africa (Bolstad, 2006: 97 – 99; Iliffe & Lott, 2008: 55 – 61; USDMA Technical Manual, 1996: 2-14 – 2-19).

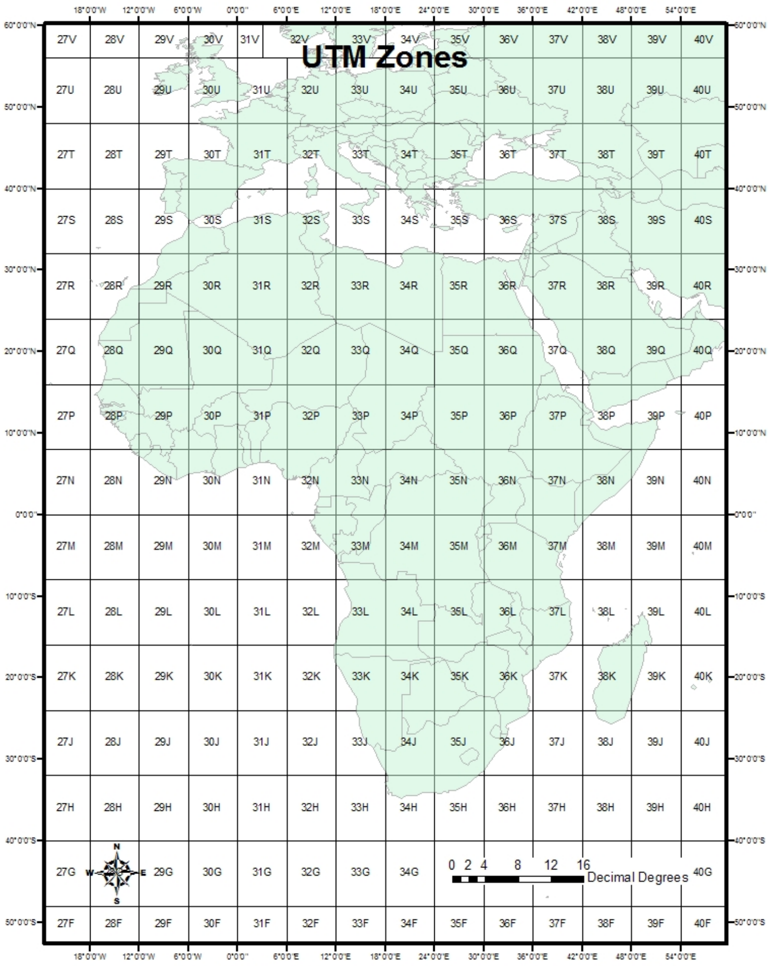

Figure 3-11: UTM Zones of Africa

14. Military Grid Reference System (MGRS). The MGRS is an alphanumeric version of a numeric UTM grid coordinate system. The globe is divided in 6º by 8º geographic areas

called a grid zone with a unique alphanumeric identifier. Grid zones are subdivided into 100 km squares with each having a letter identifier. See Figure 3-11 for a presentation of the MGRS Block of South Africa. To provide positional data the full MGRS reference need not be used and can be adjusted according to accuracy requirements. The first part provides the easting component and the second part provides the northing component of the position. The MGRS values for the same flagpole are:

35J PM in a 100 km square
35J PM 25 in a 10 km square
35J PM 2152 in a 1 km square
35J PM 215524 in a 100 m square
35 J PM 21545243 in a 10 m square
35 J PM 2154252431 in a 1 m square

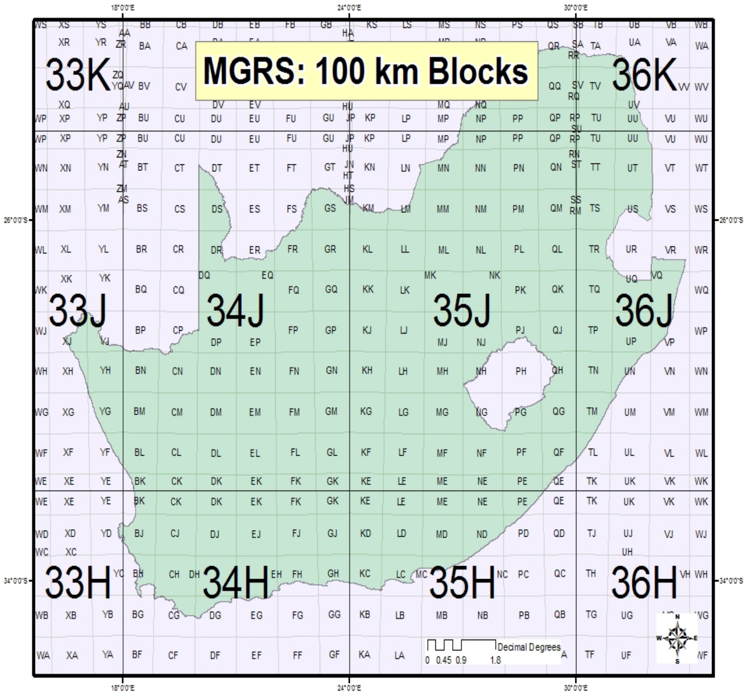

Figure 3-12: MGRS Blocks - South Africa

Both GPS receiver and Geographical Information System (GIS) packages can be used to convert coordinates from degrees, minutes and seconds to UTM and MGRS values and the other way around. Thus, the GPS receiver can be set to take coordinate measurements in any of these formats[9] (Bolstad, 2006: 97 – 98, USDMA, 1996: 3-1 – 3-5).

15. Concluding Remarks. With these few introductory remarks about reference systems it is proposed that the SANDF standardise on using WGS84 (G1150) ellipsoid and that it should also serve as the horizontal datum for positional data, including mapping projects on the African continent. IGS reference stations can serve as reference points to assist in the implementation of this approach. For operations on South African soil, map data from CDNGI referenced to the HART94 datum will be used. The difference between the two is small and should not pose any risk to operations. However, using older maps based on the Cape Datum could have a shift of coordinate values of 300 m. It is further proposed that in the absence of any tangible vertical datum for orthometric heights, EGM 2008 (or as updated) is used and that these values are used for reporting heights in mapping projects on the continent. The use of different coordinate systems such as decimal degrees, degrees-minutes-seconds, UTM or MGRS should not be a problem. It only poses a challenge when they are mixed in an operation where for instance the Air Force uses latitudes and longitudes, while the Army is using MGRS. However, in close air support operations this is addressed sufficiently in working procedures. The same approach as with horizontal data should be applied in reporting heights. Normally heights are reported in metres above MSL in mapping projects. However, the Air Force uses height measurements in feet. The user of a GPS receiver in operations should therefore understand how to select the correct datum (WGS84), the correct coordinate system applicable for the operation and the correct measurement values, i.e. metres or feet. Officers in command of operations should ensure that the use of the correct datum and measurement values are spelled out clearly in operational orders.

POSITIONAL ACCURACY STANDARDS

16. Introduction. Paper maps and charts or digital map-data displays are used for positional data in the SANDF. Navigating on foot or in vehicles in open terrain during daytime may require positional accuracies in the range of 10 m to 50 m or even worse. However, navigation during night-time in closed terrain may change this considerably, especially if navigation should take place through minefields via cleared lanes, which will require higher accuracies. Flying an aircraft at 35 000 ft from airport to airport will require relative low accuracies, while landing that aircraft in low visibility conditions may require positional data with a much higher accuracy. Similarly, navigation at sea may require 50 m

---

[9] UTM zones and the MGRS blocks can be downloaded in shape file format from http://earth_info.nga.mil.

to 500 m horizontal positional accuracies depending on the application. Different products and applications require different positional data accuracies.

17. Accuracy, Precision and Error Theory. The terms accuracy and precision are often used interchangeably. However, there is an important difference between them. Precision is the closeness of values obtained from replicate measurements. Accuracy is the closeness of the average estimated value obtained compared to the true value. In mapping and GIS projects one would strive to have high accuracy with a high level of precision as demonstrated in Figure 3-12.

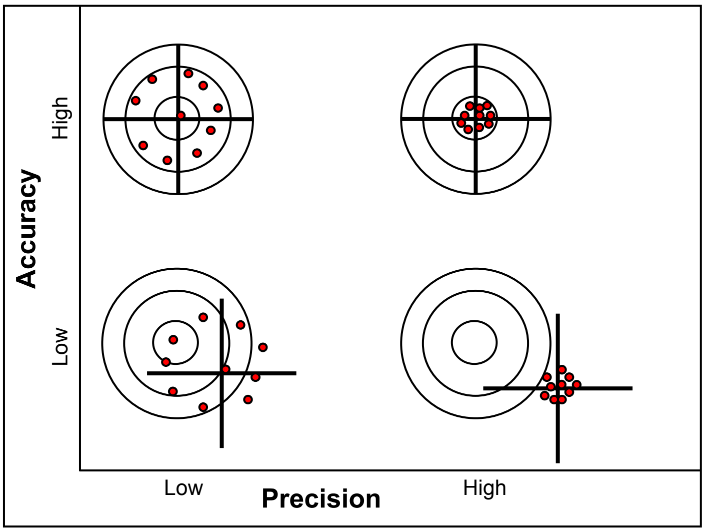

Figure 3-13: Accuracy and Precision

Notwithstanding the precision of the measuring receiver or method, the true value is an unattainable goal. Understanding measuring errors will assist in determining a level of certainty about the true value. Errors can be categorised in three classes; systematic, random and blunders.

a. Blunders or Outliers. Blunders are incorrect measurements, such as changing the x and y coordinates around, reading the coordinate values incorrectly or receiver failures. Outliers differ considerably from the parent population and are easily detected. Automated data transfer processes between receivers and processing packages strive to minimise blunders. However, they do occur from time to time and need to be explained and eradicated. Blunders can be detected by averaging measurements and any measurement larger than a pre-selected standard deviation from the mean is rejected as not a valid part of the population – e.g. selecting three standard deviations would result in the so called three sigma test.

b. Systematic Errors. Systematic errors are caused by small receiver deviations or human limitations and are hard to detect with repeated observations. They are constant and have the same sign causing a constant bias. Often receivers that are not calibrated cause systematic errors. Hardware and firmware problems in GPS receivers may cause systematic errors. These errors can be detected by using different receivers with the same or better precision characteristics to verify measurements. If the error is known one can apply mathematical models to compensate for it.

c. Random Errors. Random errors are accidental or unknown influences on the measurement that are beyond the control of the observer. They are characterised by positive and negative errors occurring with equal frequency and are normally small. Random errors are those errors that remain after blunders and systematic errors are removed and are the cause that no true value can be measured. However, they tend to display a normal frequency distribution that enables the observer to predict that the random error will probably not exceed a certain magnitude. Thus, it is possible to express a measured value at a certain probable accuracy value and confidence level (Allan, 2007: 59 – 76; USDMA, 1991: 1 - 7).

18. Accuracy and Scale. Accuracy should be placed in perspective when map data are used. It should be remembered that one millimetre on a 250 k scale map or chart represents 250 m in reality. Producing and updating paper or digital maps and charts therefore require a certain level of accuracy that needs to be adhered to in order to make them useful for decision-making. Traditionally the Army has used the 50 k scale map as the tactical operations map. The same map scale is used for close air support. In peace support operations the Army is increasingly involved in urban operations that may require 10 k or 20 k scale maps. The 250 k scale maps are used for operational planning and control in the Army, while it is also used for air support. The Air Force also use 500 k and 1 000 k scale charts for navigation. The Navy uses 8 k to 15 k as harbour charts, while 20 k to 50 k is used as approach charts and 150 k to 300 k is used for coastal and general navigation.

19. Accuracy Standards. The SANDF has no official positional accuracy standard. In light of the large variations in positional accuracy requirements discussed above and the absence of an official policy, it was accepted by Directorate Geospatial Information that international standards should be followed in this regard. The following are proposed:

a. Topographic Maps and GIS Data. The Multinational Geospatial Co-production Program (MGCP) which is an international military mapping initiative proposes a 25 m circular error probability (CEP) at a 90% confidence level as an accuracy standard for global mapping at 50 k and 100 k scales[10]. Twenty-eight defence forces worldwide are represented in the MGCP, which includes some of the most significant role-players in the field. It was therefore accepted that this proposed positional accuracy standard should be adopted by the SANDF. This also creates a level of interoperability when operations are conducted in cooperation with foreign defence forces, as in peace support operations. For larger scale maps, such as the 10 k and 20 k urban maps a higher accuracy level will be required. The NGA prescribe a 12.5 m CEP at 90% confidence level in their Urban Vector Map standard ((UVM) not available to the public). These accuracy standards generally concur with the International Standards Organisations' positional accuracy standard (ISO Standard 15046-13) and the Geospatial Accuracy Standards of the Federal Geographic Data Committee of the United States (FGDC, 1998).

b. Aeronautical Maps and Charts. The requirements of the International Civil Aviation Organisation (ICAO) standards should be followed, as is applied to aerodrome charts that require a horizontal accuracy of 2.5 m. See Appendix C for more detail on this accuracy standard.

c. Hydrographical Charts. The SA Navy's Hydrographical Office has to adhere to the prescripts of the International Hydrographical Office (IHO) according to international law. See Appendix C for more detail on this accuracy standard.

20. GPS as Navigational Aid. To attain these proposed accuracy standards accurate source data are required. Currently the majority of landward mapping projects make use of imagery as source data. Imagery needs to be orthorectified to render accurate positional data and in most cases ground control is required for this process. Ground control is currently obtained by means of GPS measurements. The Navy's Hydrographical Office uses depth soundings and other surveying techniques including GPS, to acquire source data for navigational charts. Although maps and charts are still being used as primary sources for positional data, GPS is gaining ground in a number of applications in the SANDF. The Army

---

[10] The MGCP is a purely international military initiative and the standards are not available to the public.

plans to use GPS as a navigational tool for the infantry soldier. In the Air Force and the Navy GPS is integrated with other onboard navigational instruments such as gyroscopes and accelerators, to render an integrated positional solution via a Kalman filter. The continued improvement of the accuracy and reliability of GPS makes it an attractive solution as a primary source for positional data (Collinson, 2003: 314 – 322, Discussions with system owners/users and specialists in the SANDF during April 2009).

21. Concluding Remarks. Without any official policy statement in the SANDF on positional accuracy, it should be concluded that international military standards used by the Multinational Geospatial Co-production Programme and the NGA should be used for general topographic mapping projects on the African continent. It should be augmented in the aeronautical and nautical environments by standards from the International Civil Aviation Organisation and the International Hydrographical Office as applicable. Most GPS receivers provide higher positional accuracies than can be presented on a map or chart. However, care should be taken to understand the accuracy capabilities of a specific receiver used in the field. This will be discussed in more detail.

CHAPTER 4: GPS FUNDAMENTALS

INTRODUCTION

1. In 1973 the Joint Programme Office of the Space and Missile Centre was commissioned by the United States Department of Defence to establish an all-weather space-based positioning system. The present Navigation System with Timing and Ranging (NAVSTAR) Global Positioning System (GPS) is a result of this instruction. GPS is therefore a navigation system designed and built for military use. However, over time the civilian applications of GPS exceeded the military applications in the number of users by far. The design and operations of the GPS consist of three main components, namely the space segment, control segment and the user segment. Currently the GPS Wing of the United States Air Force is managing and operating the space and control segments of the GPS. The GPS signal and time play significant roles in positioning and will be discussed separately. Aspects that influence the accuracy of GPS measurements will receive special attention, including selective denial or jamming. The planned modernisation of GPS will be mentioned with possible implications for the SANDF.

OPERATIONAL ASPECTS

2. Space Segment

a. At least twenty-four NAVSTAR satellites orbit the earth in six earth-centred orbital planes with four satellites in each plane. The orbits are nearly circular at a 55° inclination relative to the equatorial plane. Satellites are evenly spaced in the orbital plane. The orbital radius is approximately 26 600 km from the earth's centre. Satellites travel at an approximate speed of 3.9 km/s and orbit the earth every 12 h sidereal time, which correlates with 11 h and 58 min solar time and causes satellites to appear four minutes earlier every day. This placement of satellites ensures that there are at least six satellites above the horizon at any moment and at any place on earth (Hofmann-Wellenhof *et al.*, 2001: 14 – 13; Leick, 2004: 72 – 73; Kaplan & Hegarty, 2006: 69).

b. There are different ways GPS satellites can be identified. One way is to identify each orbit with a letter A, B, C, etc. and each satellite in the orbit with a number 1, 2, 3 and 4. A satellite can then be referred to as D2. Another system is to refer to a satellite's space vehicle number (SVN) assigned by the NAVSTAR programme. A third way is to use the pseudorandom noise (PRN) code of the satellite that is used by the GPS receiver to identify the satellites (Hofmann-Wellenhof *et al.*, 2001: 14 – 13; Kaplan & Hegarty, 2006: 70 – 71).

c. There are six classes of GPS satellites. The Block I satellites were launched between 1978 and 1985 with a design lifespan of four to five years. The last Block I satellite was decommissioned in 1995. Block I satellites were launched at a 63º inclination and the signal from these satellites were fully available to civilian users. The first Block II satellites were launched in 1989 at the current 55º inclination and the signal could be manipulated in what is known as selective availability. The life expectancy of Block II satellites is 7.5 years. Individual satellites lasted more than 10 years. Block IIA satellites were launched in 1990 and are equipped with corner cube reflectors that enable laser range tracking. Block IIR satellites are replenishment satellites and Block IIF satellites are follow-on satellites with a design lifespan of 15 years, while Block III satellites are planned for 2010 and beyond (Hofmann-Wellenhof *et al.*, 2001: 14 – 18; Kaplan & Hegarty, 2006: 71 – 87).

d. The navigation payload of the satellites is responsible for generating and transmitting the ranging and navigation signals. Control of the navigation payload is received from the ground control stations via the tracking, telemetry and control (TT&C) links. Two rubidium and two cesium atomic clocks also known as atomic frequency standards, are on board to ensure reliability with only one operating at any time. These atomic clocks are generating extremely stable frequencies that are converted by a frequency synthesizer into the basic frequency (f_0) of 10.23 MHz. This frequency serves as the timing reference within the payload for the ranging signal. The ranging signals are sent to the L-band subsystem where they are modulated on the carrier frequencies (L1 and L2) and amplified for transmission. The navigation data unit contains the ranging code generators that generate the C/A-code, the P-code and the navigation message. In future it will also generate the new envisaged signals for GPS modernisation. The navigation data unit also stores the navigation message data uploaded from the ground control stations and ensures that a current navigation message is transmitted to ground receivers. See Figure 4-1 for a basic schematic layout of a GPS satellite (Kaplan & Hegarty, 2006: 73).

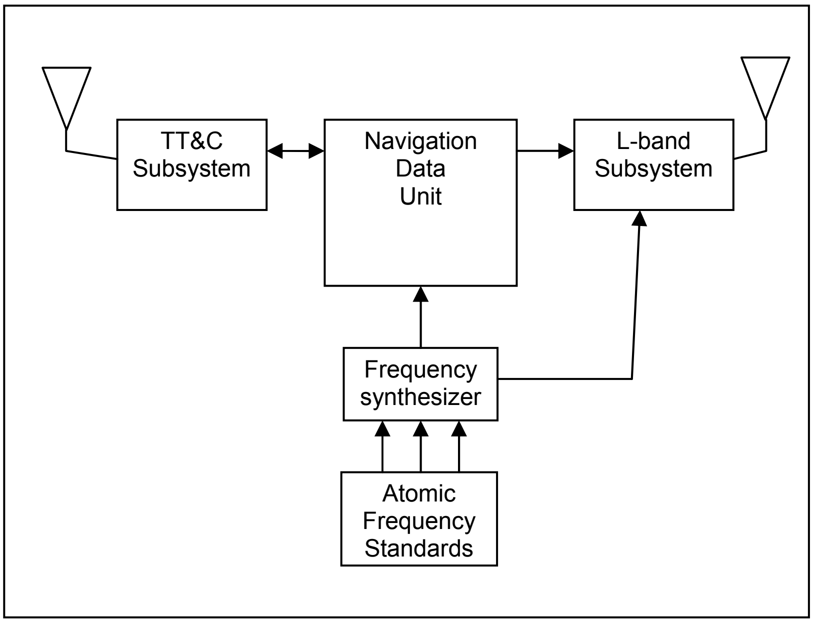

Figure 4-1: Generic Layout of a GPS Satellite's Subsystems

3. Control Segment. The control segment consists of a master control station, ground control stations and monitor stations. The master control station is located at Schriever Air Force Base, Colorado Springs, Colorado in the USA. The master control station collects satellite navigational messages from the monitor stations, updates these messages and passes it on to the ground control stations to update the satellites. The following functions are conducted by the master control station: Monitoring the satellite health status, monitoring satellite orbits, estimating and predicting satellite clock and ephemeris parameters, generating the GPS navigation message, maintaining GPS timing service and synchronising it to UTC, monitoring navigation integrity, monitoring and verifying navigation data delivered to the GPS user and command satellite manoeuvres to maintain global coverage. Five monitor stations are located at Hawaii, Colorado Springs, Ascension Island, Diego Garcia and Kwajalein. Ground control stations are collocated with monitor stations at Ascension Island, Diego Garcia and Kwajalien. A number of other tracking stations indicated in Figure 3-6 as WGS84 stations supplement these monitor stations. See Figure 4-2 for the geographic locations of the GPS control stations (Hofmann-Wellenhof *et al.*, 2001: 18 – 20; Kaplan & Hegarty, 2006: 87 – 102).

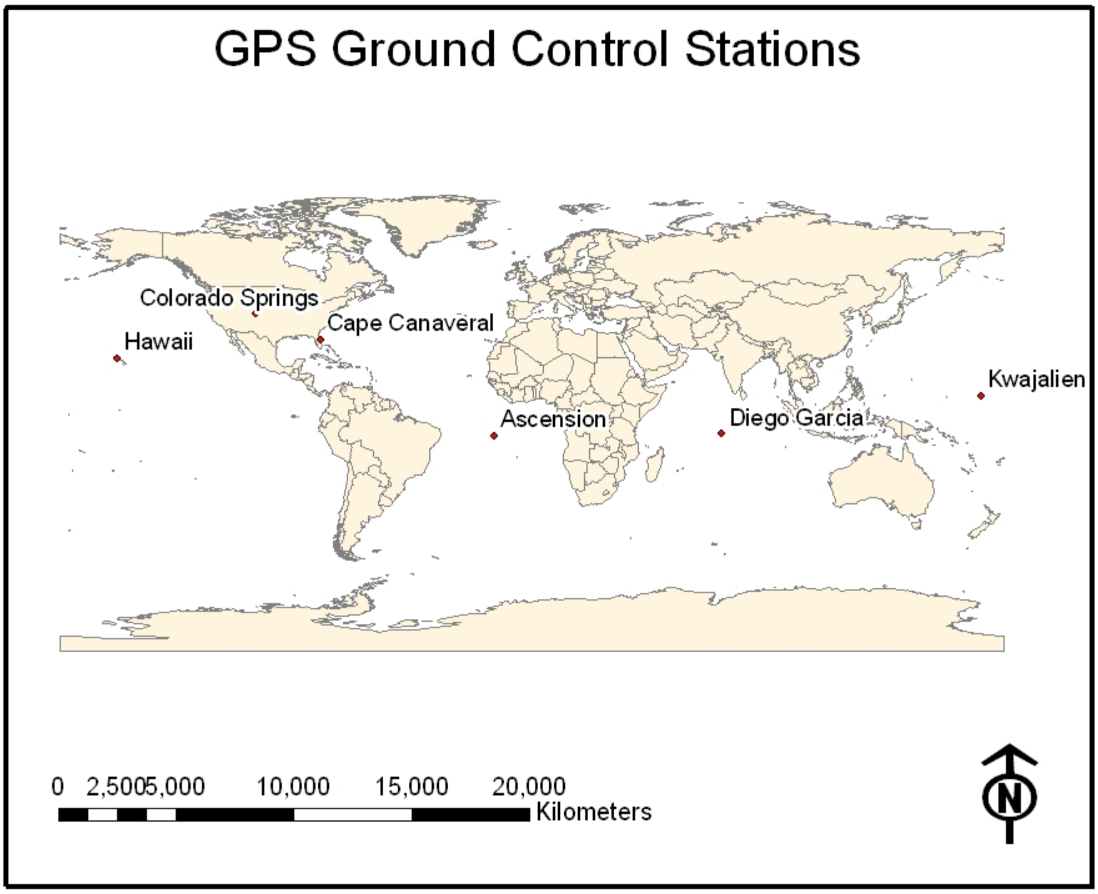

Figure 4-2: GPS Ground Control Stations

The master control station continuously monitors the satellite ephemerides and clock states. This is conducted in two components. The first one is offline processing using highly accurate models to generate reference satellite trajectories based on ECI coordinate system to ECEF transformations and calculations of gravitational and rotational forces that influence satellite orbits. The second is real time processing using a Kalman filter to calculate and estimate these forces on satellite orbits which runs with 15 min updates and has been continuously running since the early 1980s (Kaplan & Hegarty, 2006: 95 – 97, Wells, 1987: 4.9).

4. User Segment. The user segment consists of all the GPS users with various types of GPS receivers. These range from surveying receivers that render sub-centimetre accuracies, mapping receivers that render sub-metre accuracies and navigational receivers that render accuracies in the vicinity of 3 to 10 m. There are also those receivers that are embedded in control systems as found on vehicles, aircraft and naval vessels where the GPS display forms part of a control display unit. GPS receivers range from relative large and

heavy receivers with external antennas to lightweight handhelds and are even found in cellular phones and other small devices. GPS receivers can also be classified in terms of their signal acquisition and processing capabilities. The following broad categories can be established:

a. Receivers that track only the C/A-code on the L1 carrier signal. Most navigational and recreational receivers are in this category.

b. Receivers that track the A/C- and P-codes on the L1 carrier signal and the P-code on L2. These are military receivers that have the encryption keys to use the P-code on L1 and L2 and are only available to the United States military forces and its allies. When the P-code is encrypted with the W-code it is denoted as the P(Y)-code.

c. Receivers that can track the C/A-code on the L1 carrier signal as well as the L1 and the L2 carrier signals, which are known as carrier-phase measurements. These are receivers that are used for mapping and surveying solutions. Some of these receivers can also track the P(Y)-code without decryption (Kaplan & Hegarty, 2006: 106).

5. Generic Receiver Layout. Different receivers have different processing capabilities. However, a generic receiver will have multiple channels, normally 8 to 12, to allocate a channel to each satellite that is tracked. The antenna receives the satellite signal that is filtered and forwarded to a down-converter to be converted to an intermediate frequency. Consequently the intermediate frequency is sampled and converted by an analogue-digital converter. The sampled digital signal is forwarded to a digital signal processor that contains the number of channels for the specific receiver. Each channel contains the code and carrier tracking loops to perform code and carrier processing and demodulates the navigation message. Depending on the type of receiver, each channel may compute up to three different satellite-to-receiver measurements, namely pseudo-ranges, delta pseudo-ranges and integrated Doppler. The computed range or phase measurements with the demodulated navigation message are forwarded to the GPS processor that integrates with the control/display unit. See Figure 4-3 for a basic generic layout of a GPS receiver (Hofmann-Wellenhof *et al.*, 2001: 79; Kaplan & Hegarty, 2006: 107– 108; Wells, 1987: 4.17).

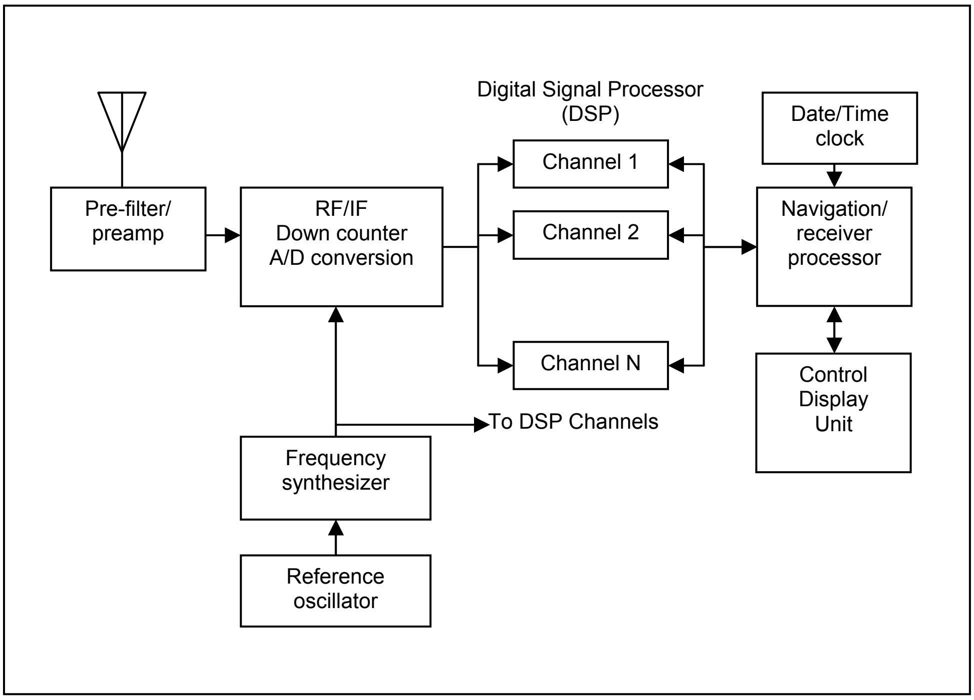

Figure 4-3: Generic Layout of a GPS Receiver

6. GPS Signals

a. Introduction. The GPS Wing of the United States Air Force provides two basic positioning services. This is the Standard Positioning Service (SPS) that renders the C/A-code on the L1 carrier signal and the Precise Positioning Service (PPS) that renders the P(Y)-code on both the L1 and the L2 carrier signals. Scientists and researchers have succeeded in also exploiting the L1 and L2 carrier signals for positioning.

b. GPS Signal Values. It was indicated that the atomic clocks onboard the GPS satellite generate a stable frequency that is converted by a frequency synthesizer into the fundamental or basic frequency (f_0) of 10.23 MHz. To compensate for relativistic effects, which include the relative faster functioning of the atomic clocks away from the gravitational forces of the earth and slower functioning at higher velocities, the f_0 is offset to appear to be 10.23 MHz at the GPS receiver. This offset renders an f_0 = 10.22999999543 MHz at the satellites. From this f_0 two carrier signals are generated by multiplying it with 154 and 120 respectively. This renders two frequencies in the L – frequency band that appears at the GPS receiver as: f_0.154 = L1 at 1 575.42 MHz and a wavelength of 19 cm and f_0.120 = L2 at 1 227.6 MHz and a wavelength of 24.4 cm. Modulated by means of direct sequence spread spectrum (DSSS) on these carrier signals are the C/A-code and the P(Y)-code. The C/A-code has a chipping rate of 1.023 x 10^6

chips/s = 1.023 MHz and a chip length of 293 m. The P(Y)-code has a chipping rate of 10.23 x 10^6 chips/s = 10.23 MHz and chip length of 29.3 m. These codes are also known as the pseudorandom noise (PRN) codes or ranging signals. See Table 4-1 for a tabular summary of GPS satellite signal properties and Figure 4-4 for a geometric presentation of these signals (Hofmann-Wellenhof *et al.*, 2001: 71 – 76; Leick, 2004: 75 – 78; Kaplan & Hegarty, 2006: 113 – 127; Merry, 2006: 29 – 30; Ashby, 2002).

Table 4-1: Summary of GPS Signal Components

S/N	Component	Factor	Frequency: MHz	Wavelength
1	Fundamental frequency	f_0	10.23	
2	Carrier L1	F_0 154	1 575.42	19.0 cm
3	Carrier L2	F_0 120	1 227.60	24.4 cm
4	C/A-code	$F_0/10$	1.023	
5	P(Y)-code	f_0	10.23	
6	Navigation message	$F_0/204\,600$	$50 \cdot 10^{-6}$	

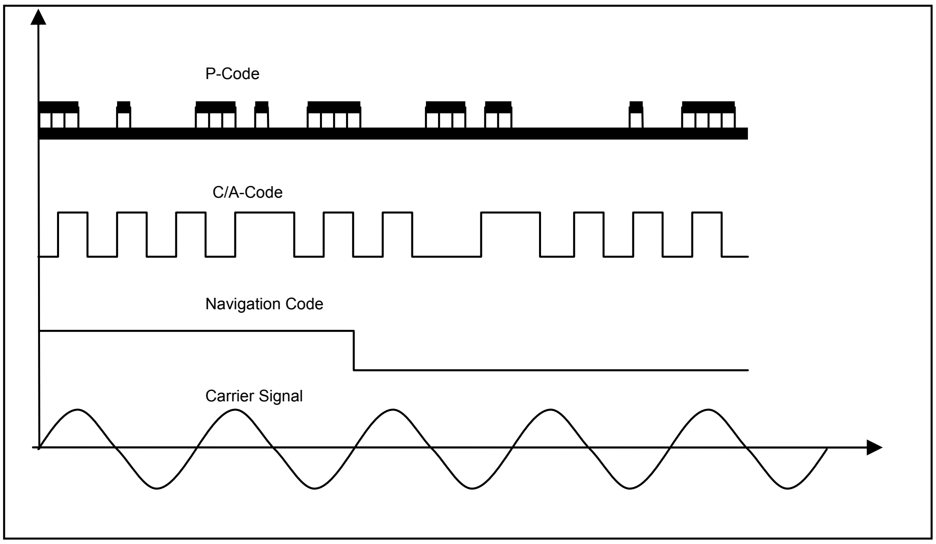

Figure 4-4: GPS Signal Structure

c. GPS Navigation Message. The C/A- and P(Y)-codes are both modulated with a 50 bps navigation message that contains all the information to compute the precise location of every visible GPS satellite and the time of transmission of the ranging signals. It is transmitted in five 300 bit sub-frames with each having ten 30 bit words. Each sub-frame contains vital information for positioning that include satellite accuracy and health, clock correction terms, satellite ephemeris data, ionosphere and universal time data and GPS almanac data (Hofmann-Wellenhof *et al.*, 2001: 76 – 77; Kaplan & Hegarty, 2006: 142 – 144; 6: 31).

d. PRN Code Structure. The DSSS modulation technique renders a digital signalling scheme in which the carrier signal is either transmitted unchanged or with a 180º phase shift over successive intervals depending on the code structure of digital 0s or 1s. This renders a predictable signal pattern that can be replicated by the GPS receiver.

e. C/A-code. Each satellite broadcasts a unique C/A-code at a 1 ms period that repeats constantly. The GPS receiver is capable of generating a replica of the received C/A-code. The receiver passes the replica C/A-code through the tracking loop until it matches the received C/A-code from the satellite. If the clocks of the satellite and the GPS receiver were perfectly synchronised, the time it takes to shift the replica C/A-code to synchronise with the satellite code would have been the correct propagation time for the signal. However, the GPS receiver clock will have a bias error from system time. Even the highly accurate atomic clocks of the satellite have an offset from system time. Thus, when the geometric satellite-to-receiver range is augmented with the two time offsets and multiplied by the velocity (c) of the signal, it renders a *pseudo-range*. How to overcome this uncertainty will be explained later. See Figures 4-5 and 4-6 for sketches explaining the synchronisation of satellite and GPS receiver signals (Hofmann-Wellenhof *et al.*, 2001: 81 – 82; Kaplan & Hegarty, 2006: 50 – 54; Merry, 2006: 29 – 30).

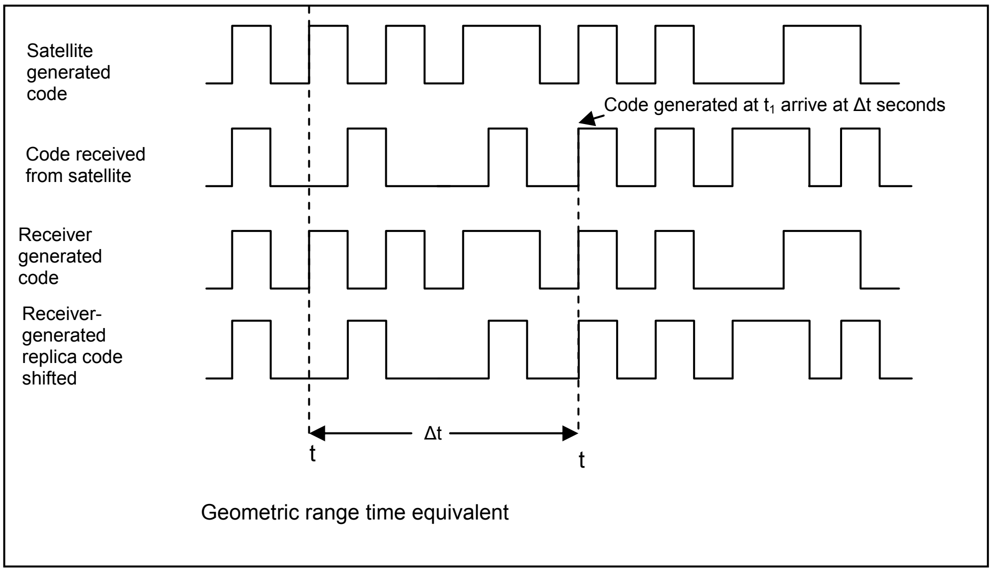

Figure 4-5: Synchronisation of Satellite and GPS Receiver Signals to Measure Time and Range

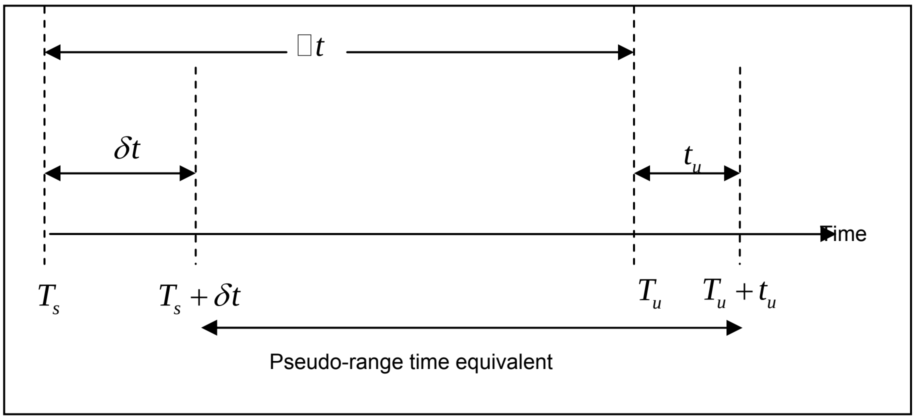

Figure 4-6: Satellite and Receiver Clock Offsets Calculated to Measure Time and Range

Where:

T_s = System time at which the signal left the satellite

T_u = System time at which the signal reached the receiver

δt = Offset of the satellite clock from system time

t_u = Offset of receiver clock from system time

$T_s + \delta t$ = Satellite clock reading at the time the signal left the satellite

$T_u + t_u$ = Receiver clock reading at the time the signal reached the receiver

$$\text{Geometric range} \quad r \quad = c\left(T_u - T_s\right) = c\Delta t \qquad 4.1$$

$$\begin{aligned} \text{Pseudo-range} \quad \rho \quad &= c\left[\left(T_u - t_u\right) - \left(T_s - \delta t\right)\right] \\ &= c\left(T_u - T_s\right) + c\left(t_u - \delta t\right) \\ &= r + c\left(t_u - \delta t\right) \qquad 4.2 \end{aligned}$$

f. P(Y)-code. The P(Y)-code is broken into 38 seven-day portions each assigned to a different satellite which then only broadcasts that portion of the code. The P(Y) does not repeat for 266 days. Each portion is assigned a PRN number that allows the GPS receiver to identify it. The encrypted P(Y)-code requires decryption keys to use it for positioning. This is only available to the United States military and its allies (Kaplan & Hegarty, 2006: 50; Merry, 2006: 30).

