PERFORMANCE COMPARISON OF WIDE AREA DIFFERENTIAL GPS SYSTEMS

TAMÁS HORVÁTH

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PREFACE

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PERFORMANCE COMPARISON OF WIDE AREA DIFFERENTIAL GPS SYSTEMS

Tamás Horváth

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

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PREFACE

This technical report is an unedited reproduction of a diploma thesis submitted in partial fulfillment of the requirements for the degree of Dipl. Ing. in the Department of Geodesy and Surveying of the Budapest University of Technology and Economics, November 2001. The research was supervised by Drs. Richard B. Langley (of the University of New Brunswick) and Gy. Graczka (of the Budapest University of Technology and Economics). Support was partially provided by the Natural Sciences and Engineering Research Council of Canada.

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TABLE OF CONTENTS

Acknowledgements......ii
Table of Contents......iii
List of Figures......v
List of Tables......vii
Appendices......viii
Acronyms......ix

1. INTRODUCTION......1
 1.1 Purpose of the Report......2
 1.2 Organization of the Report......3

2. GPS MEASUREMENT ERRORS......5
 2.1 System Errors......6
  2.1.1 Satellite Clock Errors......6
  2.1.2 Receiver Clock Errors......7
  2.1.3 Satellite Ephemeris Errors......7
 2.2 Range Errors (Atmospheric Effects)......9
  2.2.1 Ionospheric Delay......9
  2.2.2 Tropospheric Delay......12
 2.3 Receiver-Related Errors......15
  2.3.1 Multipath......15
  2.3.2 Receiver Noise......16

3 BEACON DGPS......17
 3.1 Beacon DGPS Background......17
 3.2 Test Measurements at UNB......19
 3.3 Investigation of Error Sources......32
  3.3.1 Multipath......33
  3.3.2 Signal Strength......42
  3.3.3 Noise......44
  3.3.4 DGPS Latency......45
  3.3.5 Biased Reference Coordinates......46
  3.3.6 Receiver Types......47

4 WIDE AREA DIFFERENTIAL GPS......50
 4.1 Networked DGPS Background......51
  4.1.1 NDGPS Classification......51

4.1.2 Network Elements....52
4.1.3 WADGPS Algorithms....54

5 OPERATIONAL WADGPS SYSTEMS....61
5.1 Wide Area Augmentation System (WAAS)....61
5.1.1 WAAS Background....61
5.1.2 Test Measurements at UNB....65
5.2 European Geostationary Navigation Overlay System (EGNOS)....80
5.2.1 EGNOS Background....80
5.2.2 Test Measurements at UNB....83
5.3 Canada-wide Differential GPS (CDGPS)....86
5.3.1 CDGPS Background....86
5.3.2 Test Measurements at UNB....92
5.4 Other Operational Wide Area DGPS Systems....101
5.4.1 OmniSTAR....101
5.4.2 SkyFix....103
5.4.3 StarFire....106
5.4.5 IGDG....108
5.4.6 StarFire - IGDG....110

6 CARRIER PHASE DGPS AND PRECISE POINT POSITIONING....111
6.1 Carrier Phase DGPS....111
6.1.1 Networked Carrier Phase DGPS....114
6.1.2 Long-Range RTK Positioning....115
6.2 Real-Time Precise Point Positioning (PPP)....116

7. GNSS MODERNIZATION....118
7.1 GPS Signal Modernization....118
7.2 Galileo....122

8. ARCHIVING RTCM PSEUDORANGE CORRECTIONS....124

9. CONCLUSIONS AND RECOMMENDATIONS....125

REFERENCES....127

APPENDICES....131

LIST OF FIGURES

Figure 2.1: Spatial Decorrelation of Satellite Ephemeris Errors.................................8
Figure 2.2: Solar Cycle Progression..11
Figure 3.1: Radiobeacon DGPS Reference Stations in Atlantic Canada.....................20
Figure 3.2: Beacon DGPS Test Architecture...20
Figure 3.3: NovAtel GPS- and CSI Beacon antenna on Gillin Hall roof....................21
Figure 3.4: Standalone GPS (blue) vs. Beacon DGPS-corrected (green) position errors (1)..28
Figure 3.5: Standalone GPS (blue) vs. Beacon DGPS-corrected (green) position errors (2) 30
Figure 3.6: Horizontal error distribution of the standalone solution...........................31
Figure 3.7: Horizontal error distribution of the DGPS-corrected solution..................31
Figure 3.8: Horizontal error probability distribution functions (Standalone-blue, DGPS-green)...32
Figure 3.9: Strong Multipath Environment on the Roof of Gillin Hall......................34
Figure 3.10: Typical multipath effect on consecutive days' measurements................35
Figure 3.11: Multipath effect on PRN 9 signal (time interval: 6 min 35 sec).............38
Figure 3.12: Multipath effect on PRN 9 measurement (time interval: 2 min 38 sec)..39
Figure 3.13: Signal characteristics from Partridge Island..43
Figure 3.14: Signal characteristics from Point Escuminac...43
Figure 3.15: DGPS Latency and Age..45
Figure 3.16: DGPS correction latency..45
Figure 3.17: DGPS correction age..46
Figure 3.18: Standalone GPS (blue) vs. Beacon DGPS-corrected (green) position errors (4)..48
Figure 3.19: Standalone GPS (blue) vs. Beacon DGPS-corrected (green) solution comparison..49
Figure 4.1: The Canadian Active Control System Network Configuration.................57
Figure 4.2: Network of Permanent EUREF Stations..57
Figure 4.3: Applying ionospheric corrections..60
Figure 5.1: WAAS Architecture (simplified)...63
Figure 5.2: Footprints of Inmarsat GEOs...64
Figure 5.3: WAAS test architecture...66
Figure 5.4: Standalone GPS (blue) vs. WAAS-corrected GPS (green) solution comparison..72
Figure 5.5: Age of WAAS correction...73
Figure 5.6: Standalone GPS (blue) vs. WAAS-corrected (green) horizontal position errors...74
Figure 5.7: Standalone GPS (blue) vs. WAAS-corrected (green) 3D position errors..74
Figure 5.8: Horizontal error distribution of the standalone solution...........................75

Figure 5.9: Horizontal error distribution of the WAAS-corrected solution................75
Figure 5.10: Horizontal error probability distribution functions
(Standalone-blue, WAAS corrected-green)...76
Figure 5.11: GPS satellite skyplot at Fredericton, Canada..77
Figure 5.12: GPS satellite skyplot at Kuala Lumpur, Malaysia..................................78
Figure 5.13: GPS satellite skyplot at Sidney, Australia..78
Figure 5.14: EGNOS reference station network..80
Figure 5.15: EGNOS space segment..81
Figure 5.16: EGNOS ionospheric grid points...82
Figure 5.17: EGNOS- (blue) vs. WAAS-corrected (green) horizontal position errors84
Figure 5.18: Age of EGNOS corrections..85
Figure 5.19: CDGPS reference stations...87
Figure 5.20: MSAT-1 coverage area..89
Figure 5.21: DGPS reference stations in British Columbia.......................................90
Figure 5.22: GPS·C test at UNB..94
Figure 5.23: Standalone GPS (blue) vs. GPS·C-corrected (green)
solution comparison..97
Figure 5.24: Age of GPS·C correction...98
Figure 5.25: GPS·C-corrected (green) vs. Standalone (blue) position solution...........98
Figure 5.26: Standalone GPS (blue) vs. GPS·C -corrected (green)
3D position errors...99
Figure 5.27: Horizontal error distribution of the standalone solution.........................99
Figure 5.28: Horizontal error distribution of the GPS·C-corrected solution.............100
Figure 5.29: Horizontal error probability distribution functions
(Standalone-blue, GPS·C-corrected-green)..100
Figure 5.30: OmniSTAR worldwide coverage...101
Figure 5.31: SkyFix and SkyFix Spot coverage...104
Figure 5.32: IGDG real-time positioning demonstration at JPL Mesa facility..........109
Figure 6.1: Geometric model for correction estimation..115
Figure 7.1: GPS signal modernization..120
Figure I.1: Beacon DGPS reference stations in Europe...133

LIST OF TABLES

Table 3.1: NovAtel POSA log sentence structure......24
Table 3.2: Standalone position solution (1)......27
Table 3.3: Beacon DGPS-corrected position solution (1)......27
Table 3.4: Standalone position solution (2)......29
Table 3.5: Beacon DGPS-corrected position solution (2)......29
Table 3.6: Standalone position solution (3)......41
Table 3.7: Beacon DGPS-corrected position solution (3)......41
Table 3.8: Standalone position solution (4)......47
Table 3.9: Beacon DGPS-corrected position solution (4)......48
Table 5.1: NMEA GGA sentence structure......67
Table 5.2: NMEA GSA sentence structure......68
Table 5.3: Standalone position solution......69
Table 5.4: WAAS-corrected position solution......70
Table 5.5: EGNOS-corrected position solution......83
Table 5.6: WAAS-corrected position solution......84
Table 5.7: CDGPS Reference Stations in Canada......87
Table 5.8: Standalone position solution......95
Table 5.9: GPS·C-corrected position solution......95
Table 5.10: IGDG position solution......109
Table 7.1: L2 Civil Signal Specifications......119
Table 7.2: L5 Signal Specifications......119
Table 7.3.: Comparing SPS accuracy before and after adding the new signals......121

APPENDICES

Appendix I: Beacon DGPS Reference Stations in Europe....................................132
Appendix II: NMEA GGA message logged by NavCom NCT-2000D receiver working in WAAS mode................................134
Appendix III: WAAS & EGNOS RTCA message logged by NavCom NCT-2000D receiver, decoded by Zdenek Lukes (UNB)..................136
Appendix IV: Examples of RINEX-looking correction- and corrected RINEX observation files created by RinexC.m and Endprog.m Matlab programs...140

ACRONYMS

3D	3 Dimensional
AOR-E	Atlantic Ocean Region-East
AOR-W	Atlantic Ocean Region-West
ARNS	Aeronautical Radionavigation Services
BCACS	British Columbia Active Control System
C/A	Coarse Acquisition
CACS	Canadian Active Control Station
CAT I	Category I
CBN	Canadian Base Network
CCG	Canadian Coast Guard
CDGPS	Canada-wide Differential GPS
CFC	Carrier Phase Correction
CM	Control Monitor
CS	Control Station
CS	Civil Signal
CSI	Communication Systems International
DGPS	Differential Global Positioning System
DoD	Department of Defense
DOP	Dilution Of Precision
ECAC	European Civil Aviation Conference
EGNOS	European Geostationary Navigation Overlay System
ESA	European Space Agency
ESTB	EGNOS System Test Bed
EUREF	European Reference Frame
FAA	Federal Aviation Administration
FM	Frequency Modulated
GDGPS	Global Differential GPS
GEO	Geostationary Communications Satellite
GES	Ground Earth Station
GGN	Global GPS Network
GLONASS	Global Navigation Satellite system
GNSS	Global Navigation Satellite System
GPRS	General Packet Radio Service
GPS	Global Positioning System
GPS·C	GPS Correction (Service)
GSD	Geodetic Survey Division
HDOP	Horizontal Dilution Of Precision
IGDG	Internet-based Global Differential GPS
IGP	Ionospheric Grid Point

IGS	International GPS Service
IM	Integrity Monitor
IMS	Integrity Monitor Station
IOR	Indian Ocean Region
IRC	Ionospheric Range Correction
ITRF	International Terrestrial Reference Frame
JPL	Jet Propulsion Laboratory
LF	Low-Frequency
LRTK	Long-range Real-Time Kinematic
M-code	Military-code
MEO	Middle Earth Orbit
MF	Medium-Frequency
MP	Multipath
MS	Master Station
MSAS	MTSAT based Satellite Augmentation System
MSK	Minimum Shift-Keying
NAD	North American Datum
NCC	Network Control Centre
NDGPS	Nationwide Differential Global Positioning System; Networked Differential Global Positioning
NEST Bed	Northern European Satellite Test Bed
NMEA	National Marine Electronics Association
NRCan	Natural Resources Canada
P-code	Precise-code
PDOP	Position Dilution Of Precision
POR	Pacific Ocean Region
PPP	Precise Point Positioning
PRC	Pseudorange Correction
PRF	Performance
PRN	Pseudo Random Noise
R.M.S.	Root Mean Square
RF	Radio Frequency
RFC	Rate of change of Phase Correction
RINEX	Receiver Independent Exchange format
RRC	Range Rate Correction
RS	Reference Station
RTACP	Real-Time Active Control Point
RTCA	Radio Technical Commission for Aeronautics
RTCM-SV	Radio Technical Commission for Maritime Services - Special Committee
RTG	Real Time GIPSY
RTK	Real-Time Kinematic
RTMACS	Real-Time Master Active Control Station
S/A	Selective Availability
SBAS	Satellite Based Augmentation Systems
SNR	Signal-to-Noise Ratio
SPS	Standard Positioning Service