7. Signal Propagation. The GPS signals travel at the approximate speed of light which is 299 792 458 m/s. The different GPS signals travel as a group at slightly different velocities which are differently refracted when travelling through the ionosphere. However, as indicated earlier, the navigation message has embedded correction data for this refraction (Kaplan & Hegarty, 2006: 309).

8. Code Pseudo-ranging. Knowing that the satellites are in orbits 26 600 km from the earth centre, and knowing that each satellite is broadcasting omni-directional signals (as seen by the receiver, but in fact directional from the satellite with an antenna gain of 13dBi) which travel at the velocity of light, one can create a solution to determine position. With a single satellite the receiver could be at any place on the arc of the pseudo-range explained above. With two satellites two pseudo-range intersections are created, one close to the earth's surface and another far away into space. With a third satellite a pseudo-range intersection is created that is a close approximation of the receiver position. To determine the true position one has to start with the previous equation (4.2) for pseudo-range, $\rho = r + c\left(tu - \delta t\right)$. However, we know that the satellite clocks are synchronised to Co-ordinated Universal Time (UTC) and that clock corrections are broadcasted as part the navigation message. Although there is still a satellite clock error to be corrected, it is marginally small and can be ignored for this argument. Thus, equation 4.2 can be rewritten for this argument to $\rho = r + c \cdot t_u$. To solve this equation simultaneous pseudo-range

measurements to four satellites are made to solve the four uncertainties, x_u, y_u, x_u and $c.t_u$ resulting in a system of equations as shown in Figure 4-7:

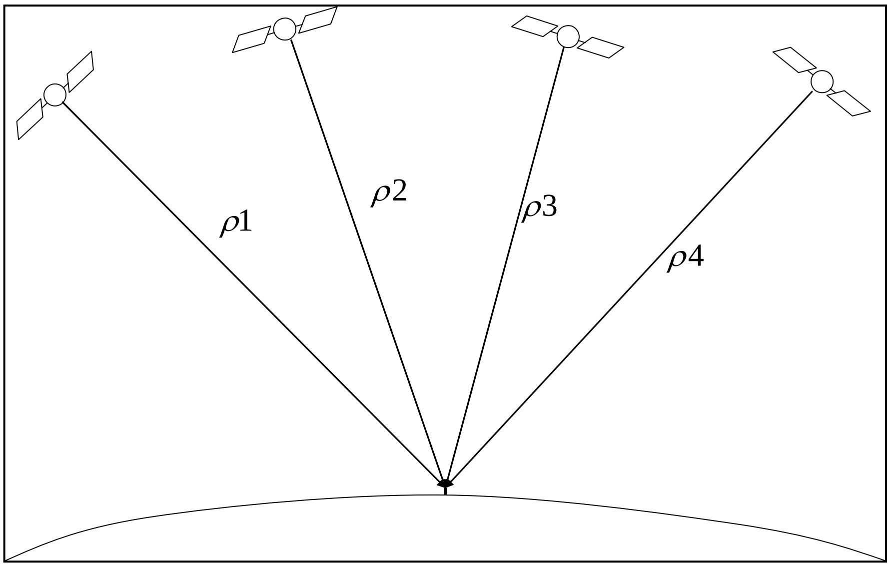

Figure 4-7: Ranging from four Satellites

$$\rho_1 = \sqrt{(x_1 - x_u)^2 + (y_1 - y_u)^2 + (z_1 - z_u)^2} + c.t_u$$

$$\rho_2 = \sqrt{(x_2 - x_u)^2 + (y_2 - y_u)^2 + (z_2 - z_u)^2} + c.t_u$$

$$\rho_3 = \sqrt{(x_3 - x_u)^2 + (y_3 - y_u)^2 + (z_3 - z_u)^2} + c.t_u$$

$$\rho_4 = \sqrt{(x_4 - x_u)^2 + (y_4 - y_u)^2 + (z_4 - z_u)^2} + c.t_u \qquad 4.3$$

Where x_{1-4}, y_{1-4} and z_{1-4} represent the three-dimensional positions of the satellites 1 – 4. When the four satellites are observed simultaneously, the four uncertainties can be resolved, which will render a position with a resolution of approximately 1% of the signal chip length. For measurements with the C/A-code this could be in the vicinity of 3 m. However, a number of external influences (which will be discussed) will impact on this measurement (Hofmann-Wellenhof *et al.*, 2001: 87 – 88; Leick, 2004: 170 – 174; Kaplan & Hegarty, 2006: 54; Merry, 2006: 24 – 32).

9. Carrier-Phase Ranging

a. Measuring Carrier-Phase. As indicated, GPS was designed to use coded pseudo-range measurements. For surveying this approach results in accuracies that are too low. Researchers and scientists found a way to use the carrier signals with much shorter wavelengths (L1 = 19 cm and L2 = 24.4 cm) to provide sub-centimetre accuracies. Switching on a GPS receiver at any given epoch (t_0) the instantaneous fractional phase (θ_0) of the carrier signal is measured by means of the Doppler frequency offset and is derived from the carrier-phase tracking loop of the receiver. For each following epoch (t_1) the value of the previous epoch (t_0) plus the advance in phase (θ_1) during the current epoch is measured by the receiver. See Figure 4-8 for a geometrical interpretation of the phase ranging. The number of full signal cycles between the satellite and the receiver is unknown and hence the *integer cycle ambiguity* (N) which needs to be treated as an unknown. However, when tracking is continued without loss of lock on the satellite, the N remains the same. Again the range represents the distance between the satellite at epoch T_s and T_u at the receiver. The phase of the carrier can be measured to better than 0.01 cycles which corresponds to millimetre accuracies (Hofmann-Wellenhof *et al.*, 2001: 89 – 90; Kaplan & Hegarty, 2006: 399 – 401; Merry, 2006: 53 – 55; Wells, 19987: 3.5 & 4.15).

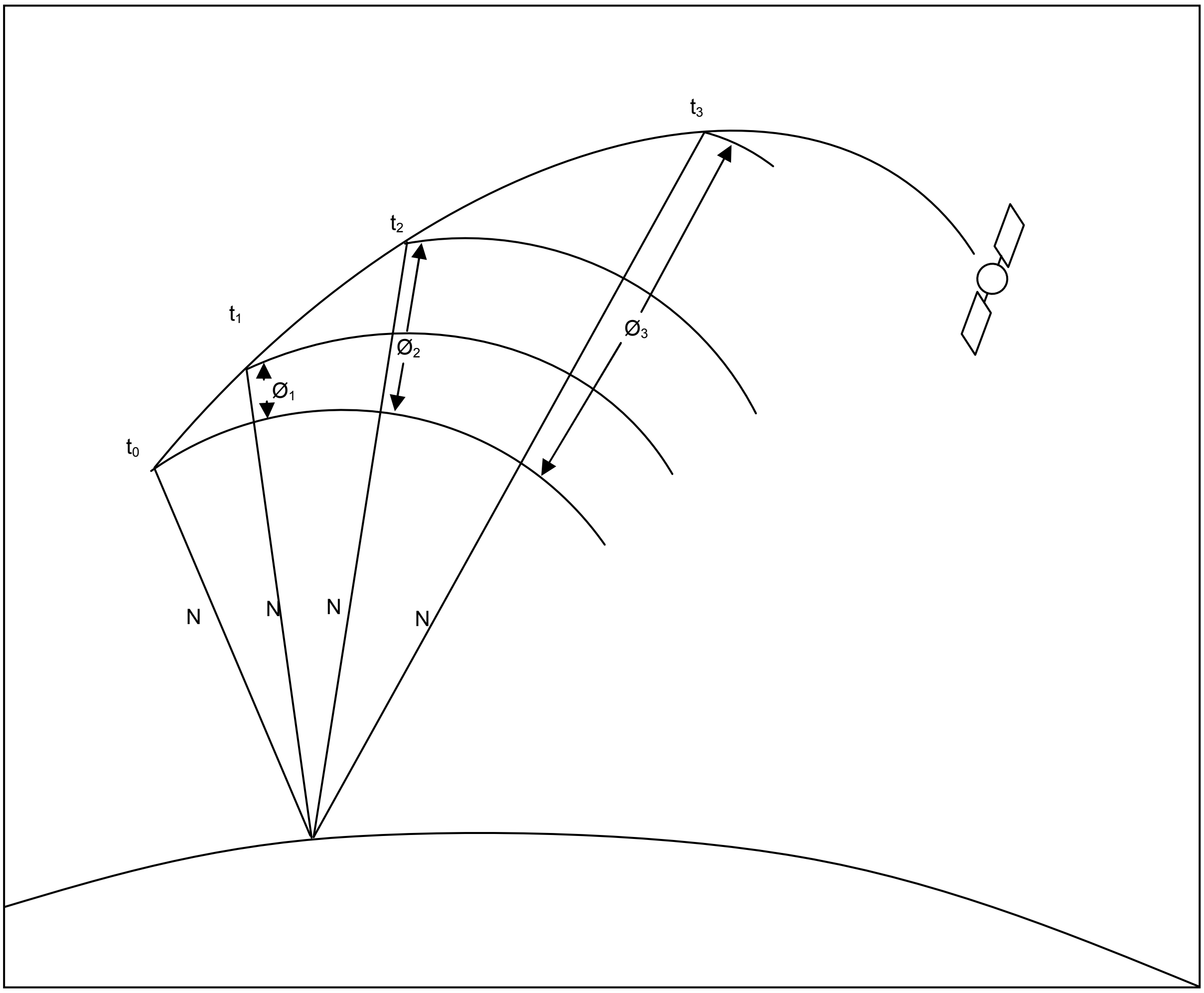

Figure 4-8: Measuring Time and Range with Carrier Signals

b. <u>Solving Cycle Ambiguity</u>. A variety of techniques are used to solve cycle ambiguity, such as using the pseudo-range measurement to approximate the extent of the ambiguity, augmenting it with wide-lane and narrow-lane measurements. Wide-lane is a technique using both carrier frequencies (L1 and L2) for tracking a satellite and subtracting the frequencies from each other in order to render a wavelength of approximately 86 cm that is significantly smaller to work with to solve the cycle ambiguity.

$$f_{wl} = 1\,575.42 - 1\,227.6 = 347.82 \text{ MHz}$$

$$\lambda_{wl} = 86.25 \text{ cm} \tag{4.4}$$

Research to improve the capacity of solving cycle ambiguity is continuing. It is estimated that the addition of the L5 signal at 1 176.45 MHz will allow the construction of an extra wide-lane metric which will enable a very rapid ambiguity resolution. It is estimated that L5 will only be available in 2015. However, when the cycle ambiguity is solved, it remains fixed in the solution as long as the GPS receiver maintains lock on the satellite signal. When lock is lost, called *cycle slip*, the cycle ambiguity needs to be resolved again. Any object that may obstruct the line of sight between the receiver and the satellite may cause a cycle slip (Kaplan & Hegarty, 2006: 401 – 418; School of Surveying & Spatial Information Systems, 2010: Chapter 3).

10. Concluding Remarks. Different entities in the SANDF use different types of GPS receivers as indicated earlier. Users should understand the capabilities of the specific receiver and ensure that receivers procured are indeed capable of delivering the required capabilities. However, the next section will discuss GPS measurement errors that will highlight the capabilities and limitations of the different receivers further.

GPS MEASUREMENT: ERRORS AND BIASES

11. Introduction. A number of factors influence the accuracy of GPS measurements. These can be categorised as those related to the satellite, such as clock and orbit errors and satellite geometry, those related to the propagation of the GPS signal through the atmosphere, sun activity and drag, and those related to the GPS receiver, including thermal noise and clock drift. Some errors are related to obstructions at the point of measuring, for instance multipathing. To put measurement errors in perspective, it should be remembered that a delay of one millisecond translates to a 300 km pseudo-range error. For this reason significant measures are taken to prevent them.

Satellite Clock Error. Satellite clocks that are used to generate the fundamental signal are very stable as discussed earlier. These clocks are digitally synchronised because of inherent offsets and linear drift over time. The master control centre monitors these clocks and updates them with clock correction parameters that are rebroadcasted by the satellites as part of the navigation message. Because these correction parameters are computed to predict actual satellite clock errors, some residual errors remain. This may cause range measurement errors in the order of 0.3 m to 4 m depending on the type of satellite and the age of the correction parameters. The range errors will therefore be the smallest just after the correction parameters were uploaded. At 24 h later the clock drift could cause measurement errors of up to 4 m. Several other factors remain that may cause the clock to be in error, including the inability of the master control centre to perfectly determine the clock offset, the limited number of data bits in the navigation message to fully communicate the predicted clock error and orbit ephemeris and the delay between the clock error estimate upload and the time the satellite broadcasts the navigation message. Clock corrections are available from GPS monitor networks such as the IGS that can be used to improve the accuracy of measurements. Another assured way of minimising the effect of satellite clock error on range measurements is to make use of a differential GPS (DGPS) which will be discussed in the next section under Measurement Augmentation (Kaplan & Hegarty, 2006: 304 – 305; Merry, 2006: 37; US DOD, 2008: A6-A10).

12. Satellite Orbit Error. Similar to clock updates, satellite ephemerides are monitored and updated to the satellites that rebroadcast it via the navigation message. Because of similar reasons, satellite ephemeris calculations have embedded errors in the range of one to six metres. Fortunately the effects on range measurements are only in the order of 0.8 m. Although more corrected satellite clock and orbit ephemeris data are available a couple of days after measurements were taken to conduct post processing on these field measurements, this is not available for users that navigate or do real-time surveying. Range error due to orbit errors can be eliminated to a large extent by using DGPS or Precise Point Positioning techniques to be discussed in the next section under Measurement Augmentation (Kaplan & Hegarty, 2006: 305 – 306; Merry, 2006: 35 – 37).

13. Dilution of Precision. In its latest policy release (September 2008) on Standard Positioning Service Performance Standard, the GPS Wing indicated that each satellite is updated once a day with correction parameters for both clock and orbit errors. The sum of satellite errors for that specific satellite constitutes a *user equivalent range error* referred to as *UERE*. However, the effects of clock and orbit errors are magnified by poor satellite dispersion in the sky, referred to as satellite geometry. See Figure 4-9 for a sketch of the effect of satellite geometry. Satellites that are clustered in one segment of the sky render poor satellite geometry, while an overall equal dispersion renders more precise range measurements. With the close cluster the intersection at the receiver is large and the dilution of precision (DOP) is large, normally with a value of six or more. With an open dispersion the intersection is small, the precision of measurements is much higher and the DOP is low with a possible value of two. The positional dilution of precision (PDOP) is the most general concept and is built on a model that provides for the three elements of position, namely x, y and z in terms of the UERE. Horizontal dilution of precision (HDOP) and vertical dilution of precision (VDOP), make provision for horizontal and vertical dilution of precision, while TDOP provides for a time dilution of precision. Higher grade GPS receivers can be set to collect data below a selected DOP threshold. Thus, when the DOP exceeds the set value, the receiver will sound a warning and ultimately stop measurements. These receivers also render a function to plan data collection by projecting the predicted DOP for 24 h in advance. The operator can then estimate when the DOP values will be at an acceptable level for data collection (Kaplan & Hegarty, 2006: 322 – 823; Merry, 2006: 42, US DOD, 2008: A6-A10).

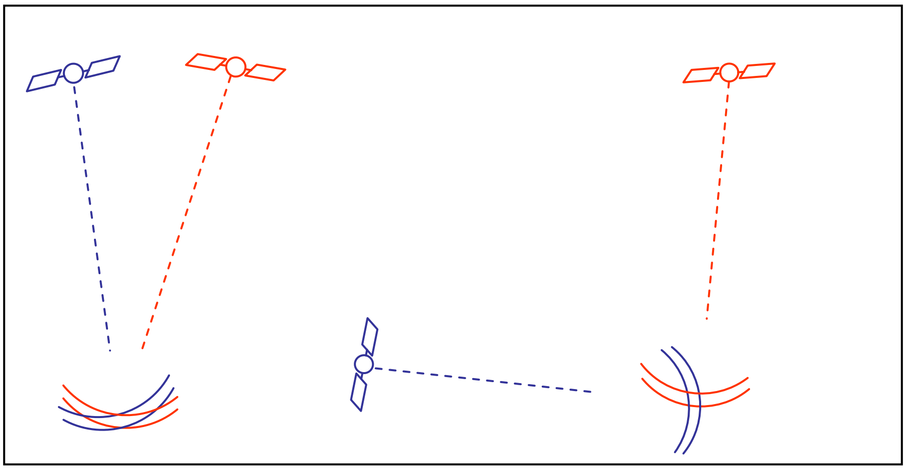

Figure 4-9: Satellite Geometry - Dilution of Precision

14. Ionosphere

a. Introduction. The propagation speed of a wave can be expressed in terms of the level of refraction of the medium it travels through. In a dispersive medium such as the ionosphere, the propagation velocity of carrier signals differs from the velocity of the signals carrying the signal information. Thus, signals travel together in a group, but at slightly different velocities.

b. Influence of the Sun. The ionosphere is the dispersive medium located between 70 km and a 1 000 km above the earth's surface. The sun's ultraviolet rays ionise the gas molecules of the ionosphere, resulting in the release of free electrons. These free electrons influence the propagation of electromagnetic waves (GPS satellite signals). This ionospheric effect is proportional to the total electron content (TEC), calculated from a cross-section of a vertical 1 m^2 column along the path of the signal. The TEC fluctuates as a function of solar radiation, latitude, season and local time. Values of TEC are dependent on solar radiation which reaches its peak at midday and is at its lowest at midnight and early morning. These TEC values are also a function of sunspot activity which has a 10 to 11 year cycle. A number of sources predicted the lowest turning point for the current cycle (24) to be during 2005. However, as can be seen from Figure 4-10, the lowest turning point of cycle 24 was 2009 with the next predicted high during 2014. The ionospheric effect is higher for signals from satellites that are low on the horizon and lower for satellites at zenith. It is therefore important to eliminate measurements from satellites that are low on the horizon by setting an elevation mask of between 10° and 15°, provided that the receiver has such a capability (Kaplan & Hegarty, 2006: 310 – 312; Merry, 2006: 39 – 40).

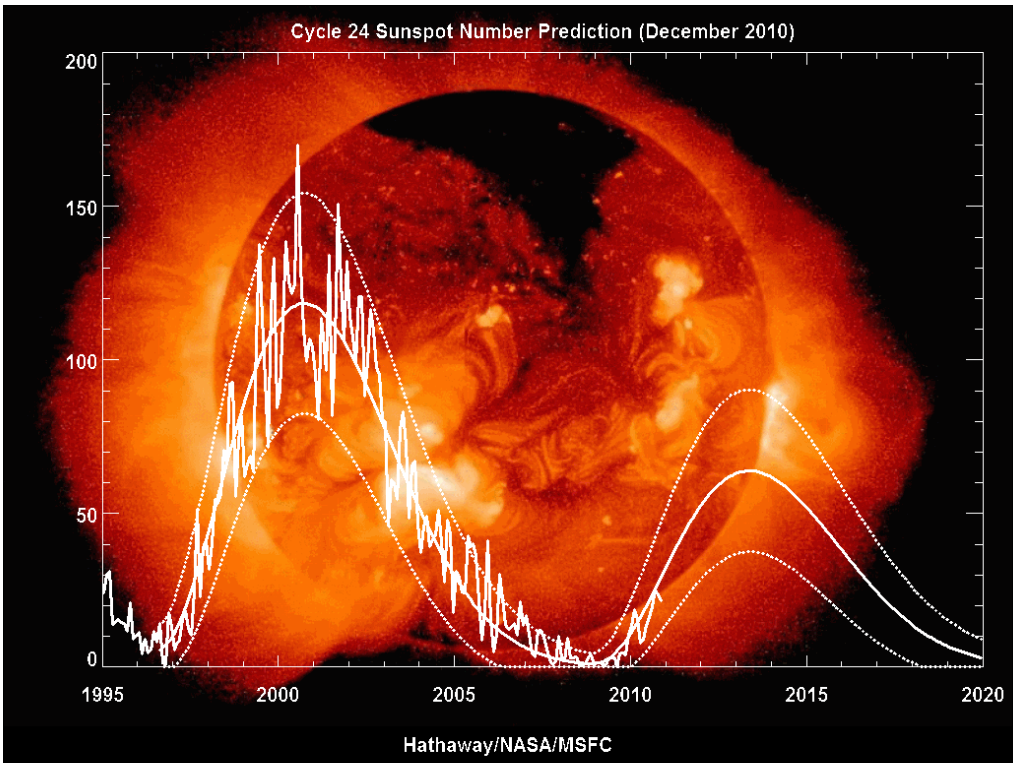

Figure 4-10: Sunspot Activity since 1995[1]

c. <u>Ionospheric Effect</u>. The ionospheric effect (d_{ion}) causes the code and the navigation message to be delayed, while the carrier-phase signals are advanced, a phenomenon referred to as *ionospheric divergence*. The higher frequencies pass through the ionosphere with greater ease than lower frequencies. The magnitude of the delay on the data carrying signals is equal to the advance of the carrier signals. Models to calculate TEC and the refraction on the GPS satellite signals passing the ionosphere are part of the navigation message. The enhancement or increasing effect on range measurements can be equated as:

$$d_{ion} \approx \frac{40,3}{f^2}.TEC.\sec\theta \qquad 4.6$$

In Equation 4.6 f is the carrier frequency in Hz and θ is the zenith angle of the satellite. The ionospheric effect is one of the largest sources of

---

[1] Source: http://solarscience.msfc.nasa.gov accessed during December 2010.

measurement errors in a single frequency GPS receiver. However, because the delay is frequency dependent, it is possible to eliminate its effect almost completely by making range measurements with dual frequency receivers. The dual frequency receiver can measure the time difference between the propagation delays of the two frequencies. The delay factor can then be used to correct the GPS measurements in processing software. Unfortunately the P(Y)-code is not available to civilian users. The new envisaged civilian signal L2C will enhance civilian GPS receivers to neutralise the ionospheric effect. Currently civilian GPS receivers that can use carrier-phase measurements on L1 and L2 are required for this technique. With DGPS this effect can also be eliminated to a large extent (Hofmann-Wellenhof *et al.*, 2001: 99 – 106; Leick, 2004: 211 – 215; Kaplan & Hegarty, 2006: 310 – 312, Merry, 2006: 39).

15. Troposphere. The troposphere (d_{trop}) is the lower part of the atmosphere (40 km above the earth) that is non-dispersive for electromagnetic frequencies up to 15 GHz. In the troposphere carrier-phase frequencies and the data carrying frequencies are equally delayed. This delay is dependent on the local temperature, pressure and humidity. The dry component of the troposphere that extends to about 40 km above the earth, accounts for almost 90% of the delay and can be predicted fairly accurately. The wet component extends to about 10 km above the earth and is more unpredictable. Various models are used to calculate the dry, wet and combined delaying effects of the troposphere on the GPS signals. Variable models are used for measurements with signals from satellites at zenith, called *zenith delay*, satellites low on the horizon called *vertical delay* and satellites at an arbitrary elevation called *slant delay*. Signal delay is larger for signals from satellites on the horizon relative to those at the zenith. A model to calculate d_{trop} can be equated as:

$$d_{trop} = 2,27.10^{-3} \cdot \left[P + \left(\frac{1255}{T} + 0,05 \right) \cdot e - \tan^2 \theta \right] \cdot \sec \theta \qquad 4.7$$

In Equation 4.7 P represents the atmospheric pressure, T is temperature in Kelvin, e is the water vapour pressure and θ the zenith angle of the GPS satellite. The range error at sea level can vary from about 2.4 m for measurements from satellites at zenith to 25 m for satellites at an elevation of 5° above the horizon. It is therefore important to reject measurements from satellites below a cut-off elevation. An elevation mask of between 10° and 15° is proposed. Tropospheric delay can also be eliminated to a large extent by using

DGPS techniques (Hofmann-Wellenhof *et al.*, 2001: 106 – 118; Kaplan & Hegarty, 2006: 314 – 319; Merry, 2006: 37 – 38).

16. <u>GPS Signal Availability and Integrity</u>

a. GPS satellites are placed in such a fashion that at least six satellites are available at any place on earth at any time. However, this does not mean that the placement of these satellites in the sky is such that it will deliver the required PDOP at the required mask level for a required level of accuracy. This unavailability may only last for a relative short time periods. Kaplan and Hegarty tested and argued that with 24 satellites available and a mask level of 7.5º and a PDOP threshold of 6.0 the GPS constellation provided a 99,98% availability. The maximum unavailability measured was only 10 min at latitudes beyond 60º N and 60º S. In an estimate where two satellites were removed from the constellation, coverage was 99,903% with unavailability up to 25 min. However, with three satellites removed from the constellation availability drops to 99.197% with unavailability up to 65 min. In this scenario parts of Southern and Northern Africa will be affected (Kaplan & Hegarty, 2006: 334 – 345).

b. Selective availability (SA) is something that remains in the mind of GPS users. According to US military specifications the master control centre should be able to adjust the fundamental frequency and therefore also the code signals and the transmitted time. This may cause a horizontal range error in the vicinity of 100 m and was intended to deny adversaries the use of GPS in conflict. Selective availability was used during the Gulf War in 1991 but deactivated soon because more American troops used civilian receivers than military ones and the GPS proved to be very useful for navigation in the desert. It was officially deactivated on 2 May 2000 and will most probably not be used again. Reasons for this are that SA can be neutralised with DGPS and many life support systems including ambulances, shipping, aircraft and large transport fleets navigate by GPS. Enabling SA may cause havoc. The ability to apply selective denial or jamming has also improved lately and allowed adversaries to manipulate or deny the use of GPS signals in the theatre of operations. This will be discussed in more detail in paragraph 19 (Hofmann-Wellenhof *et al.*, 2001: 15 – 20).

c. Although integrity anomalies will be rare, it is possible. It is for instance not possible for the monitor stations to monitor all 24 satellites 24 h every day. Thus, if any integrity issue occurs, it may take up to a few minutes for the control centres to restore the situation and that may be too long for an aviation solution. The clock failure that occurred on one of the GPS satellites on 28 July 2001 can be cited as an incident of integrity failure (Kaplan & Hegarty, 2006: 345 – 360).

17. Receiver Errors

a. Tracking Loops. Measurement errors are induced by receiver tracking loops and may be one of the major sources of error measurements in stand-alone GPS receivers.

b. Clock Errors. A receiver clock is normally a low accuracy quartz crystal oscillator which re-initialises every time the receiver is switched on. However, this is solved at every measurement epoch by using the received navigation message for pseudo-range measurements and by double differencing for carrier-phase measurements.

c. Antenna Phase Centre. A GPS antenna has a physical and electrical phase centre. The physical centre can be measured. The electrical phase centre is the point where the broadcasted GPS signal is received. Thus, this is the actual point of measurement and it may deviate from the physical centre with one to two centimetres. In navigational receivers this will have no relevant effect, but for survey purposes it should be addressed. Using the same type of antennas and orienting them in the same direction on the baseline may minimise this effect. The antennas can also be calibrated, using a well surveyed point (Hofmann-Wellenhof *et al.*, 2001: 124 – 125, Kaplan & Hegarty, 2006: 104 – 106, Merry, 2006: 42).

18. Signal Reflection and Shadowing. The reflection of GPS signals from nearby surfaces, such as high-rise buildings or passing vehicles, causes the receiver to make erroneous measurements, resulting from *multipathing*. On an aircraft the tail and wings may cause multipathing. The reflected signal normally arrives at the receiver later than the direct signal. When the delay is large, the receiver will be able to reject the reflected signals. However, when the reflecting surface is close to the receiver antenna, the arrival time of the reflected signals will arrive fractions of nanoseconds later at the receiver antenna; it will be

difficult for the receiver to discern between direct and reflected signals. Signals from satellites low on the horizon tend to render more multipath measurements than satellites at zenith. The two opposing requirements of using signals from low orbiting satellites to render lower PDOPs and possible multipath measurements from the same low orbiting satellites need to be balanced by setting appropriate mask levels for the prevailing circumstances. The size of the multipath errors in tracking different satellites may be different and is difficult to model due to the wide variety of circumstances that may cause multipathing. Shadowing is when GPS signals are obstructed by objects, for instance foliage. Under thick tree cover the shadowing effect may be so severe that a GPS receiver can only track reflected signals. Multipathing and shadowing can not be corrected by DGPS as with other errors and biases. Both the reference station and the rover station in a differential solution may record different multipath measurements, which may cause larger errors than normal. Thus, both these effects pose a serious challenge for making accurate measurements. An assured way to prevent multipathing and shadowing is to avoid reflecting surfaces and obstructions, such as foliage. In aircraft and vehicle mountings it may require reconstruction to remove reflective surfaces or the use of absorbent materials. Antenna design, such as a choke ring design and a built-in base plate that can prevent measurements with reflected signals can help to prevent multipathing measurements. Another approach is to make measurements over a longer time period. Satellite positions change over time and the multipathing effect will also change, allowing averaging and therefore minimising of the multipath effect. Measurements between 10 to 30 min may suffice for this purpose (Hofmann-Wellenhof *et al.*, 2001: 125 – 131, Kaplan & Hegarty, 2006: 279 – 295, Merry, 2006: 41).

19. Selective Denial. Selective denial or jamming is a military concept and has to do with interference applied to the reception of GPS satellite signals to deny an adversary the use of GPS signals for positioning, navigation or timing. Two approaches can be followed. Use a stronger signal in the same frequency band to disrupt the broadcasted GPS satellite signals in a limited area of operations at the receiver. The other approach, also known as *spoofing*, is to broadcast similar signals as the GPS satellites that can take over the adversary's receivers and gradually lead them astray. A limitation of both approaches is that the signals come from mainly one direction and is dependent on line of sight. Dispersion of transmission is also possible to some extent. Military receivers use null-steering antenna techniques to make them jamming resistant. The exclusive use of the P(Y)-code for military receivers is another approach to minimise chances of being jammed. The GPS signal level at the receiver is in the vicinity of -130 dBm or -158.5 dBW. This is a relatively low level signal and can therefore be jammed easily. Civilian receivers that use C/A-code and carrier signals are not designed to withstand the application of jamming techniques. Jamming devices can be

bought on the open market and an Internet search will render numerous results[2]. There is also the possibility of unintentional disruption of GPS satellite signals. Examples of typical radiolocation services which could cause interference include air traffic control radars and electronic aids for air navigation. These services transmit on frequency bands close to the L2 frequency and the intended L5 frequency. It is inevitable that some of the out-of-band energy from these signals in adjacent bands or energy resulting from the malfunctioning of these transmitters will interfere with the reception of GPS receivers. There is even evidence that television transmissions have disrupted GPS receiver functioning. GPS jammers can be bought on the market for private use. Because the SANDF is using civilian type GPS receivers, jamming is a very relevant challenge. This will be addressed in more detail in Chapter 5 where the results of GPS jamming tests are discussed (Kaplan & Hegarty 2006: 243 – 248; US DOD, 2008: 7; Frossel & Olsen 2003; Richardson, 2003; Whitman, 2002; Lekkerkerk 2008: 83 - 84).

20. GPS Modernisation. In January 1999 the United States government announced the modernisation of GPS. Modernisation will include the addition of two new signals, L2C and L5. The L2C signal will be available on the L2 frequency and is intended for non-safety of life applications. The L5 signal at 1 176.45 MHz resides in the aeronautical radio navigation band and is intended for the safety of life applications. The combination of the L1 and L5 signal will enhance aviation significantly. These signals will provide SPS users with more accurate and quicker measurement capabilities. The additional signals will also improve GPS robustness to interference. If one signal is experiencing interference, the receiver can switch to another signal. It is envisaged that L2C will be available on the Block IIR satellites, while L5 will be available on the Block IIF satellites. It is further envisaged that the Block III satellites will be launched in 2013. The current worldwide economic situation may postpone this programme. However, it is planned that upgrades will allow civilian users to acquire sub-metre accuracies and provide higher signal power to meet military anti-jamming requirements (Kaplan & Hegarty, 2006: 145 – 150).

21. Concluding Remarks. The SANDF uses exclusively civilian type GPS receivers. More advanced receivers can be configured to mitigate certain errors in the measurements by selecting satellites above a certain elevation, low signal to noise ratios and DOP levels, while others can merely use factory settings. GPS modernisation will enable higher accuracies with navigational type receivers that will be within the accuracy requirements for

---

[2] http://www.tayx.co.uk/gmt10-gps-l1-l2-l5-jammer.html accessed in February 2009 is an example of a website that markets commercial jammers.

mapping purposes. Other augmentation techniques that can further improve GPS measurements will be discussed in the next section. However, it is relatively easy to jam any civilian type GPS receiver and it poses a serious challenge for using GPS receivers as navigational receivers in operations. It is beyond the scope of this study to address this issue satisfactorily and requires additional research.

GPS MEASUREMENT AUGMENTATION

22. Introduction. Error measurements and biases caused by satellite and receiver deficiencies and propagation media discussed above can be corrected by making use of two broad augmentation techniques, namely DGPS and external sensors. DGPS in principle utilises a GPS receiver located at a reference point with a known position to collect data that is thereafter used to correct measurements of the roving GPS receiver. As the position of the reference station is known, the extent of the errors measured are known and therefore the "known error" for each epoch can be used to correct the measurements of the roving receiver for each corresponding epoch. External sensors are used to collect satellite health and propagation media data continuously in order to correct measurements taken with the roving receiver. Two approaches can be followed to correct the measurements of the roving receiver. Live data links, including radios or the Internet between the reference station (or external sensor) and the roving receiver can be used to correct measurements on-the-fly. The other approach is to collect data separately at both the reference station and the roving receiver on a storage medium, such as a hard drive and conduct post-processing. These approaches are termed kinematic and static solutions respectively.

23. DGPS. Two approaches can be followed, namely absolute and relative DGPS. With absolute DGPS the coordinates of the reference or base station should be known to the highest possible or required accuracy level in the same ECEF coordinate system that is required for the roving GPS receiver. The deviations of measurements taken at the reference station during the time of measurement can then be used to correct the measurements taken with the roving receiver. With relative DGPS the coordinates of the reference station may not be known that accurately, for instance in the case of DGPS application to land on an aircraft carrier. A differential correction can be applied to both pseudo-range and carrier-phase measurements. Pseudo-range measurements may render solutions of sub-metre accuracies, while carrier-phase measurements may render sub-centimetre accuracies. In order to conduct differential corrections, both the reference station and the roving receiver should observe the same satellites simultaneously and measurements should be taken over the same time period in order to ensure that common errors are experienced. This places some constraints on the distance between the reference

station and the roving receiver, also known as the baseline. In theory the error sources are very similar over baseline distances of less than 200 km where one metre accuracies can be routinely achieved with C/A-code measurements. Two to three metre accuracies can be attained with measurements over a 1 000 km baseline (Hofmann-Wellenhof *et al.*, 2001: 136 – 137; Kaplan & Hegarty, 2006: 379 – 390; Merry, 2006: 47).

24. Error Correction. Satellite clock errors are the easiest to correct by means of DGPS. Clock error measurements measured by the reference station are simply used to correct the measurements of the roving receiver. Satellite orbit errors are equally corrected by means of measurements from reference stations. Over short baselines of less than 25 km the errors caused by ionospheric and tropospheric refraction are relatively small. However, over longer baselines, extending 500 km or more, these errors can be significant. Refraction by the ionosphere can be eliminated by using dual frequency receivers and DGPS further improves the capacity to resolve it. Tropospheric delays on GPS satellite signals are influenced by the satellite elevation above the horizon as discussed earlier. This delay also changes over distance as troposphere characteristics change, especially where land masses meet water masses. This is even further complicated if there are significant height differences between the reference station and the roving receiver such as when located in an aircraft. Different receivers use different position solution techniques, including wide-lane, narrow-lane, Kalman filter and least-squares. Unless both receivers use the same technique, error correction may be inconsistent. The solution of specific errors is seldom addressed separately, but rather as a total position solution. It may be possible to identify specific satellites, such as low elevation satellites that lead to unacceptable measurements, and to neutralise these deficiencies by applying an elevation filter. It should be noted that errors caused by multipath and receiver noise cannot be corrected with DGPS or other augmentation systems (Kaplan & Hegarty, 2006: 379 – 391).

25. Attainable Accuracies. The positional solution with DGPS will depend on the type of GPS receiver and the type of measurement that is used. Carrier-phase provides higher accuracies than C/A-code and dual frequency (L1 and L2) provides higher accuracies than single carrier measurements. The baseline length between the reference station and the roving receiver also influences the attainable accuracy. This theoretical approach will be tested by measurements with various receivers and different baseline distances to develop an empirical model that can be used for both stand-alone and DGPS measurements. Table 4-2 indicates the margin of positional accuracies that is attainable with a stand-alone and DGPS respectively and is useful for comparison purposes (Hofmann-Wellenhof *et al.*, 2001: 133; Varner, 2000: 50; Merry, 2006: 43).

Table 4-2: Attainable Accuracies with Stand-alone and DGPS

S/N	**Error Source**	**Stand-alone GPS**	**DGPS**[3]
1	Satellite clock	< 3 m	Eliminated
2	Satellite orbit	< 3 m	0.0 m
3	Tropospheric refraction	< 1 m	0.0 m
4	Ionospheric refraction	5 – 10 m	0.0 m

26. Ground Based Augmentation Systems (GBAS). A variation of DGPS is the installation of a network of permanent "base stations" that can be used for differential correction, using both post-processing and on-the-fly correction. These augmentation systems can be very small, such as those used at an airport for landing assistance. Larger systems are for instance, networks that are used in a high activity area e.g. Gauteng, and national systems such as the TrigNet system of CDNGI which provide coverage of South Africa. These systems include a master station that integrates the measurements from the different stations to provide network solutions. When the stations are dispersed as in the CDNGI system, smaller networks are established within the larger system to render an area specific solution, for instance for Cape Town, Gauteng and Durban. Various methods are used to communicate the corrected measurements to the rover stations, including radio links or the Internet (using cellular phones or other GPRS technologies) making use of Network Transport of the Radio Technical Commission for Maritime Services (RTCM) via Internet Protocol (NTRIP). Two approaches can be followed with a network DGPS. Firstly, one can use an individual reference station in the network, normally the closest, to provide differential corrected data to the rover receiver in real-time or using post-processing. The rover receiver will always communicate via the control station to the reference station that implies a fractional delay. The second method is to use a number of reference stations in which case the master station or the rover receiver has to apply statistical weighting to the values from the different reference stations, based on the distance from each station (Hofmann-

---

[3] The quality of the receiver as well as the length of the baseline between the base and the roving receivers has an impact on the accuracy of measurements. This will be demonstrated with measurements values in Chapter Five.

Wellenhof *et al.*, 2001: 137 – 138, Kaplan & Hegarty, 2006: 446 – 449, Merry, 2006: 47 – 50, 22).

27. Satellite Based Augmentation System (SBAS). A geostationary satellite can be used to retransmit the differential corrections over a wider area. Two such systems are the wide area augmentation system (WAAS) of the United States Federal Aviation Authority and the European Geostationary Navigation Overlay System (EGNOS). They use multiple reference stations (25 and 30 respectively) and also use multiple geostationary satellites rendering large footprints. The entire United States and Canada are covered by WAAS, while EGNOS provides complete coverage of Europe and Northern Africa. The aim of WAAS and EGNOS is to improve measurements with stand-alone GPSs taking C/A-code measurements, resulting in accuracies of less than 3 m. These services are not available in Southern Africa and verification of measurements will thus not be possible. However, SBAS enabled receivers can be used in Northern Africa to exploit the EGNOS signals. It is also foreseen that the EGNOS signals may be deployed to cover South Africa and by implication also the rest of Africa. Negotiations in this regard are still ongoing. There are also commercially available SBAS services in Africa and South Africa, such as OMNISTAR. Utilisation of these services involves purchasing a receiver with a decoder and subscribing to the service. The service includes range correcting data and quality assurance in that the service provider can use its reference stations to monitor the accuracy of the service. Accuracies of sub-metre level are possible (Kaplan & Hegarty, 2006: 432 – 446; Merry, 2006: 50; Mireault, 2008; Personal communication, E. Avenant, CSIR (SAC), 2009).

28. Precise Point Positioning (PPP). Precise Point Positioning is a technique developed by the Jet Propulsion Laboratory (JPL) of NASA in the 1990s. Post-processing is not conducted with measurements from a reference station, but the precise satellite clock and orbit data provided by an external network, such as the IGS are used. The provided clock and orbit predictions are used to conduct differential corrections with special software. Because no reference station is used, the datum is hidden in the satellite coordinates. A variation of this approach is to take measurements and convert them to receiver independent exchange format (RINEX) and then to send it to a service provider such as AUSPOS, SCOUT, Auto Gipsy or CSRS-PPP to conduct the corrections on your behalf. The data correction is carried out in two ways:

a. Relative Positioning. Data from nearby stations are used with precise ephemeris data to conduct differencing. The positions of the known reference stations are treated as fixed at the epoch of observation resulting in relative accuracies of one to two centimetres.[4]

b. Absolute Positioning. The precise ephemeris and clock corrections of the satellites are used. The satellites' positions are treated as fixed, leading to two to five centimetre accuracies[5].

One challenge is that the precise clock and orbit data are only available approximately two weeks after the measurement. A rapid solution which can provide sub-decimetre accuracies is available 90 min after measurement. Precise point positioning should be exploited as a solution to render accurate measurements in areas where very few reference stations are available or where reference stations cannot be placed (Kaplan & Hegarty, 2006: 449 – 454; Merry, 2006: 74 – 75; Gao & Chen, 2004; Ovstedal *et al.*, 2006; Mireault *et al.*, 2008, King *et al.*).

29. Concluding Remarks. Differential GPS can be used to improve GPS measurements significantly and is used primarily in the mapping environment of the SANDF. Other possible applications of DGPS are military surveying, demarcation of obstacles such as minefields, target acquisition by special forces, the artillery and approaching of airfield in low visibility conditions. In this case base or reference stations can be deployed at temporary airfields in operations that could assist precision landings in low visibility conditions. This type of implementation of DGPS would require radio assisted transmissions to facilitate receiving correctional data from a base station and needs to be investigated by system owners as required. Some mapping entities in the SANDF are or were using SBAS. Commercial SBAS can be replaced by using (no subscription fees) the TrigNet system for post-processing or real-time correction of field measurements. The possible deployment of the EGNOS signal to Southern Africa should significantly improve the usability of navigational type GPS receivers for mapping. Acquiring DGPS measurements elsewhere on the African continent may require the deployment of additional base stations. Maximum baselines for these measurements need to be investigated. Precise Point Positioning should also be investigated as an alternative to correct field measurements taken beyond reasonable baseline lengths. To collect sufficient ground control data for large mapping projects may be a daunting task. This may require using data from navigational GPS measurements, this

---

[4] The Australian Positioning Service can be accessed at http://www.ga.gov.au/geodesy/sgc/wwwgps/ .

[5] The Canadian Spatial Reference System – Precise Point Positioning can be accessed at http://ess.nrcan.gc.ca/2002_2006/gnd/csrs_e.php.

being the only available alternative in some remote areas. The risk is that the accuracy of these measurements is unknown. Therefore, attainable accuracies with navigational GPS receivers and how to improve the accuracy need to be investigated. The earmarked modernisation, especially the L2C code, may improve the accuracy of navigational GPS receivers to the required level for mapping purposes. However, this will only be practical in the future, as some time will elapse before a large number of GPS receivers that utilise the new codes will be in the hands of travellers and adventurers who are the basis of this data source.

CHAPTER 5: GPS IN THE FIELD – APPLICATIONS

INTRODUCTION

1. In order to confirm the attainable levels of precision and accuracy with different types of GPS receivers a small network consisting of five points were laid out in the vicinity of Air Force Base Waterkloof (AFBWK). These points were selected specifically to minimise multipath and shadowing of GPS satellite signals. A further consideration was to select stable points which would not be influenced significantly by weather and temperature changes. The accessibility of these points for future use as calibration points was also considered. For this purpose all points were placed on permanent building structures within protected areas. Two points were located at Trig Beacons at Schanskop and Zwartkop. Point No 2 at the reservoir at Radcliffe is close to a high-rise water tank that may cause some multipath. The points were established by fixing self-centring-plates, provided by HartRAO, with an adhesive onto the selected buildings. For the Trig Beacons 30 cm antenna poles, provided by OPTRON Geomatics, were used.

2. The positions of the measuring points presented on an aerial photograph background acquired by the SAC of the CSIR are displayed in Figure 5-1. Figure 5-2 and 5-3 indicate distances of the network.

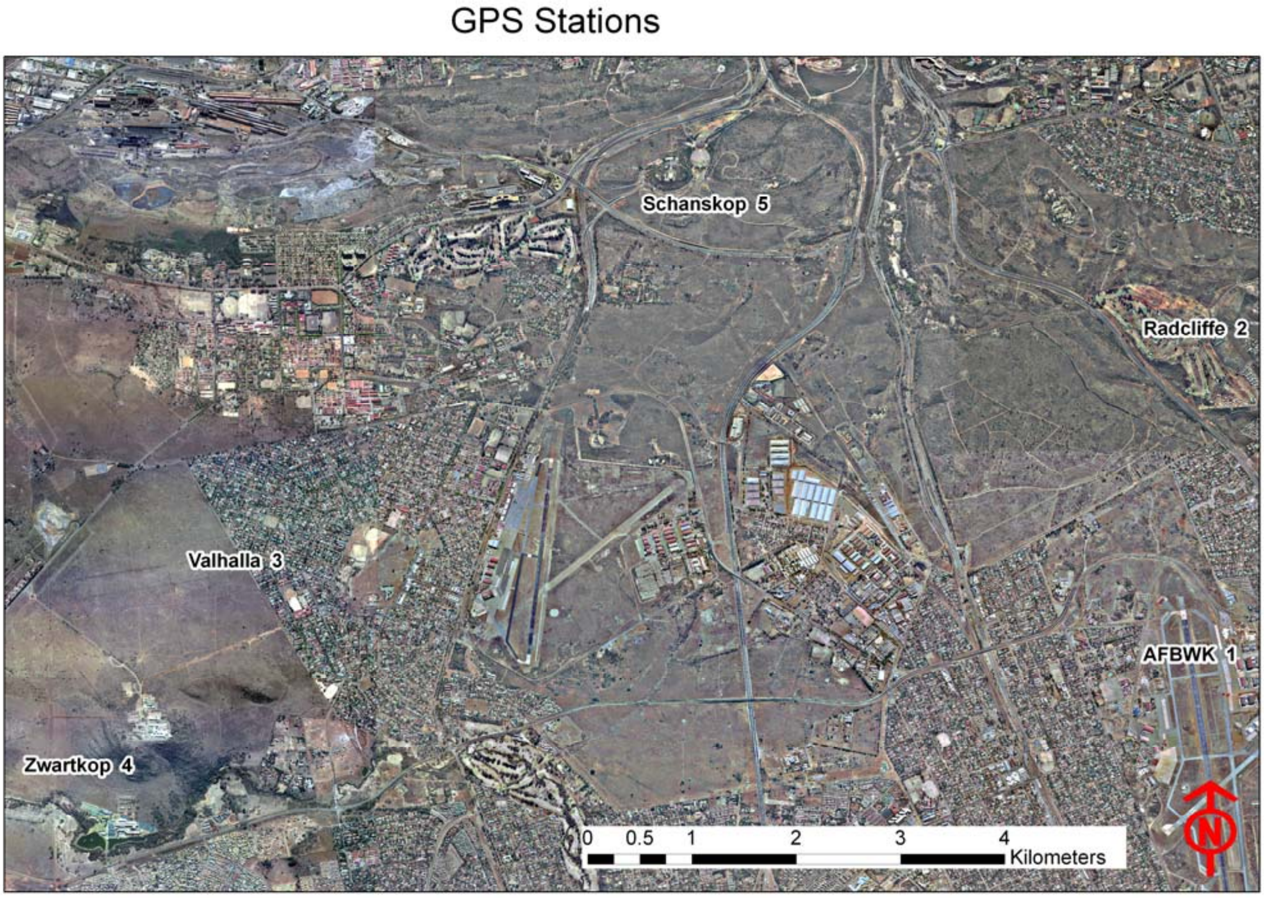

Figure 5-1: Location of GPS Station Positions in Local Network.

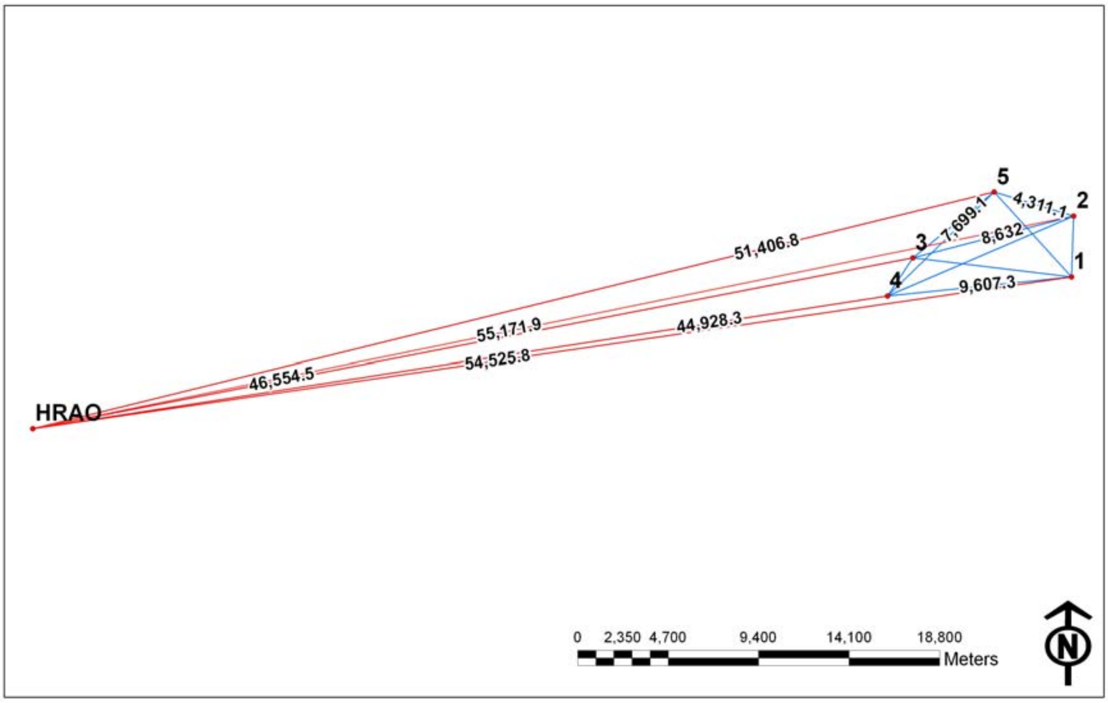

Figure 5-2: Distances between Stations (Global View - WGS 84, UTM Projection, Z35S

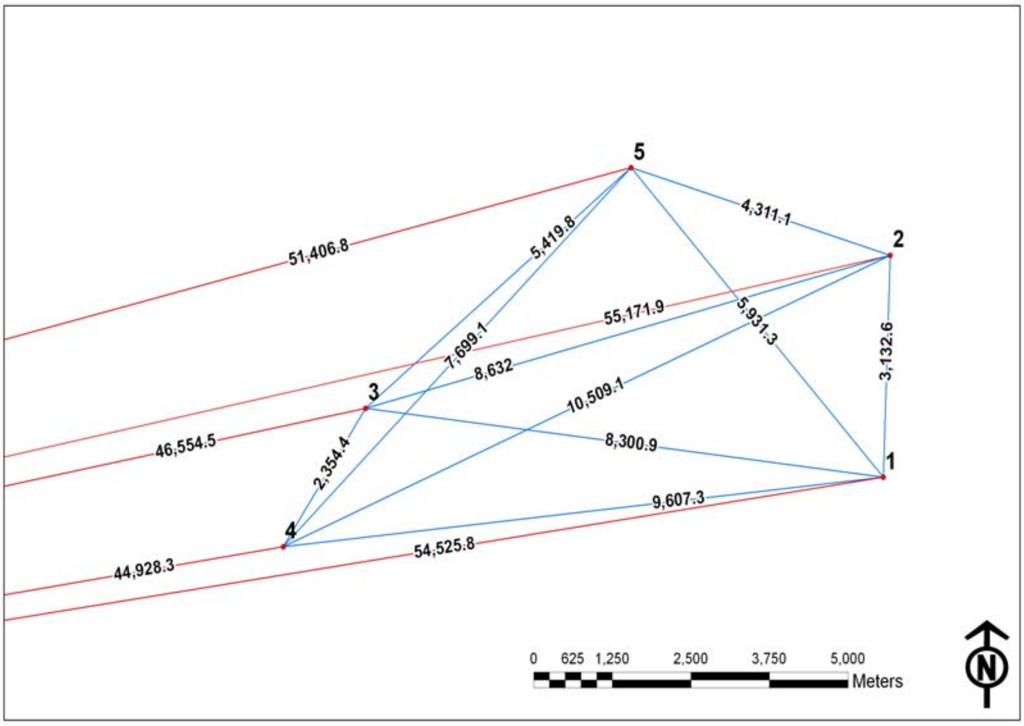

Figure 5-3: Distances between Stations (Focused View - WGS 84, UTM Projection, Z35S)

MEASUREMENTS WITH GEODETIC TYPE GPS RECEIVERS

3. The objective was to measure these points to the highest level of accuracy possible so that they can serve as reference (calibrating) points for other measurements. This was done by deploying Topcon GB-1000 geodetic type GPS receivers at each point of the Network for approximately 24 h on 3 to 4 March 2010. This was followed with a similar measurement one week later on 10 to 11 March 2010. Data collected with these receivers were processed with the HRAO station as discussed in paragraph 8 and 9 of Chapter 2. The ellipsoidal coordinate values with standard deviations are presented in Table 5-1.

Table 5-1: Topcon GB-1000 measurement values of Network - Precision

Name	Latitude	Longitude	Ell.Height (m)	Std Dev n (m)	Std Dev e (m)	Std Dev u (m)
1	25°48'59.05113"S	28°13'29.80979"E	1525.806	0.003	0.003	0.007
2	25°47'17.27190"S	28°13'32.89137"E	1575.416	0.003	0.003	0.007
3	25°48'29.78848"S	28°08'33.49215"E	1458.849	0.003	0.003	0.007
4	25°49'33.65783"S	28°07'46.92209"E	1565.014	0.003	0.003	0.007
5	25°46'38.36577"S	28°11'04.21041"E	1554.492	0.003	0.003	0.007
HRAO	25°53'24.37593"S	27°41'13.13139"E	1414.156	0	0	0

4. It can be accepted that the closeness to the central value or mean is a representation of the precision of the measurement as indicated when measurement accuracy and error theory were discussed. From the measured values it can be seen that the standard deviation for both latitude (Std Dev n) and longitude (Std Dev e) values are 3 mm, while the value for heights (Std Dev u) is 7 mm. These levels of precision are much higher than is needed for munitions, navigation or mapping in the SANDF. The purpose of these surveyed points is merely to serve as reference for other measurements and calibration of other receivers.

5. It is important to determine the repeatability of measurements at these high levels of precision. For this purpose measurements were processed at different time intervals. An additional advantage of this approach is to indicate the influences on GPS measurements that were discussed in Chapter 4. The standard deviation is again used as a measure of precision. One hour measurements at the different stations over the time period 3 March 2010 at 11:00 to 4 March 2010 at 06:00 local time delivered interesting results as indicated in Figures 5-4 to 5-8. The 19 hour continuous measurement was divided in one hour segments and processed with Topcon Tools to determine deviations from the mean.

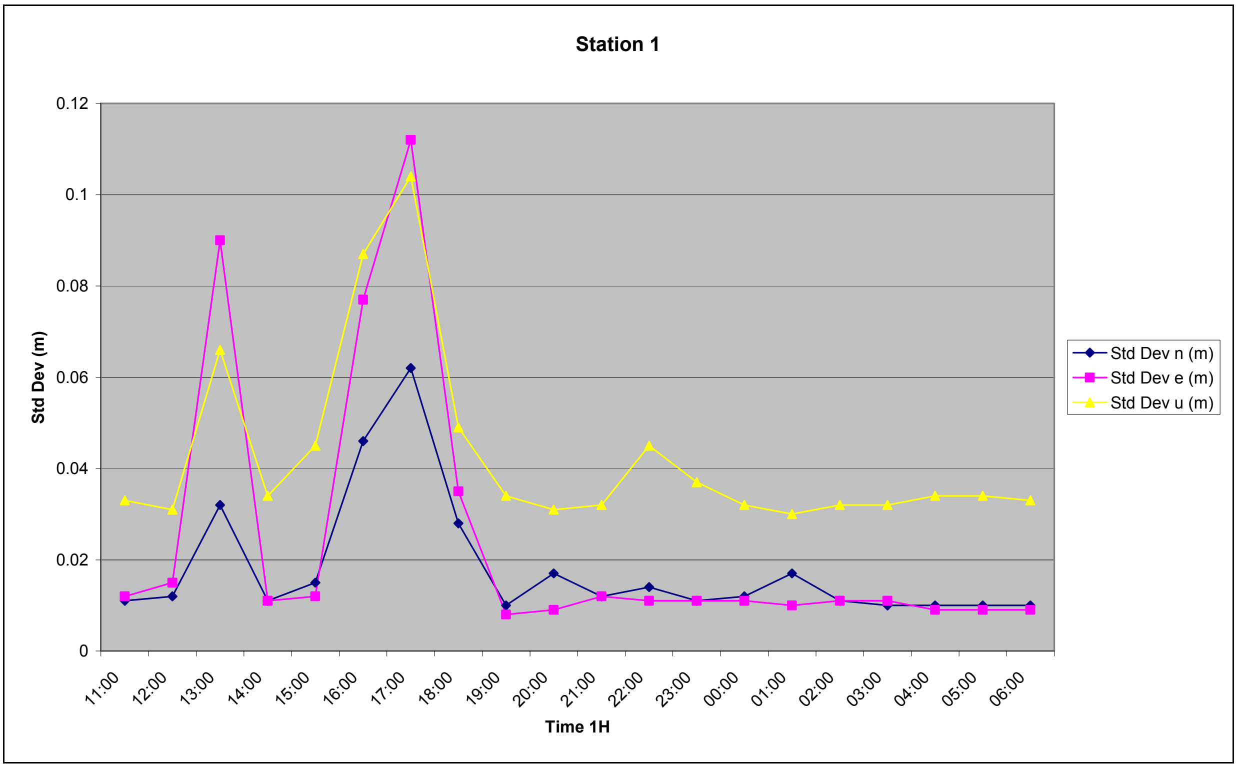

Figure 5-4: Station 1 - 2010_03_03 (1H)

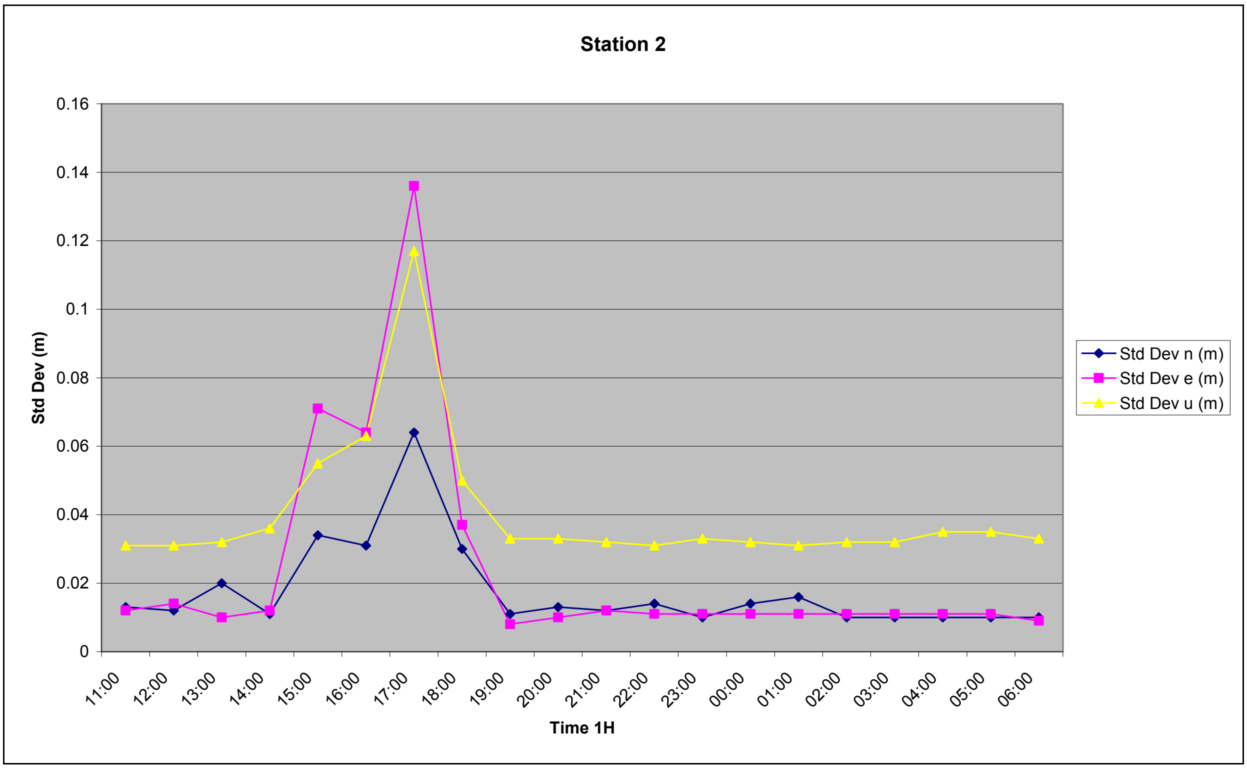

Figure 5-5: Station 2 - 2010_03_03 (1H)

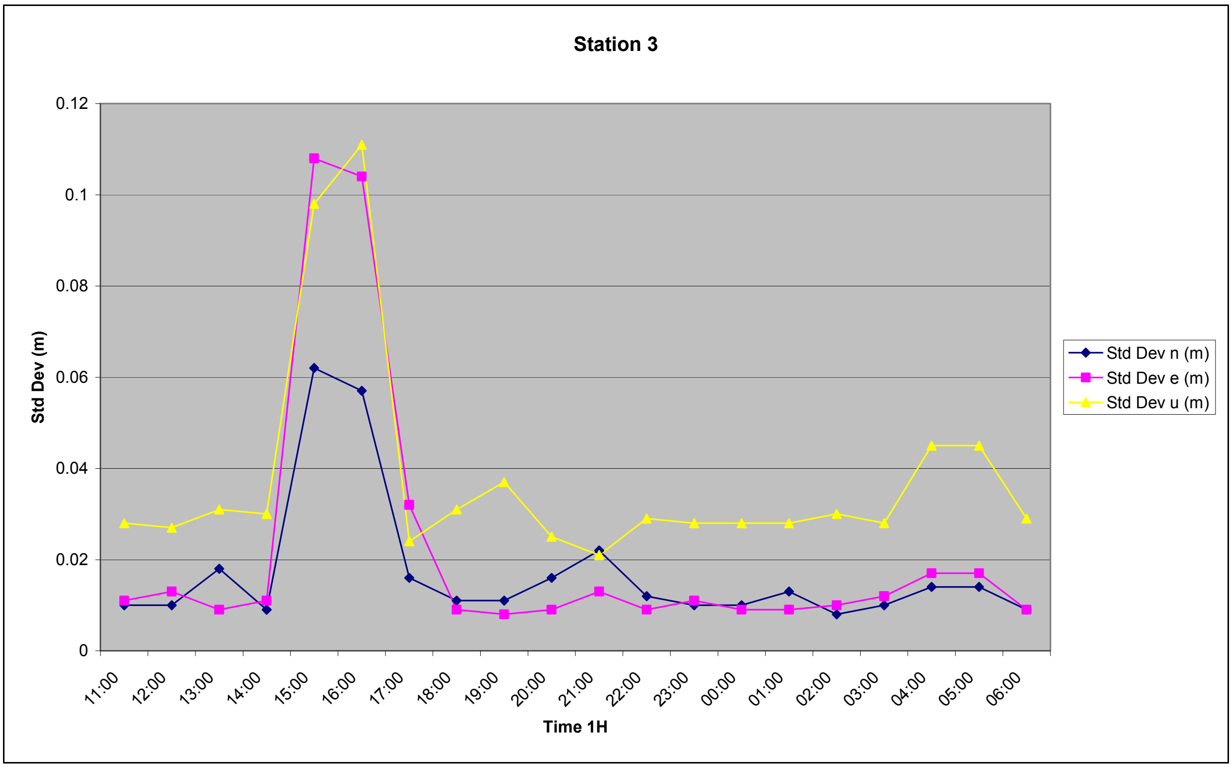

Figure 5-6: Station 3 - 2010_03_03 (1H)

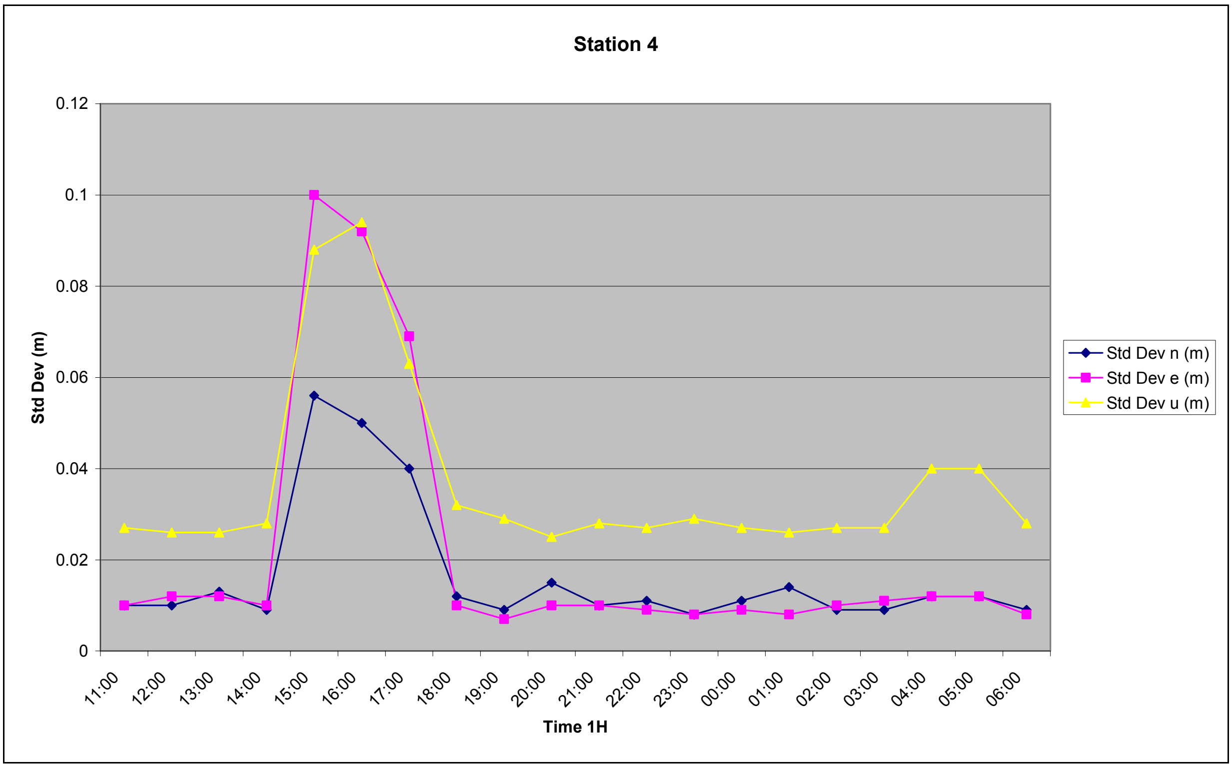

Figure 5-7: Station 4 - 2010_03_03 (1H)

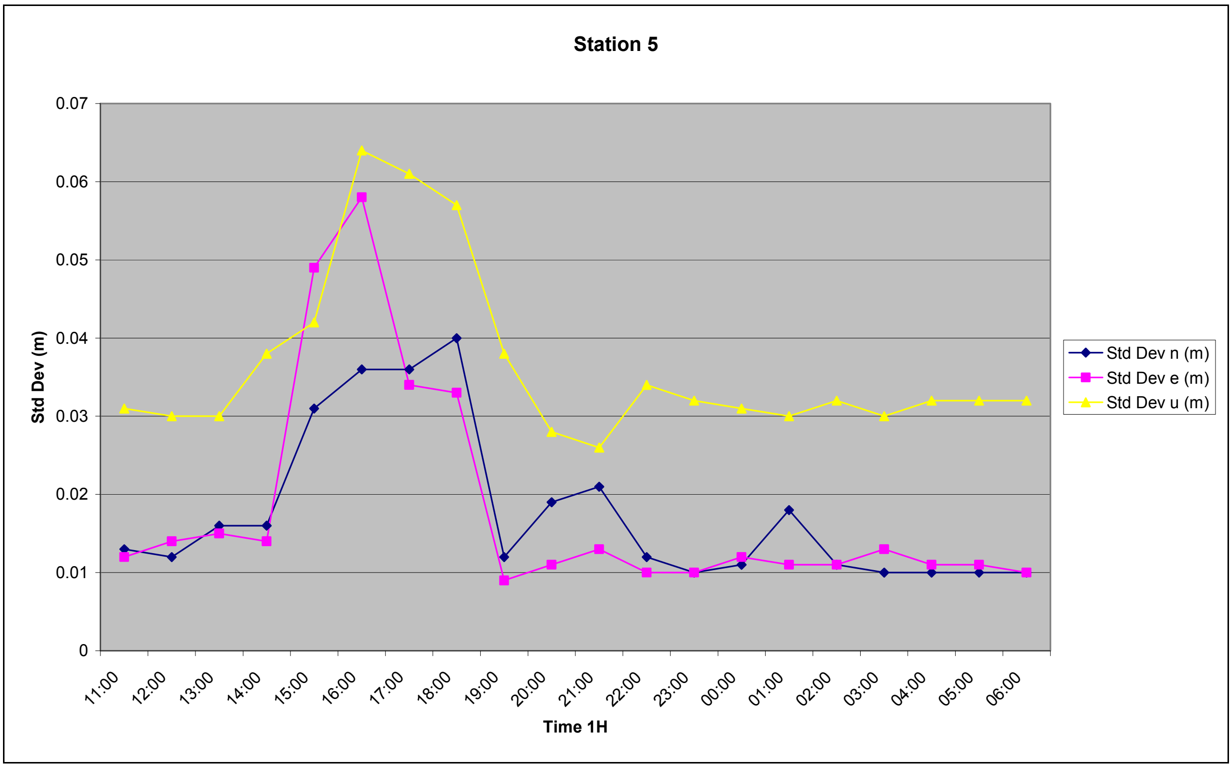

Figure 5-8: Station 5 - 2010_03_03

6. From the graphs of each station it can be seen that the standard deviation for both the latitude and longitude values are in the vicinity of 1 cm, while the standard deviation for the height values are between 2 and 3 cm throughout the measurement period. However,

between 14:00 and 18:00 the values peaked to between 6 and 14 cm. At Station 1 there was an earlier peak at about 12:00 to 1400. Stations 3 and 4 both experienced fluctuations at about 03:00 to 06:00. Station 4 at Zwartkop is an ideal location with almost no possibility of multipath or shadowing. The fact that the peak is present at all stations over the same period and that the measurement precision (standard deviation) returns to previous levels after the peak eliminates GPS receiver deficiencies as a reason for these peaks in the deviations. When the number of satellites tracked by the GPS receivers is investigated (shown in Figure 5-9) it seems that there was a drop from 11 to 9 satellites over the period of the peak measurement which could contribute to this peak. However, the number of satellites tracked drop even further to eight between 19:00 and 20:00 and jumped irregularly between 20:00 and 23:00 with relatively little impact on the precision of measurements throughout the network. When the PDOP values are investigated (shown in Figure 5-9) it can be seen that the values varied over the measurement period. At the start of the measurement the PDOP values are high, but vary over the observation period with no convincing peaks or dips that correlate with the changes in measured values.