SS	Signal Strength
STD. DEV.	Standard Deviation
SV	Satellite Vehicle
TCP/IP	Transmission Control Protocol/Internet Protocol
TEC	Total Electron Content
TEQC	Translation, Editing, Quality Check
UHF	Ultra High Frequency
UNB	University of New Brunswick
UTC	Coordinated Universal Time
VACP	Virtual Active Control Points
VDOP	Vertical Dilution Of Precision
VHF	Very High Frequency
VPN	Virtual Private Network
VRS	Virtual Reference Station
VSAT	Very Small Aperture Terminal
WAAS	Wide Area Augmentation System
WADGPS	Wide Area Differential Global Positioning System
WAP	Wireless Application Protocol
WCT	Wide Area Correction Transform
WGS	World Geodetic System
WMS	Wide area Master Stations
WRS	Wide Area Ground Reference Station

CHAPTER 1

INTRODUCTION

The absolute positioning accuracy achievable using the Global Positioning System (GPS) depends on the accuracy of the measurements used. The measurements are affected by GPS system errors including satellite ephemeris and clock errors, range errors caused by atmospheric effects (ionosphere and troposphere) and receiver errors including those caused by vehicle dynamics, multipath and receiver noise. Differential GPS (DGPS) techniques have been widely adopted to overcome some of these measurement errors. The basic idea of all DGPS systems is the following: two (or more) GPS receivers simultaneously tracking the same satellites are affected by approximately the same error sources in their pseudorange measurements. If one of the receivers (the Reference or Base Station) is operated at a location whose coordinates are very precisely determined by previous measurements, then the errors related to the individual error sources in the pseudorange measurements can be computed. The errors then can be transmitted in form of pseudorange corrections. The other receiver (Remote or Rover Station) applying these corrections to the pseudoranges it measures can determine its position with higher accuracy than it could by operating in standalone mode. With the different DGPS techniques available, GPS positioning accuracy is improved to range from several metres to less than a metre. The achievable DGPS positioning accuracy depends primarily on the adopted differential technique, the receiver equipment used and the type of GPS measurements employed [Abousalem, 1996].

Before 2 May 2000, Selective Availability (S/A), the intentional degradation of positioning accuracy by the U.S. Department of Defense played a decisive role in poor standalone GPS accuracy. As S/A was turned off, GPS suddenly became more useful to the average citizen. The achievable accuracy provided by autonomous vehicle navigation systems made drivers get to the right house, not just to the right neighbourhood. Hikers, boaters, other hobby GPS users are now satisfied with the system's new performance. On the other hand air navigation along with other safety critical applications still cannot rely only on standalone GPS. Their need for higher accuracy, integrity, and availability is only matched by some kind of differential GPS technique. Surveying, mapping, precise agriculture, 911 services, and many others also benefit from various types of DGPS systems.

1.1 Purpose of the Report

The main goal of this report was to compare the performance of numerous DGPS/WADGPS systems operating worldwide. At the University of New Brunswick in Fredericton, Canada I had the opportunity to analyze the performance of such systems in real-time. The basic question that motivated this report is how much DGPS improves standalone GPS accuracy after S/A is gone? One single-station and a number of networked DGPS systems have been investigated concentrating on positioning accuracy.

Various performance statistics are presented to compare the different systems. The report also provides a brief description of carrier phase DGPS and a revolutionary technique: real-time single-point positioning using precise satellite ephemerides and clock corrections. Since GPS is changing rapidly, future system modernization and its effect is also mentioned. Finally an alternative DGPS post-processing technique is presented briefly.

1.2 Organization of the Report

- Chapter 1 is the introduction, the main goal of the report is defined here.
- Chapter 2 summarizes GPS measurement errors and their effects on Differential GPS along with mitigation techniques.
- Chapter 3 gives background information on the Canadian marine radiobeacon DGPS system and presents the results of real-time test measurements carried out at the University of New Brunswick (UNB), Fredericton.
- Chapter 4 introduces following chapters providing basic information on Wide Area Differential GPS (WADGPS).
- Chapter 5 contains the analysis of three WADGPS systems based on test measurements at UNB and briefly presents other operational systems.
- Chapter 6 provides information on carrier phase DGPS and real-time Precise Point Positioning.

- Chapter 7 summarizes the future modernization of GPS and its effects on satellite positioning. Galileo, the new GNSS system is also mentioned here.
- Chapter 8 presents a DGPS post processing technique based on archived corrections.
- Chapter 9 summarizes the results of the tests, and provides recommendations for future research in this field.

CHAPTER 2

GPS MEASUREMENT ERRORS

GPS, originally planned to be an autonomous system, is affected by different error sources, which limit its performance. Achievable accuracy greatly depends on the presence of these errors. This chapter gives an overview of the errors and provides different techniques used to mitigate their effect. Since the purpose of the diploma thesis is to analyze several types of differential GPS techniques, the errors were investigated in a DGPS perspective.

GPS measurements are affected by the following error sources:

- System errors: satellite ephemeris errors,
  clock errors (satellite, receiver).
- Range errors: atmospheric effects (ionosphere, troposphere).
- Receiver-related errors: multipath, receiver noise,
  errors caused by vehicle dynamics,
  receiver location.

2.1 System Errors

2.1.1 Satellite Clock Errors

GPS receivers determine their three-dimensional position by measuring signal travel time from at least four satellites. Therefore it is vital to know the time of data transmission and reception very precisely. In the ideal case, satellites would transmit their position at time epochs exactly synchronized with GPS system-time. However, in reality there is always a small synchronization error (bias and drift) between satellite-clock and system-clock. The offset can be in the millisecond range. Using a second-order polynomial, whose coefficients are included in the broadcast navigation message, the users can mitigate the effect of satellite clock errors. Since the precision of the broadcast satellite clock model is limited, residual errors may result. These residual errors in distance units are currently less than 1.5 metres.

Two receivers watching the same satellite observe exactly the same satellite clock error. Therefore differential GPS of any type completely eliminates this error source. Satellite clock error is independent of the distance separating the reference station and the user. In absolute positioning the application of real-time precise clock corrections (provided by IGS and other organizations) instead of the broadcast message will minimize the effect of satellite clock errors.

2.1.2 Receiver Clock Errors

GPS receiver clocks, just like satellite clocks, are not perfectly synchronized with GPS system-time. Moreover the cheap quartz oscillators in the receivers are much less precise than the atomic frequency etalons used in satellites. Receiver clock offsets may range from tens of nanoseconds to several milliseconds or more depending on synchronization and steering techniques used. In differential GPS and in single point positioning receiver clock errors (polynomial coefficients) are estimated along with the station unknown coordinates [Abousalem, 1996]. Receiver clock errors are receiver-related, thus they are baseline independent.

2.1.3 Satellite Ephemeris Errors

GPS satellite orbit errors are caused by not perfectly modelling the satellite dynamics. Broadcast ephemerides are accurate typically within 3 metres [IGS, 2001]. Differential GPS over short baselines eliminates orbit errors to a large degree, so does single point positioning using precise ephemerides. Unlike clock errors, residual satellite ephemeris errors depend on the baseline length between the reference station and the remote station. At widely separated stations (e.g., WADGPS) these errors are unequal because of their *spatial decorrelating* behaviour. The computed satellite position contains the same error in both reference- and user cases, but they will have different errors in their respective computed ranges because of differences in viewing angles. The actual error depends on the ephemeris error vector's orientation in space relative to the range vectors to the satellite from each of the two sites.

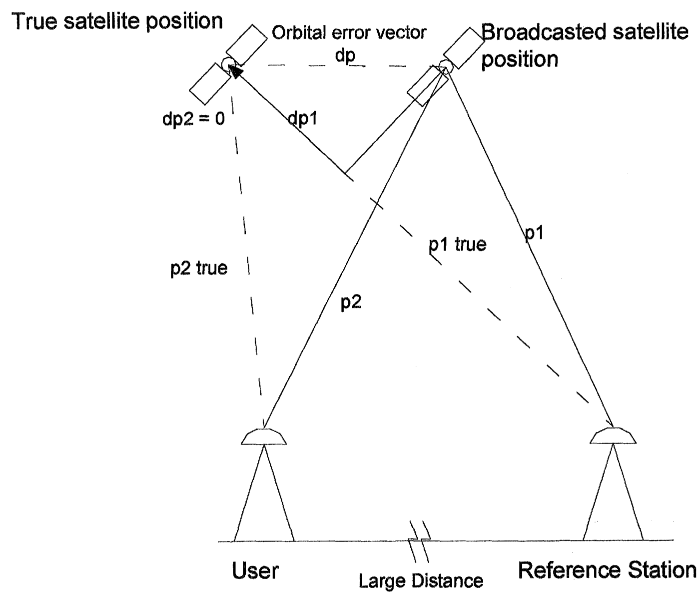


Figure 2.1: Spatial decorrelation of satellite ephemeris errors [Abousalem, 1996]

The reference station calculates corrections containing compensation for the dp1 error component. In this extreme example showed above (Figure 2.1) the orbit error does not cause positioning error in case of the remote receiver (dp2=0) because dp is essentially orthogonal to the range vector from the user receiver. When we naively apply the corrections arriving from the base station we actually introduce error to the local measurements [Abousalem, 1996]. As the separation distance grows between the reference station and the user, the difference in viewing angle becomes larger too, so does the difference between the computed range errors. The error is roughly proportional to the distance from the reference station [Loomis et al., 1991].

2.2 Range Errors (Atmospheric Effects)

Signals transmitted by GPS satellites pass through Earth's atmosphere before they reach the receiver antenna. During this travel, signals interact with charged particles as well as with neutral atoms and molecules. The speed and direction of propagation changes due to this interaction, signals are refracted. Signals received at the endpoints of a long baseline had to travel along different paths in the ionosphere and troposphere, resulting in different delay effects.

2.2.1 Ionospheric Delay

The vertical total electron content (TEC) of the ionosphere (upper part of the atmosphere, 50-1000 km) varies with location. The satellite elevation angles are different for receivers observing from different locations. These two factors (TEC, elevation angle) affect mainly the ionospheric delay. Vertical delay varies from a few metres to 10-20 m and sometimes more [Parkinson and Spilker, 1996]. This vertical delay must be multiplied by an "obliquity factor" which accounts for the angle of incidence with which GPS signals penetrate the ionosphere. The obliquity factor is the ratio of delays at any elevation angle to the vertical delay. It varies from 1.0 at 90 deg to about 3.0 at 5 deg. It is weakly a function of mean ionospheric height (in a simplified thin shell model):

$$Ob(el,H) = \sec\left[\sin^{-1}\left(\frac{R_e}{R_e + H}\cos(\pi/2 - el)\right)\right] \tag{2.1}$$

[Hansen, 2000.]

where

el is the elevation angle,

R_e is the radius of Earth,

H is the altitude of the thin shell (350 km applied here).

Ionospheric delay varies with time. TEC varies within the day, reaching its maximum approximately at 14:00 local time. TEC also varies with the number of sunspots within an approximately eleven-year period. In the year 2000 the sunspot cycle reached its maximum amplitude, from now on this effect is getting weaker until around 2006-2007 (see Figure 2.2).

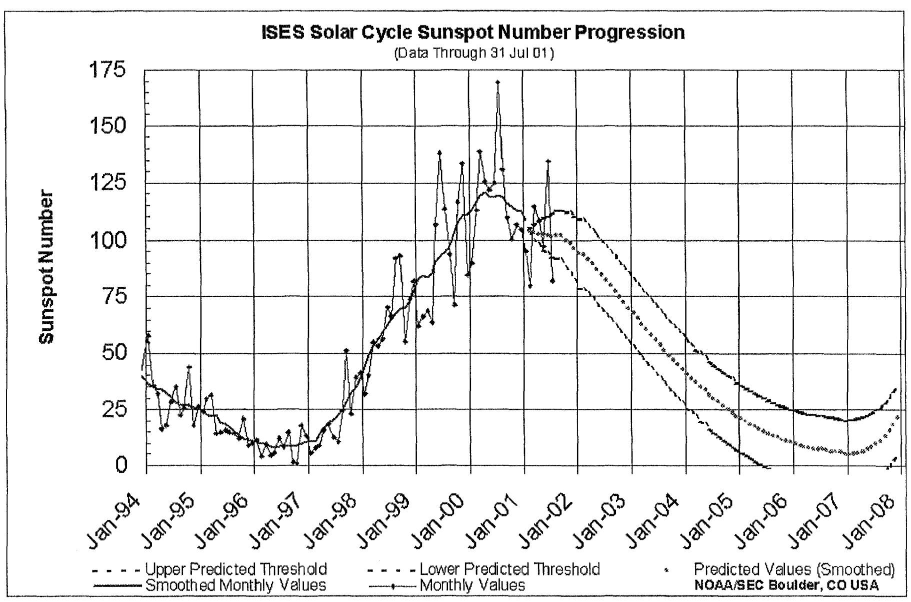


Figure 2.2: Solar Cycle Progression [http://www.sec.noaa.gov/SolarCycle/]

Typical ionospheric vertical delay values given here refer to “quiet” days; during ionospheric storms they can be multiplied to reach extreme levels.

There are two ways of mitigating the ionospheric delay: one is to measure it, the other one is to model it. The ionosphere is a dispersive medium for radio waves; that is, its refractive index is a function of the frequency [Langley, 1995]. Therefore it is possible to measure and remove almost all of the delay directly with dual-frequency receivers. With single frequency receivers we have to lean on different ionospheric models, which are reported to remove 50-80% of the ionospheric delay. Such models are the standard Klobuchar-model, broadcast by the GPS satellites, the Bent-model, the IRI 95 (International Reference Ionosphere 1995), and others, using recent solar flux measurements or monthly averages for TEC prediction. These models are working quite well in the ±20 to ±60 degree-latitude region of Earth, but they are poor predictors at the equatorial and polar regions [Loomis et al., 1991].

Conventional short-baseline differential GPS effectively mitigates ionospheric errors. On the other hand, in case of large spatial separations, this error tends to decorrelate. The ionospheric error, unlike the orbital error, does not behave linearly over large distances. Decorrelation distance can vary between 200 to 1000 km depending on the ionospheric activity [Loomis et al., 1991].

2.2.2 Tropospheric Delay

The troposphere is the lower part of the atmosphere (0-9~16 km). This is the region where “weather happens”. As GPS signals travel through the troposphere their speed and direction of propagation changes – they are refracted. Due to the fact that the speed of the signals in a non-ionized medium (neutral atmosphere) is less than that in vacuum, GPS signals are delayed compared to travelling in vacuum. Meteorological conditions, such as pressure, temperature, and humidity of the troposphere determine the refractive index (n) of air and hence the refractivity (N). Refractivity of air can be expressed as follows:

$$n = \frac{c}{v} \tag{2.2}$$

$$N = 10^6 \cdot (n-1) \tag{2.3}$$

$$N = K_1 \frac{M}{M_d}\frac{P}{T} - \left(K_1 \frac{M}{M_d} - K_2\right)\frac{e}{T} + K_3 \frac{e}{T^2} \tag{2.4}$$

[Langley, 1995]

where

c is the vacuum speed of light,

v is the speed of propagation of GPS signal,

T is the temperature (K),

P is the total (barometric) pressure of gases,

e is the partial pressure of water vapour,

K_1, K_2, K_3 are empirically determined constants,

M and M_d are the molar mass of moist and dry air.

The first term of the equation is referred to as hydrostatic-, the remaining part as the water vapour component. Tropospheric delay is a function of the refractivity of air,

$$d_{trop}^{z} = 10^{-6} \int_{r_s}^{r_a} N(r) dr \tag{2.5}$$

[Langley, 1995]

where

r is the geocentric radius,

r_s is the the radius of the Earth's surface,

r_a is the the radius of the top of the neutral atmosphere,

and thus, it is also made up of hydrostatic and water vapour (or wet) constituents. The two components are usually written as the product of a zenith delay term and a mapping function, which maps the increase in delay with decreasing elevation angle:

$$d_{trop} = d_h^z m_h(\varepsilon_s) + d_{wv}^z m_{wv}(\varepsilon_s) \tag{2.6}$$

[Langley, 1995]

where

d^z_h is the zenith delay due to the hydrostatic component,

d^z_{wv} is the zenith delay due to the water vapour,

m_h is the hydrostatic mapping function,

m_{wv} is the water vapour mapping function,

ε_s is the non-refracted elevation angle at the ground station.

The neutral atmosphere is a non-dispersive medium up to about 30 GHz (ignoring resonance effects due to water vapour), therefore tropospheric delay cannot be measured directly – we have to model it. The hydrostatic component typically accounts for about 90% of the total delay. Fortunately this part can be modelled very accurately (few millimetres) by measuring the total surface pressure. There are several models available (e.g. Saastamoinen hydrostatic zenith delay model). Wet delay, on the other hand cannot be modelled accurately since the water vapour content of the neutral atmosphere is inhomogeneous. It varies both spatially and temporally. Based on surface meteorology, a model prediction gives at best 1-2 cm accuracy [Langley, 1995]. Tropospheric models work well above 15-degree mask angles. Below that tropospheric refraction can result in significant delays. The wet component can reach 2-3 m at about 5 degrees elevation angle, depending on the atmospheric conditions [Parkinson and Spilker, 1996]. The accuracy degrading effect of the tropospheric delay is typically smaller than that of the ionospheric delay.

Separation distances between receivers cause decorrelation of pressure, temperature, and humidity in the troposphere, therefore the resulting delay varies from station to station. In a network of DGPS reference stations (WADGPS), algorithms must account for both ionospheric and tropospheric decorrelation effects to avoid residual atmospheric errors [Abousalem, 1996].

2.3 Receiver-Related Errors

2.3.1 Multipath

Multipath is caused by extraneous signal reflections from nearby metallic objects, ground or water surfaces reaching the antenna. This has a number of effects: it may cause signal interference between the direct and the reflected signal leading to noisier measurement, or it may confuse the tracking electronics of the hardware resulting in a biased measurement that is the sum of the satellite-to-reflector distance and the reflector-to-antenna distance [Rizos, 1999]. Multipath error is unique to each GPS station, it cannot be removed by differential techniques. At the reference stations, the antenna site should be selected very carefully to a avoid reflective environment. At the user station, especially in kinematic applications it is often impossible to avoid a strong multipath environment.

GPS receiver and antenna manufacturers come up with newer and newer *hardware designs* to mitigate multipath. One can reduce the ground-bounce multipath effect by using ground plane or choke ring antennas. Gain-pattern-forming techniques have been developed to further reduce antenna sensitivity to multipath at low elevation angles. The application of microwave absorbing material on the surfaces close to the antenna can also reduce the effect of multipath. Manufacturers have succeeded in efficiently reducing signal tracking correlator spacing, disallowing long delay multipath from being erroneously tracked [Bisnath and Langley, 2001].

There are also *software solutions* to mitigate the multipath effect including elevation angle mask applications and multipath estimation using filtering techniques (e.g., Kalman-filtering). Another approach developed by Bisnath and Langley [2001] avoids the estimation of multipath; instead it de-weights the affected observations. More on the multipath effect is covered in Section 3.3.

2.3.2 Receiver Noise

The receiver noise is also a unique characteristic of each individual GPS receiver. It arises primarily from limitations of receiver electronics. It is a result of thermal noise intercepted by the antenna, noise from the receiver oscillator and other hardware components. Receiver noise is typically proportional to the wavelength of the tracked signal. According to receiver type and characteristics, receiver noise levels vary from 0.1 to 1% of the wavelength [Abousalem, 1996]. For C/A code pseudorange measuremets the noise level varies between 0.3-3m. The effect of this error source can be mitigated using state-of-the-art equipment, especially at the reference stations.

CHAPTER 3

BEACON DGPS

The purpose of this chapter is to provide background information on conventional single-station Differential GPS and to determine the achievable accuracy by this technique. A number of beacon DGPS tests and their results are described here, followed by the investigation of possible accuracy degrading effects.

3.1 Beacon DGPS Background

There are a number of ways how differential corrections can be computed and transmitted to the user community. The utilization of marine radio beacons was the first solution for covering large areas with pseudorange DGPS correction broadcasts. Radio Beacons transmit standard RTCM SC-104 (Radio Technical Commission for Maritime Services Special Committee 104, Version 2.1) corrections (Message Types 3, 5, 6, 7, 9, and 16) in the low-frequency (LF) and medium-frequency (MF) bands of the electromagnetic spectrum (275-335 kHz). According to the International Telecommunication Union designations, the low-frequency band extends from 30 to 300 kHz and the medium-frequency band from 300 kHz to 3 MHz [Langley, 1993]. LF/MF transmission is advantageous because of signal propagation characteristics at these frequencies. LF/MF signals typically have no propagation difficulties even in stressful environments like urban canyons or valleys surrounded by high mountains. On the other hand, the bandwidth of LF signals is very narrow which causes a physical limitation for the transmitted data amount. The structure of the correction data must be very compact to efficiently exploit the available bandwidth. A subcarrier of the beacon is modulated by minimum shift-keying (MSK), an efficient digital communications technique requiring minimal frequency bandwidth for a given data transmission rate [Langley, 1993]. Transmission rates of 100 and 200 bits per second are being used.

The beacons were originally located along continental coasts providing DGPS service primarily for marine applications. The first years of use in the 1980's proved that beacon DGPS can satisfy not only watercraft navigation needs but is beneficial for all kinds of terrestrial applications too. In North America from the early 1990's the beacon network is being expanded inland. There is a plan to cover the whole United States with beacon DGPS stations (Nationwide Differential Global Positioning System, NDGPS, 145 stations). Beacon DGPS is also available in Europe along the coasts (see Appendix I, Figure I.1) but an inland network has not been developed there.

The improvement in GPS positioning accuracy by beacon DGPS was significant in the S/A era when standalone positioning was only about 100 m accurate (2drms) horizontally. Single-station DGPS improved this accuracy to 1-5 m in the relative vicinity (within 500 km) of the beacon station, with losing roughly one metre of accuracy every 100 km. After S/A was turned off and standalone GPS became 10 times more accurate the importance of conventional DGPS was reduced and the rapid beacon network development slowed down. Although many new technologies emerged in the last decade the once built reference stations are still maintained and operational.

3.2 Test Measurements at UNB

To determine and compare the achievable accuracies with standalone GPS and beacon DGPS a series of test measurements have been carried out at the University of New Brunswick (UNB), Fredericton, Canada. Fredericton is the capital city of New Brunswick province, which is one of the four Atlantic provinces of Canada (Prince Edward Island, Nova Scotia, Newfoundland, and New Brunswick). In Canada the marine radiobeacon DGPS reference station network is maintained and the pseudorange corrections are broadcast by the Canadian Coast Guard (CCG). A typical CCG DGPS station comprises control stations (CSs), reference stations (RSs), their associated integrity monitors (IMs) to ascertain the status and the integrity of the broadcast, and the LF/MF radio beacon transmitter to broadcast DGPS information to users. A control monitor (CM) located at a 24 hour staffed Coast Guard operational site maintains two-way communications via dial up lines with the DGPS stations. The CM monitors the status of the system [Canadian Coast Guard, 2001].

According to CCG, the service provides a horizontal accuracy of 10 metres or better, 95 % of the time in all coverage areas [Canadian Coast Guard, 2001]. Figure 3.1 shows radiobeacon stations across Atlantic Canada, with two stations (Partridge Island and Point

Escuminac) in New Brunswick. Fredericton is located 80 km northwest from Partridge Island and 180 km southwest from Point Escuminac.