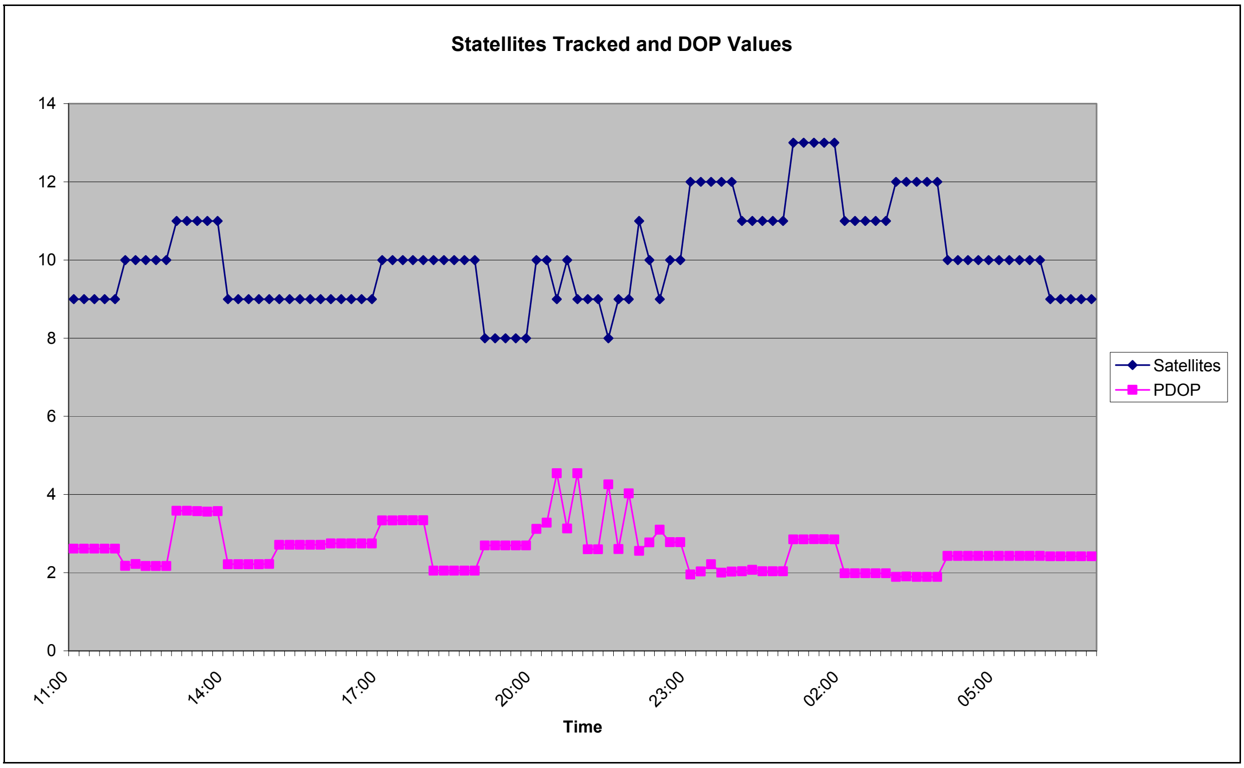

Figure 5-9: Satellites and PDOP Values

7. When the behaviour of the ionosphere during the time of measurement is investigated, it can be observed that the electron density or Total Electron Content (TEC) peaked between 200 km and 600 km above the earth and that the peak was much higher at 14:00 than at 18:00 when it tended to subside as can be seen in Figure 5-10. When the TEC between 200 km and 600 km is evaluated it can be seen that it is at its highest at 300 km

above the earth where after it subsides. At 250 km the peak marginally shifts to the right and peaks between 11:00 and 17:00 as indicated in Figure 5-11. It can be deduced that the combination of the peak in the TEC of the ionosphere, the drop in the number of satellites tracked and the equivalent rise in PDOP values contributed to the sharp peak in the standard deviations observed over the whole network between at 12:00 and 18:00 on 3 March 2010. These influences on the precision of measurement also align with the discussion on GPS measurement errors and biases discussed in Chapter 4

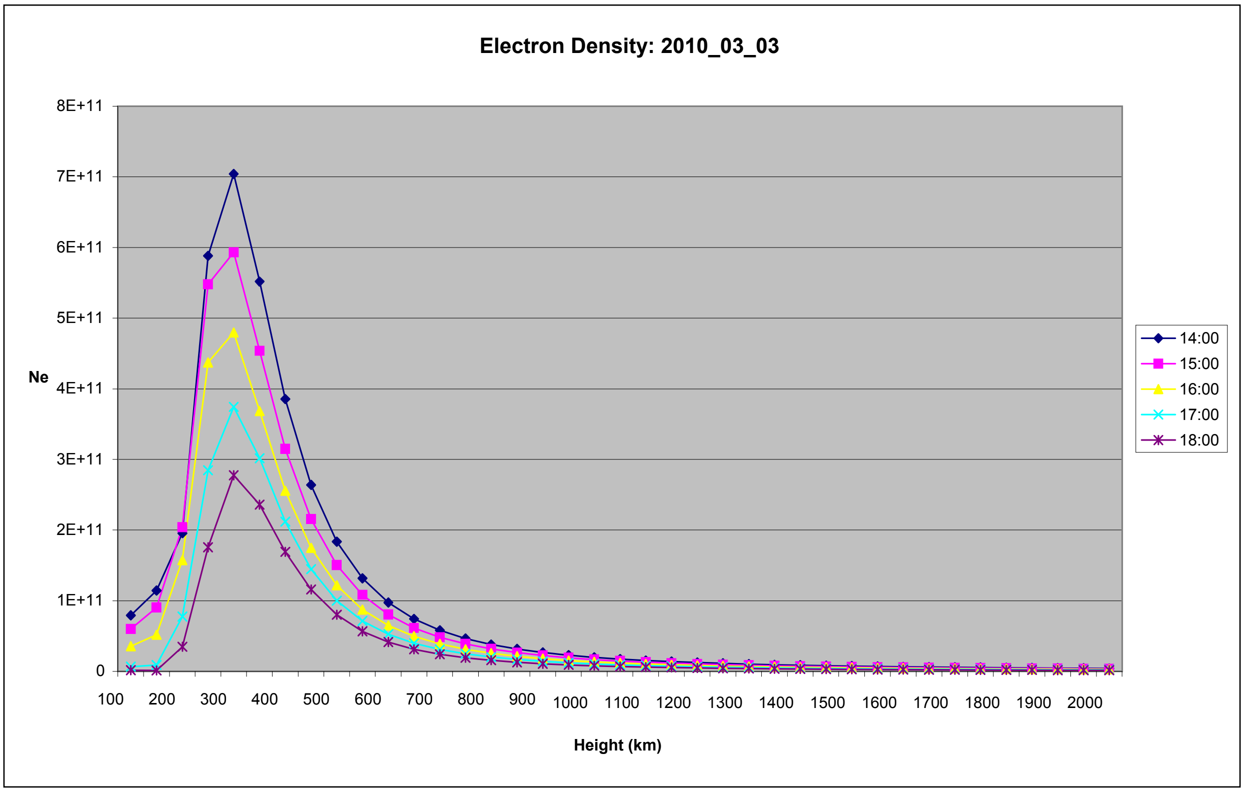

Figure 5-10: Electron Content: 100 km to 2 000 km

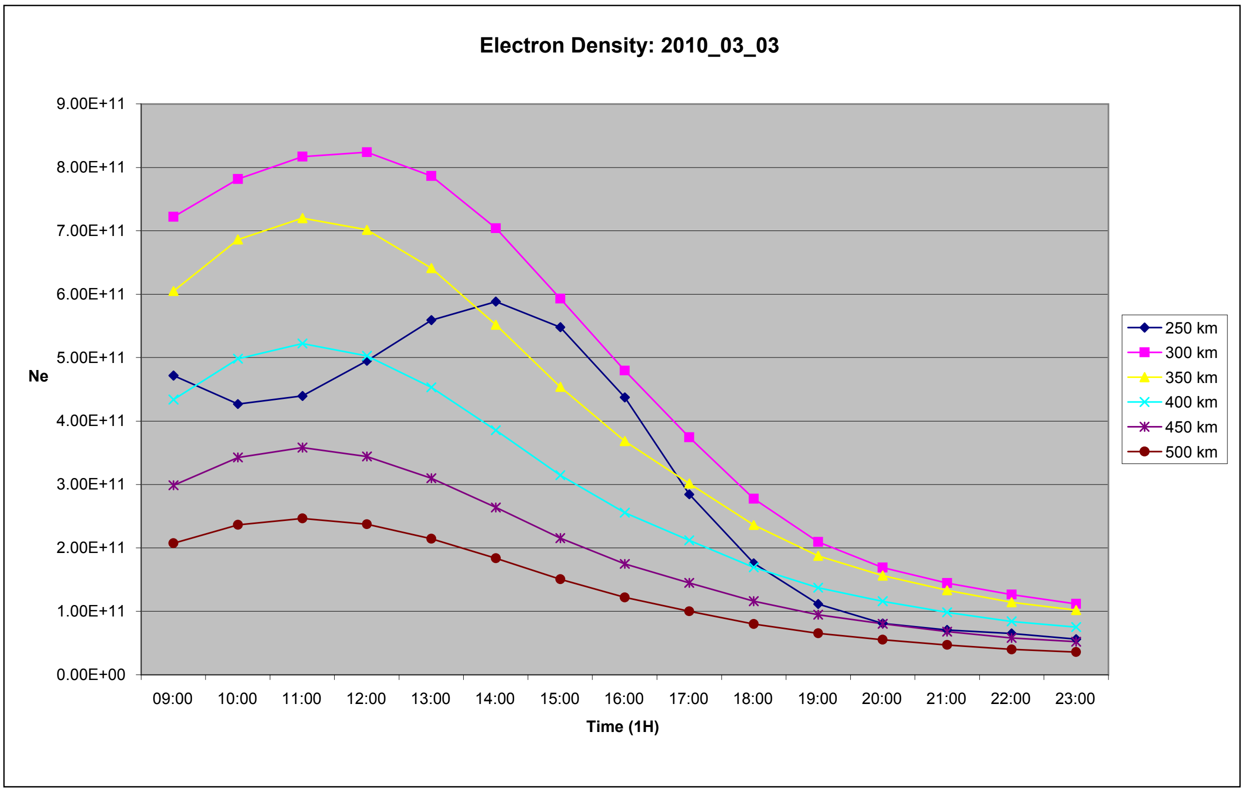

Figure 5-11: Electron Density: 09:00 - 23:00[1]

8. The positive correlation between the TEC and GPS precision can be graphically presented as indicated in Figure 5-12. Take note that the linear trend-lines in the graph only present the time period between 13:00 and 17:00 and only the ionosphere levels between 250 km and 350 km were selected for the comparison. These are the ionospheric parameters which had an influence on the GPS measurements.

---

[1] : Source: http://modelweb.gsfc.nasa.gov accessed in May 2010.

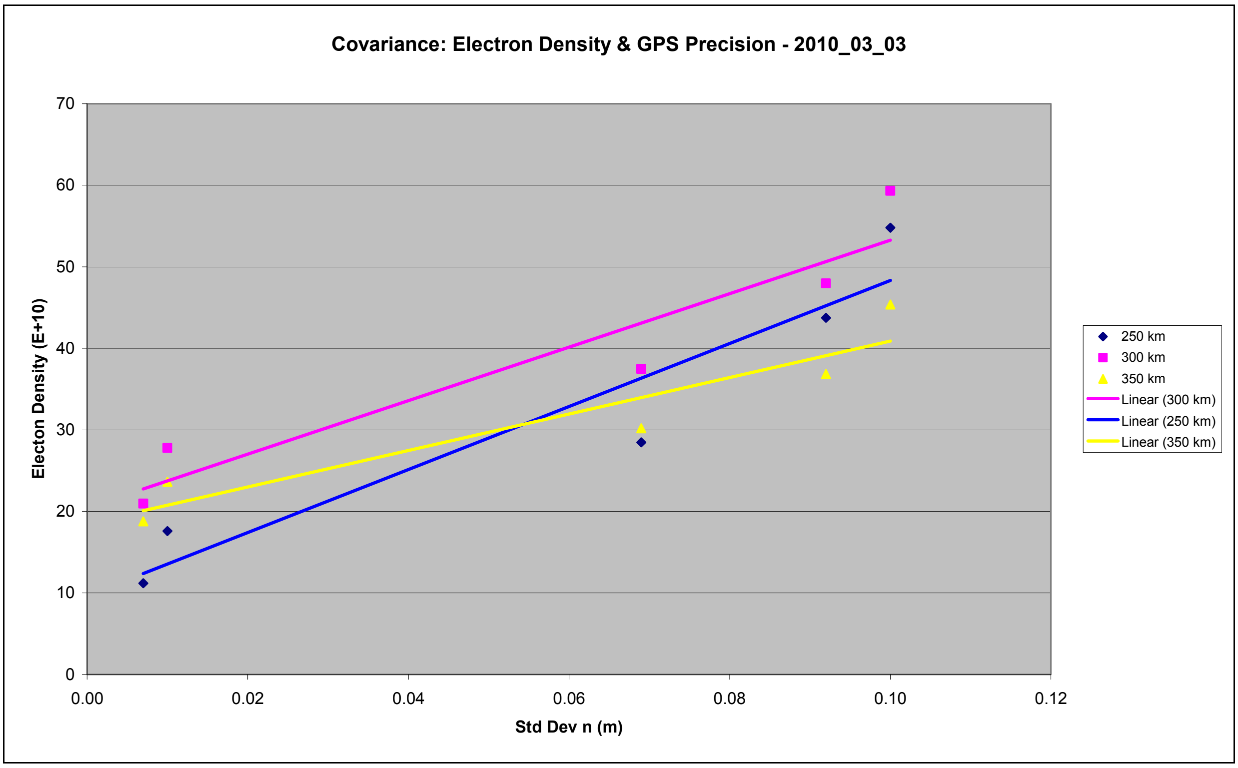

Figure 5-12: Correlation between Electron Density and GPS Precision

9. The positive correlation between the TEC and the GPS precision is revealed by the correlation coefficient that is presented in Table 5-2:

Table 5-2: Correlation between Electron Density and GPS Precision on 2010_03_03

	250 km	300 km	350 km
Covariance	0.266	0.046	0.065
Correlation Coefficient	0.422	0.168	0.095

10. The figures for the measurements on 10 March 2010 were as follows (Table 5-3):

Table 5-3: Correlation between Electron Density and GPS Precision on 2010_03_10

	200 km	250 km	300 km	350 km
Covariance	0.100	0.297	0.509	0.428
Correlation Coefficient	0.415	0.517	0.688	0.705

11. The finding that the TEC values peak between 12:00 and 18:00 local time is confirmed by a global ionosphere model dated 17 April 2002. See Figure 5-13. From the model it can also be seen that the TEC is a function of location and time which is at its highest between 40^{o} latitude and between approximately 12:00 and 18:00 local time. Thus, the TEC and its influence in GPS measurements will be on its lowest between 21:00 and 11:00 local time.

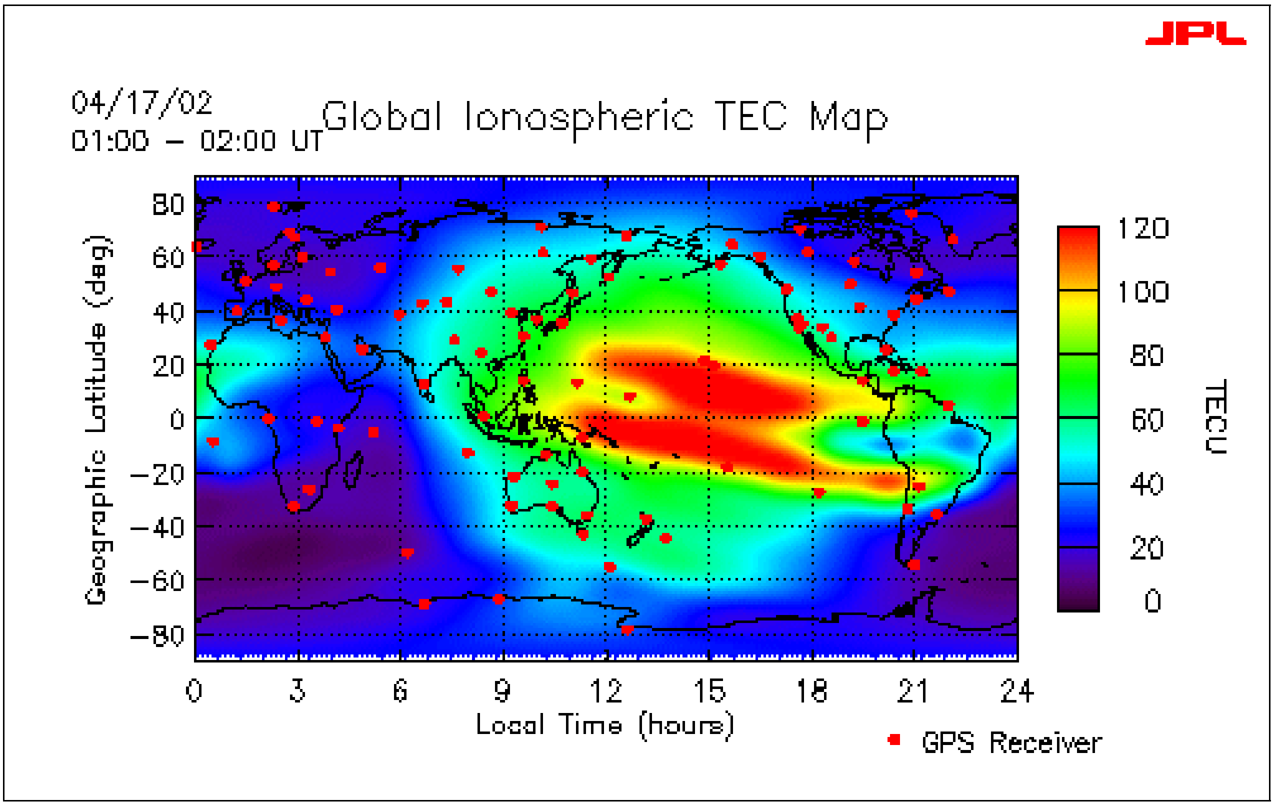

Figure 5-13: Global Ionosphere Model[2]

12. When two hour period measurements were processed, the peak between 14:00 and 18:00 still persisted throughout the network as indicated in Figures 5-14 and 5-15.

---

[2] Model obtained form the JPL website at http://iono.jpl.nasa.gov/gim_demo.html accessed November 2010.

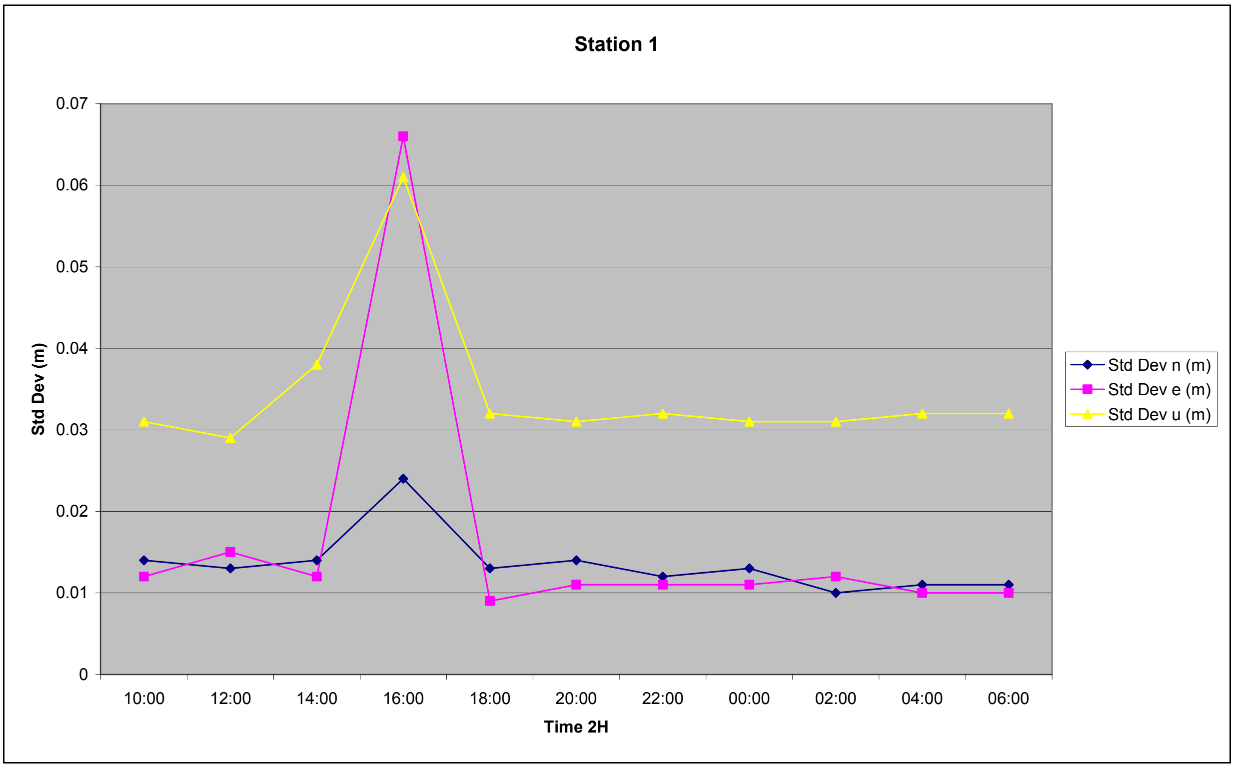

Figure 5-14: Station 1 - 2010_03_03 (2H)

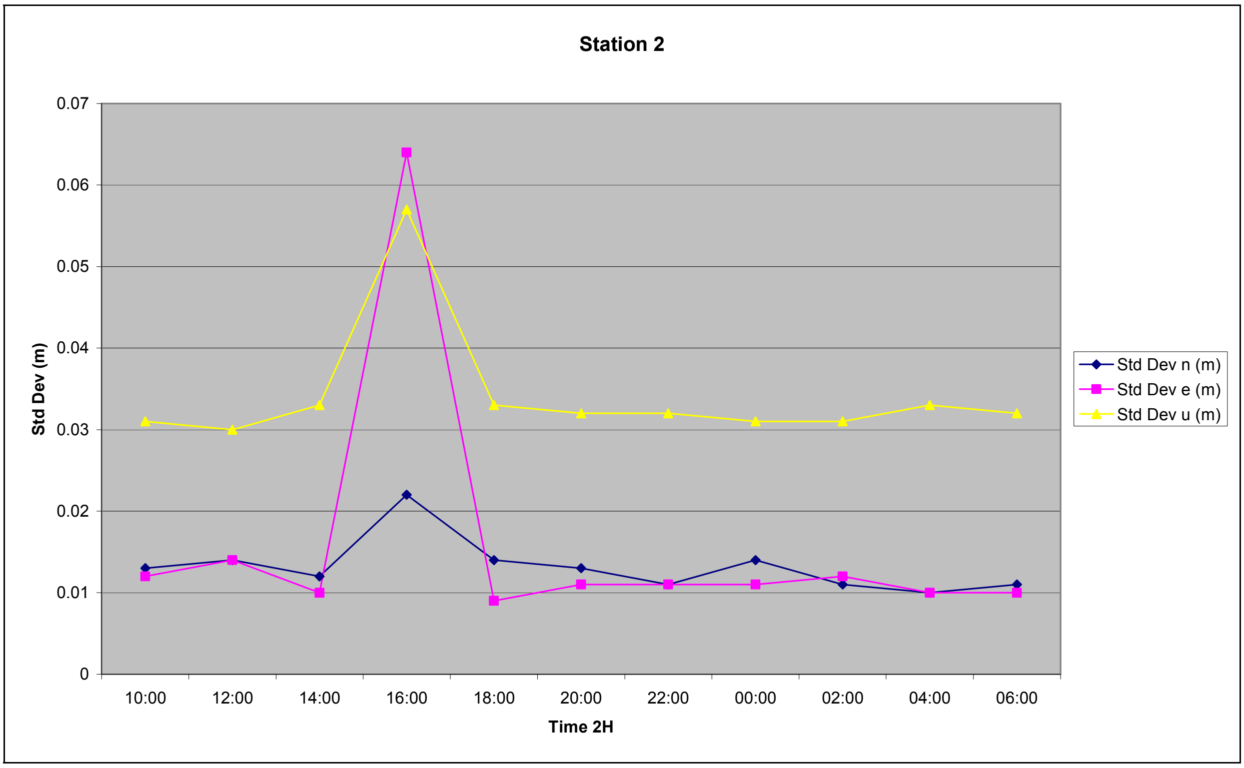

Figure 5-15: Station 2 - 2010_03_03 (2H)

13. The peak continues when the time interval is increased to three hours as indicated in Figures 5-16 and 5-17.

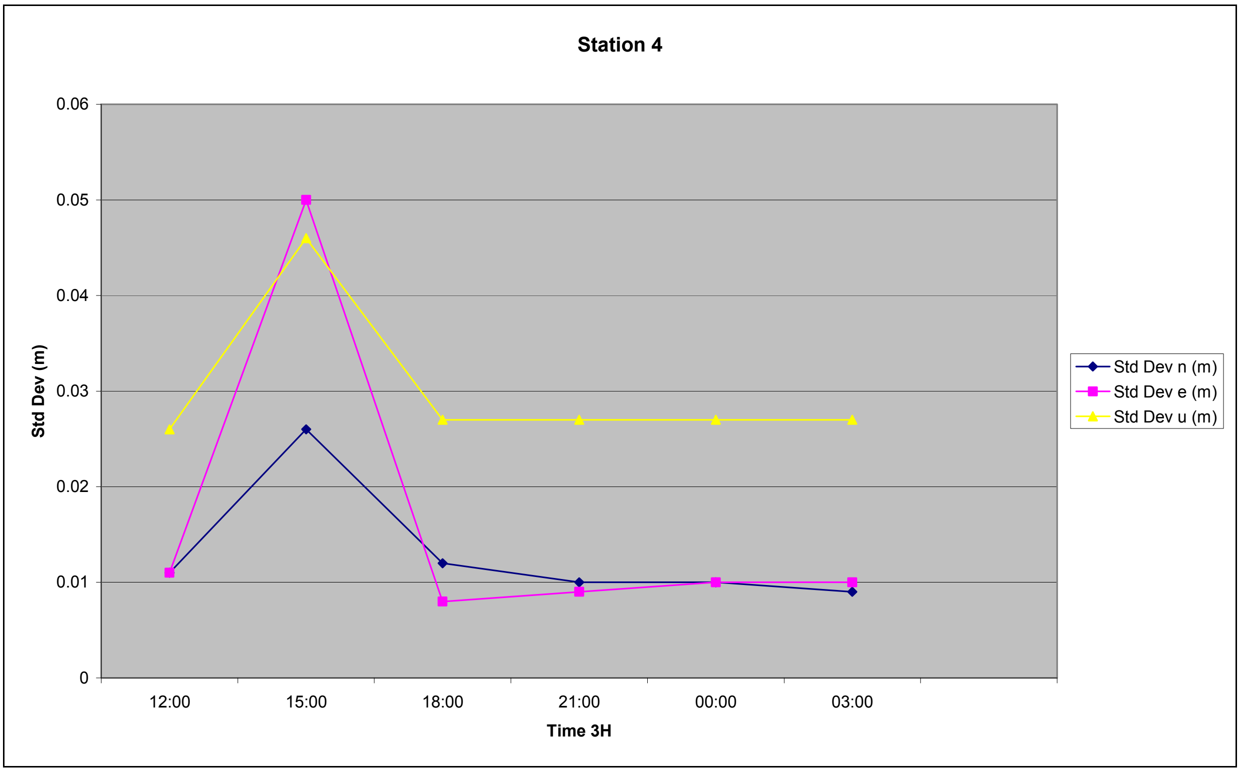

Figure 5-16: Station 4 - 2010_03_03 (H3)

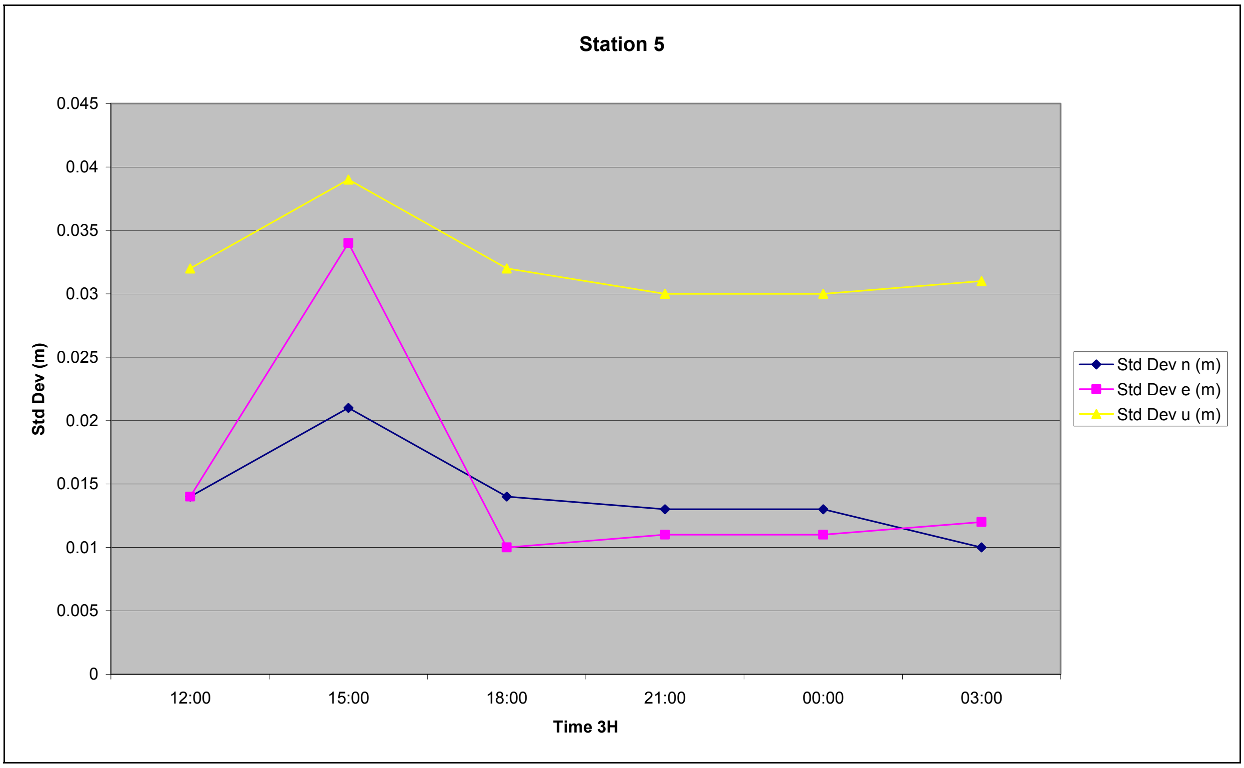

Figure 5-17: Station 5 - 2010_03_03 (3H)

14. A similar trend was experienced with the measurements on 10 to 11 Mar 10 as indicated in Figures 5-18, 5-19 and 5-20.

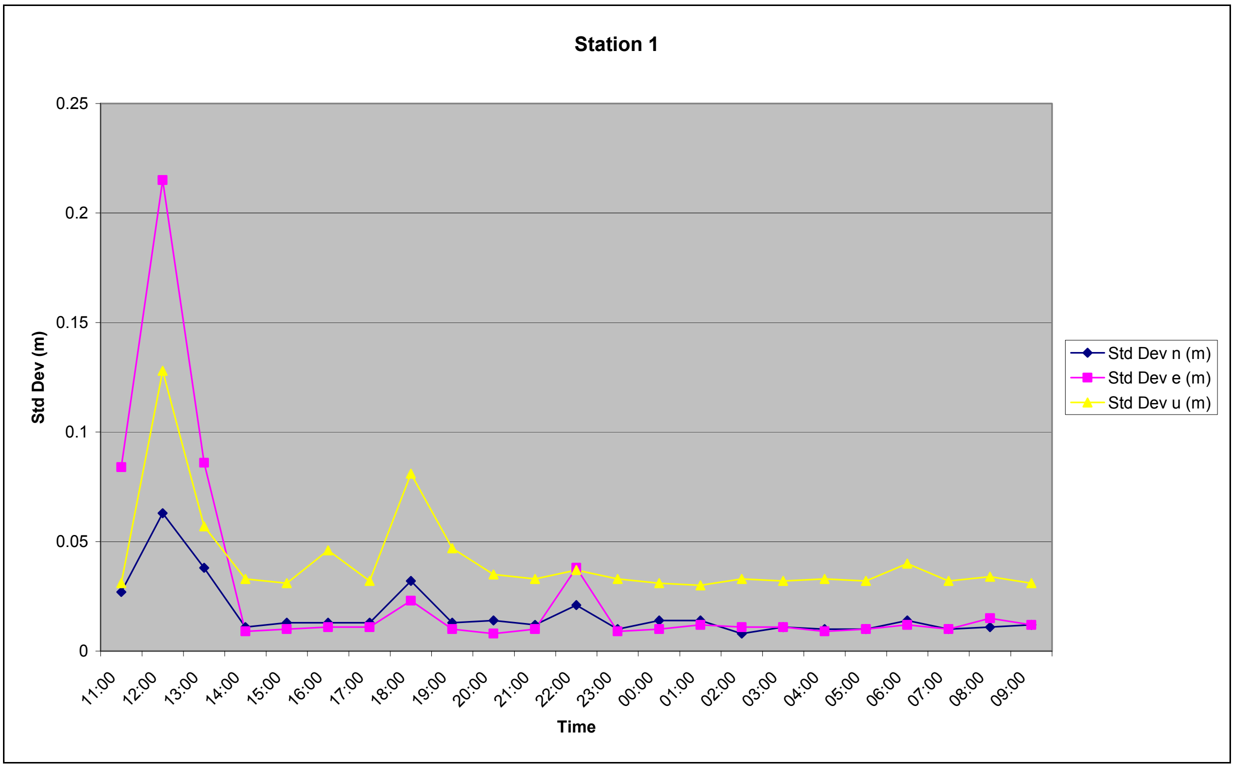

Figure 5-18: Station 1 - 2010_03_10 (1H)

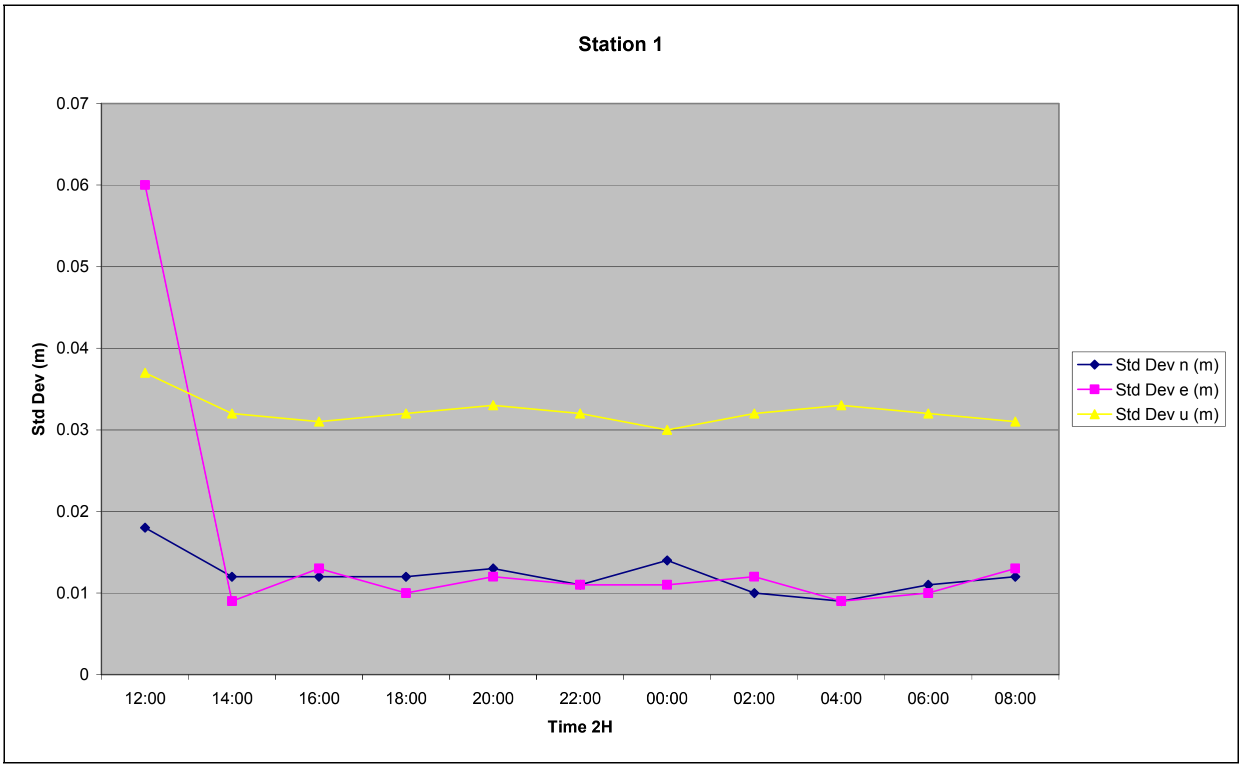

Figure 5-19: Station 1 - 2010_03_10 (2H)

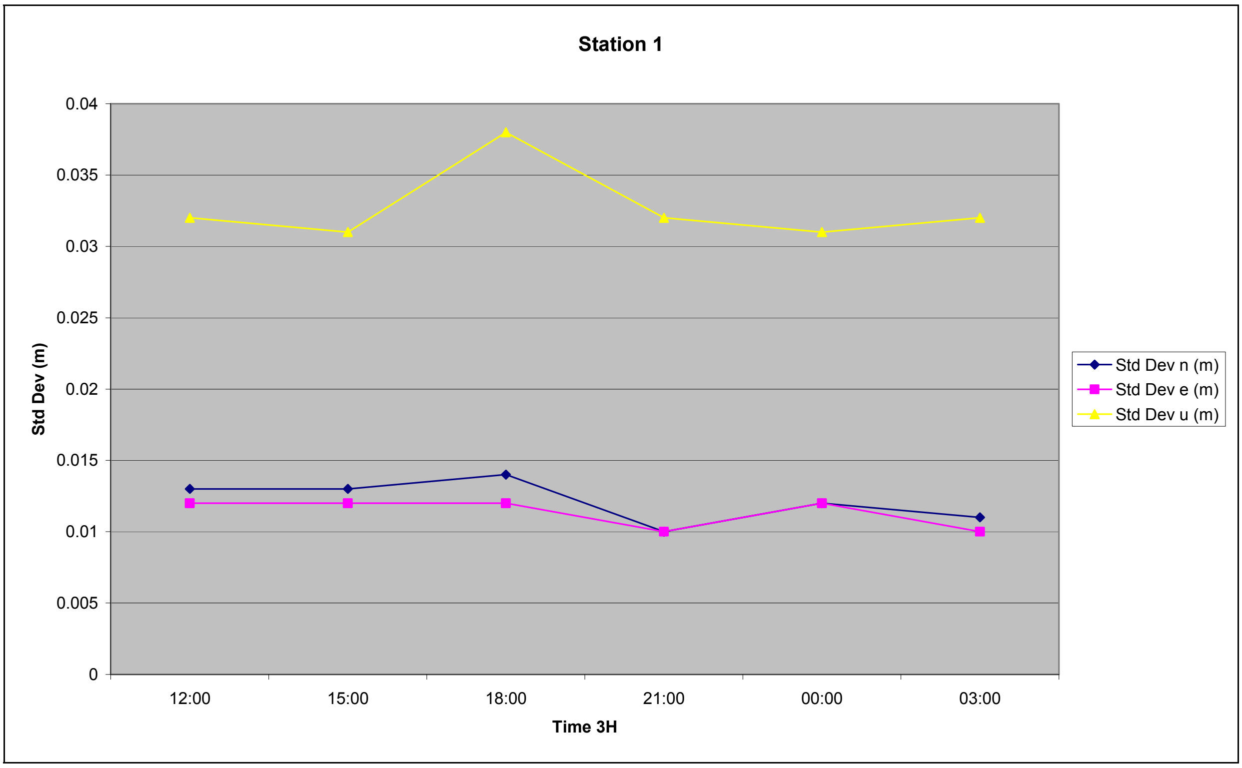

Figure 5-20: Station 1 - 2010_03_10 (3H)

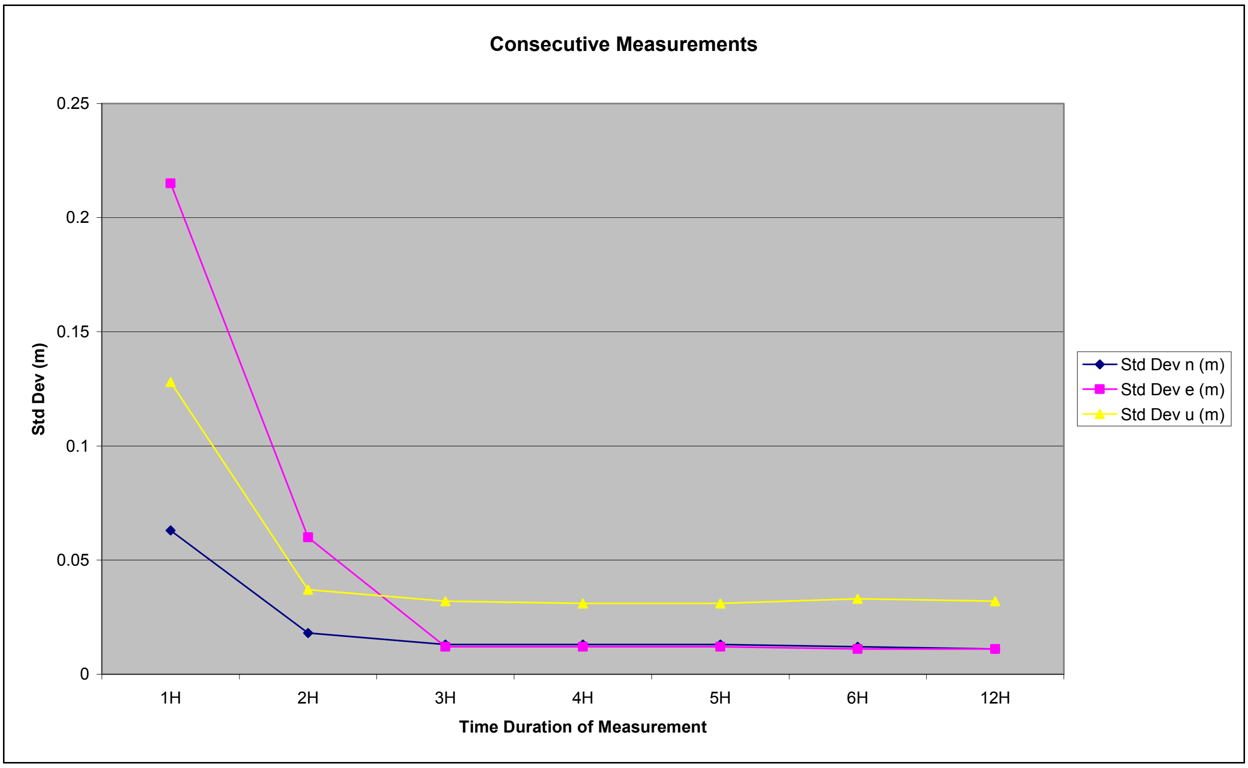

Figure 5-21: Consecutive Measurements

15. With an increase in the measurement intervals, the precision increased and the peak disappeared. Precision increased as the measurement period increased with consecutive measurements as is indicated in Figure 5-21. Measurements started from 12:00, initially with

a one hour measurement increasing hourly to a 6 h measurement and ultimately to a 12 h measurement. With a three hour measurement the precision of the latitude and longitude values drops to approximately 11 mm and the height values to 32 mm. The level of precision does not increase significantly with a further increase in the measurement period and is almost the same at the 12 h measurement. When the observation period is increased to 24 h the precision of the latitude value drops to 3 mm, the longitude to 4 mm and the height to 9 mm. With a 48 h measurement the latitude and longitude values are both 3 mm and the height value 7 mm as indicated in Table 5-1.