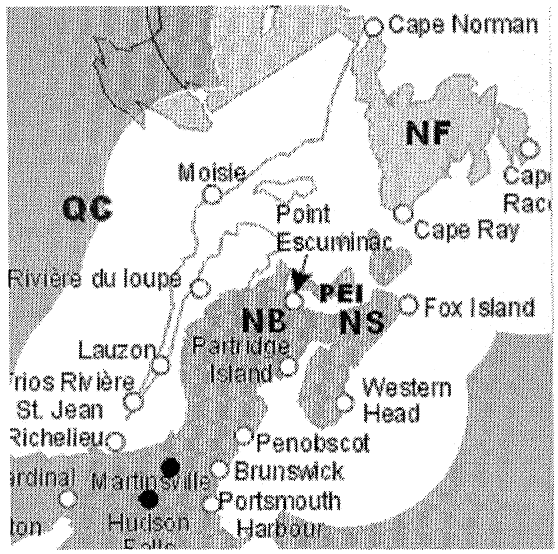


Figure 3.1: Radiobeacon DGPS reference stations in Atlantic Canada

Real-time, static GPS observations have been carried out in the first two weeks of April 2001. Figure 3.2 shows the system architecture used in the tests.

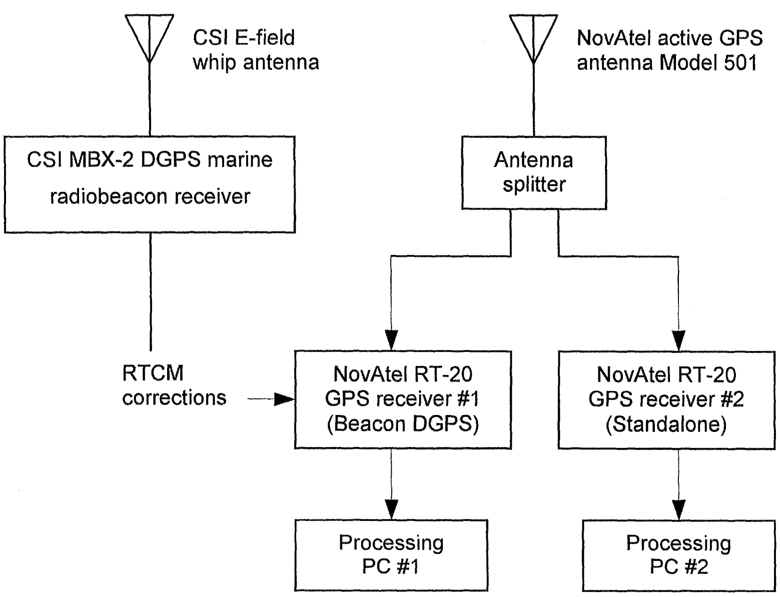


Figure 3.2: Beacon DGPS test architecture

Two identical NovAtel RT-20 (GPSCard OEM-2) GPS receivers (NovAtel Communications Ltd. is a Canadian corporation) have been used along with a CSI (Communication Systems International Inc.) MBX-2 marine radiobeacon DGPS receiver.

The NovAtel GPSCard OEM-2 series receiver is a 12-channel, parallel tracking, C/A code GPS receiver operating on the L1 (1575.42 MHz) frequency. The receiver uses carrier-smoothed code measurements to provide position fixes. A single NovAtel Active GPS Antenna (Model 501) was connected to the two GPS receivers with the help of an antenna splitter. Theoretically this way the two receivers were fed with the same signal (the remaining difference in the received signal strength and signal to noise density ratio (S/N_0) was due to the different levels of signal loss and added noise on the two coax cables between the splitter and the receivers and to the slightly different receiver thermal noise levels of the two devices). The GPS antenna was mounted on the roof of Gillin Hall, UNB over a reference mark on a pillar (see Figure 3.3).

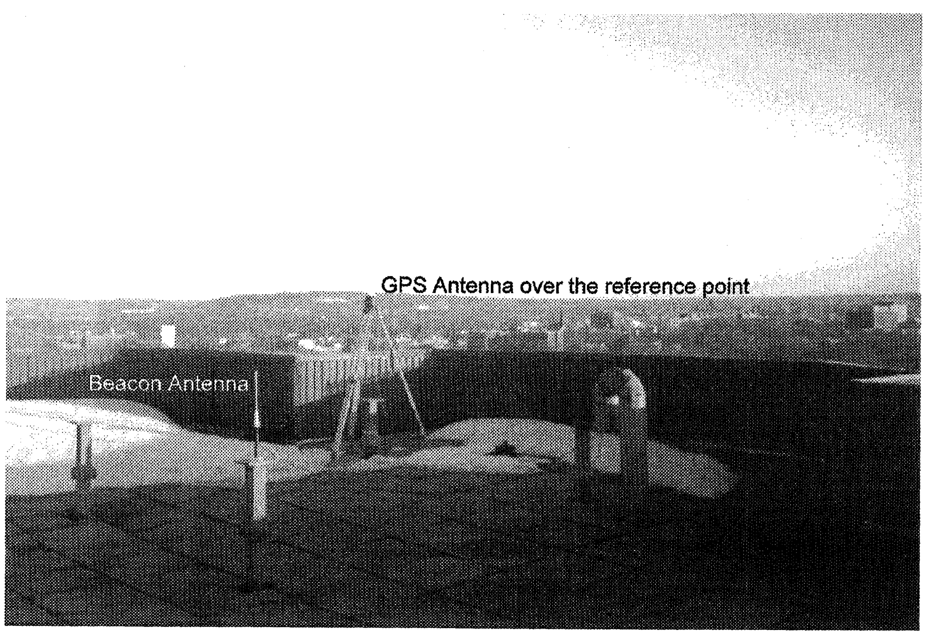


Figure 3.3: NovAtel GPS- and CSI Beacon antenna on Gillin Hall roof

The coordinates of the reference point were determined in August 2001 by the precise point positioning software of the Natural Resources Canada's Geodetic Survey Division (GSD) using dual frequency 1Hz data (two 8-hour sessions). The resulting coordinates in ITRF97 (Epoch 1997.0) reference frame are:

Lat = 45-57-00.9834 (North),

Lon = -66-38-32.2376 (East),

Height = 18.446 m (ellipsoidal height).

These coordinates are referred to as "known coordinates" in the thesis. Knowing that GPS receivers if working in standalone mode provide position fixes in WGS 84 datum and not ITRF, we introduced errors in the results. The new WGS 84 realizations (G730 or G873) are coincident with ITRF at about the 10-centimeter level. For these realizations there are no official transformation parameters. This means that one can consider that ITRF coordinates are also expressed in WGS 84 at the 10 cm level [ITRF, 1998]. The reason why the reference coordinates had to be determined after the DGPS test measurements is that the old coordinates used in recent years (although in WGS 84) were not reliable, the difference between the old and new coordinates is ~30-40 cm in each component.

A beacon DGPS antenna (E-field whip antenna) was placed on the same roof close to the GPS antenna (see Figure 3.3). The CSI beacon receiver connected to the DGPS antenna provided RTCM Message Type 9 pseudorange correction data stream. One of the NovAtel receivers operated in standalone mode, the other one was connected to the beacon receiver and generated DGPS-corrected position fixes.

To communicate with the GPS receivers NovAtel WinSat (Version 1.03) software has been used. The receiver's GPSCard is capable of responding to over 30 different *input* *commands* (e.g. ECUTOFF, which sets the elevation cut-off angle for usable satellites). The GPSCard has three major *logging formats*:

- NovAtel Format Data Logs (ASCII/Binary)
- NMEA Format Data Logs (ASCII)
- RTCM Format Data Logs (Binary)

It is capable of executing more than 30 NovAtel format *log commands*. Each log is selectable in ASCII and Binary formats. Any format can be selected individually or simultaneously over the same COMn ports [GPSCard, 1994].

Positioning accuracy investigation required information on standalone and differential position solution, therefore POSA (Computed Position) message type was output by both receivers and was logged on the two processing computers simultaneously. The POSA log contains the last valid position (minimum 4 satellites in view) referenced to the Active GPS Antenna phase centre and time of the position fix (see Table 3.1).

Structure:

$POSA	week	seconds	lat	lon	hgt	undulation	datum	lat std	lon std
hgt std	sol status	*xx	[CR][LF]						

Field #	Field type	Data description	Example
1	**$POSA**	Log header	$POSA
2	**week**	GPS week number	673
3	**seconds**	GPS seconds into the week	511251.00
4	**lat**	Latitude of position in WGS-84 datum, in degrees (DD.dddddddd)	51.11161874
5	**lon**	Longitude of position in WGS-84 datum, in degrees (DDD.dddddddd) A negative sign implies South latitude	-114.03922149
6	**hgt**	Height position in metres with respect to mean sea level (MSL) A negative sign implies West longitude	1072.436

7	**undulation**	Geoidal separation, in metres, where positive is above spheroid and negative is below spheroid	-16.198
8	**datum**	Current datum (WGS-84)	61
9	**lat std**	Standard deviation of latitude solution element, in metres	26.636
10	**lon std**	Standard deviation of longitude solution element, in metres	6.758
11	**hgt std**	Standard deviation of height solution element, in metres	78.459
12	**sol status**	Solution status (0 - Solution computed, 1 - Insufficient observations, 2 - No convergence,….,6 – Not yet converged from cold start)	0
13	***xx**	Checksum	*12
14	**[CR][LF]**	Sentence terminator	[CR][LF]

Table 3.1: NovAtel POSA log sentence structure (Examples from 1994 - with SA)

The pseudorange corrections broadcast by CCG are in NAD83(CSRS) datum (North American Datum of 1983, Canadian Spatial Reference System), therefore the corrected solution will also be in NAD83. To get ITRF97 solution the coordinate-shift between ITRF and NAD83 had to be subtracted from the raw DGPS results. The ITRF97-NAD83 shifts for the reference point as determined by GSD are:

North: 1.08 m

East: -0.01 m

Up: -1.16 m.

Depending on the analyzed error sources, several other message types (PXYA: Computed Cartesian Coordinate Position, RGEA: Channel Range Measurements, DOPA: Dilution of Precision, etc.) were also logged.

The NovAtel GPSCard is able to work as a monitor station. It can transmit RTCM standard message types 1 and 16, and as well accept input of message types 1, 2, 9 and 16 when operating as a remote differential station. The ACCEPT command is used to control the processing of the input data (e.g. RTCM corrections). As soon as the NovAtel receiver gets the corrections, it applies them automatically providing a corrected position solution.

In the first test on 03-04 April 2001 POSA, sentences have been logged from both receivers, one in standalone mode the other in differential mode. Position data was collected using a 5-minute sample interval (in the following observations, the sampling interval has been raised first to 60 seconds, later to 1 second because the 5-minute data rate did not provide a statistically representative sample). The elevation mask angle was set to 10 degrees. The MBX-2 Beacon Receiver was operated in full manual mode, which means that the reference station frequency and the MSK rate was set manually. The closest DGPS reference station, Partridge Island was chosen (Lat: 45-14-12.82 N, Lon: -66-03-13.68 E; frequency: 295.0 kHz; MSK rate: 200 bps). 21h 50m data have been logged (03 April 15h 50m – 04 April 13h 40m, UTC). The applied undulation value of –21.681 m was offered by the receiver. (The geoid is below the reference ellipsoid in Fredericton).

The collected data has been processed with a conversion program (ConvertC.m) written in Matlab. The program transforms geographical coordinates to Cartesian coordinates, subtracts the known coordinates from every epoch's measurements and finally transforms the coordinate differences to a local topocentric coordinate system. The resulting north (N), east (E), and up (U) values are position errors, where zero means the reference point position:

(φ,λ,h)known → (X,Y,Z) known,

(φ,λ,h)measured → (X,Y,Z) measured,

Delta(X,Y,Z) = (X,Y,Z) measured - (X,Y,Z) known,

Delta(X,Y,Z) → (N,E,U).