16. The accuracy of the measurements with the Topcon GB-1000 can only be determined by comparing it with measurements with another receiver with a higher and known accuracy. For this reason measurements were taken by means of an antenna splitter from the same antenna of the HRAO ITRF station at HartRAO, effectively creating a zero-baseline test. Thus, HRAO was taken as a reference measurement. The HRAO receiver is an Ashtech UZ-12 supplied by JPL and conforms to the highest accuracy standards. It uses an Ashtech 701945E_M choke ring antenna.[3] All external influences that could cause the GPS receivers to take inaccurate measurements needed to be eliminated. These aspects were addressed as follows:

a. Satellite Clock and Orbit Errors. The precise clock and orbit correction data were downloaded from the IGS website and measurements were processed with this data to eliminate their effects.

b. Ionospheric and Tropospheric Effect. The fact that the same antenna was used by both receivers ensured that the effect of both the ionosphere and the troposphere were exactly the same for both receivers.

c. Satellite Availability. The same antenna was used over the same time period. Thus, the same satellites were used by both receivers and therefore GDOP values are the same.

d. Multipathing and Shadowing. The HRAO station is placed according to IGS specifications that require the site to be free of any multipathing or shadowing.

---

[3] More specifications about the HRAO setup can be acquired at http://igscb.jpl.nasa.gov/igscb/station/log/ hrao_20090212.log.

e. Receiver Clock Errors and Receiver Noise. These are the only factors that could cause the two receivers to measure differently. The HRAO receiver uses a hydrogen maser that is extremely stable and is accurate to approximately one second per one million years. The HRAO station has been providing IGS data for more than 14 years and has been included in the ITRF solution. It can therefore be used with confidence as a reference.

17. The measurements obtained over the period 14 to 22 September 2010 with the Topcon GB-1000 at HartRAO (the same receiver that was used at Station 3), were processed with WGS84 as the reference ellipsoid and heights are in ellipsoidal values. Results were processed with the Topcon Tools software. For this purpose the HRAO station was fixed at the ITRF 2005 (2008/01/09) epoch values to ensure values were comparable with the rest of this study. The results were exported in ellipsoidal coordinate values. However, only the deviations of the TopconGB-100 from the HRAO receiver for the nine days measurement period are contained in Table 5-4 in metre values, including precision, PDOP values and RMS.

Table 5-4: Topcon GB-1000 measurements comparison with the HRAO receiver - Accuracy

Date	Δ N (m)	Δ E (m)	Δ h (m)
2010_09_14	0	0	0
2010_09_15	0	0	0.001
2010_09_16	0	0	0.001
2010_09_17	0	0	0
2010_09_18	0	0	0.001
2010_09_19	0	0	0.001
2010_09_20	0	0	0.001
2010_09_21	0	0	0.001
2010_09_22	0	0	0.001

18. From these values it can be seen that the two receivers for all practical purposes measured the same values. The deviations of the Topcon GB-1000 from the HRAO receiver are in the vicinity of 1 mm and can be attributed to receiver noise. Measurements with the Topcon GB-1000 receiver can therefore be considered as accurate to an indiscernible level for the purposes of this study.

MEASUREMENTS WITH MAPPING TYPE GPS RECEIVERS

19. The same procedure as with the Topcon GB-1000 was followed when measurements were obtained with a mapping type GPS, the Trimble ProXH fitted with a Zephyr antenna, at Station 3. To make comparable measurements, datasets were differentially corrected similar to the Topcon GB- 1000. The measurements were taken to simulate operational conditions. For this reason the ProXH was used only with the onboard battery pack that renders approximately an eight hour measurement period. Measurements were therefore repeated to ascertain the repeatability of the attainable accuracies and precision levels.

20. Results of these measurements at Station 3 were downloaded from the GPS receiver and processed with the Topcon Tools software are contained in Table 5-5.

Table 5-5: Trimble ProXH measurement values at Station 3 - Precision

Name	Latitude	Longitude	Ell.Height (m)	Std Dev n (m)	Std Dev e (m)	Std Dev u (m)
2010_03_23	25°48'29.78874"S	28°08'33.49214"E	1458.783	0.014	0.01	0.029
2010_03_24	25°48'29.78885"S	28°08'33.49243"E	1458.799	0.012	0.01	0.029
2010_03_25	25°48'29.78891"S	28°08'33.49187"E	1458.784	0.014	0.013	0.026
2010_03_26	25°48'29.78871"S	28°08'33.49222"E	1458.781	0.014	0.013	0.025
2010_03_27	25°48'29.78843"S	28°08'33.49258"E	1458.808	0.014	0.012	0.026

21. The first obvious result evident from Table 5-5 is that the precision of measurements for the longitude and latitude values are in the vicinity of 10 mm to 14 mm, while the height values are 25 mm to 29 mm. However, when the hourly measurements are evaluated certain trends can be seen as depicted in Figures 5-22 to 5-25.

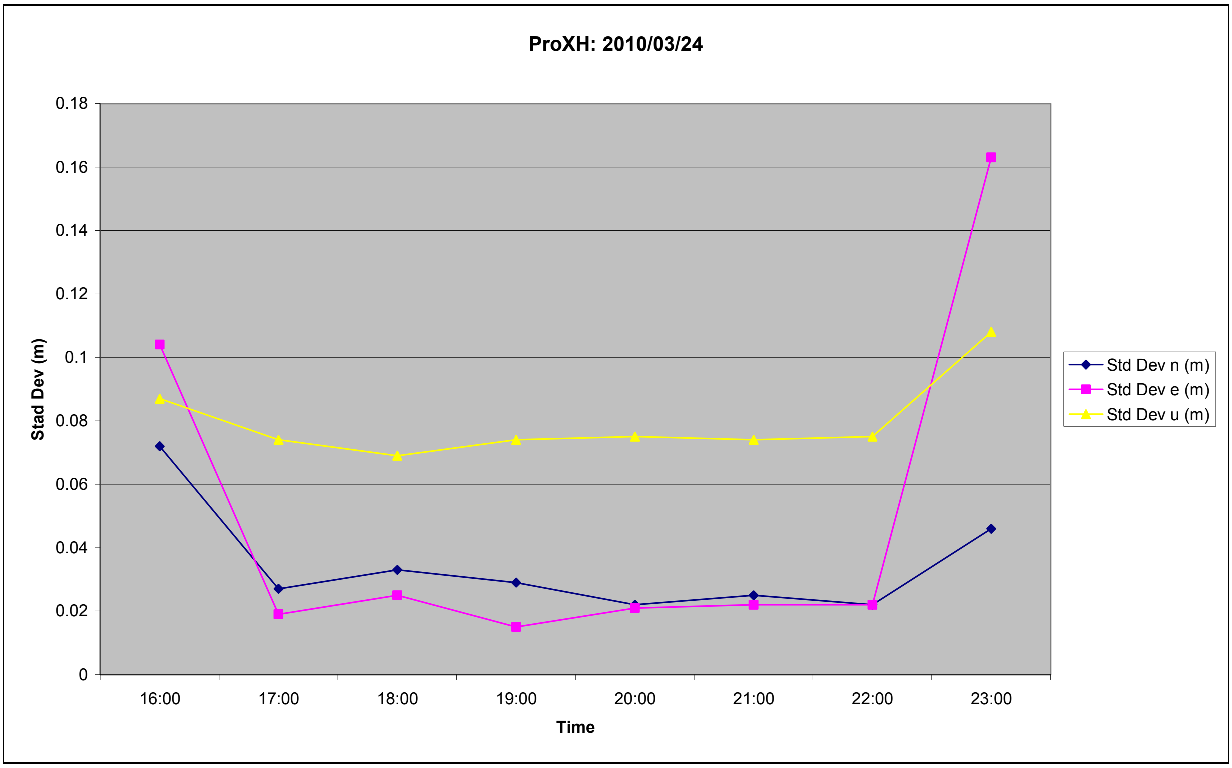

Figure 5-22: Station3 - ProXH - 2010_03_24

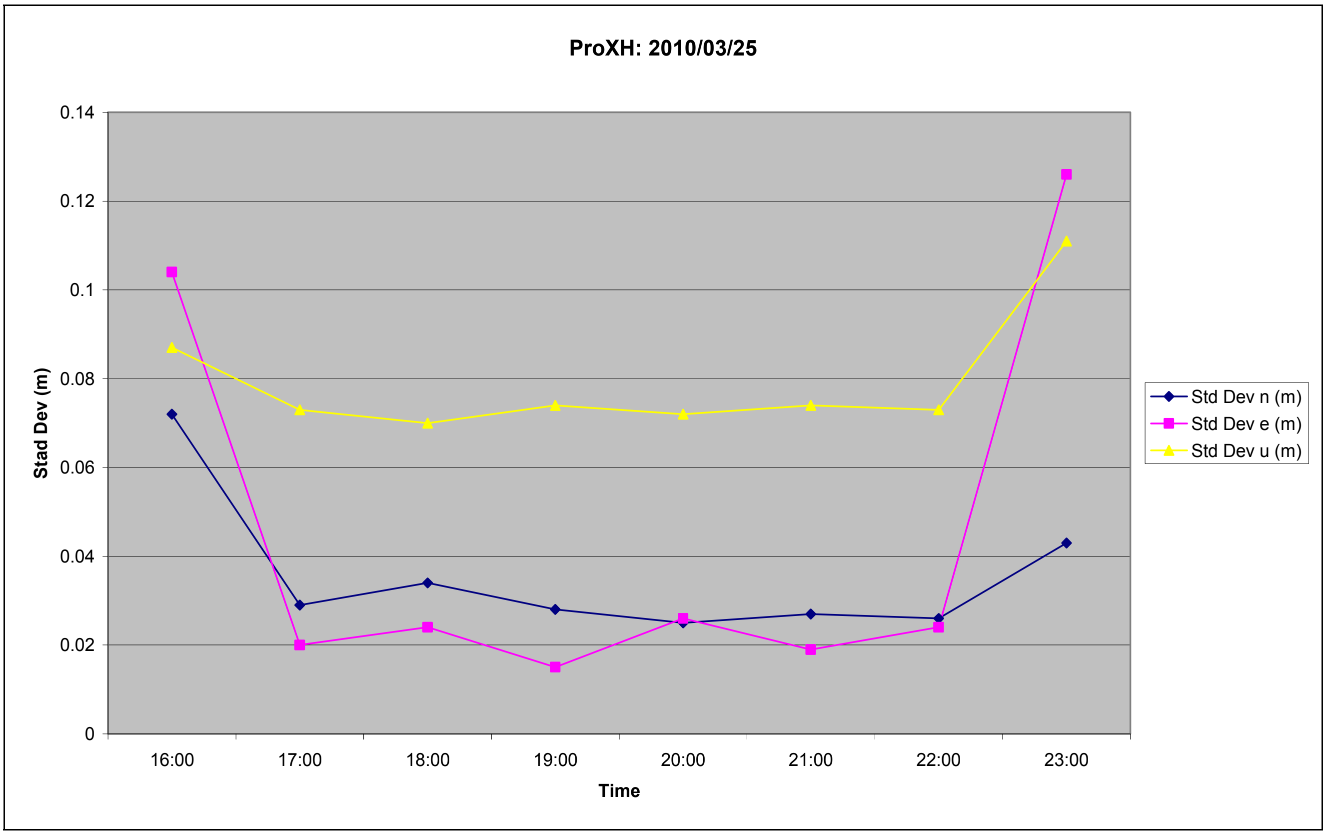

Figure 5-23: Station 3 - ProXH - 2010_03_25

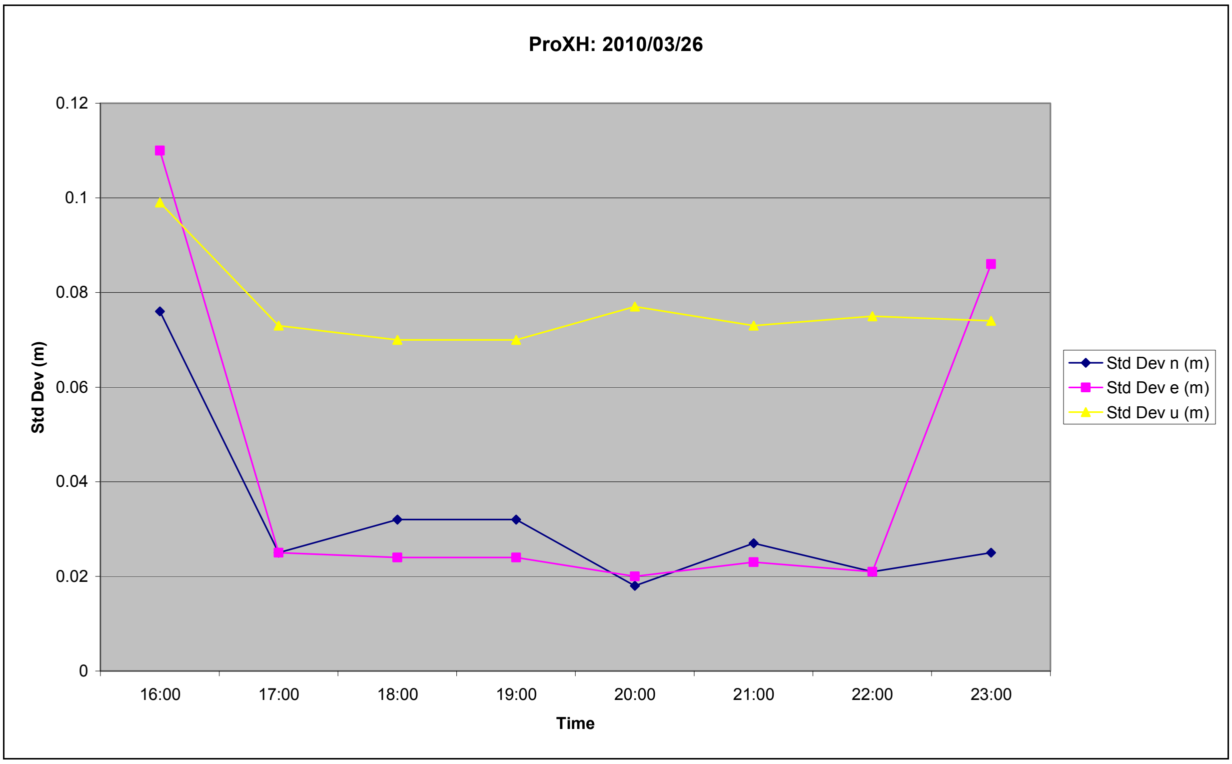

Figure 5-24: Station 3 - ProXH - 2010_03_26

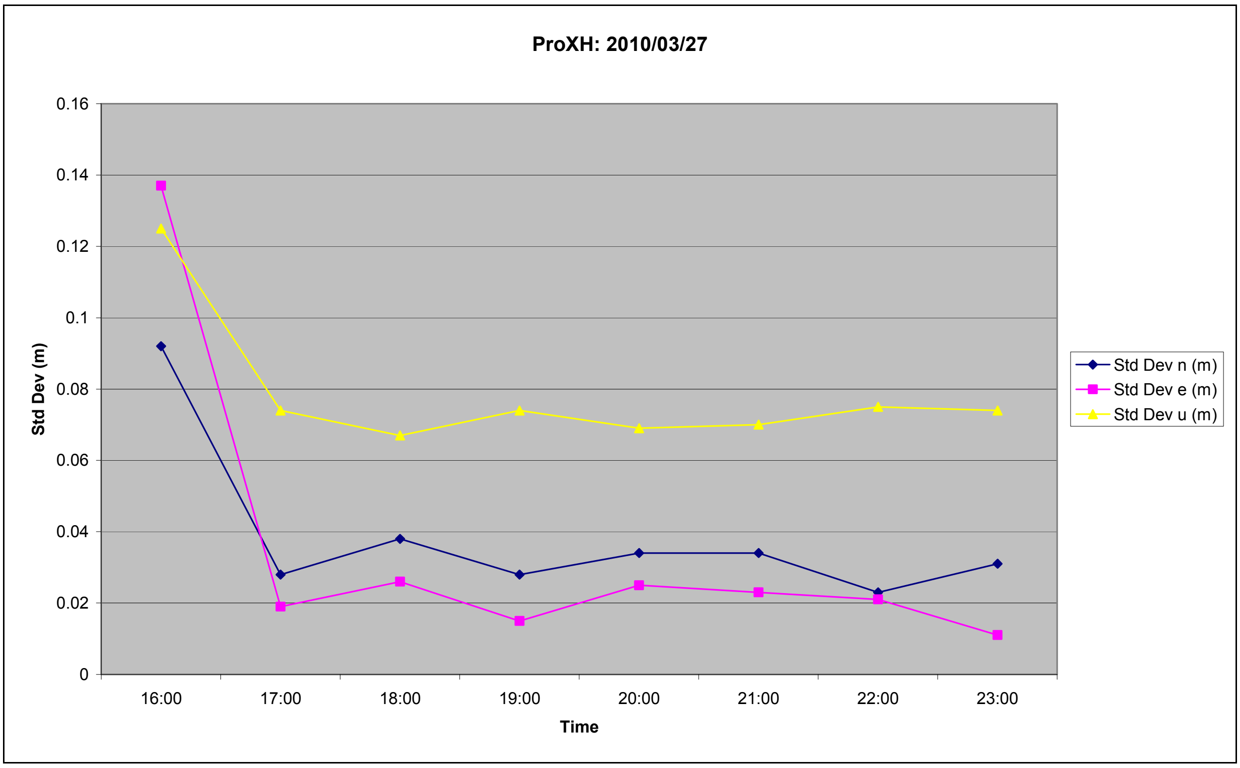

Figure 5-25: Station 3 – ProXH - 2010_03_27

22. At the start of the measurement at 16:00 the precision of measurements of the latitude and longitude values are in the vicinity of 60 mm to 140 mm and drops to 20 mm at about

17:00. The reason for this can be attributed to the ionospheric effect at the time of the day as previously discussed.

23. The steep rise in the values at the end of the measurement is repeated at three consecutive days. To understand this rise, the measurements were processed in 20 min intervals and compared with variables of the rest of the measurement. The results are presented in Figure 5-26 and Table 5-6. From these values it can be seen that the steep rise from 23:00 correlates with a drop in the number of satellites observed and a corresponding rise of the DOP values.

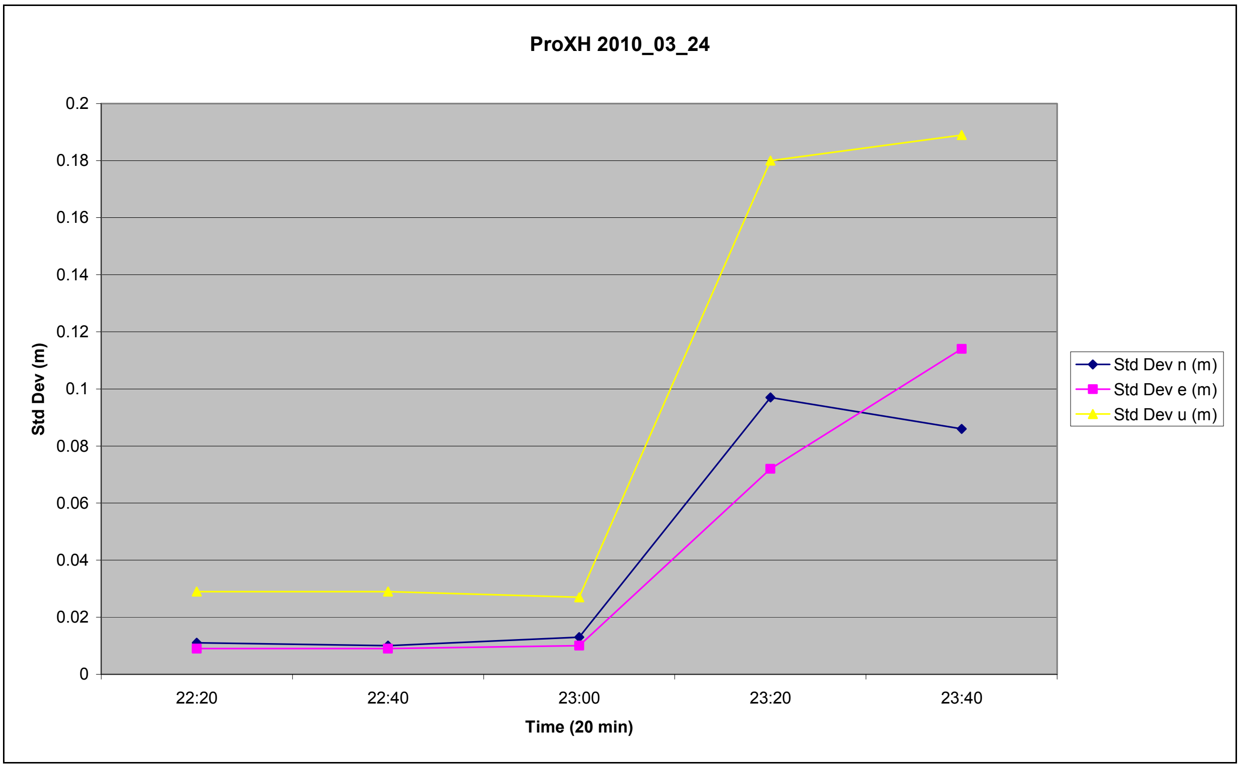

Figure 5-26: Station 3 - ProXH - 2010_03_24 (20 min intervals)

Table 5-6: Trimble ProXH measurement values at Station 3 on 2010_03_24 (20 min intervals)

Start Time	Std Dev n (m)	Std Dev e (m)	Std Dev u (m)	GPS Satellites	PDOP	HDOP	VDOP
22:20	0.011	0.009	0.029	10	2.107	0.851	1.928
22:40	0.01	0.009	0.029	9	2.344	0.975	2.132
23:00	0.013	0.01	0.027	8	2.28	1.065	2.016
23:20	0.097	0.072	0.18	8	2.631	1.438	2.203
23:40	0.086	0.114	0.189	7	4.523	2.321	3.882

24. As in the case with the Topcon GB-1000 GPS receivers, the precision of measurement with the ProXH increases as the measurement period increases and the peaks of shorter period measurements disappear. Consecutive measurements were processed from 18:00 onwards until a measurement period of 5 hours. This was done to use the most precise measurements for the analysis. It seems that maximum precision is also reached after 3 hours as indicated in Figure 5-27.

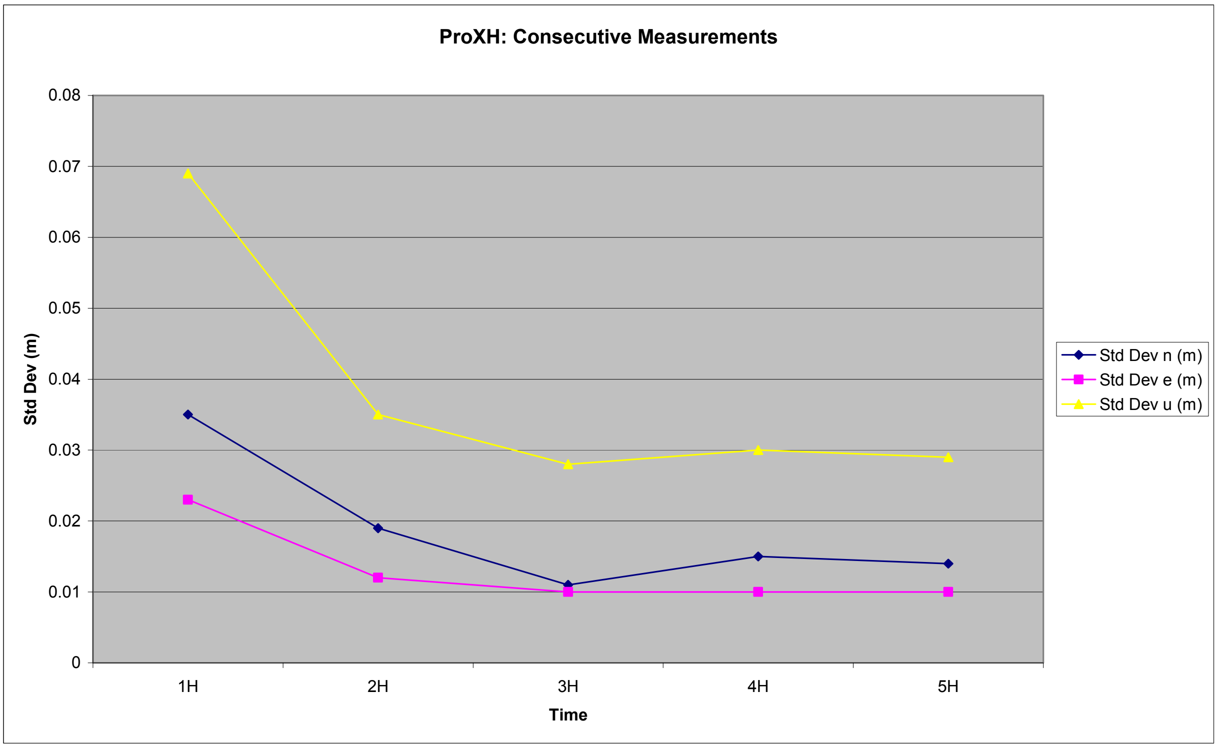

Figure 5-27: Station 3 - Consecutive Measurements - 2010_03_23

25. Having established that the Topcon GB-1000 is taking measurements at acceptable accuracy levels as discussed in paragraph 17, the accuracy of the ProXH at Station 3 can be determined by comparing it with measurements with the Topcon GB-1000 at Station 3. This is conveniently done by converting the ellipsoidal coordinate values of both the Topcon GB-1000 and the Trimble ProXH with XForm to UTM plane coordinates. The Trimble ProXH coordinates presented in Table 5-5 can then be subtracted from the Topcon GB-1000 coordinates in Table 5-1. Comparison analysis was conducted in MS Excel to indicate deviations in metre values. The UTM coordinates of Station 3 with the Topcon GB-1000 are presented in Table 5-7 as eastings (E), northings (N) and ellipsoidal height (h) in metre values.

Table 5-7: Topcon GB-1000 UTM Coordinates at Station 3

E (m)	N (m)	h (m)
614542.145	7145050.97	1458.849

Table 5-8: Trimble ProXH UTM Coordinates at Station 3 – Accuracy

Date	E (m)	N (m)	h (m)	∆E (m)	∆N (m)	∆h (m)
2010_03_23	614542.145	7145050.962	1458.783	0.0000	0.0080	0.0660
2010_03_24	614542.154	7145050.958	1458.799	-0.0090	0.0120	0.0500
2010_03_25	614542.138	7145050.956	1458.784	0.0070	0.0140	0.0650
2010_03_26	614542.148	7145050.963	1458.781	-0.0030	0.0070	0.0680
2010_03_27	614542.158	7145050.971	1458.808	-0.0130	-0.0010	0.0410

26. It is clear from Tables 5-7 and 5-8 that the measured values obtained with the Trimble ProXH receiver deviates approximately 1 cm in the horizontal plane and 6 cm in height from those obtained using the Topcon GB-1000. There is also a relative consistency in the measurement values obtained with the Trimble ProXH. The Trimble ProXH is a mapping receiver and is marketed to provide accuracy values in the vicinity of 10 to 15 cm. Measurements over extended periods and processing it with the Topcon Tools software probably rendered these higher accuracy levels. In practical applications the Trimble ProXH will probably not be used in this role, but will be making measurements over shorter time periods.

MEASUREMENTS WITH NAVIGATIONAL TYPE GPS RECEIVERS

27. Infantry soldiers in the SANDF are using navigational type GPS receivers. These receivers perform excellently in this role. However, it will be important to understand at what levels of precision and accuracy these receivers can be used. It should be remembered that data from these receivers cannot be post-processed under operational conditions. It is a stand-alone measurement that only makes use of C/A-code on L1. Two types of these receivers were deployed at the same Station 3 where the Topcon GB-1000 and the Trimble ProXH receivers were deployed. Measurements with the Garmin receivers were made to simulate operational conditions. These receivers will generally collect data continuously over a period of 12 h. Measurements were set to 30 second intervals to be comparable with measurements made with the other GPS receivers. The reference ellipsoid used was WGS 84. These receivers use an unknown geoid model to produce orthometric heights. Thus, XForm 4.4 was used to convert ellipsoidal coordinates to UTM plane coordinates and height measurements using EGM 2008 to ellipsoidal heights.

28. Data collected with these receivers were processed in Excel to calculate measurement averages and standard deviations which will be discussed in the following paragraphs.

29. Results of the Garmin CSX 60 receiver are depicted in Figures 5-28 and 5-29:

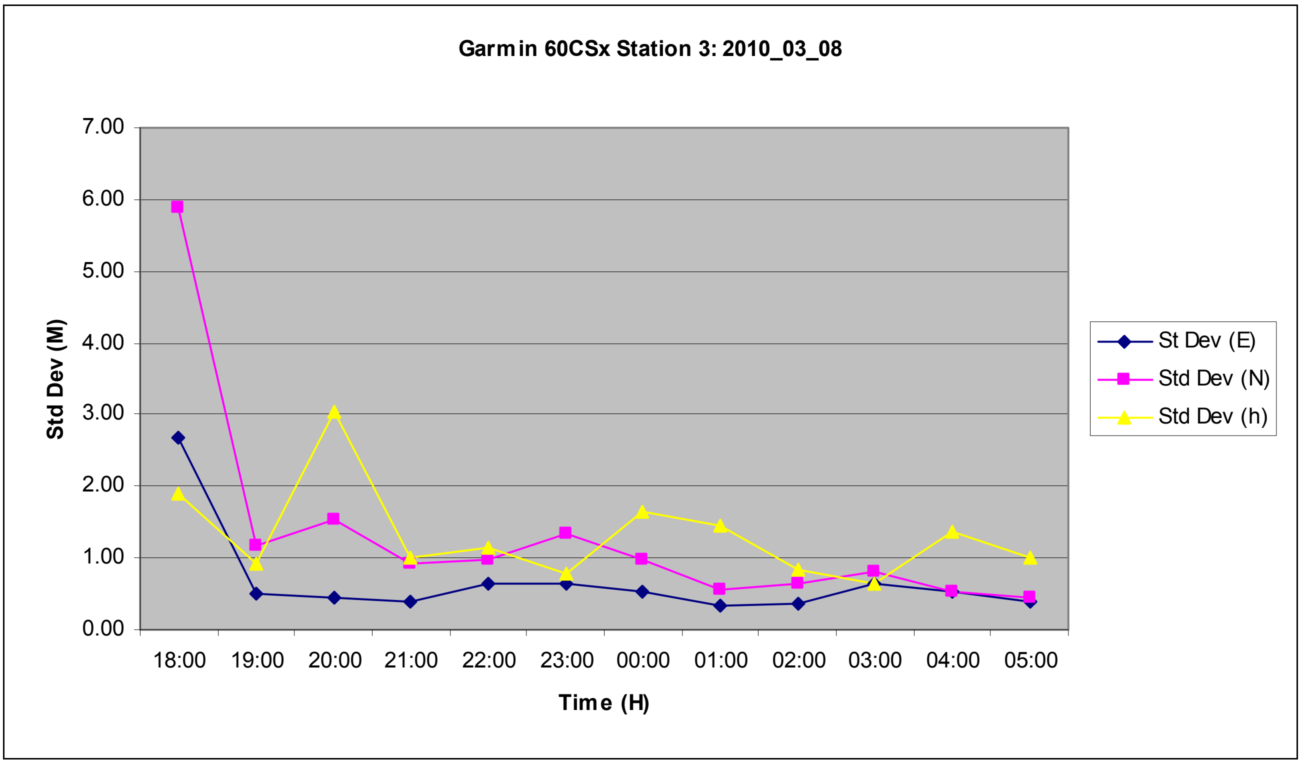

Figure 5-28: Station 3: Garmin GPSMap 60CSx - 2010_03_08

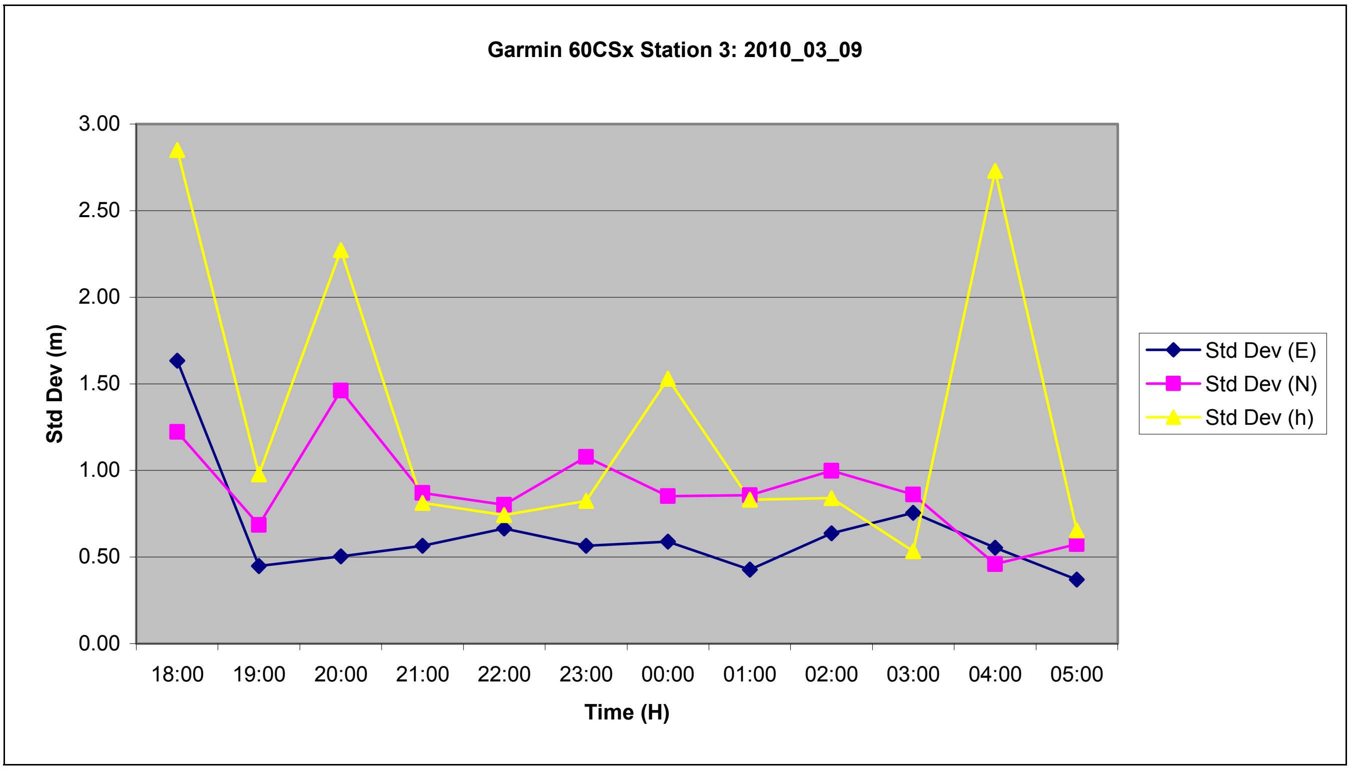

Figure 5-29: Station 3 - Garmin GPSMap 60CSx - 2010_03_09

30. The results of the Garmin eTrex are presented in Figures 5-30 and 5-31:

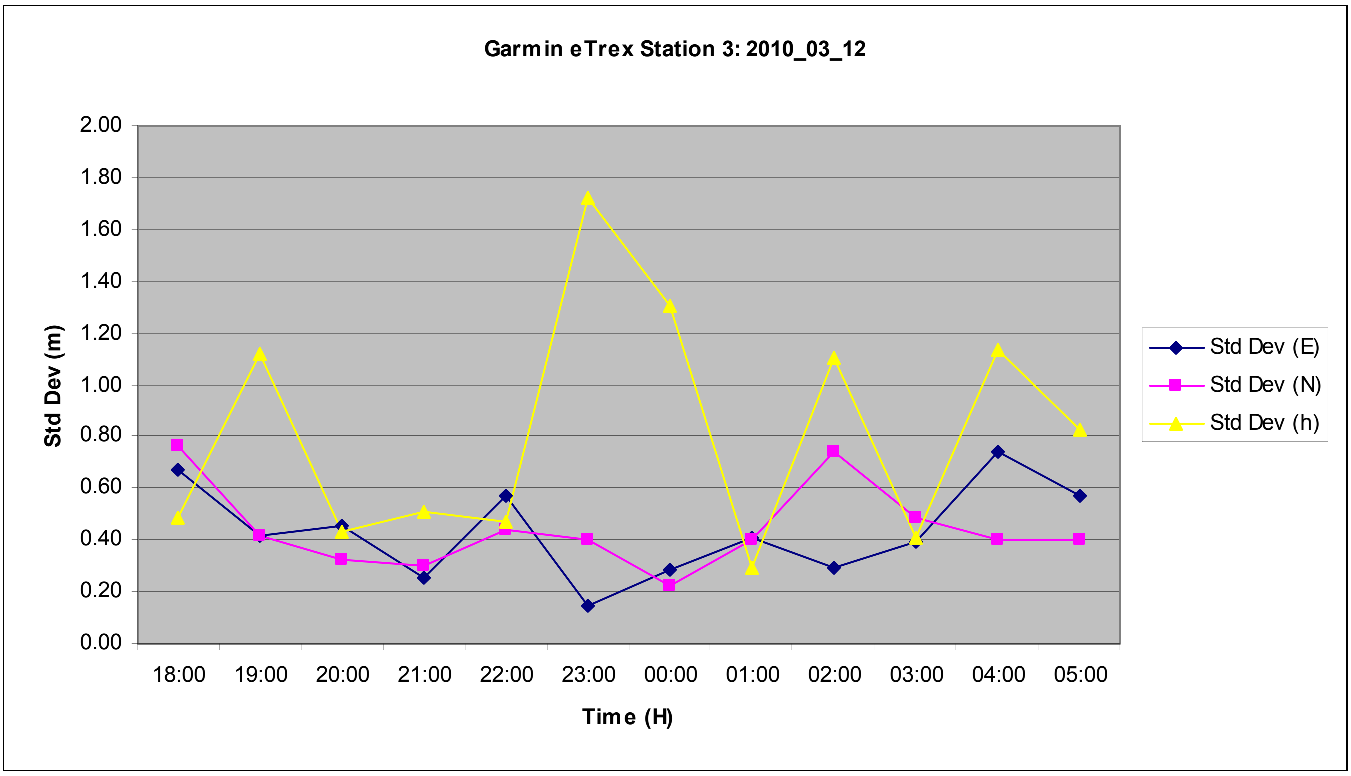

Figure 5-30: Station 3: Garmin eTrex - 2010_03_12

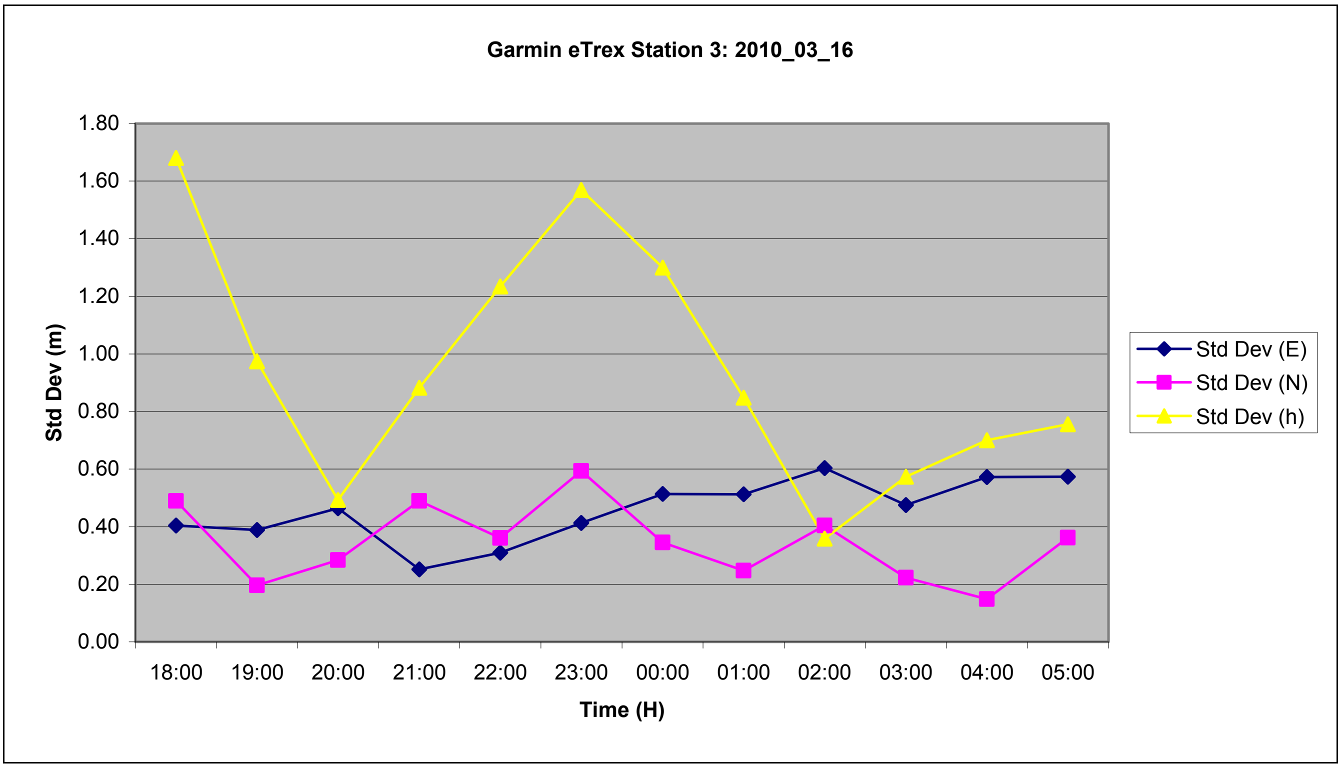

Figure 5-31: Station 3 – Garmin eTrex - 2010_03_16

31. From these graphs it can be seen that the hourly standard deviations of the Garmin GPSMap 60CSx GPS receiver varies generally between 1 and 2 m, while that of the eTrex varies between 0.5 and 1.5 m. The number of satellites tracked and the DOP values are not downloadable from these GPS receivers. It is therefore not possible to evaluate the fluctuations in these measurements.

32. The accuracy of the Garmin receivers can be determined by comparing their measurement values with measurements of the Topcon GB-1000 receiver at Station 3. The comparison process was similar to that conducted with the Trimble ProXH in paragraph 25. Measurements were taken over three days with a total measurement time of 36 hours at 30 second intervals. Height measurements were converted to ellipsoidal heights. From Table 5-9 it can be seen that measurements with the Garmin GPSMap 60CSx GPS receiver was in the vicinity of 0.2 m to 3 m distant (Std Dev 1.17 m to 3.42 m over the total measurement period of 36 hours) from the values of the Topcon GB-1000 that is taken here as a reference position.

Table 5-9: Garmin GPSMap 60CSx UTM Coordinates at Station 3 - Accuracy

GPS Receiver	E (m)	N (m)	h (m)
Topcon GB-1000	614542.145	7145050.970	1458.849
Garmin 60CSx	614542.357	7145051.013	1461.930
Std Dev (m) of 60CSx	1.17	1.61	3.42
∆ (m)	**-0.21**	**-0.04**	**-3.08**

33. The accuracy values of measurements taken the Garmin eTrex receiver over three days compared with the Topcon GB-1000 are as indicated in Table 5-10:

Table 5-10: Garmin eTrex UTM Coordinates at Station 3: Accuracy

GPS Receiver	E (m)	N (m)	H (m)
Topcon GB-1000	614542.145	7145050.970	1458.849
Garmin eTrex	614541.423	7145050.817	1459.277
Std Dev (m) eTrex	0.93	0.98	2.85
∆ (m)	**0.72**	**0.15**	**-0.43**

34. Garmin receivers will normally not be used for measurements over such extended periods. These are navigational type receivers and measurements taken under different circumstances may render different results. It must also be indicated that measurements were taken from 19:00 to 05:00 the next day when the influence of ionosphere was on its lowest. Measurements with the GPSMap 60CSx reveal the effect of the ionosphere at the start of measurement. Although the eTrex appear to be the more precise and accurate receiver in this analysis, the GPS MAP 60CSx is a more advanced receiver and delivers more accurate data in other tests in this study. The inability to evaluate the number of satellites tracked and DOP values precluded the use of these to improve the analysis.

35. This confirms that the Garmin receivers used in this study may be used with confidence for navigation and the collection of ground control for mapping projects at 50 k scale and smaller that requires a CEP of 25 m. See also the positional standard requirements discussed in Appendix C. Various efforts have been made to improve the precision and the accuracy of measurements with Garmin receivers. Two can be mentioned; the one by Schweiger and Gläser and the other by the E. Ralini of the Osaka City University. However, these solutions require that the receiver is connected to a computer during the time of the measurements. This will be a difficult solution to be implemented during operations and mapping receivers can then rather be used. Officials at Garmin South Africa were approached during March 2010 to establish if there is a way to access other observables

such as DOP values, signal-to-noise ratio and the possibility to implement an elevation mask. These officials were very helpful, but Garmin finds itself in a total different market and will not spend energy and effort on this endeavour. Thus, it was found impractical and was not explored further (Schwieger and Gläser, 2009; E Ralini, 2009).

INCREASING BASELINES FOR DIFFERENTIAL GPS MEASUREMENTS

36. Collecting ground control points for mapping projects in areas of operations may require that the base stations should be located much further away from the network. In the initial part of this Chapter the HRAO base station was used, which is approximately 50 km from the network. In Chapter 3 the use of IGS stations as possible base stations was mentioned. However, these stations are sparsely populated on the Continent as indicated in Figure 3-10. To assess the effect of an increased baseline with these IGS stations in mind, measurements were post-processed with TrigNet stations with increasing distances from the 5 station network in Pretoria. The requirement was that the base station and the rover station should observe the same satellites simultaneously; the number of satellites and the DOP values should stay within limits as discussed above and the effects of the ionosphere should be considered. The effect of the ionosphere could be very different at the base station from that at the rover station and may cause deviations in measurements. Another consideration could be not to post-process measurements but to use stand-alone GPS measurements. The post-processed results for the Topcon GB-1000 receivers over a 12 hour measurement period on 3 March 2010 are presented in Table 5-11. Measurements were processes as indicated in Chapter 2, paragraphs 8 and 9. Thus, the precision of measurements is a result of the processing with Topcon Tools and values are presented as standard deviations on latitude (n), longitude (e) en height (u) in metre values. Take note that after processing the standard deviations will be the same for all stations in the network. Thus, a single line in the table presents the whole network's values for that baseline.

Table 5-11: Topcon GB-1000 GPS: Increasing Baselines - Precision

TrigNet Base	Std Dev n (m)	Std Dev e (m)	Std Dev u (m)
KRUG (50 km)	0.003	0.004	0.01
VERG (100 km)	0.005	0.005	0.013
KSTD (220 km)	0.007	0.007	0.02
BFNT (400 km)	0.012	0.02	0.035
DEAR (670 km)	0.014	0.019	0.042
SUTH (1000km)	0.017	0.033	0.054
CTWN (1300km)	0.023	0.069	0.067

37. From Table 5-11 it can be seen that the precision of measurements of the longitude values decreased from 3 mm to 23 mm with an increase of baseline from 50 km to 1 300 km. Latitude precision decreased from 4 mm to 69 mm and height values decreased from 10 mm 67 mm. For military mapping requirements this reduction in precision is insignificant. To determine what happened with the accuracy of these measurements, it can be compared with the measurement values in Table 5-1. This argument is based on the fact that measurements with the Topcon GB-1 000 were established to be accurate as discussed in paragraph 17 and indicated in Table 5-4. The post-processed coordinates of both instances were converted to UTM plane coordinates to allow one to subtract the TrigNet processed coordinates from the HRAO coordinates to render the delta values. Only the delta values in metres are included in Table 5-12.

Table 5-12: Topcon GB-1000: Increasing Baselines - Accuracy

TrigNet Base	∆E (m)	∆N (m)	∆h (m)
KRUG (50 km)	0.023	0.001	0.048
VERG (100 km)	0.023	0.011	-0.025
KSTD (220 km)	0.034	0.03	0.019
BFNT (400 km)	0.072	0.066	-0.094
DEAR (670 km)	0.065	0.055	0.049
SUTH (1000km)	0.106	0.07	0.097
CTWN (1300km)	0.066	0.06	0.34

38. From Table 5-12 it can be seen that the accuracy of the E values decreased from 23 mm at a 50 km baseline to 66 mm at 1 300 km baseline, the N values from 1 mm to 70 mm and the h values from 48 mm 97 mm. Note that height values have deviated significantly at the 400 km baseline (Bloemfontein).

39. What will be the break-even baseline distance where similar or better measurements will be attained with stand-alone GPS measurements? The precision of stand-alone GPS measurements cannot be determined because the processing software provides the values as single points. However, the accuracy of these points can be compared with the initial measurements made with the Topcon GB-1000 post processed with the HRAO base station oven a 48 h period as indicated in Table 5-1. Again the coordinates were converted to UTM plane coordinates for comparison purposes. The results for the stand-alone Topcon GB-1000 measurements on 3 March 2010 for a 12 h period are tabulated in Table 5-13. Only the delta values are indicated.

Table 5-13: Topcon GB-1000 GPS stand-alone measurements - Accuracy

Station Name	∆E (m)	∆N (m)	∆h (m)
1	-0.108	-0.153	0.038
2	-0.109	-0.128	-0.163
3	-0.127	0.026	-0.533
4	-0.08	0.016	-0.172
5	-0.112	0.086	-0.2

40. Comparing results of Table 4-12 with results of Table 5-13 it can be seen that accuracy of the post-processed values over increasing baselines from 50 km to 1 300 km is generally better than using stand-alone GPS measurements. Similar results were obtained with the measurements on 10 Mar 10. Thus, the break-off point using increased baselines is probably much further than the 1 300 km. The add-on uncertainty of using unchecked (stand-alone) field measurement increases the need to process field measurements over extended baselines. This also indicates that using a survey type GPS such as the Topcon GB-1000 with base station data to conduct differential post-processing could render coverage for mapping projects on the Continent as indicated with the 1 000 km buffers in Figure 3-10. Using geodetic type receivers such as IGS stations and scientific processing software will deliver sub-centimetre results over global baselines. However, this will not be a typical military application.

41. Measurements with a mapping type GPS receiver such as the Trimble ProXH located at Station 3 over an 8 hour measurement period were processed with increasing baselines. Measurements were repeated for four consecutive days from 23 to 26 March 2010. The data of 25 March 2010 are presented in Table 5-14. Similar results were obtained with measurements during the other days.

Table 5-14: Trimble ProXH: Increasing Baselines - Precision

TrigNet Base	Std Dev n (m)	Std Dev e (m)	Std Dev u (m)
KRUG (50 km)	0.012	0.01	0.03
VERG (100 km)	0.017	0.014	0.039
KSTD (220 km)	0.027	0.025	0.076
BFTN (400 km)	0.047	0.03	0.078
DEAR (670 km)	0.063	0.037	0.1
SUTH (1000 km)	0.079	0.05	0.119
CTWN (1300 km)	0.087	0.049	0.139

42. From Table 5-14 it can be seen that the precision of latitude values of measurements with the Trimble ProXH decreased from 12 mm at a 50 km baseline to 87 mm with a 1 300 km baseline. Longitude precision values decreased from 10 mm to 49 mm and height values from 30 mm to 139 mm. These values are within the limits that are required for military positional standards.

Table 5-15: Trimble ProXH: Increasing Baselines - Accuracy

TrigNet Base	∆E (m)	∆N (m)	∆h (m)
KRUG (50 km)	0.002	-0.018	0.12
VERG (100 km)	-0.002	-0.03	0.174
KSTD (220 km)	-0.04	-0.053	0.095
BFTN (400 km)	0.17	0.241	0.327
DEAR (670 km)	0.187	0.238	0.746
SUTH (1000 km)	0.214	0.29	1.083
CTWN (1300 km)	0.395	0.317	1.389

43. Accuracy of measurements with the Trimble ProXH receiver on 25 March 2010 with increasing baselines can also be compared with the measurements with the Topcon GB-1000 in Table 5-1. From Table 5-15 it can be seen that the accuracy of the E values reduced from 2 mm to 395 mm, the N values from 18 mm to 317 mm and the h values from 120 mm to 1.3 m. These values are still within the limits of military positional standards. However, the same question can be asked in this regard; will it be better to post-process over this long baseline or rather use stand-alone GPS measurements? The accuracy values of the ProXH (not deferentially corrected) are presented in Table 5-16.

Table 5-16: Trimble ProXH stand-alone measurements - Accuracy

Date	∆E (m)	∆N (m)	∆h (m)
2010_03_23	-0.628	1.522	-1.781
2010_03_24	-0.166	0.992	-1.753
2010_03_25	-0.293	0.860	-1.508
2010_03_26	-0.411	0.839	-1.762

44. From Tables 5-15 and 5-16 it can be seen that the post-processed values with baselines exceeding approximately 670 km are marginally better than stand-alone values. Thus, stand-alone or post-processed strategies with mapping type GPS receivers utilising baselines between 600 km and 1 000 km can be used with almost the same results. However, it will be better to use shorter baselines in the vicinity of 500 km with mapping type receivers to provide data with higher accuracies.

45. Setting up an own base station can be risky and probably not worth the value of the mapping project. However, there could be a better approach, for instance using Precise Point Positioning (to be discussed in the next section). In closing, it should be realised that the measurements of both these GPS receivers were taken over relatively long observation periods; 12 and 8 h respectively. Collecting positional data in operational conditions may require measurements with a mobile platform (kinematic measurements) that may cause lower precision and accuracy levels. Due to positional uncertainties when a mobile platform such as a vehicle is used, the comparison of precision and accuracy will not be valid. However, when measurements are planned, all aspects that may impact on the accuracy and precision including the availability of satellites, DOP values and the effect of the ionosphere, especially with extended baselines, should be considered as was illustrated with these few examples.

PRECISE POINT POSITIONING TECHNIQUES

46. Relative PPP measurements are obtained when the values of other IGS stations close to the point are taken for post-processing and are very similar to the differential processing technique discussed in the previous section. The Australian Positioning Service (AUSPOS) provides a relative PPP service using the GRS80 ellipsoid[4] and IGS stations close to the station in question as discussed in Chapter 4 paragraph 28. The values of the network on 3 March 2010 were submitted for processing. The precision of the measurements processed by AUSPOS is provided in Cartesian coordinate values as indicated in Table 5-17.

Table 5-17: Topcon GB-1000 measurements with relative PPP (AUSPOS) - Precision

Name	X (m)	Y (m)	Z (m)	Δx (m)	Δy (m)	Δz (m)
1	5063301	2717757	-2761431	0.0045	0.003	0.003
2	5064501	2718499	-2758632	0.0045	0.003	0.003
3	5067493	2710637	-2760591	0.0045	0.003	0.003
4	5067434	2709134	-2762407	0.0045	0.003	0.003
5	5066902	2715085	-2757544	0.0065	0.005	0.003

47. The accuracy of these measurements can be calculated by comparing them to the Topcon GB-1000 measurements post-processed with the HRAO base station. The comparison of the accuracy of the values from the AUSPOS service is as indicated in Table 5-18 in UTM plane coordinate values followed by the deltas:

---

[4] The GRS80 ellipsoid is practically the same as WGS84. However, the flattening factor (f-1 = 298.257 222 101) differs from WGS84. See H. MORITZ (1979): Report of Special Study Group No 539 of I.A.G., Fundamental Geodetic Constants, presented at XVII General Assembly og I.U.G.G., Canberra. Accessed during July 2011 at www.gfy.ku.dk/.

Table 5-18: Topcon GB-1000 measurements with relative PPP (AUSPOS) - Accuracy

Name	E (m)	N (m)	H (m)	∆E	∆N	∆h
1	622785.685	7144076.481	1525.959	-0.056	-0.035	-0.153
2	622900.658	7147206.994	1575.545	-0.054	-0.038	-0.129
3	614542.199	7145051.006	1458.951	-0.054	-0.036	-0.102
4	613228.444	7143097.26	1565.15	-0.044	-0.04	-0.136
5	618770.228	7148441.853	1554.606	-0.054	-0.037	-0.114

48. From Table 5-18 it can be seen that the AUSPOS values are significantly worse than post-processing with the HRAO base station. However, where the user does not have access to an IGS base station, this service can render excellent results and can be considered as a solution for mapping projects.

49. The other service is the absolute PPP solution. In this technique no specific base station is used but the clock and ephemeris correction data from a number of base stations operated by this service are used to correct the *in situ* GPS measurements. The Canadian Spatial Reference System (CSRS) is such a service that uses the ITRF (2005) stations and thus by implication WGS84 as reference ellipsoid. The values of measurements taken on 3 March 2010 using the 5 station network locations occupied with the Topcon GB-1000, processed by the CSRP-PPP are presented in Table 5-19.

Table 5-19: Topcon GB-1000 measurements with absolute PPP (CSRS) – Precision

Station	Latitude	Longitude	Height	Std Dev n (m)	Std Dev e (m)	Std Dev u (m)
1	-25 48 59.0502	-25 48 59.0502	1525.834	0.002	0.005	0.011
2	-25 47 17.2708	28 13 32.8929	1575.443	0.002	0.005	0.011
3	-25 48 29.7873	28 08 33.4937	1458.852	0.002	0.005	0.011
4	-25 49 33.6567	28 07 46.9233	1565.044	0.002	0.005	0.011
5	-25 46 38.3646	28 11 04.2118	1554.526	0.003	0.007	0.014

Table 5-20: Topcon GB-1000 measurements with absolute PPP (CSRS) - Accuracy

Name	E (m)	N (m)	H (m)	∆E (m)	∆N (m)	∆h (m)
1	622785.68	7144076.475	1525.834	-0.051	-0.029	-0.028
2	622900.647	7147206.99	1575.443	-0.043	-0.034	-0.027
3	614542.189	7145051.006	1458.852	-0.044	-0.036	-0.003
4	613228.434	7143097.256	1565.044	-0.034	-0.036	-0.03
5	618770.214	7148441.852	1554.526	-0.04	-0.036	-0.034

50. From both Tables 5-19 and 5-20 it can be seen that the precision and accuracy of the CSRS-PPP are comparable or slightly better than the AUSPOS results. The advantage of this processing is that the user does not need to deploy any base stations. The service is also relatively easy to use, although users should remember that precise clock and ephemeris data are only available approximately two weeks after measurements were taken.

51. For users with mapping type GPS receivers the results using a Trimble ProXH were as contained in Tables 5-21 and 5-22

Table 5-21: Trimble ProXH measurements with absolute PPP (CSRS) - Precision

Date	Latitude	Longitude	Height	Std Dev n (m)	Std Dev e (m)	Std Dev u (m)
2010_03_23	-25 48 29.7955	28 08 33.4893	1458.457	0.047	0.041	0.113
2010_03_24	-25 48 29.7904	28 08 33.4901	1458.065	0.047	0.041	0.114
2010_03_25	-25 48 29.7913	28 08 33.4937	1458.446	0.046	0.041	0.113
2010_03_26	25 48 29.7893	28 08 33.4884	1458.38	0.046	0.041	0.113

Table 5-22: Trimble ProXH measurements with absolute PPP (CSRS) - Accuracy

Date	E (m)	N (m)	H (m)	∆E (m)	∆N (m)	∆h (m)
2010_03_23	614542.064	7145050.755	1458.457	0.0810	0.2150	0.3920
2010_03_24	614542.088	7145050.911	1458.065	0.0570	0.0590	0.7840
2010_03_25	614542.187	7145050.883	1458.446	-0.0420	0.0870	0.4030
2010_03_26	614542.041	7145050.945	1458.38	0.1040	0.0250	0.4690

52. Comparing Tables 5-21 and 5-22 with the results obtained with the results of Table 5-15 using increased baselines over different distances, it can be seen that the post-processing with the station 50 km distant provides better results than absolute PPP. However, when the baseline is increased to 400 km and more the results of PPP are comparable and better. This confirms the previous assessment that absolute PPP may be a solution to be considered when sub-metre accuracy levels are required with a mapping type receiver. For surveying purposes a survey type GPS receiver will provide better results, but the task at hand will determine if these results are acceptable.

FIELD MEASUREMENTS WITH NAVIGATIONAL GPS RECEIVERS USING ONLY C/A-CODE

53. Having established levels of precision and accuracy obtainable with DGPS using different receivers, observation periods and baseline lengths, and having compared these results with obtainable values using navigational GPS, the use of navigational GPS in its

primary role should be investigated. Navigational type GPS receivers are used widely in the SANDF for different solutions, ranging from weapon platforms to handhelds by infantrymen. The objective here will be to determine how accurately these receivers can be used for positional data. Data were collected over extended periods. Only a few examples will be presented to highlight certain trends, otherwise the analysis will be too extensive without providing additional arguments.

54. These receivers will primarily be used in a mobile role. It is therefore not possible to compare measurements with a specific predestined point. However, the geometry of these measurements can be compared to referenced aerial photography provided by SAC. The Trig Beacons of CDNGI at Stations 4 and 5 can be used as fixed points for this analysis. When the positions of Stations 4 and 5 measured with the Topcon GB 100 receivers are exported to ArcGIS the values of these stations can be compared to their physical location on the aerial photography. See Figures 5-33 and 5-34 for these positions.

Figure 5-32: Geometry of Station 4 (Zwartkop)

Figure 5-33: Geometry of Station 5 (Schanskop)

55. Both positions of these stations exported from the Topcon GB-1000 to ArcGIS appear to be almost exactly at the beacons. At closer inspection the measured position values seem to be offset approximately 35 cm north, north-east relative to the beacons. A number of reasons can be presented to explain this offset. The first and obvious is that the values of the trigonometric beacons are in the HART 94 (ITRF 91) reference frame and the GPS measurements are in WGS 84 (ITRF 2005) reference frame. Generally, features referenced to these beacons are used to geometrically rectify these high resolution images (10 cm resolution). This offset generally agrees with continental drift that can be observed in the velocity values of the ITRF HRAO base station as demonstrated in Figure 3-6 in Chapter 3. Another observable effect is the off-nadir photography as clearly can be seen in these images. The northern sides of the beacons and walls at Schanskop and Zwartkop can be seen, which indicates that the camera was tilted to the south when these images were taken. Any height different from the focal plane will therefore have an offset. A third possibility is that the offset at the two beacons is a compromise to find a general fit to all the reference points used in the registration process of these images.

56. The first observation consisted of walking while carrying a mapping and navigational GPS receiver. Measurements were taken while en route in the suburb of Valhalla which is located between Stations 4 and 5. Care was taken to minimise multipathing and shadowing, while measurements were generally taken at times when the ionospheric effect was low. Measurements with the mapping GPS that will serve as a benchmark track were post-

processed with the TrigNet station at Silverton, approximately 20 km distant. The reference ellipsoid was WGS84 and the base station values were in ITRF 2005(2008/01/09). See Figure 5-35 for the benchmark track.

Figure 5-34: Trimble ProXH Track - Valhalla

Figure 5-35: Trimble ProXH Track Valhalla (South)

Figure 5-36: Trimble ProXH Track Valhalla (North)

57. Figures 5-36 and 5-37 illustrate the benchmark track generated during walking (carrying the Trimble ProXH) on the concrete edge of the road; the edge is approximately 30 cm wide. From these two images it can be seen that the track or breadcrumbs generated by the Trimble ProXH follow the concrete edge of the road closely, with deviations where the trees caused shadowing and/or loss of lock.

58. The same route was walked while carrying three Garmin GPS receivers; a Garmen GPS Map60CSx and two eTrex's. The 60CSx and one eTrex_2 were carried in a pouch to simulate operational measurements. The other eTrex_1 was carried as a handheld to get maximum accuracy from the receiver. The route was walked consecutively to establish repeatability using the same receivers, the same way on the same route. Results with these receivers at the same two intersections were as follows (see Figures 5-38 and 5-39):

Figure 5-37: Garmin GPSMap 60CSx Track (in Pouch) - South

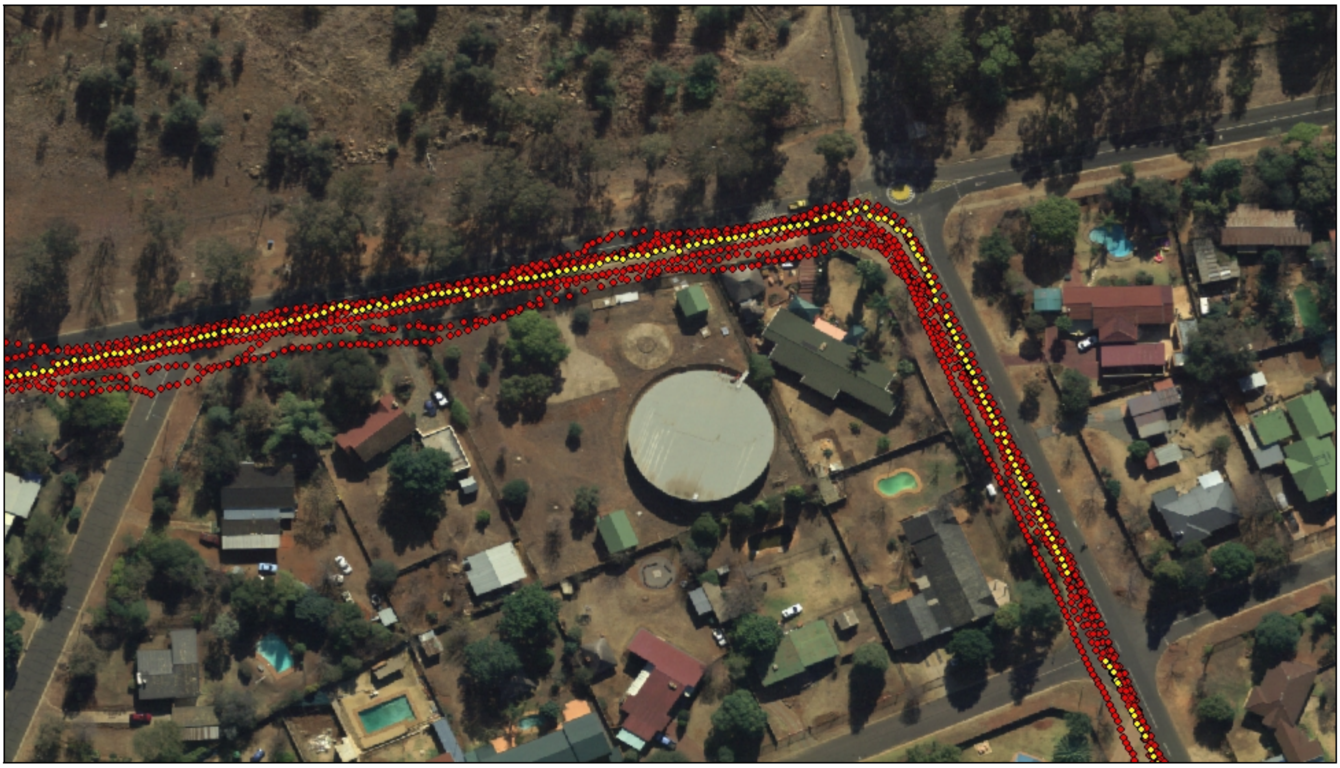

Figure 5-38: Garmin GPSMap 60CSx (in Pouch) - North

59. The Garmin GPSMap 60CSx's tracks are generally 5 meters from the concrete edge of the road. At some instances the 60CSx is as accurate as the ProXH, while from time to time it deviates further than 5 m. It should be kept in mind that the 60CSx is a navigational receiver and that it performs excellently in this role. It should also be kept in mind that at a

1:50 k scale a distance of 25 m on the earth equals a distance of 0.5 mm on the map. Thus, applied mindfully data from this receiver can be used to collect ground control data for mapping purposes.

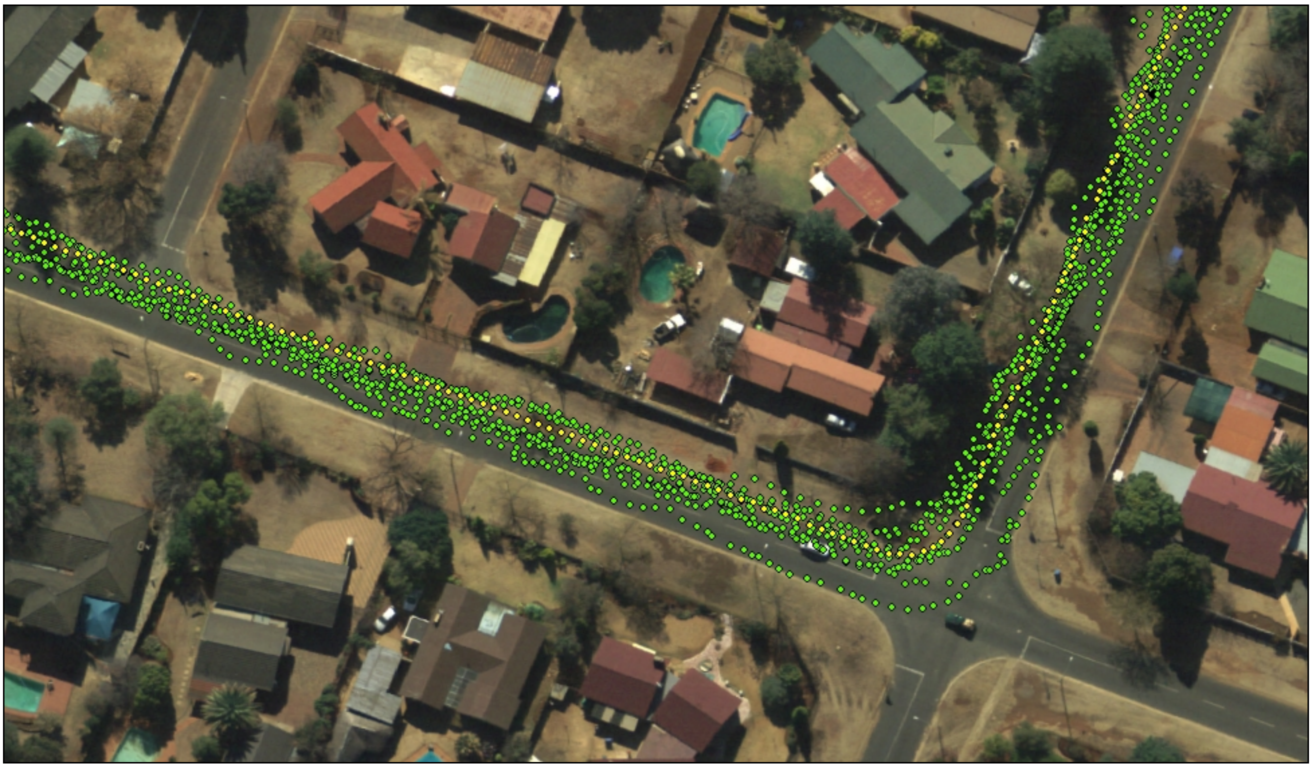

Figure 5-39: Garmin eTrex 1 (in Hand) South

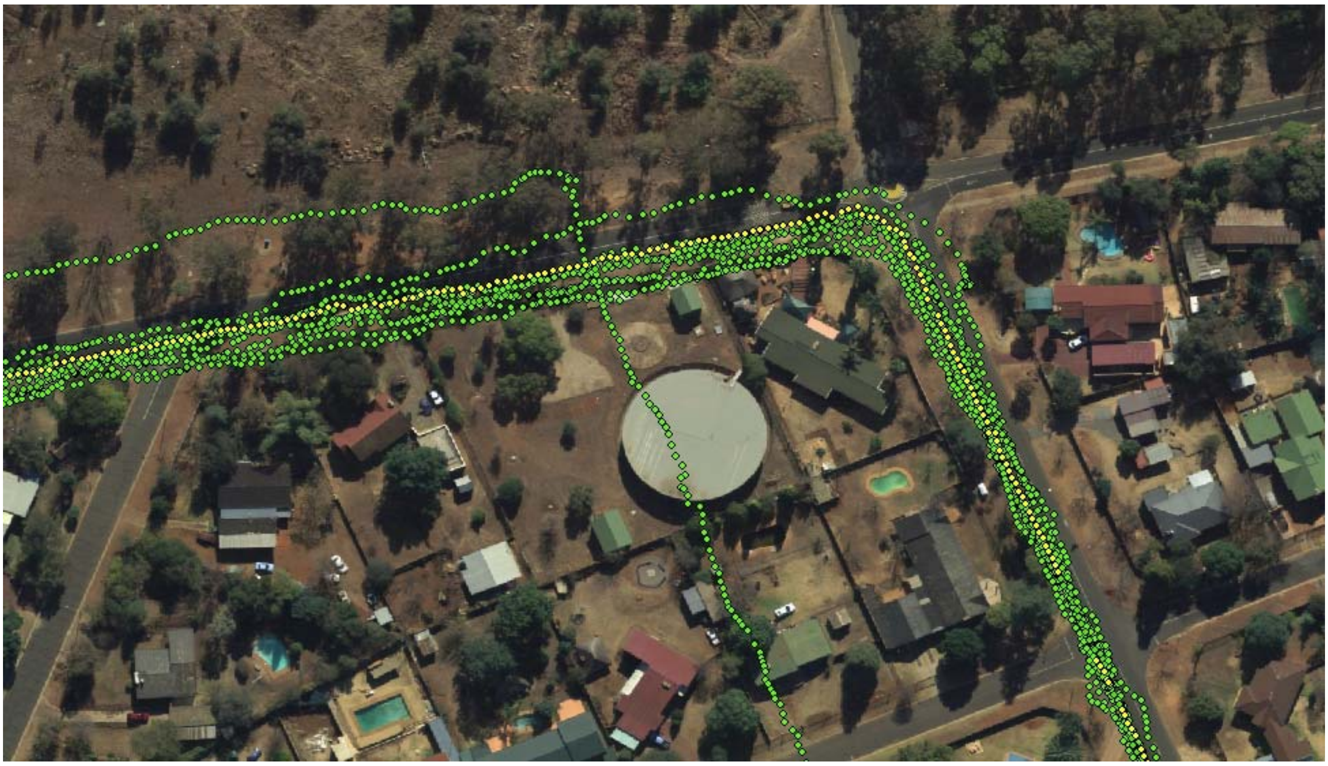

Figure 5-40: Garmin eTrex 1 (in Hand) – North

60. From Figures 5-40 and 5-41 it can be seen that the eTrex_1 performs expectedly worse than the 60CSx. Generally measurements were 7 m distant from the concrete edge of the road. Take note of the significant deviation at the North Section shown in Figure 5-41. This deviation extended 65 m from the concrete edge of the road, which is a compromising deviation if the user is not aware of it. An explanation for this large deviation is not easy to find as it was produced by the handheld eTrex that was to render maximum accuracy. The deviation lasted for approximately one kilometre after which the track joined the general trend of the other tracks. The direction of movement on this route changed three times through almost 180ºdegrees that negates shading of GPS signals by the torso as the reason for this deviation. Users must be mindful of these types of unexpected and inexplicable deviations. Using more than one receiver in operations is therefore important.