The program computes statistical values of these errors:

Mean is the average of a particular dataset, this value shows the bias of the results from zero, $Mean = \frac{\sum_{i=1}^{n} x_i}{n}$, where n is the number of epochs, x_i is the measured value at epoch i,

Max (abs) is the absolute value of the maximum error for each component,

2 times the standard deviation (2 std. dev.) gives information on the precision of the data, $2std.dev. = 2 \cdot \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}}$, where $\bar{x}$ is the mean,

2 times the horizontal standard deviation (2 hor. std. dev.) is the resultant deviation of the horizontal components $2hor.std.dev = 2 \cdot \sqrt{std.dev._N{}^2 + std.dev._E{}^2}$,

***2 times the root mean square** (2 r.m.s.)* indicates positioning accuracy, $2r.m.s. = 2 \cdot \sqrt{\frac{\sum_{i=1}^{n} (x_i - a)^2}{n-1}}$, where a is a given value (in this case it is the "known" E, N, U value of the reference point, that is zero),

Twice the distance root mean square (2drms) implies horizontal accuracy $2drms = 2 \cdot \sqrt{r.m.s._N{}^2 + r.m.s._E{}^2}$.

These numbers represent precision and accuracy at approximately the 95 percent probability level.

Table 3.2 and 3.3 show the results of the first experiment:

	N error	E error	U error
Mean [m]	-0.33	0.07	4.13
Max (abs) [m]	12.02	5.93	23.73
2 std. dev. [m]	5.65	3.52	10.27
2 hor. std. dev. [m]	6.66		
2 r.m.s. [m]	5.69	3.52	13.19
2drms [m]	6.69		

Table 3.2: Standalone position solution (1)

	N error	E error	U error
Mean [m]	-0.13	-0.29	1.04
Max (abs) [m]	10.79	7.58	15.62
2 std. dev. [m]	4.14	2.36	6.32
2 hor. std. dev. [m]	4.77		
2 r.m.s. [m]	4.15	2.43	6.66
2drms [m]	4.81		

Table 3.3: Beacon DGPS-corrected position solution (1)

DGPS corrections improved the accuracy of all three components (N, E, U). The 6.5 metre improvement in height is very significant but the 1-1.5 metre improvement in the horizontal components is less than expected. Since Fredericton is located within the 100 km radius of Partridge Island I expected 1-2 m (2drms) accuracy instead of almost 5 metres. It is clear that the achieved accuracy is better than the CCG-reported 10 metres, but worse than I expected based on the 1m/100km rule of thumb. Figure 3.4 shows the horizontal error comparison of standalone GPS and DGPS:

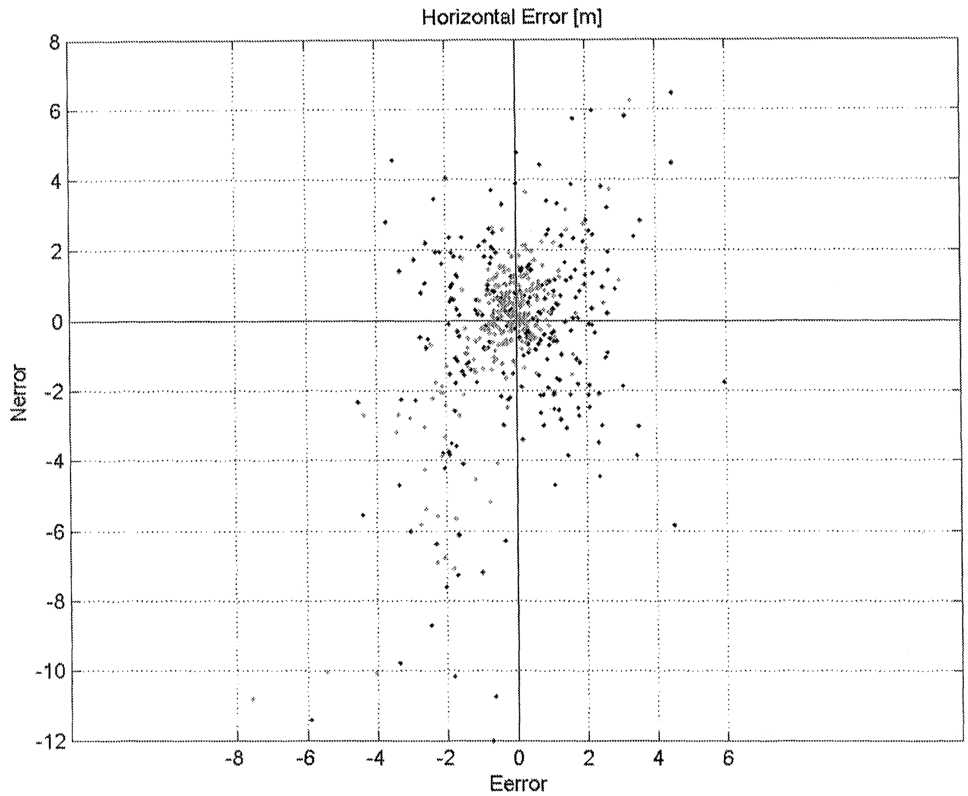


Figure 3.4: Standalone GPS (blue) vs. Beacon DGPS-corrected (green) position errors (1)

We can recognize the accumulation of DGPS position fixes around 0,0 compared to standalone solution, but they are still widely scattered, the 4.77m 2 hor. std. dev. is large.

Achievable accuracy degrades with the increasing distance from the base station. To check the rate of degradation, in the second test measurement corrections from Point Escuminac station (Lat: 47-04 N, Lon: -64-47 E; frequency: 319.0 kHz; MSK rate: 200 bps) have been applied. 15h 40m data (10 April 21h 05m – 11 April 12h 45m, UTC) have been logged using 60-second data rate. Table 3.4 and 3.5 show the results of the second test.

	N error	E error	U error
Mean [m]	0.46	-0.55	3.16
Max (abs) [m]	23.29	6.23	32.66
2 std. dev. [m]	5.67	2.88	9.04
2 hor. std. dev. [m]	6.36		
2 r.m.s. [m]	5.74	3.09	11.03
2drms [m]	6.52		

Table 3.4: Standalone position solution (2)

	N error	E error	U error
Mean [m]	-0.66	-0.67	1.74
Max (abs) [m]	18.44	7.46	14.52
2 std. dev. [m]	3.59	2.20	5.22
2 hor. std. dev. [m]	4.22		
2 r.m.s. [m]	3.83	2.58	6.28
2drms [m]	4.62		

Table 3.5: Beacon DGPS-corrected position solution (2)

Although Point Escuminac is 100 km further from Fredericton than Partridge Island the results show similar accuracies in both cases. The mean errors and maximum errors became larger in the second test, whereas the standard deviations decreased resulting in somewhat better r.m.s. values than in test 1. (Although the data for the two tests was not collected on the same day, the general comparison of the two is useful.) The scatterograms on Figure 3.5 show the same problem as before. The DGPS deviation is large and the position fixes are widely spread around the known coordinates.

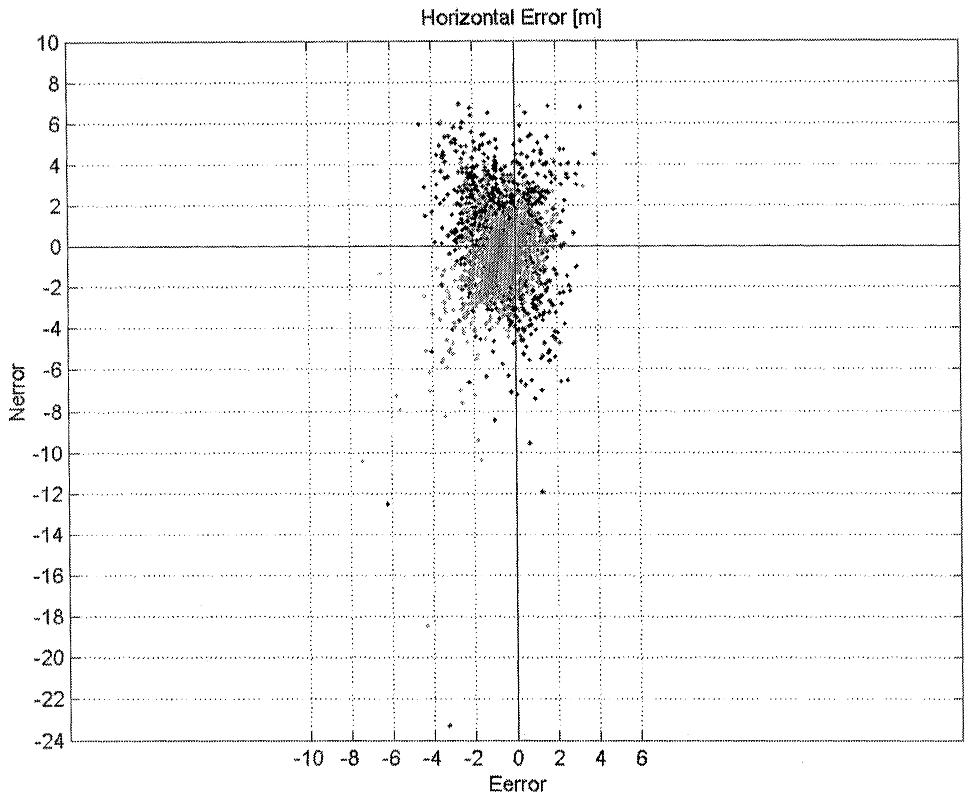


Figure 3.5: Standalone GPS (blue) vs. Beacon DGPS-corrected (green) position errors (2)

The histograms based on the second data set on Figures 3.6 and 3.7 show that the majority of the position fixes were within 2 metres using corrections and 4 metres without corrections.

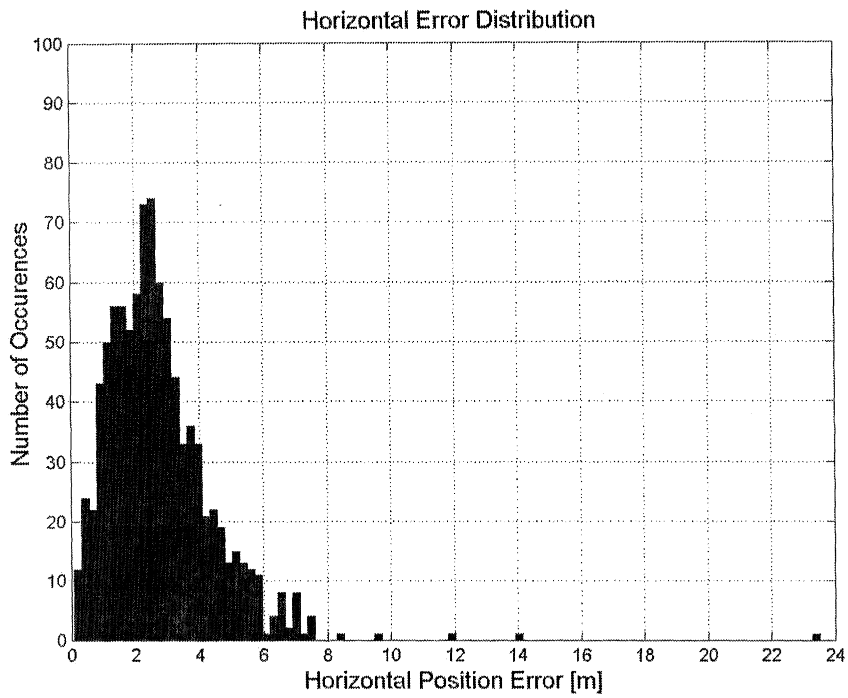


Figure 3.6: Horizontal error distribution of the standalone solution

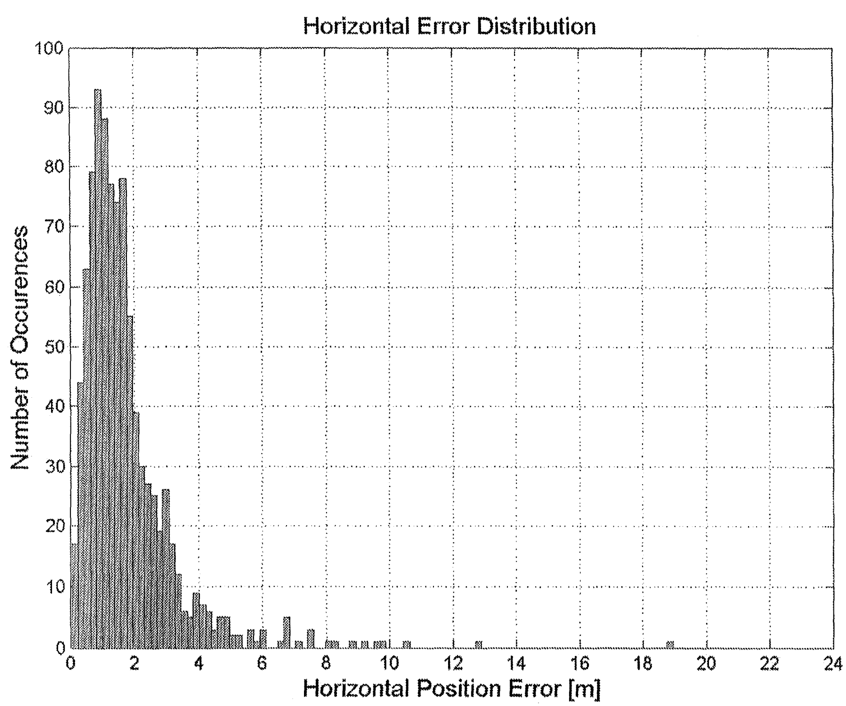


Figure 3.7: Horizontal error distribution of the DGPS-corrected solution

The probability distribution functions (test 2) on Figure 3.8 show accuracies no worse than a certain level for a certain percentage of time [Takács, 2000]. The steeper the probability distribution function the higher the accuracy.