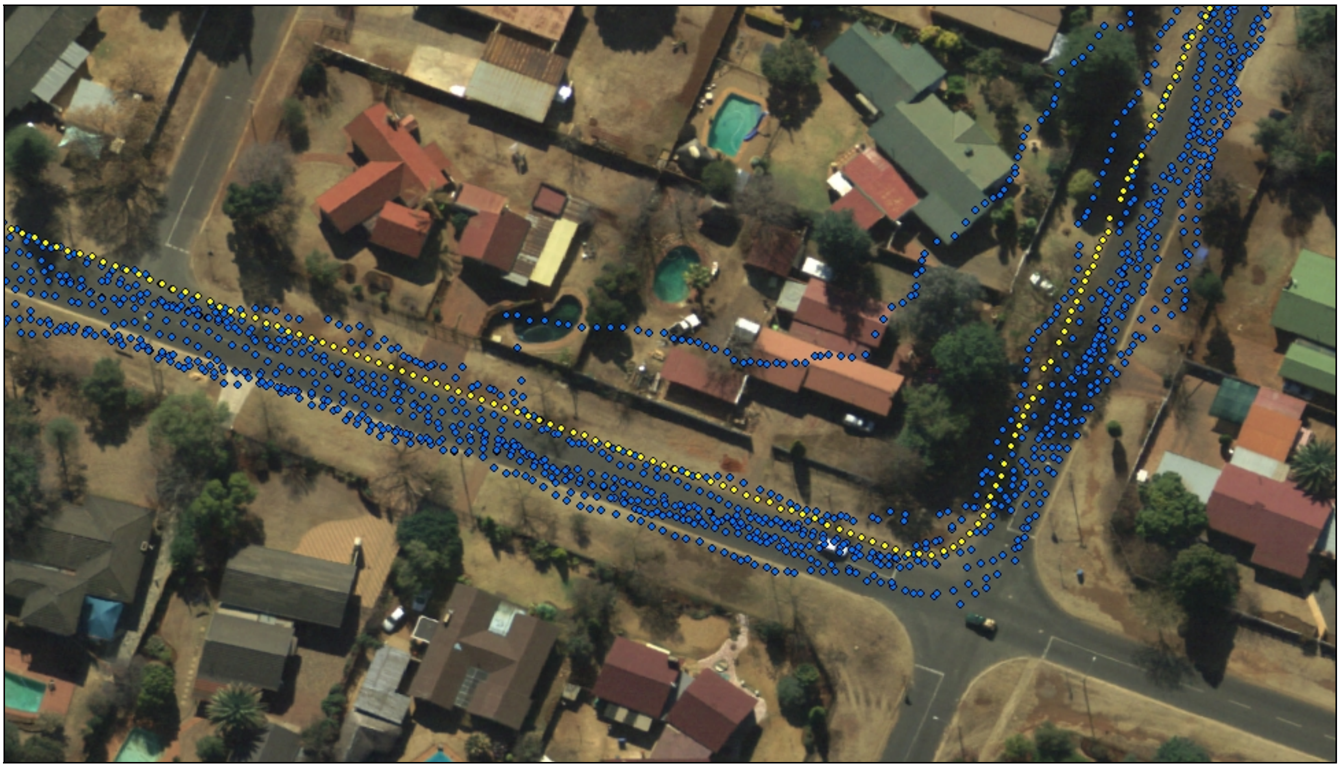

Figure 5-41: Garmin eTrex (in Pouch) - South

Figure 5-42: Garmin eTrex 2 (in Pouch) - North

61. Figures 5-42 and 5-43 shows that the eTrex_2 in the pouch performed expectedly worse than the handheld eTrex_1, except for the large deviation described above. Having explained the expected accuracy levels obtained form these receivers by walking a route, the next step was to investigate attainable accuracies with these receivers while driving a vehicle.

62. The approach adopted was to mount the GPS antenna on the left side of the vehicle and to drive close to the left hand side of the left lane to minimise uncertainties of the vehicle's location on the road. This approach also allows the driver to repeat the same track. Understandably it is not possible to drive as accurate as one can walk on the edge of the road. A large number of tracks were captured this way. The Zephyr antenna of the Trimble ProXH GPS was mounted on an antenna pole to the left of the vehicle slightly higher than the vehicle canopy to reduce multipath signals reflected from the rooftop. A patch antenna of the Trimble Juno GPS was mounted on the left fender above the left wheel and the three Garmin GPS receivers used previously were placed to the left of the front window of the vehicle to simulate operational navigation or collection of data. A track through Pretoria was selected that contained highways, rural areas, suburban areas, inner city areas with high-rise buildings and thick bush areas. This track was expected to provide extensive multipathing and shadowing. This was chosen on purpose to simulate typical operational conditions for navigation or data collection. See Figure 5-44 for a benchmark track with the Trimble ProXH receiver.

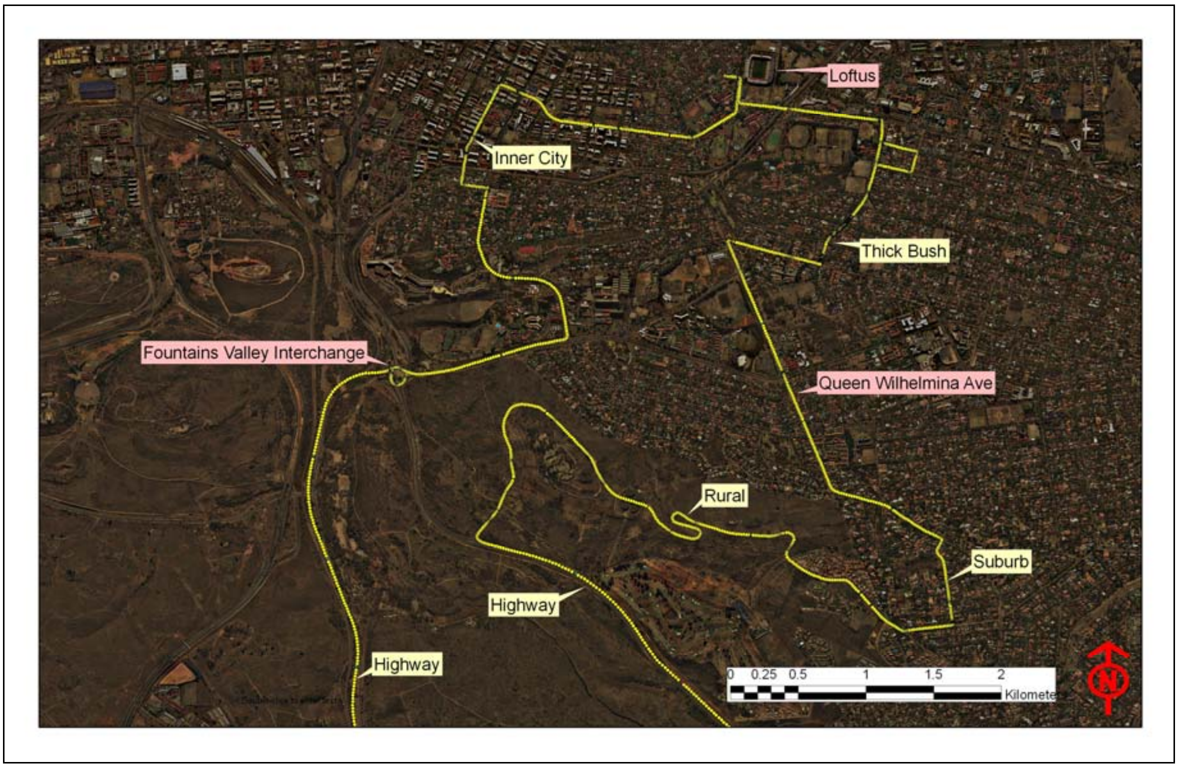

Figure 5-43: Trimble ProXH Track though Pretoria

63. The track of the Trimble Pro XH is again used as a benchmark for the navigational type of GPS receivers. In this case specific prominent road features were used as identifiable ground control points. These features include the yellow line (on the left) on “highways”, intersections, small traffic circles, large traffic circles, street blocks; driving on both sides of a road augmented the data capturing To gather maximum reference points the capturing intervals were set to 1 s intervals. Navigational GPS receivers were configured not to lock on to road features so as to obtain unbiased tracks. Data of the ProXH was post processed with the TrigNet base station at Silverton (approximately 20 km distant). Base station values were in ITRF 2005 (2008/01/09).

Figure 5-44: ProXH Tracks - Intersection

64. From Figure 5-45 it can be seen that the Trimble ProXH receiver can be used to collect reference data or ground control data at an intersection for a mapping project. A further observation is the high level of repeatability of these measurements as indicated by the different colours of the bread crumbs that represent consecutive measurements on different days and different time periods. More data to confirm this are available but tends to clutter the presentation. However, it should be possible to use these tracks for precise navigation and ground control for mapping projects at 5 k to 25 k with a CEP of 12.5 m. The process of geometrically rectifying images for mapping is beyond the scope of this work and will not be discussed here.

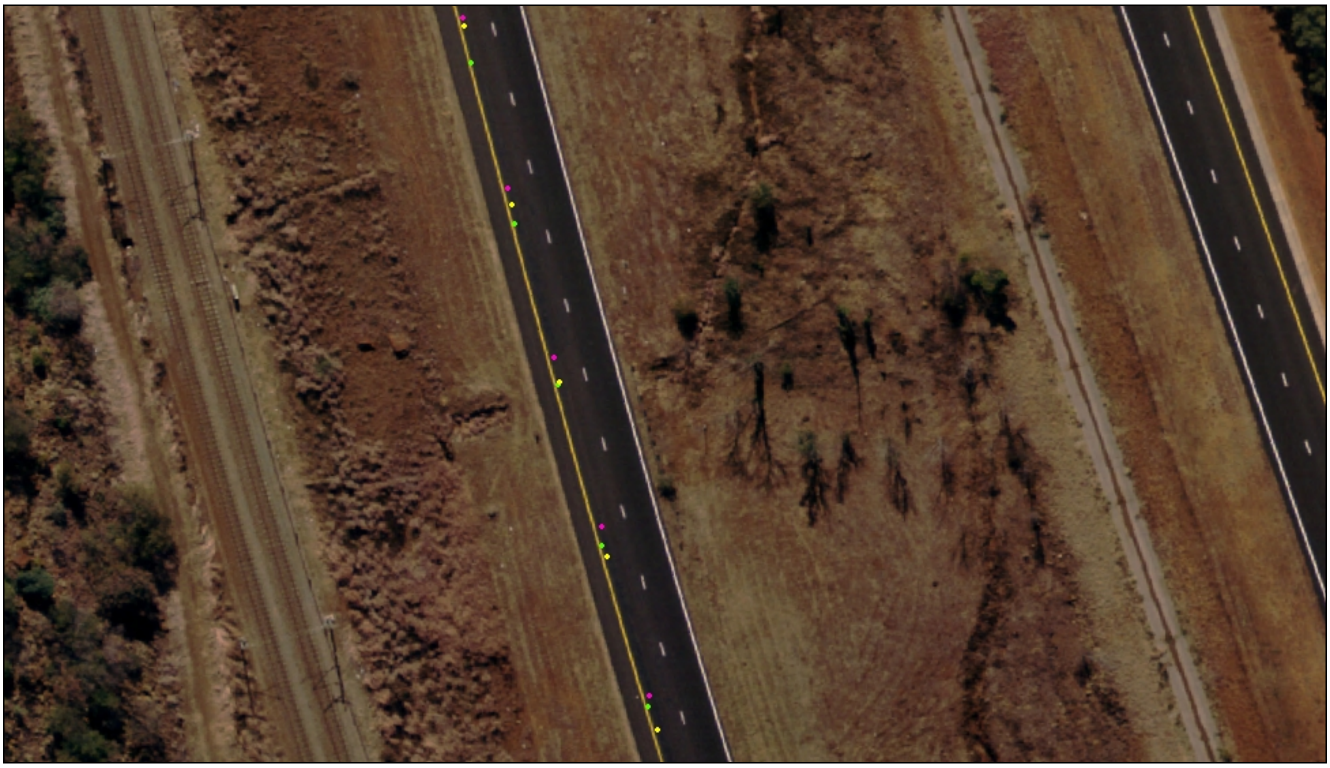

Figure 5-45: ProXH Tracks - Highway

65. From Figure 5-46 it can be seen that the speed along a straight stretch has almost no effect on the accuracy on collected data and that it will be possible to use it for rectifying an image. How will the navigational GPS receivers perform in this regard? First the Garmin GPSMap 60CSx will be used for the intersection shown here in Figure 5-47:

Figure 5-46: Garmin GPSMap 60CSx - Intersection

66. From the image in Figure 5-46 it can be seen that the breadcrumbs of the Garmin GPSMap 60CSx creates uncertainty. The implication is that because the breadcrumbs generally deviate approximately 5 m from the “true” track, the intersection is too small to create a clear picture. From the performances of the Garmin eTrex receivers in the previous analysis it should be concluded that the general deviation of approximately 7 m will increase the level of uncertainty at this intersection. Thus, larger features need to be selected.

Figure 5-47: Garmin GPSMap 60CSx - Highway

67. From Figure 5-48 is can be seen that on the highway similar trends were evident as were found while walking and carrying the Garmin GPSMap 60CSx receiver. Sometimes accuracy equalled that of theTrimble ProXH and occasionally it deviated up to 5 m from the “true” track.

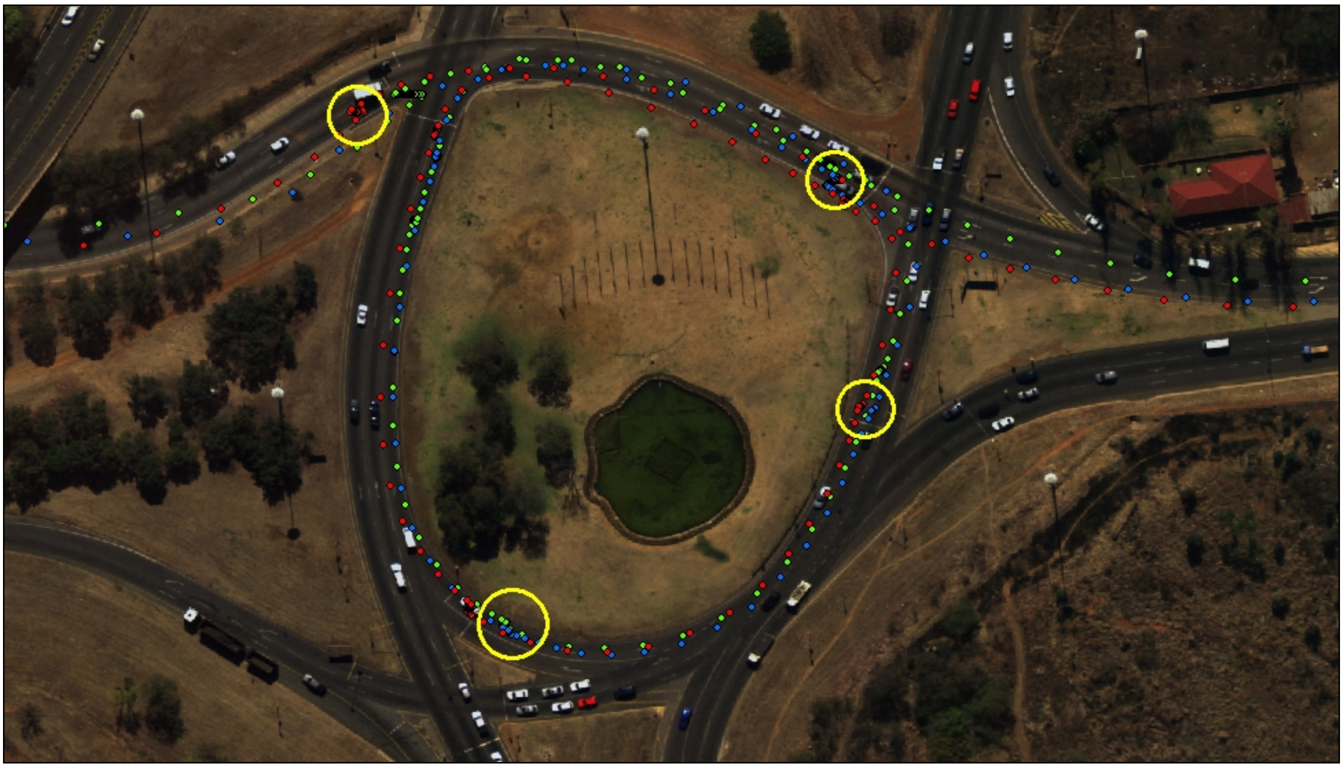

Figure 5-48: Garmin GPSMap 60CSx Track - Fountains Valley Traffic Circle/Interchange

Figure 5-49: Garmin GPSMap 60CSx Track - Traffic Circle

68. From the image in Figure 5-49 it can be seen that larger features like the Fountain Valley Circle can be captured more accurately with a navigational type GPS. However, stopping along the road, for instance at traffic lights, creates a cluster of breadcrumbs that may cause uncertainty about the "true" track (indicated with yellow circles). Garmin GPS

receivers use a filter to predict direction of movement. This function produced excellent results for navigation. However, when direction is changed quickly it tends to carry on along the predicted track. This delayed effect on the breadcrumbs can be seen in the image with the small traffic circle in Figure 5-50. It is this same effect that created some problems collecting tracks at the intersection above depicted in Figure 5-47. One needs to be mindful of this effect when navigating and/or collecting data for mapping projects.

Figure 5-50: ProXH and eTrex Tracks - Inner City (Sunnyside, Pretoria)

Figure 5-51: ProXH and eTrex Tracks - Tree Cover (Brooklyn – Pretoria)

69. In Figure 5-51 it can be seen that the Trimble ProXH (yellow track) has not captured the full track in the inner city, where high-rise buildings cause multipathing and shadowing, resulting in loss of lock on the L1 and L2 carrier signals. Under dense tree cover as indicated in Figure 5-52 the same effect can be observed. However, the Garmin eTrex (purple track) could carry on collecting the whole track during both outings. One way to overcome this restriction with the Trimble ProXH is to use the data unprocessed or to conduct only code processing. In this way the Pro XH is used similarly as the eTrex that only use the C/A-code measurements to collect tracks. The advantage of the higher accuracy of the ProXH (using L1 and L2 with post processing) will be lost by applying this technique.

70. In rural areas the roads are normally narrower or may even just be a cart track, leading to higher accuracies. Open savannah areas will reduce possibility of multipathing or shadowing, while thick bush will cause the opposite. It should also be kept in mind that a specific GPS receiver may have a constant bias. Routes should therefore be planned to collect data while encircling features and creating in this way, a large loop around or in the area of interest. Driving in one general direction only, with a receiver which exhibits a constant bias may cause a built-in offset correlating with the bias of the receiver. Driving in two opposite directions will reveal this offset. There are also other settings on a Garmin GPS that the operator should consider when field tracks are captured, for instance the default factory setting of 10 000 incidents or breadcrumbs per track. These aspects will be discussed in more detail in Appendix D.

SATELLITE BASED AUGMENTATION SYSTEM TESTED

71. During a visit to Germany in September 2010 a rudimentary test was conducted to see what the effect of EGNOS will be on taking measurements with a navigational GPS used in this study. The operator walked on the left side of the sidewalk next to the road and came back on the opposite side of the sidewalk. This measurement was repeated on two consecutive days (red and yellow tracks). A Google Earth image was used as background data. See Figure 5-53 for the Garmin tracks on the sidewalk. It was found that the measurements taken with a Garmin eTrex receiver with EGNOS activated deviate between 3 and 4 metres from the possible true track and are seemingly better than those taken without any augmentation presented in Figures 5-40 to 5-43. However, more tests will have to be conducted to verify this. The expected improvements on accuracy with EGNOS activated are available in Section 3 and 4 of the Service Definition Documentation Open Serve document on the EGNOS website at http://ec.europa.eu/enterprise/policies. This test correlates with these specifications. There are also specifications for agricultural, marine and aviation applications that will deliver application specific results. The tests in this study are relevant because the largest number of GPS receivers in the SANDF will be low accuracy handheld receivers applied in the role as tested.

Figure 5-52: Garmin eTrek Tracks with EGNOS Activated

CONCLUDING REMARKS

72. From the analyses it can be concluded that navigational type GPS receivers can be used for collecting ground control in the horizontal plane for mapping projects at scales of 50 k and smaller. The operator should be mindful of the fact that accuracies are much lower than mapping type GPS receivers. To overcome this, the project should be planned to collect features that are generally bigger than 25 m in diameter and are scattered evenly throughout the area of interest. The vehicle should be driven at a constant slow speed when direction is changed regularly. The operator should plan to collect where it will not be necessary to stop too frequently as this causes tracks with uncertainty. On straight stretches speed has no direct impact on the accuracy of the receiver. Narrower roads can be captured with higher accuracies. Capturing tracks on wide double and triple lane highways can be problematic. The yellow edge mark of the road is not always visible from aerial photography or satellite imagery, but in most cases the edge of the road can be seen. The effects of the ionosphere, multipathing and shadowing should be considered. It will be wise to use more than one receiver for the same track to ensure a backup and to counter unexpected deviations as indicated earlier. The availability of EGNOS will improve the accuracy of navigational GPS receivers. The principles explained here are equally applicable to purely navigational tasks.

SELECTIVE DENIAL OR INTENTIONAL JAMMING

73. The susceptibility of civilian type GPS receivers to jamming were tested by means of a rudimentary setup of a Rhode and Schwarz SML-B3 signal generator connected to an omni-directional choke ring GPS antenna. The signal generator can generate signals in the spectrum 9 kHz to 3.3 GHz with an output level of −140 dBm to +19 dBm. The signal generator, GPS antenna and Topcon GB-1000 GPS receiver were supplied by HartRAO. The antenna was tilted in the horizontal plane to project the jamming signal in a specific direction to control some of the signal emissions for measuring purposes. See Figure 5-54 below. The signal generator was set to generate a frequency modulation (FM) signal on the L1 band at 1 575.42 MHz. The signal output strength was tested between -3 dBm and 17 dBm.

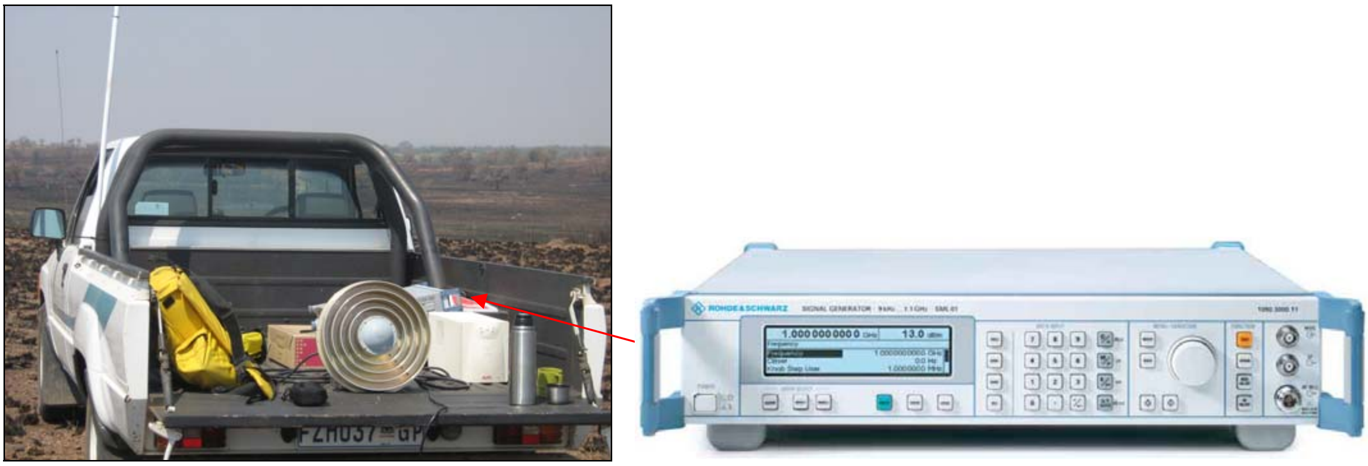

Figure 5-53: Photo of Jammer Setup

74. The tests were conducted at the General Piet Joubert Training Area north of Pretoria. Broken terrain with savannah vegetation was selected to simulate operational conditions and to indicate the effect of terrain on jamming. To depict the effect of terrain a viewshed from the jammers perspective was created with data supplied by SAC and CDNGI. The green shaded areas in Figure 5-55 are those that were in direct line of sight and are therefore “visible” to the jammer.

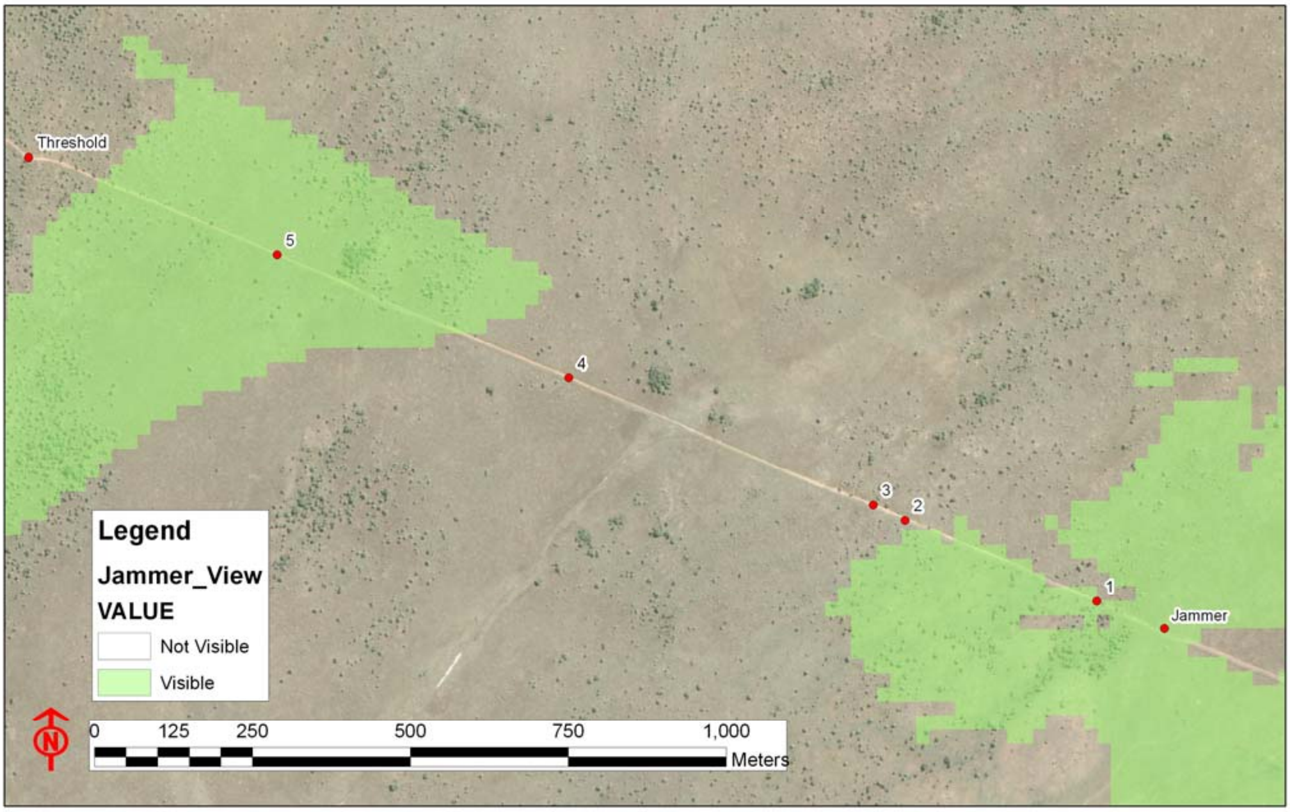

Figure 5-54: Viewshed of GPS Jamming Tests

75. The same GPS receivers used earlier in this study were used in the jamming test. In the initial test the jammer was set at 13 dBm and the GPS receivers were carried in a north-westerly direction away from the jammer. The jammer was able to disrupt all GPS receivers to a distance of approximately 2 km close to “Threshold”. Points 1 to 4 in Figure 5-56 indicate positions where the Garmin GPSMap 60CSx and the eTrex GPS receivers could obtain a position. These positions are in “dead ground” as indicated in the figure and indicate the shading effect of terrain. The Trimble and Topcon GPS receivers could not establish any position in this test. The position at Point 5 was possible with the Garmin GPS receivers by shading the jamming signal with the operator’s body. Closer to the jammer this was not possible. Other objects, such as a zinc pail and a stainless steel bowl were also used to estimate their shading effects. In this test it was found that the zinc pail did not protect the GPS, but that the stainless steel bowl was very effective and protected the GPS within a few metres from the jammer’s antenna. The metallurgic composition of these objects were not evaluated and was merely a rudimentary test that needs to be followed with more controlled tests to establish how a jammer’s signal can be effectively shaded with other objects when terrain does not render sufficient protection.

76. The GPS receivers were then deployed on the 2 km threshold. The GPS receivers were allowed to lock on to the available GPS satellites to establish a position. At the time of measurement 12 GPS and five GLONASS satellites were available. The signal generator output power was set to -3 dBm and progressively increased until the different receivers could not establish a position. A general observation is that the Garmin eTrex, which is the less sophisticated receiver, exhibited better resistance than the 60CSx to jamming. The Trimble ProXH performed the best of the receivers and this can be attributed to the Zephyr antenna design. The more sophisticated receiver, the Topcon GB-1000, was the easiest to jam on lower power levels (receiver sensitivity will play a role here). Refer to Table 5-26 that indicates these receivers’ ability to attain a position at different jamming signal strengths. In the table (P) indicates the ability to determine a position and NP indicates no position.

Table 5-23: GPS Receiver Jamming Resistance (P = Position, NP = No position)

Signal Strength dBm	Garmin	Garmin eTrex	Trimble ProXH	Topcon GB-1000
-3	P	P	P	P
0	P	P	P	NP
1	P	P	P	NP
4	P	P	P	NP
7	P	P	P	NP

9	P	P	P	NP
10	NP	P	P	NP
12	NP	P	P	NP
13	NP	NP	P	NP
15	NP	NP	P	NP
17	NP	NP	NP	NP

77. These tests were conducted to indicate how easy it is to jam civilian type GPS receivers. Using more appropriate equipment, such as directional antennas and higher signal outputs could render more significant results. Jamming is dependent on line of sight and terrain can shade the GPS receiver. However, to deploy a number of aerial jammers could not be too difficult, in which case the shading effect of terrain can be neutralised. Thus, the possibility to jam or spoof civilian type GPS receivers and protective measurements needs to be investigated further.

UNINTENTIONAL JAMMING

78. The unintentional jamming of GPS receivers by RADARS used in the SANDF that use the L-band was tested[5]. Tests with two of these RADARS, the ESR 220 or Kameelperd and Tactical Mobile Radar were conducted. It was found that none of these RADARS influenced the GPS receivers to the extent that they could not establish a position. The signal-to-noise ratio that indicates the strength of the GPS satellite signal at the receiver was not influenced visibly. It was only with measurements next to the Kameelperd that some influences could be observed, but it was not sufficient to prevent the receivers of establishing position. It can therefore be deducted that these RADARS will not influence or jam GPS receivers during operations

---

[5] More can be read about these RADARS at the Reutech website at http://www.rrs.co.za/products accessed during December 2010.

CHAPTER 6: SUMMARY OF CONCLUSIONS

79. Reference Systems. Using GPS for positional data in the SANDF requires that universal standards be established for reference systems that can be used throughout for setting up receivers for navigation and for collecting data. These same reference standards should also be applied in the mapping projects of the SANDF to ensure compatibility across systems. It is realised that existing systems may have legacy or different reference frames embedded. In these cases the geospatial officers attached to operations should assist operational commanders to understand the impact on operations and publish guidelines in operational orders. However, in this study it was proposed that WGS84 is used for the reference ellipsoid and the current published values of the ITRF be taken as the realisation of this datum throughout the African continent. It is therefore of paramount importance that the applicable ITRF epoch is understood and used correctly for a specific task. IGS stations can be used as base stations for differential corrections. Height measurements with GPS receivers could be in ellipsoidal (WGS84) values, while heights on maps and charts will be in orthometric values. The conversion of ellipsoidal heights to orthometric heights can be conducted with geoid models such as EGM 2008 and will be the responsibility of the geospatial officer attached to the operation. In mapping projects this will be conducted by the responsible cartographer. On South African soil the HART94 datum will be used and height above mean sea level as published on the CDNGI maps.

80. Accuracy Standards. Positional accuracy standards should be applied for each specific environment as required. For topographic mapping projects in the SANDF the positional accuracy standards of the Multinational Co-production Programme for 50 k to 100 k products and the NGA's UVM standard for 10 k to 25 k products will be used, while the S57 and ICAO standards will be applied in the maritime and aeronautical environments respectively.

81. GPS Theory. The SANDF is dependent on civilian type GPS receivers and will most probably not be able to use the military type GPS receivers that make use of the encrypted P(Y)-code. Three broad categories namely navigational, mapping and survey or geodetic GPS receivers are used and were discussed. Navigational receivers produce stand-alone solutions that make use of the C/A-code modulated on the L1 carrier signal and can attain accuracies of up to 3 m. Mapping and surveying receivers make use of the C/A-code as well as the L1 and L2 carrier signals and are capable of attaining sub-metre accuracies. Differential GPS, PPP and SBAS are augmentation techniques to improve accuracy and efficiency. Absolute PPP should be considered as a proposed solution for mapping projects where IGS or AFREF reference stations are lacking. There is great expectation for the

possible expanding of the EGNOS footprint to include the rest of Africa which will improve the attainable accuracies with C/A-code measurements. Details of this plan are not yet available. The proposed GPS modernisation to include two new signals, namely the L2C and L5 signals, will improve accuracy and presumably also improve resistance to interference or jamming.

82. Attainable Accuracies. Measurements were conducted to indicate attainable accuracies. A number of aspects that influence these accuracies were demonstrated and users should be mindful of these aspects. Different receivers and systems can render different accuracies and again the user should be aware of these capabilities. It was established that after three hours both the geodetic and the mapping receivers reached optimal accuracy levels. It was also established that augmentation of GPS measurements such as differential post-processing and PPP can eliminate most influences that cause less than optimal measurements. The influence of multipathing and shadowing by features such as high-rise buildings in urban areas and foliage were demonstrated. These influences should be prevented when navigational GPS receivers are used. The influence of the ionosphere is significant on measurements between about 12:00 and 20:00 local time. Measurements should therefore rather be taken during the early morning or at night. Another measure to minimise the effect of the ionosphere is to set elevation masks of 10º or 15º as was discussed under GPS Fundamentals (Effect of the Sun). It was established that civilian type navigational GPS receivers can be used with confidence for navigation and mapping projects at 50 k scale and smaller. For larger scale mapping projects mapping type GPS receivers should rather be used. Sufficient preparation and planning are required to ensure that the correct approach for the task is selected. This was discussed at length under Field Measurements with Navigational GPS Receivers in Chapter 5 and is summarised under Concluding Remarks in paragraph 5-75. More detail about this is included in Appendix D. It was indicated that a GPS receiver can fail unexpectedly and backup measures should be put in place.