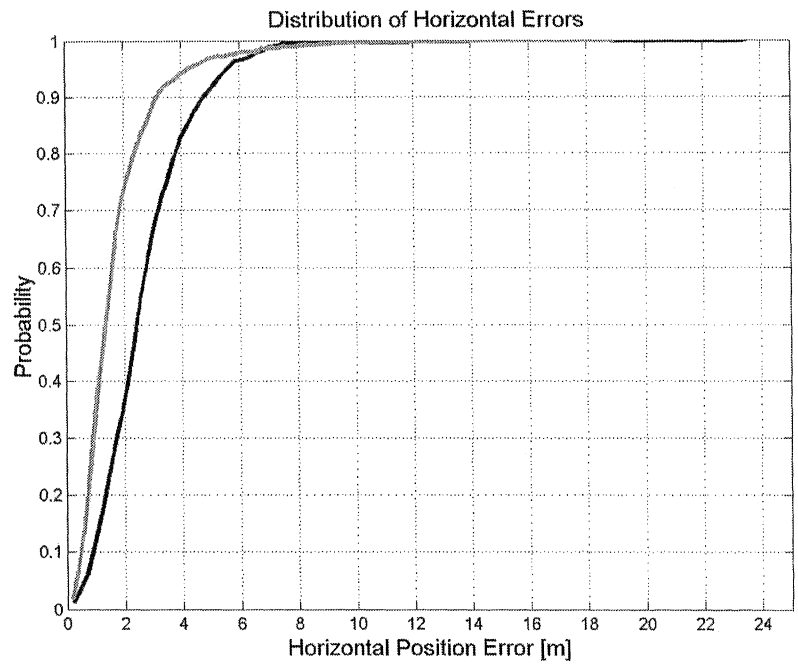


Figure 3.8: Horizontal error probability distribution functions

(Standalone-blue, DGPS-green)

3.3 Investigation of Error Sources

The two above presented test measurements did not provide as good results as I expected. What is the trouble source of these poor results?

- Strong multipath environment?
- Weak signals arriving from Partridge Island?

- Noise?
- DGPS latency?
- Biased reference coordinates?
- Receiver type?

3.3.1 Multipath

Multipath errors of code pseudoranges can be divided into three categories:

- diffuse forward scattering from a widely distributed area, causing C/A-code pseudorange errors up to 10 m,
- specular reflection from well-defined objects or reflective surfaces with range errors of 2-6 m,
- fluctuations of very low frequency, usually associated with reflection from the surface of water causing range errors of about 10 m.

In severe cases of multipath, loss of lock may even occur [Hofmann-Wellenhof et al., 1997]. Multipath effect on carrier phase measurements is significantly smaller than on code, it can amount a maximum of about 5 cm. The impact of multipath error on kinematic positioning is greater than that on static positioning. For a stationary receiver the propagation geometry changes slowly, making the multipath parameters constant for perhaps several minutes. But in mobile applications (e.g. car navigation), a receiver can experience rapid fluctuations in fractions of a second [Weill, 1997]. In the kinematic case, where position updates are computed with high frequency, the error propagates into an incorrect position solution, whereas in the static case with long data sets the multipath error propagates mostly into the residuals (implying a less precise solution) [Rizos, 1999].

According to previous measurements carried out on the surveyed point on the Gillin Hall roof we can state that the multipath effect at this location is relatively strong. The obstructions in the vicinity of the antenna are well defined (see Figure 3.9), they cause specular reflection resulting in expected errors of 2-6 m.

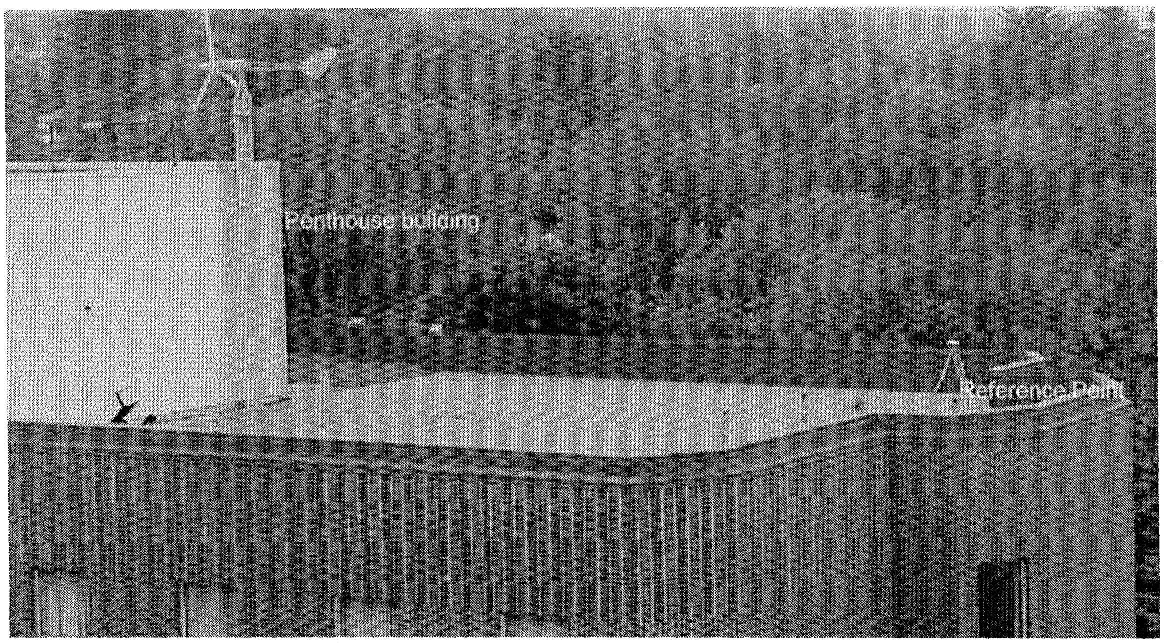


Figure 3.9: Strong Multipath Environment on the Roof of Gillin Hall

How large is the error contribution of multipath on the NovAtel positioning? Unfortunately there is no general mathematical model to determine or predict the effect of the multipath on a position solution. The best way to prove the presence of multipath is to make repeated measurements on consecutive days. The satellite configuration repeats over a location on Earth approximately every 24 hours. Therefore multipath effect is repeated too on consecutive days at the same time with a 4-minute shift. (The period is not exactly 24h, because the sidereal day is 4 minutes less than Universal Time day). If we see curves with the same characteristics we can affirm that it is due to multipath (e.g. on Figure 3.10 the effect of multipath error on positioning for the same baseline is shown on two consecutive days):

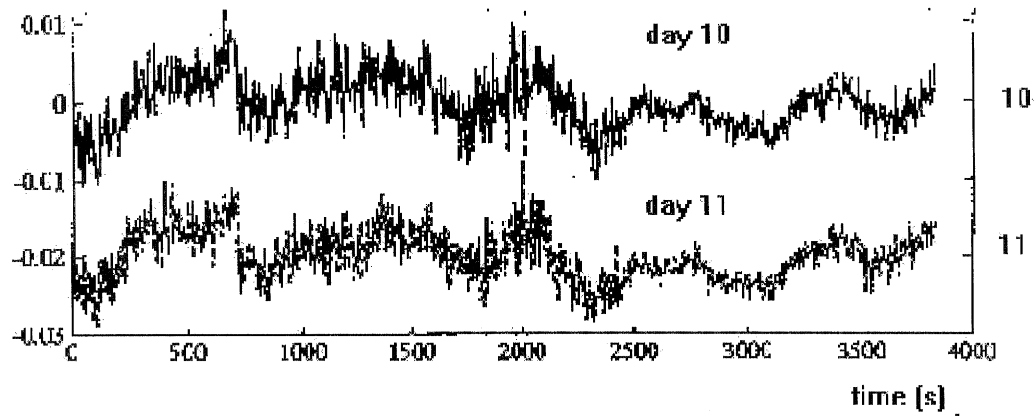


Figure 3.10: Typical multipath effect on consecutive days' measurements

However, multipath effect on a pseudorange observation may be measured using a combination of single-frequency carrier-phase and pseudorange data [Rizos, 1999]:

Carrier phase measurement on L1:

$$L_1 = \rho + \lambda N + Mp_{L1} + c(t - T) - d_{ion} + d_{trop} + \varepsilon \quad [\mathrm{m}] \tag{3.1}$$

Pseudorange measurement on L1:

$$C/A = \rho + Mp_{C/A} + c(t - T) + d_{ion} + d_{trop} + \eta \quad [\mathrm{m}] \tag{3.2}$$

Linear combination of L_1 and C/A:

$$C/A - L_1 = -\lambda N + Mp_{C/A} - Mp_{L1} + 2d_{ion} + \eta - \varepsilon \quad [\mathrm{m}] \tag{3.3}$$

Taking the time differential of these differences we get the following equation:

$$\delta(C/A - L_1) = \delta Mp_{C/A} - \cancel{\delta Mp_{L1}} + 2\cancel{\delta d_{ion}} + \delta(\eta - \varepsilon) \quad [\text{m}] \tag{3.4}$$

where:

L_1 is the carrier phase measurement on L1 frequency,

C/A is the code measurement on L1 frequency,

ρ is the geometric distance between the satellite- and the receiver antennas,

c is the vacuum speed of light,

t is the receiver clock offset from GPS time,

T is the satellite clock offset from GPS time,

d_{ion} is the ionospheric delay on L1,

d_{trop} is the tropospheric delay on L1,

λ is the wavelength of L1,

N is the carrier phase ambiguity,

Mp_{L1} is the carrier phase multipath,

$Mp_{C/A}$ is the code multipath,

ε is the carrier phase noise,

η is the code noise.

If we consider that the change in carrier phase multipath is negligible comparing with the pseudorange multipath, furthermore the change in the ionospheric effect is small too, there are two significant factors left: the change in the C/A-code multipath and the change in noise (eq. 3.4). The resulting quantity is equal to the time-differenced C/A-code multipath (plus noise) with an expected quasi-sinusoidal variation in time. With this kind of analysis one cannot calculate the exact value of code multipath but it is useful to demonstrate its presence and gives an estimate of its magnitude. Even though the initial value is unknown the accumulating sum of delta(C/A-L1) characterizes the multipath effect well.

NovAtel GPSCard's RGEA log type (Channel Range Measurements) contains both code and carrier phase raw measurements for all satellites in view. On 09 April 2001 1Hz data has been collected in order to show the multipath effect at the reference point. Ground-bounce multipath is usually stronger on signals coming from low elevation angle satellites, we also expect strong multipath from the penthouse wall (see Figure 3.9), Figure 3.11 shows multipath phenomenon on signal of a setting satellite (PRN 9). The anomalous feature at the end of the sample showing much higher amplitude is probably signal scattering. As the satellite moved towards the horizon, the signals reached the edge of the building, which caused diffuse signal scattering and finally the satellite was blocked.

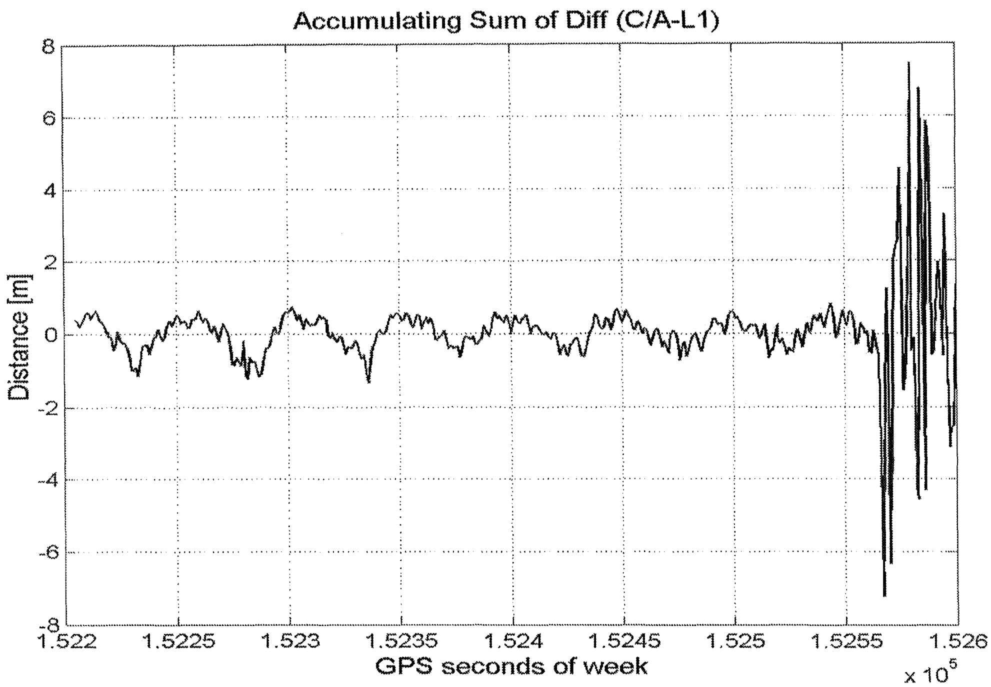


Figure 3.11: Multipath effect on PRN 9 signal (time interval: 6 min 35 sec)

Typical pseudorange errors show sinusoidal oscillations of periods of 6 to 10 minutes (depending on the distance to the reflector the period can be shorter or longer) [Langley et al., 1995]. The multipath effect changes in a quasi-sinusoidal pattern partly because satellites are moving, hence the receiver-satellite geometry changes (and thus the angle of incidence and reflection of the signal with respect to the reflective surface changes). The sinusoidal curve is clearly recognizable on Figure 3.12, which shows the first two and a half minutes of the previous plot:

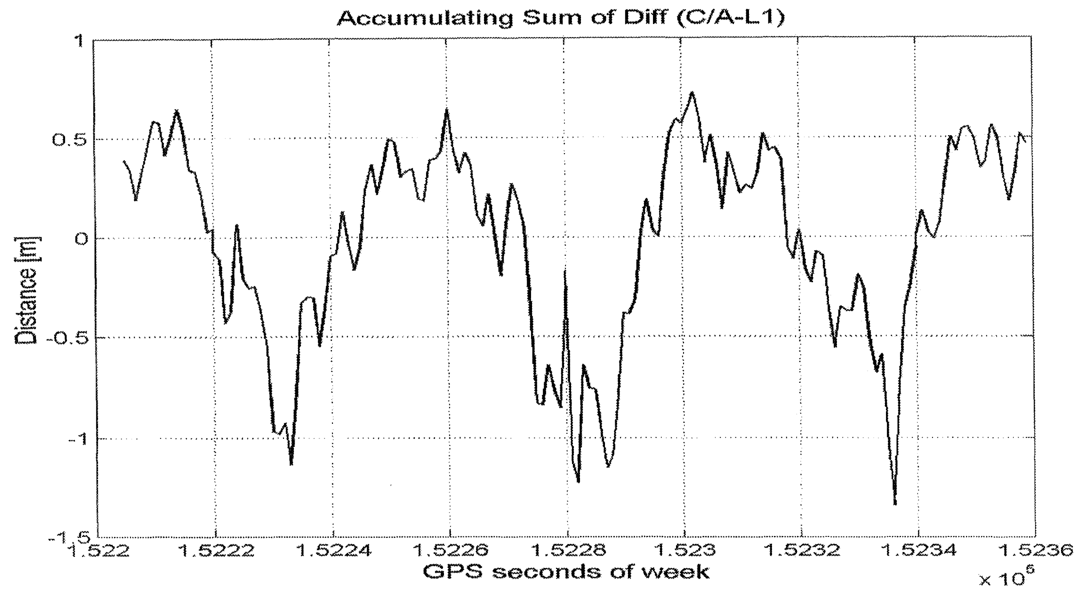


Figure 3.12: Multipath effect on PRN 9 measurement (time interval: 2 min 38 sec)

The period of oscillation in this case is approximately one minute. The closer the reflectors are the smaller the period and the amplitude are. It is clear that the change in the multipath on this particular satellite is more than 1 metre. Given the surrounding reflectors this value can go up to 6-7 meters depending on the elevation angle and azimuth of the satellite. The theoretical maximum of C/A-code multipath is approximately half of chip length of the code, that is, 150 m when the reflected/direct signal amplitude ratio is 1. Multipath effects, when averaged over a long enough time (several minutes to a quarter of an hour, or more), will be considerably reduced [Langley et al., 1995].

In order to provide quantitative information on multipath at the reference point, results of previous dual-frequency observations have been used. Earlier this year a dual-frequency short-baseline test has been carried out using the "known" point on Gillin Hall roof and another reference point on the neighbouring building's (Head Hall) roof. Data collected with Ashtech Z-12 receivers was processed by TEQC (Translation, Editing, Quality Check) software's quality check function that provides, among many other parameters, code multipath results. TEQC makes use of linear combinations formed by carrier and code measurements on both L1 and L2 frequencies. At the end of the derivation we get the following equations for code multipath:

$$MP1 = P1 - \left(\frac{2}{\alpha - 1} + 1\right) \cdot L1 + \left(\frac{2}{\alpha - 1}\right) \cdot L2, \tag{3.5}$$

$$MP2 = P2 - \left(\frac{2\alpha}{\alpha - 1}\right) \cdot L1 + \left(\frac{2\alpha}{\alpha - 1} - 1\right) \cdot L2, \tag{3.6}$$

where

$MP1$ is the code multipath (+ receiver and system noise) on L1,

$MP2$ is the code multipath (+ receiver and system noise) on L2,

$P1$ is the pseudorange measurement on L1,

$P2$ is the pseudorange measurement on L2,

α is a constant, $\alpha = \left(\frac{f_1}{f_2}\right)^2$, where f_1 and f_2 are the L1, L2 carrier frequencies.

The receivers were collecting data for 2 ½ hours at 1Hz data rate. The resulting multipath values for Head Hall point are:

$MP1$: 0.43m

$MP2$: 0.34m

Multipath on Gillin Hall:

$MP1$: 0.67m

$MP2$: 0.61m

These values prove that the Gillin Hall reference point considering the multipath effect, was not the best choice for the DGPS test measurements. Taking into account that the NovAtel receiver is not a geodetic receiver (like the Ashtech Z-12s), the multipath effect on the DGPS measurements could easily reach the metre level, or higher.

In order to reduce multipath error the elevation cut-off angle has been raised from 10 to 25 degrees. Getting less multipath, on the other hand results in higher VDOP, the gain in the horizontal accuracy became counterbalanced by huge height errors. The data set was logged on 05 April 2001 between 13h 45m and 18h 00m, UTC (4h 15m data) with 5-minute data interval. Table 3.6 shows the standalone, Table 3.7 the DGPS solution:

	N error	E error	U error
Mean [m]	-0.85	0.65	1.94
Max (abs) [m]	17.78	28.20	94.35
2 std. dev. [m]	3.09	3.32	14.04
2 hor. std. dev. [m]	4.53		
2 r.m.s. [m]	3.52	3.56	14.56
2drms [m]	5.01		

Table 3.6: Standalone position solution (3)

	N error	E error	U error
Mean [m]	0.27	0.36	1.48
Max (abs) [m]	5.32	8.03	27.36
2 std. dev. [m]	2.81	3.00	10.41
2 hor. std. dev. [m]	4.11		
2 r.m.s. [m]	2.87	3.09	10.83
2drms [m]	4.21		

Table 3.7: Beacon DGPS-corrected position solution (3)

This test proved that part of the position errors were originating from the multipath environment. A more reliable test would be to set up the same equipment at a multipath-free location.

3.3.2 Signal Strength

To successfully apply differential corrections, the broadcast signals have to be "healthy". The CSI Receiver provides four different characteristic measures of signal quality. CSI's official monitoring software (CSI Beacon Receiver CommandCenter) enables the user to monitor these values:

PRF (Performance) is the number of valid decoded RTCM messages received as a percentage of total messages received. PRF is expressed in %, and is a useful indicator of the DGPS data link quality. The higher the PRF, the higher the data update rate to the GPS receiver.

SNR (Signal-to-Noise Ratio) is the ratio between the desired signal and unwanted noise on the selected frequency. This ratio is expressed in decibels (dB). The higher the SNR, the better the quality of the signal.

SS (Signal Strength) is a numeric representation of the field strength of the received signal. The higher the number, the stronger the received signal [CSI, 1996].

LOCK shows whether the receiver is able to track the corrections or not. This y/n value depends on the three other measures.

The latency of a pseudorange correction increases and the position accuracy consequently degrades, if the DGPS correction signal is weak. This will usually occur as the reference station-user distance increases. The four abovementioned measures give a clear view why we usually should choose the closest station. 1-hour samples of the monitoring software's real-time output have been analysed to compare signal characteristics of corrections coming from Partridge Island (PI) and Point Escuminac (PE). The first plot (Figure 3.13) shows the results from the closer reference station, the second (Figure 3.14) displays those from the further one.

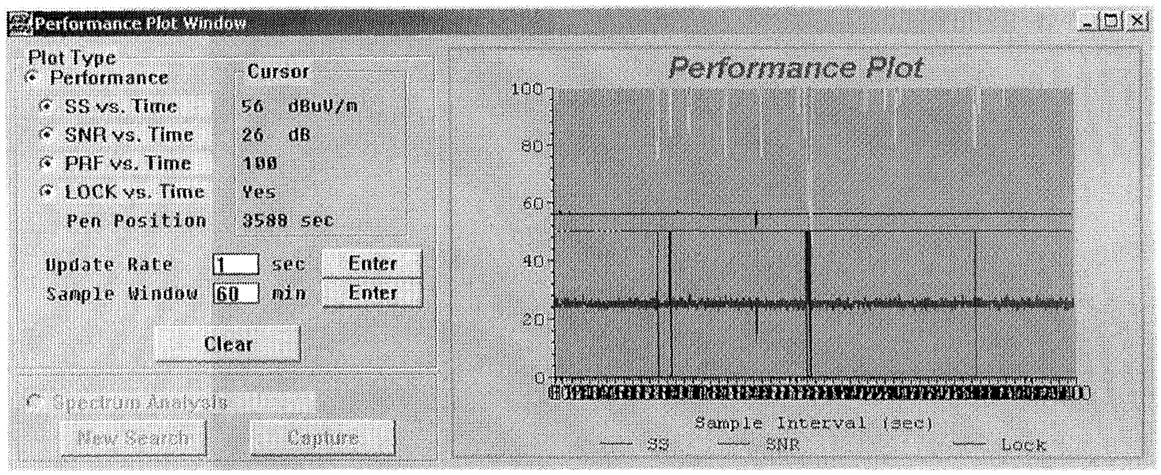


Figure 3.13: Signal characteristics from Partridge Island

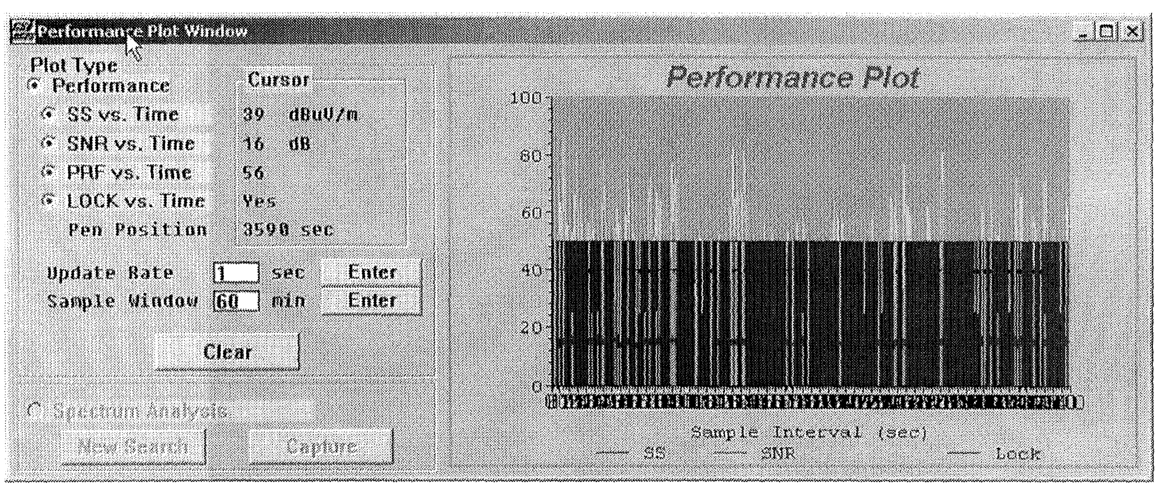


Figure 3.14: Signal characteristics from Point Escuminac

Conspicuous is the fact that the receiver has lost lock on signals from PE significantly more times. The performance in case of PI was almost always 100 %, whereas the same measure for the further station was much lower, the mean value was about 56 %. Signal strength for PI was 56 dBμV/m and 39 dBμV/m for PE. Finally the signal-to-noise ratio was 10 dB lower (16 dB) for PE than for PI (26 dB).