83. Jamming. It was demonstrated that civilian type GPS receivers can easily be disrupted. This is a serious vulnerability that needs further investigation and special measures need to be developed to ensure survival on the battlefield. This is highlighted further when it is considered that the SANDF plans to conduct decisive actions by means of night operations when navigation is significantly more difficult. It is suggested that this topic be investigated further in a separate study.

APPENDIX A: REFERENCES

1. Allan, A.L. 2007. *Principles of Geospatial Surveying*. Whittles Publishing, Dunbeath Scotland.

2. Ashby, N. 2002. Relativity and the Global Positioning System. *Physics Today*, May. Access at htpp://www.ift.unesp.br during April 2009.

3. Bolstad, P. 2006. *GIS Fundamentals*, 2nd Edition 2006. Eider Press, White Bear Lake, Minnesota.

4. Chief Director Surveys and Mapping, 2010. *Datums and Coordinate Systems*. Pamphlet accessible at http://www.ngi.gov.za/index.php/Geodesy-GPS/datums-and-coordinate-systems.html updated during November 2010.

5. Collinson, R.P. 2003. *Introduction to Avionics Systems*, 2nd Edition. Kluwer Academic Publishers, Dordrecht, The Netherlands.

6. Forssell, B. and Olsen T.B. 2003. Jamming GPS: Susceptibility of some civil GPS receivers. *GPS World*.14.1 (Jan).

7. Gao, Y. and Chen, K. 2004. Performance Analysis of Precise Point Positioning Using Real-Time Orbit and Clock Products. *Journal of Global Positioning Systems* (2004) Vol. 3, No. 1-2: 95-100. Accessed at http://www.gmat.unsw.edu.au/wang/jgps during April 2009.

8. Hofmann-Wellenhof, B., Lichtenegger, H. and Collins, J. 2001. *GPS Theory and Practice*, 5th Revised Edition. Springer Wein, New York.

9. Illife, J. and Lott, R. 2008. *Datums and Map Projetctions*. 2nd Edition. Whittles Publishing, Dunbeath, Caithness, Scotland.

10. Kaplan, E.D. and Hegarty, C.J. 2006. *Understanding GPS Principles and Applications*, 2nd Edition. Artech House, 685 Canton Street, Norwood.

11. King, M., Edwards, S. and Clarke, P. *Precise Point Positioning: Breaking the Monopoly of Relative GPS Processing.* Accessed at ftp://stella.ncl.ac.uk during April 2009.

12. Leick, A. 2004. *GPS Satellite Surveying*. 3rd Edition. John Wily and Sons. Canada.

13. Lekkerkerk, H. 2008. *GPS Handbook for Professional GPS Users*, C Media Productions.

14. Leslie, M.W. 2008. The Measure of Time. *Inside GNSS*, July/August.

15. Merry C. L. 2003. *The African Geoid Project and its Relevance to the Unification of African Vertical Reference Frames*. Paper presented at the 2nd FIG Regional Conference Marrakech, Morocco, December 2-5.

16. Merry, C.L. 2006. *Introduction to the Global Positioning System*, 4th Edition. Technical notes for use by the University of Cape Town.

17. Merry, C.L. 2007. Augmentation Systems for GPS. *PositionIT*, May/June.

18. Merry, C.L. 2008. GPS and the Geoid. *PositionIT.* July/August.

19. Chandler, G. and Merry, C.L. 2010. South African Geoid 2010: SAGEOID 10. *Poisition IT*, June.

20. Mireault, Y., Tetreault, P., Lahaye, F., Heroux, P. and Kouba, 2008. Precise Point Positioning: A new, timely service from Natural Resources Canada *J. GPS World* 19.9 (Sept).

21. Ovstedal, O., Kjorsvik, N.S. and Gjevestad, J.G.O. 2006. *Surveying using GPS Precise Point Positioning*. Accessed at http://www.fig.net/pub/fig2006/papers/ during April 2009.

22. Realini, E. 2009. *goGPS – a navigation software to enhance the accuracy of low cost GPS receivers*. Presentation at the Free and Open Software Conference of 2009 accessed at http://download.osgeo.org/osgeo/foss4g/2009 during April 2010.

23. Richardson, D. 2003. GPS Proves Jam Resistant. *Armada International No 3 of 2003.*

24. School of Surveying & Spatial Information Systems at the University of New South Wales, Australia. Updated May 2010. *Principles and Practice of GPS Surveying*. Accessed at www.gmat.unsw.edu.au/snap/gps/ gps_survey during April 2009.

25. Schwieger, V. and Gläser, A. 2009. *Possibilities of Low Cost GPS Technology for Precise Geodetic Applications.* Accessed at www.fig.net/pub/fig.2009 during April 2010.

26. United States Defence Mapping Agency's Technical Manual 8400.1, 1991. *Error Theory as Applied to Mapping, Charting and Geodesy*.

27. USA Federal Geographic Data Committee's *Geospatial Positioning Accuracy Standards*. 1998. FGDC-STD-007-1-1998 accessed at http://fgdc.er.usgs.gov/fgdc.html during April 2009.

28. USA Defence Mapping Agency's Technical Manual 8358.1, 1996, *Datums, Ellipsoids, Grids and Grid Reference Systems*.

29. USA National Mapping Agency's Technical Report 8350. 2000. Department of Defence World Geodetic System. 3rd Edition.

30. USA Department of Defence. 2008. *Global Position System Standard Positioning Service Performance Standard*, 4th Edition.

31. Varner, C.C. 2000. UCGE Report Number 20129. *DGPS Carrier Phase Network and Partial Derivative Algorithms.* University of Calgary, Alberta, Canada.

32. Wells. D. 1987. *Guide to GPS Positioning*. 2nd Edition. Fredericton, New Brunswick, Canada.

33. Whitman. 2002., Keeping our bearings. *U.S. News & World Report*. Vol. 133, Issue 15.

34. Wonnacott, R. 2005. *AFREF: Background and Progress towards a Unified Reference Frame for Africa*. Paper presented at the FIG Working Week at Cairo, Egypt 16 – 21 April 2005. Accessed at http://www.fig.net/pub/montley_articles/june_2005 during October 2010.

35. Wonnacott, R. 2008. *The African Reference Frame Project and South Africa's TrigNet System*. Paper presented at the International Committee on GNSS, Pasadena, California on 9 December 2008. Accessed at http://www.oosa.unviena.org/pdf/icg during October 2010.

APPENDIX B: DATUMS USED IN AFRICA

Local Geodetic Datums		Reference Ellipsoids and Parameter Differences			No. of Satellite Stations Used	Transformation Parameters				
Name	Code	Name	DA(M)	Df x 10^4		Cycle No.	Pub Date	DX(m)	DY(m)	DZ(m)
NORTH SAHARA 1959 Algeria	NSD	Clarke 1880	-112.145	-0.54750714	3	0	1993	-186 +/-25	-93 +/-25	310 +/-25
VOIROL 1960 Algeria	VOR	Clarke 1880	-112.145	-0.54750714	2	0	1993	-123 +/-25	-206 +/-25	219 +/-25
VOIROL 1874 Algeria/Tunisia	VOI	Clarke 1880	-112.145	-0.54750714		0	1997	-73	-247	227
ADINDAN Burkina Faso	ADI-E	Clarke 1880	-112.145	-0.54750714	1	0	1991	-118 +/-25	-14 +/-25	218 +/-25
ARC 1950 Botswana	ARF-A	Clarke 1880	-112.145	-0.54750714	9	0	1991	-138 +/-3	-105 +/- 5	-289 +/-3
ARC 1950 Burundi	ARF-H	Clarke 1880	-112.145	-0.54750714	3	0	1991	-153 +/-20	- 5 +/-20	-292 +/-20
ADINDAN Cameroon	ADI-F	Clarke 1880	-112.145	-0.54750714	1	0	1991	-134 +/-25	-2 +/-25	210 +/-25
MINNA Cameroon	MIN-A	Clarke 1880	-112.145	-0.54750714	2	0	1991	- 81 +/-25	- 84 +/-25	115 +/-25
POINTE NOIRE 1948 Congo	PTN	Clarke 1880	-112.145	-0.54750714	1	0	1991	-148 +/-25	51 +/-25	-291 +/-25
AYABELLE LIGHTHOUSE Djibouti	PHA	Clarke 1880	-112.145	-0.54750714	1	0	1991	- 79 +/-25	-129 +/-25	145 +/-25
EUROPEAN 1950 Egypt	EUR-F	International 1924	-251	-0.14192702	14	0	1991	-130 +/-6	- 117 +/-8	-151 +/-8
OLD EGYPTIAN 1907 Egypt	OEG	Helmert 1906	-63	0.00480795	14	0	1987	-130 +/-3	+110 +/-6	-13 +/-8
MASSAWA Eritrea (Ethiopia)	MAS	Bessel 1841	739.845	0.10037483	1	0	1987	639 +/-25	405 +/-25	60 +/-25
ADINDAN Ethiopia	ADI-A	Clarke 1880	-112.145	-0.54750714	8	0	1991	-165 +/-3	-11 +/-3	206 +/-3

M'PORALOKO Gabon	MPO	Clarke 1880	-112.145	-0.54750714	1	0	1991	-74 +/-25	-130 +/-25	42 +/-25
LEIGON Ghana	LEH	Clarke 1880	-112.145	-0.54750714	8	0	1991	-130 +/-2	29 +/-3	364 +/-2
BISSAU Guinea-Bissau	BID	International 1924	-251	-0.14192702	2	0	1991	-173 +/-25	253 +/-25	27 +/-25
DABOLA Guinea	DAL	Clarke 1880	-112.145	-0.54750714	4	0	1991	-83 +/-15	37 +/-15	124 +/-15
ARC 1960 Kenya	ARS-A	Clarke 1880	-112.145	-0.54750714	24	0	1997	-157 +/-4	- 2 +/-3	-299 +/-3
ARC 1950 Lesotho	ARF-B	Clarke 1880	-112.145	-0.54750714	5	0	1991	-125 +/-3	-108 +/-3	-295 +/-8
LIBERIA 1964 Liberia	LIB	Clarke 1880	-112.145	-0.54750714	4	0	1987	-90 +/-15	40 +/-15	88 +/-15
ADINDAN *Mean Solution* *(Ethiopia and Sudan)*	ADI-M	Clarke 1880	-112.145	-0.54750714	22	0	1991	-166 +/-5	-15 +/-5	204 +/-3
ARC 1950 *Mean Solution* *(Botswana,Lesotho,Malawi, Swaziland, Zaire, Zambia, Zimbabwe)*	ARF-M	Clarke 1880	-112.145	-0.54750714	41	0	1987	-143 +/-20	-90 +/-33	-294 +/-20
ARC 1960 *Mean Solution* *(Kenya and Tanzania)*	ARS-M	Clarke 1880	-112.145	-0.54750714	25	0	1991	-160 +/-20	-6 +/-20	-302 +/-20
POINT 58 *Mean Solution* *(Burkina Faso and Niger)*	PTB	Clarke 1880	-112.145	-0.54750714	2	0	1991	-106 +/-25	-129 +/-25	165 +/-25
TANANARIVE OBSERVATORY 1925 Madagascar	TAN	International 1924	-251	-0.14192702		0	1987	-189	-242	-91
ARC 1950 Malawi	ARF-C	Clarke 1880	-112.145	-0.54750714	6	0	1991	-161 +/-9	-73 +/-24	-317 +/-8
ADINDAN Mali	ADI-C	Clarke 1880	-112.145	-0.54750714	1	0	1991	-123 +/-25	-20 +/-25	220 +/-25
MERCHICH	MER	Clarke 1880	-112.145	-0.54750714	9	0	1987	31	146	47

Morocco								+/-5	+/-3	+/-3
SCHWARZECK Namibia	SCK	Bessel 1841	653.135*	-0.10037483	3	0	1991	616 +/-20	97 +/-20	-251 +/-20
MINNA Nigeria	MIN-B	Clarke 1880	-112.145	-0.54750714	6	0	1987	-92 +/- 3	-93 +/- 6	122 +/- 5
ADINDAN Senegal	ADI-D	Clarke 1880	-112.145	-0.54750714	2	0	1991	-128 +/-25	-18 +/-25	224 +/-25
SIERRA LEONE 1960 Sierra Leone	SRL	Clarke 1880	-112.145	-0.54750714	8	0	1997	-88 +/-15	4 +/-15	101 +/-15
AFGOOYE Somalia	AFG	Krassovsky 1940	-108	0.00480795	1	0	1987	-43 +/-25	-163 +/-25	45 +/-25
CAPE South Africa	CAP	Clarke 1880	-112.145	-0.54750714	5	0	1987	-136 +/-3	-108 +/- 6	-292 +/-6
ADINDAN *Mean Solution* *(Sudan and Ethiopia)*	ADI-M	Clarke 1880	-112.145	-0.54750714	22	0	1991	-166 +/- 5	-15 +/-5	204 +/-3
ADINDAN Sudan	ADI-B	Clarke 1880	-112.145	-0.54750714	14	0	1991	-161 +/- 3	-14 +/- 5	+205 +/- 3
ARC 1950 Swaziland	ARF-D	Clarke 1880	-112.145	-0.54750714	4	0	1991	-134 +/-15	-105 +/-15	-295 +/-15
ARC 1960 Tanzania	ARS-B	Clarke 1880	-112.145	-0.54750714	12	0	1997	-175 +/- 6	-23 +/- 9	-303 +/-10
CARTHAGE Tunisia	CGE	Clarke 1880	-112.145	-0.54750714	5	0	1987	-263 +/- 6	6 +/-9	431 +/- 8
EUROPEAN 1950 Tunisia	EUR-T	Intrnational 1924	-251	-0.14192702	4	0	1993	-112 +/-25	-77 +/-25	-145 +/-25
VOIROL 1874 Tunisia/Algeria	VOI	Clarke 1880	-112.145	-0.54750714		0	1997	-73	-247	-227
ARC 1950 Zaire (Congo)	ARF-E	Clarke 1880	-112.145	-0.54750714	2	0	1991	-169 +/-25	-19 +/-25	-278 +/-25
ARC 1950 Zambia	ARF-F	Clarke 1880	-112.145	-0.54750714	5	0	1991	-147 +/-21	-74 +/-21	-283 +/-27
ARC 1950 Zimbabwe	ARF-G	Clarke 1880	-112.145	-0.54750714	10	0	1991	-142 +/- 5	-96 +/- 8	-293 +/-11

Source: http://earth-info.nga.mil/GandG/coordsys/onlinedatum/CountryAfricaTable.html accessed July 2009.

APPENDIX C: MILITARY DATA STANDARDS USED IN THE SANDF

MULTINATIONAL GEOSPATIAL CO-PRODUCTION PROGRAMME STANDARD

1. Introduction. This abstract from MGCP documentation only address positional accuracy. The MGCP Quality Assurance (QA) process prescribes various quality checks that need to be applied on vector data captured from satellite imagery. The main goal of the MGCP is the production of high resolution vector data at the 50 k and 100 k map density. All data produced, at any density, will meet a minimum Horizontal Circular Error (CE (90%)) accuracy of 25 m. This can be regarded as a statement about the level of ambition concerning absolute positional accuracy.

2. Components of Positional Error In the MGCP production the absolute positional error can be regarded as composed of one part stemming from the orthorectification process and another part stemming from the process of vectorising objects from the rectified satellite imagery. The MGCP Imagery Benchmarking Process states that the accuracy of the final rectified imagery products must not exceed 15 m absolute circular error with a 90% confidence level. From error propagation for the determination of line objects in the MGCP project, it is concluded that in order to achieve the minimum level for absolute accuracy in MGCP, the error stemming from the digitising process must not exceed 18 m.

3. Definition of Significant Points. The requirements on absolute positional error as defined above apply to significant points. Significant points in the MGCP context are defined as:

   a. Digitised points on well defined features, such as corners of rectangular buildings.

   b. Arbitrary points on well defined linear objects such as the median line of a road.

   c. Well defined, but not necessarily digitised points.

4. For other geometries such as boundaries of fuzzy objects, the Horizontal Circular Error (CE (90%)) accuracy of 25 m has to be regarded as a level of ambition, which depending on available sources etc., cannot always be guaranteed to be met. The approach to be followed is to zoom to an appropriate scale or further where problematic areas are found. Table 1 recommends possible zoom factors based on the source imagery:

Table 1: Zoom Factor for Imagery Source Type

QA Scale	**Quickbird**	**Ikonos**	**Spot**	**Radar** (GeoSAR X- and P-band)
Overview Scale	1:10,000	1:10,000	1:40,000	1:20,000
Check Scale	1:5,000	1:5,000	1:25,000	1:10,000
Zoom In Scale	1:3,000/ 1:1,500	1:2,500/ 1:1,000	1:10,000/ 1:5,000	1:5,000

5. Visual Positional Accuracy Check

a. For each 10 km x 10 km section, get a general overview and select ideally 20 arbitrary but well defined points/features. Measure and record the distance between the vector point/feature and compare it to its corresponding position on the imagery.

b. Are features captured in their exact position relative to the imagery – or does the line, point or area geometry not match the feature, e.g. is the point captured right at the centre of a point feature?

c. Are well defined features correctly captured relative to adjacent features, e.g. all buildings are placed on the correct side of a road?

d. Is the generalisation of features in accordance with the Extraction Guide?

e. Any measurement that is greater than 18 m and any other discrepancies found, must be pointed out in a QA Report.

The implication of this QA standard is that the imagery used for vector data capturing should have been correctly orthorectified to enable accurate capturing and this requires ground control points collected by means of a GPS.

ICAO D9881 STANDARD

Abstract from the ICAO D9881 standard that is used by the SA Air Force (Directorate Aviation Safety).

1. Areas of Coverage. For the purpose of this document, the requirements for accuracy, integrity and resolution are provided for the following areas:

   i. Area 1: Entire area of a State

   ii. Area 2: Terminal control area

   iii. Area 3: Aerodrome/heliport area

   iv. Area 4: Category II or III operations area

2. Area 1 – The State. Area 1 covers the entire state. Every obstacle within Area 1 whose height above the ground is equal to or greater than 100 m must be collected and recorded in the obstacle database in accordance with the Area 1 numerical requirements specified in Table 1.

Table 1: Terrain Data Requirements for Area 1 – the State

Areas/Attributes	Area 1 — the State
Horizontal Accuracy	50.0 m
Data Integrity	Routine (10 -3)
Vertical Accuracy	30.0 m
Vertical Resolution	1.0 m
Confidence Level	90%
Post Spacing	3 arc second (90 m)

3. Area 2 – Terminal Control Area. Area 2 is the terminal control area as defined in the Aeronautical Information Publication (AIP) of the State, limited to a maximum of 45 km from the ARP. For airfields which do not have a legally defined Terminal Area (TMA), Area 2 is the area covered by a radius of 45 km from the ARP excluding sub-areas where flight operations are restricted due to high terrain or “no fly” conditions. Within an area covered by a 10 km radius from the ARP, terrain data must be collected in accordance with the Area 2 numerical requirements listed in Table 2. In the area between 10 km and the TMA boundary or 45 km radius (whichever is smaller), terrain that penetrates the horizontal plane 120 m

above the lowest runway elevation must be collected and recorded in accordance with the Area 2 numerical requirements listed in Table 2. In the area between 10 km and the TMA boundary or 45 km radius (whichever is smaller), terrain that does not penetrate the horizontal plane 120 m above the lowest runway elevation must be collected and recorded in accordance with the Area 1 numerical requirements listed in Table 2. In those portions of Area 2 where the flight operations are prohibited due to very high terrain or other regulations, terrain must only be collected and recorded in accordance with the Area 1 numerical requirements listed in Table 2. See Figure 1 for a graphical presentation.

Table 2: Terrain Data Requirements for Area 2

Areas/Attributes	Area 2 — Terminal Airspace
Horizontal Accuracy	5.0 m
Data Integrity	Essential (10 -5)
Vertical Accuracy	3.0 m
Vertical Resolution	0.1 m
Confidence Level	90%
Post Spacing	1.0 arc second (30 m)

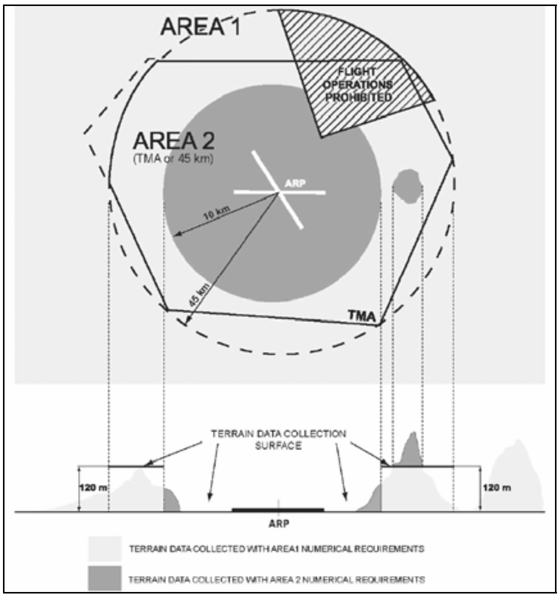

Figure 1: Areas 1 and 2 for Terrain

4. <u>Area 3 — Aerodrome/Heliport Area</u>. When surveying vertical objects, the horizontal spatial extent to be surveyed must include the aerodrome surface movement area plus a buffer of 50 m or the minimum separation distances specified in Doc 9157, whichever is

greater. When surveying vertical objects from a runway, the horizontal spatial extent to be surveyed must cover the area that extends from the edge(s) of the runway(s) to 90 m from the runway centreline(s). See Figure 2. All vertical objects and terrain in the horizontal spatial extent region that extend more than 0.5 metres above the horizontal plane passing through the nearest point on the aerodrome surface movement area may be hazardous for surface movement and must therefore be surveyed. Numerical requirements for terrain data in the aerodrome mapping area are listed in Table 3.

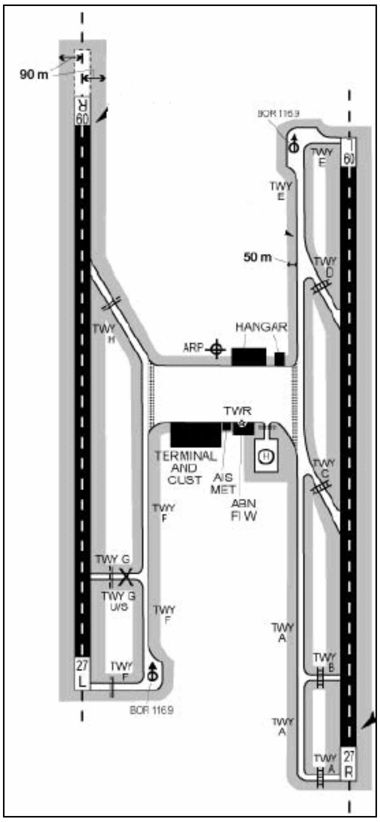

Figure 2: Exclusion of Interior Region for Aerodrome Mapping

Table 3: Terrain Data Numerical Requirements to Support Aerodrome Mapping

Attributes/Area	Area 3 Aerodrome Mapping
Horizontal Accuracy	0.5 m
Data Integrity	Essential (10-5)
Vertical Accuracy	0.5 m
Vertical Resolution	0.01 m
Confidence Level	90%
Post Spacing	0.6 arc second (20 m)

5. <u>Area 4 — CAT II and III Operation Area</u>. Area 4 is defined as the Radar Altimeter Area for CAT II/III Precision Approach procedures. The area extends from the runway threshold to 900 m (3000 ft) from the threshold. It is 120 m (400 ft) wide and centred on an extension of the runway centreline. See Figure 3. At those airports where runways are equipped for CAT II or III operations, terrain data requirements for Area 4, provided in Table 4, must apply.

Table 4: Terrain Data Requirements for Area 4

Areas Attributes	Area 4 — CAT II/III Operation Area
Horizontal Accuracy	2.5 m
Data Integrity	Essential (10-5)
Vertical Accuracy	1.0 m
Vertical Resolution	0.1 m
Confidence Level	90%
Terrain Publication Timeliness	As required
Post Spacing	0.3 arc second (9 m)

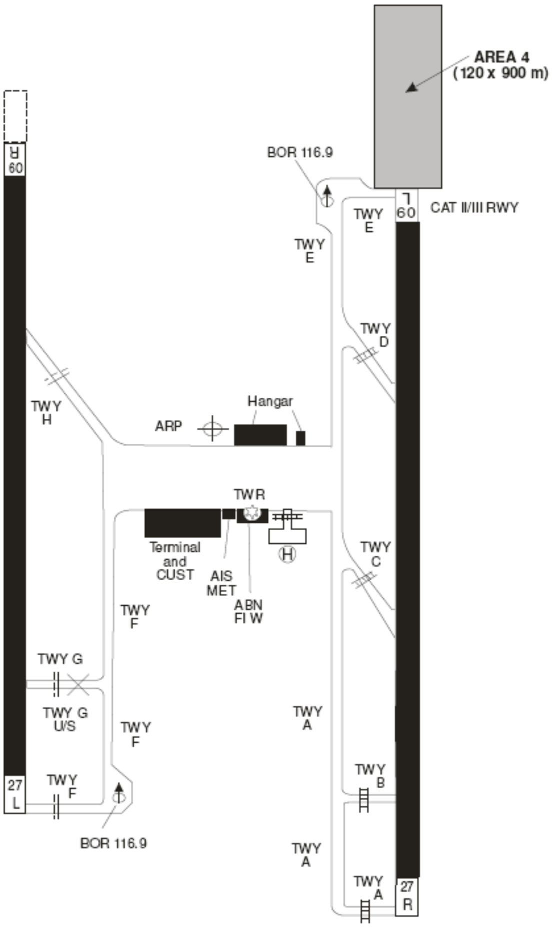

Figure 3: Terrain Data Collection Surface — Area 4

S-57 DATA STANDARD

Positional abstract from the S-57 standard that is used by the SA Naval Hydrographer.

1	2	3		4	5
ZOC	**Position Accuracy**	**Depth Accuracy**		**Seafloor Coverage**	**Typical Survey Characteristics**
A1	± 5 m + 5% depth	=0.50 + 1%d		Full area search undertaken. Significant seafloor features detected and depths measured.	Controlled, systematic survey high position and depth accuracy achieved using DGPS or a minimum three high quality lines of position (LOP) and a multibeam, channel or mechanical sweep system.
		Depth (m)	Accuracy(m)		
		10	± 0.6		
		30	± 0.8		
		100	± 1.5		
		1000	± 10.5		
A2	± 20 m	= 1.00 + 2%d		Full area search undertaken. Significant seafloor features detected and depths measured.	Controlled, systematic survey achieving position and depth accuracy less than ZOC A1 and using a modern survey echosounder and a sonar or mechanical sweep system.
		Depth (m)	Accuracy(m)		
		10	± 1.2		
		30	± 1.6		
		100	± 3.0		
		1000	± 21.0		
B	± 50 m	= 1.00 + 2%d		Full area search not achieved; uncharted features, hazardous to surface navigation are not expected but may exist.	Controlled, systematic survey achieving similar depth but lesser position accuracy less than ZOC A2 and using a modern survey echosounder, but no sonar or mechanical sweep system.
		Depth (m)	Accuracy(m)		
		10	± 1.2		
		30	± 1.6		
		100	± 3.0		
		1000	± 21.0		
C	± 500 m	= 2.00 + 5%d		Full area search not achieved, depth anomalies may be expected.	Low accuracy survey or data collected on an opportunity basis such as soundings on passage.
		Depth (m)	Accuracy(m)		
		10	± 2.5		
		30	± 3.5		
		100	± 7.0		
		1000	± 52.0		
D	Worse than ZOC C	Worse than ZOC C		Full area search not achieved, large depth anomalies may be expected.	Poor quality data or data that cannot be quality assessed due to lack of information.
U	Unassessed - The quality of the bathymetric data has yet to be assessed.				

1. Zone of Confidence (ZOC). The allocation of a ZOC indicates that particular data meets minimum criteria for position and depth accuracy and seafloor coverage defined in this Table. ZOC categories reflect a charting standard and not just a hydrographic survey standard. Depth and position accuracies specified for each ZOC category refer to the errors

of the final depicted soundings and include not only survey errors, but also other errors introduced in the chart production process. Data may be further qualified by Object Class "Quality of Data" (M_QUAL) sub-attributes as follows:

a. Positional Accuracy (POSACC) and Sounding Accuracy (SOUACC) may be used to indicate that a higher position or depth accuracy has been achieved than defined in this Table (e.g. a survey where full seafloor coverage was not achieved could not be classified higher that ZOC B; however, if the position accuracy was, for instance, ± 15 m, the sub-attribute POSACC could be used to indicate this).

b. Swept areas where the clearance depth is accurately known but the actual seabed depth is not accurately known may be accorded a "higher" ZOC (i.e. A1 or A2) providing positional and depth accuracies of the swept depth meets the criteria in this Table. In this instance, Depth Range Value 1 (DRVAL1) may be used to specify the swept depth. The position accuracy criteria apply to the boundaries of swept areas.

2. Position Accuracy. Position Accuracy of depicted soundings at 95% CI (2.45 sigma) with respect to the given datum. It is the cumulative error and includes survey, transformation and digitizing errors etc. Position accuracy need not be rigorously computed for ZOCs B, C and D, but may be estimated based on type of equipment, calibration regime and historical accuracy.

APPENDIX D: GPS FIELD MANUAL

1. This section will elaborate on the preparations that need to be made before collection of positional data with a GPS receiver will commence. First and foremost the task at hand needs to be understood for it will determine the type of planning and equipment that is needed.

2. Plan the Task. The following salient points may assist in the planning of the data collection excursion.

    a. Determine where the task will be conducted. Will it be in an own controlled environment or should access permission be obtained, such as in national parks or privately owned land/area? Determine the correct authorities and procedures.

    b. Use maps and imagery to plan access and routes. Determine the extent of the target area and the proposed features, such as ground control points (GCPs) that need to be collected. Allocate sufficient time to travel as well as to collect the data. Remember travelling time in the field is significantly slower.

    c. Plan safety aspects, especially on military training areas and shooting ranges, for instance:

        i. Areas to be avoided or no-go areas.

        ii. Safety clothes when working in dangerous areas, e.g. special head gear when working on construction sites or clothes for extreme climates.

        iii. Security rope when on ladders, rooftops, etc.

        iv. Special vehicle licences when needed.

    d. Determine the need for a base station.

        i. Determine if there is a fixed or known point that is available that has been surveyed before. Are the coordinates known and reliable? Are the datum and projection of the coordinates known? Is there an ITRF or other base station in the vicinity?

ii. Determine if a new point needs to be established. The following may be of importance:

  (1) Plan to avoid multipath. Thus, avoid high-rise buildings and/or reflective surfaces close to the point. Ensure antennas are fitted with base plates to prevent reflection from low elevations.

  (2) Ensure that it is situated on stable ground. Avoid areas that are known to be unstable, such as areas with varying underground water levels or close to disturbed areas where large excavations took place.

  (3) Determine how accessible it is and if it can be visited any time without restriction?

  (4) Is it safe to put up the base station at the selected point?

iii. Plan the monitoring of data collection at the base station during the excursion to ensure it is operating continuously and properly.

iv. Plan the quality control to ensure base data are accurate/usable.

v. When base data are radio transmitted from the base station to the roving receiver, this needs to be planned and tested beforehand.

vi. Plan the excursion to be conducted under favourable conditions. The following aspects may be considered:

  (1) The ionosphere effect on measurements as discussed earlier. Early mornings or late nights will generally provide better results. After midday until 18:00 should be avoided. At lower latitudes this may shift to a later timeslot.

  (2) The forecast of satellite availability and associated DOP values. Some GPS software allows for this and can be used to plan the excursion accordingly.

  (3) Avoid reflective surfaces and shadowing as discussed.

3. Prepare Equipment. After the task has been planned the equipment needs to be prepared and tested. The following needs to be confirmed.

   a. Ensure GPS receivers are in working condition.

   b. Ensure that the settings such as the datum, measurement units, elevation mask, locking interval, etc. are set correctly on all GPS receivers.

   c. Charge batteries and ensure that chargers and or solar panels with fittings are tested and packed. Ensure correct wall-plug fittings for chargers and other equipment. Ensure enough batteries of the correct type are packed for the task.

   d. Make sure enough space is available on receivers' internal memory and data cards. A good principle is not to erase all data from receivers or format data cards. You do not know when old data on the receiver or data card is needed again by somebody else. Create only sufficient space for the task at hand by erasing some of the oldest data.

   e. Pack measuring tapes to determine antenna heights in the field.

   f. Check and pack GPS poles, tripods and carrying bags. A 30 cm antenna pole to be used at Trig Beacons in the RSA can be handy.

   g. Test and pack power and antenna cables.

   h. If a computer is used as a data logger the necessary GPS software must be loaded and tested. Ensure USB – serial port conversion cables and software is loaded and working. Ensure chargers and or solar panels with correct fittings are tested and packed.

   i. GPS receivers and computers need to be protected against the elements when extended field measurements are taken. The protective cases of expensive equipment may suffice and where these are not available a cooler box may be handy.

   j. The following prove to come in handy during field measurements:

      i. A coil of strong rope, tie-downs and bungee-cords to fix antenna poles to other structures on rooftops and other places.

ii. A multi-tool such as a Leatherman®.

iii. A couple of locks and chains to lock up base or static stations when these cannot be guarded. Sometimes you can access a relatively safe place, such as a rooftop, a fenced in tennis court or a swimming pool to establish a base station, but often there is no means to lock a gate. Beware of multipathing, which can result when locating a GPS antenna too close to a fence.

k. Ensure and test that base or reference data provider's websites are accessible and available. It may require registering and acquiring passwords or even subscription.

l. Ensure that the data dictionary is downloaded to the GPS receivers when attribute data of features need to be captured with the positional data. Ensure that the terminology of the data dictionary is understood by every operator.

m. Ensure that other equipment, such as laser range finders are operational and measurement data formats are properly integrated with the GPS software.

n. Ensure that other software that may be needed, such as GeoRover for integrating digital photos with GPS tracks are loaded and functional.

o. Synchronise time settings on data loggers, computers and digital cameras that will be used.

4. <u>Garmin Receiver Settings</u>. Garmin receivers are navigational instruments and special care should be taken when these receivers are used for collecting ground control data for mapping projects. The following settings are important.

a. Ensure the correct datum is selected. On the Main Menu select Setup and under Setup select Units.

b. On the Main Menu select Tracks and set Track Log to "On", on the Track Log Setup menu "Wrap When Full" should be switched off (unselected) and on the Data Card Setup the "Log Track To Data Card" should be activated (selected). Garmin receivers are factory set to lock only 10 000 incidents per track. Thus, when "Wrap When Full" is selected and the 10 000 limit is reached the receiver will capture the additional incidents over the beginning of the track and that part will be lost. Thus, by switching off “Wrap When Full”, the receiver will warn the operator that the track is full. The operator can save the track to the data card and the “Track Log” can be cleared for work to continue.

c. On the Main Menu select Tracks. On the Tracks Setup menu the “Record Method” and “Interval” should be set to a preferred time interval and not on “Auto”. If set on “Auto” some of the incidents or bread crumbs will be weeded out when the track is saved to save space on the micro SD card. A full track of 10 0000 incidents without additional annotation will be in the vicinity of 1 to 1,5 MB that approximates 2 h and 46 min of capturing at one second intervals. Some of the Garmin receivers that are used in the SANDF are equipped with a 2 GB micro SD cards of which 1 GB is allocated to the background maps. Thus, approximately 800 full tracks can be stored on the remaining 1 GB space on the micro SD card. Bigger micro SD cards are also available and background maps are helpful, but not essential for capturing mapping data.

d. On the Main Menu select Setup and Map. On the Map Setup – General the “Lock On Road” should be switched off. If this function is switched on the track will lock to the centreline of the road of the background map and the readings may be incorrect depending on the accuracy of the background map. If the GPS tracks are intended to verify the accuracy of available data, this will be futile. “Lock On Road” should therefore be switched off.

5. Conduct Field Measurements. All planning and preparatory steps were taken to conduct the measurements. Stay with the original collection plan, but be ready to adjust the plan on the spot if necessary. However, the client agreed to the collection plan and expects results accordingly. Remember also that an equal dispersion of GCP over the area remains a prerequisite for the effective rectification of an image. A detailed field record or log of the collection excursion is of paramount importance. The following should be included:

a. Names of the operators involved and name of the team leader.

b. Date, time and place of collection.

c. Description of the feature or GCP. Attribute data should be logged according to the data dictionary.

d. A sketch and or photos of the feature.

e. The type and serial numbers of the GPS receiver and antenna used for collecting the data.

f. Name given to the feature on the GPS receiver, for instance Point 1, 2, 3,. A, B, C or description according to data dictionary.

g. Name of base station/s used.

6. Confirm GPS settings, e.g. minimum PDOP values, elevation masks, logging interval, etc. Monitor GPS receivers from time to time to visually check the logging values. Be mindful not to mask satellite signals during setup or checking of receivers.

7. Quality Control. Quality control can be conducted in the field. The following should be considered.

a. Confirm readings of a specific receiver by taking readings at a known or surveyed point.

b. Take the first measurement of the day at the last point of the previous day.

c. Download GPS data and assess published precision and PDOP values.

d. Geometrically assess downloaded GPS data by visualising it in a GIS programme. Outliers and multipath measurements can be easier spotted.

e. Conduct spot-checks on the collected data to determine precision and accuracy.

8. Download Data, Quality Control and Publish. Data can be downloaded from GPS receivers in the field and e-mailed back to the office or stored on removable media. It is wise to make backups of all data when it is downloaded in the field. The cost of additional removable media is insignificant in comparison with the cost of a new collection excursion. A strong antivirus programme should be in place to protect data on computers and removable media. When data are downloaded at the office, backups can be made on the respective servers. An alternative is to write data to CDs or DVDs for long term storage. When data

are secured it needs to be post-processed, quality checked and published in the formats that were agreed on with the client.