3.3.3 Noise

- Cable loss:

The GPSAntenna has been designed for use with the NovAtel Standard 5–meter coaxial cable. In the test measurements greater lengths of cables were required for longer installation runs. The Radiobeacon Antenna is equipped with a 60 cm pigtail cable. The antenna extension cable may be up to 150 m in length. The antenna is also equipped with a separate ground wire. For proper operation, this ground wire must be connected to a suitable ground point. The overall effect of the longer then optimal cable lengths is negligible.

- Antenna type:

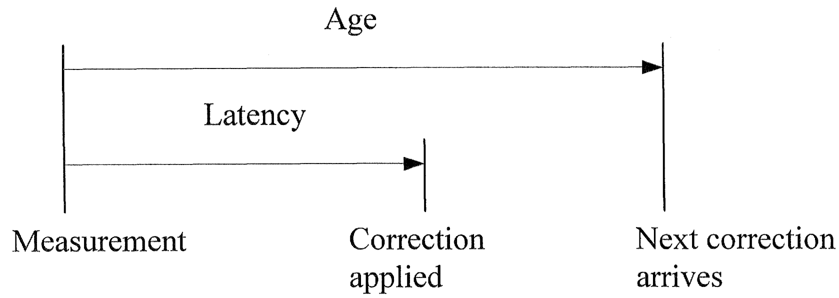
The applied CSI radiobeacon antenna was an E-field whip antenna. This type is typically more sensitive to noise, resulting in lower SNR, than a B-field loop antenna.

- GPS Receiver noise:

See Section 2.3.3. NovAtel RT-20 is no longer a state-of-the-art receiver. Related noise may be significant, perhaps many tens of centimetres.

3.3.4 DGPS Latency

DGPS latency is the "total elapsed time from the time of reference station measurement to when the user applies the correction" (calculation time + communication



delay) [Hogan, 2001].

Figure 3.15: DGPS Latency and Age [Hogan, 2001]

The CCG beacon DGPS latency for Message Type 9 (pseudorange corrections) at 200 bps rate varies between 1 and 4 seconds (see Figure 3.16), correction age varies between 4.5 and 5 seconds (see Figure 3.16).

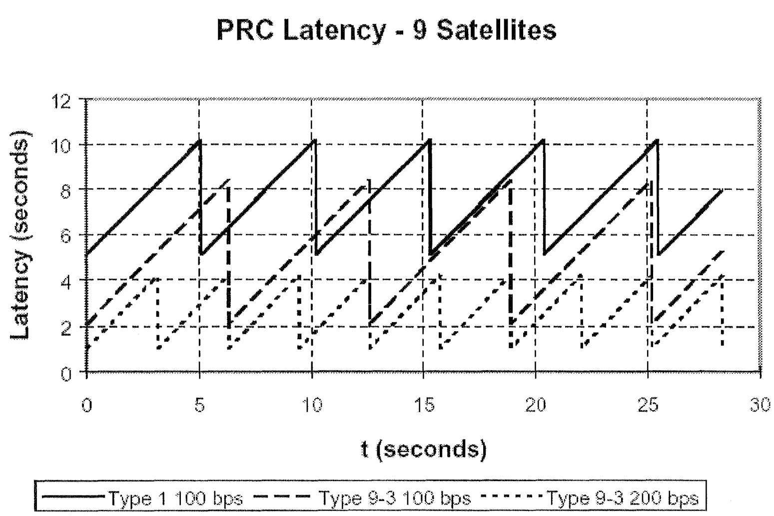


Figure 3.16: DGPS correction latency [Canadian Coast Guard, 2001]

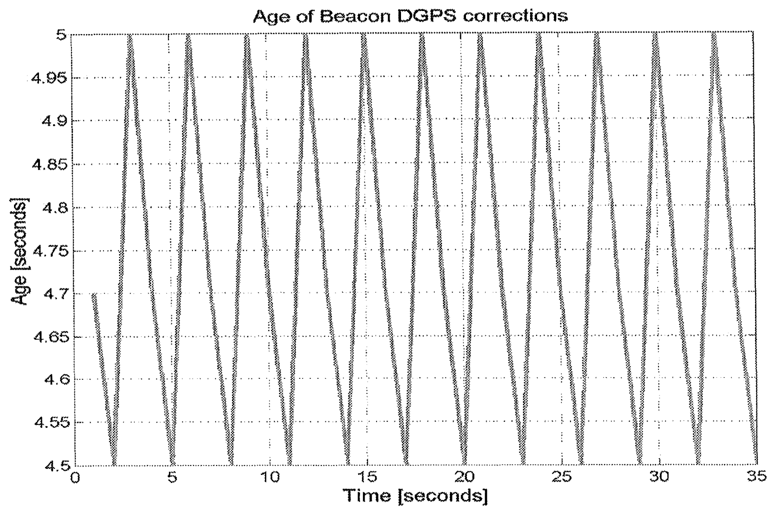


Figure 3.17: DGPS correction age (result of the test measurement)

In the S/A era, low PRC latency was vital because the transmitted corrections, mainly due to satellite clock dithering, changed very rapidly. Today this is not a problem anymore, even a 10-20 second latency would not end up in large position errors.

3.3.5 Biased Reference Coordinates

The "known" coordinates of the reference point on the pillar were determined by precise point positioning (PPP) software based on only two 8-hour observation sessions. Although the two sets of resulting coordinates agreed to a couple of centimetres their average is not the best result which could be obtained. In order to have a more accurate position estimate, the reference point was re-observed along with a number of high precision Canadian Base Network (CBN) points this summer. The computation of the

GPS network is currently under way. The PPP result and the network solution are expected to agree within a few centimetres.

3.3.6 Receiver Types

The NovAtel RT-20 is now an old receiver design. GPS hardware and software techniques developed a lot since this receiver first appeared on the market. Since all other chapters of the report contain results of test measurements carried out with a state-of-the-art technology receiver, positioning differences had to be checked between the two receivers. Therefore on 12-13 September 2001 a new Beacon DGPS test was carried out using NavCom NCT-2000D receivers (specifications are provided in Section 5.1.2). The basic test procedure architecture did not change, only the receivers were replaced. 24-hour 1Hz data was logged using a 10-degree cutoff angle. One of the receivers applied Partridge Island Reference Station's pseudorange corrections. The results in Tables 3.8 and 3.9 confirm the conjecture about significant differences between the two reveivers' performance. Standalone positioning shows approximately 2 metres better horizontal accuracy (2drms). NavCom's DGPS results are more than 1.5 metres better (2drms). (Observing conditions were not necessarily identical during the NovAtel and NavCom

	N error	E error	U error
Mean [m]	0.33	-0.24	-3.44
Max (abs) [m]	8.93	3.85	11.76
2 std. dev. [m]	4.07	2.32	7.36
2 hor. std. dev. [m]	4.69		
2 r.m.s. [m]	4.13	2.37	10.08
2drms [m]	4.76		

Table 3.8: Standalone position solution (4)

	N error	E error	U error
Mean [m]	0.08	0.01	-0.14
Max (abs) [m]	9.35	4.25	11.62
2 std. dev. [m]	2.54	1.46	4.81
2 hor. std. dev. [m]	2.93		
2 r.m.s. [m]	2.55	1.46	4.82
2drms [m]	2.93		

Table 3.9: Beacon DGPS-corrected position solution (4)

tests.)

On the horizontal error scatterogram (Figure 3.18) the accuracy improving effect of DGPS is reflected. Besides the reasonably good solutions we can see outlier position fixes that made the overall performance statistics worse.

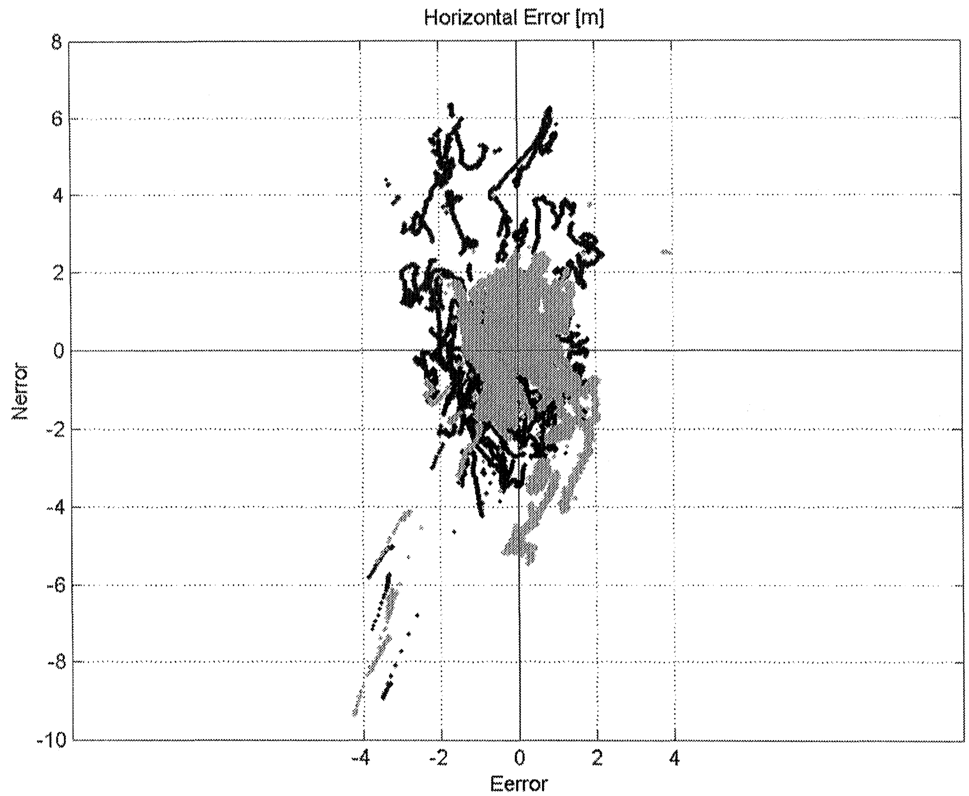


Figure 3.18: Standalone GPS (blue) vs. Beacon DGPS-corrected (green) position errors (4)

Figure 3.19 shows that the number of satellites dropped to 5 around 101 hrs causing a constant HDOP value of 3 for more than half an hour. The effect on horizontal DGPS positioning is visible on the north component plot at the same time. The age of the corrections often exceeded 10 seconds, without significant degrading effect. The huge spikes after 105 hrs mean that the receiver could not generate DGPS position fixes because of the fewer than 4 satellites in view.

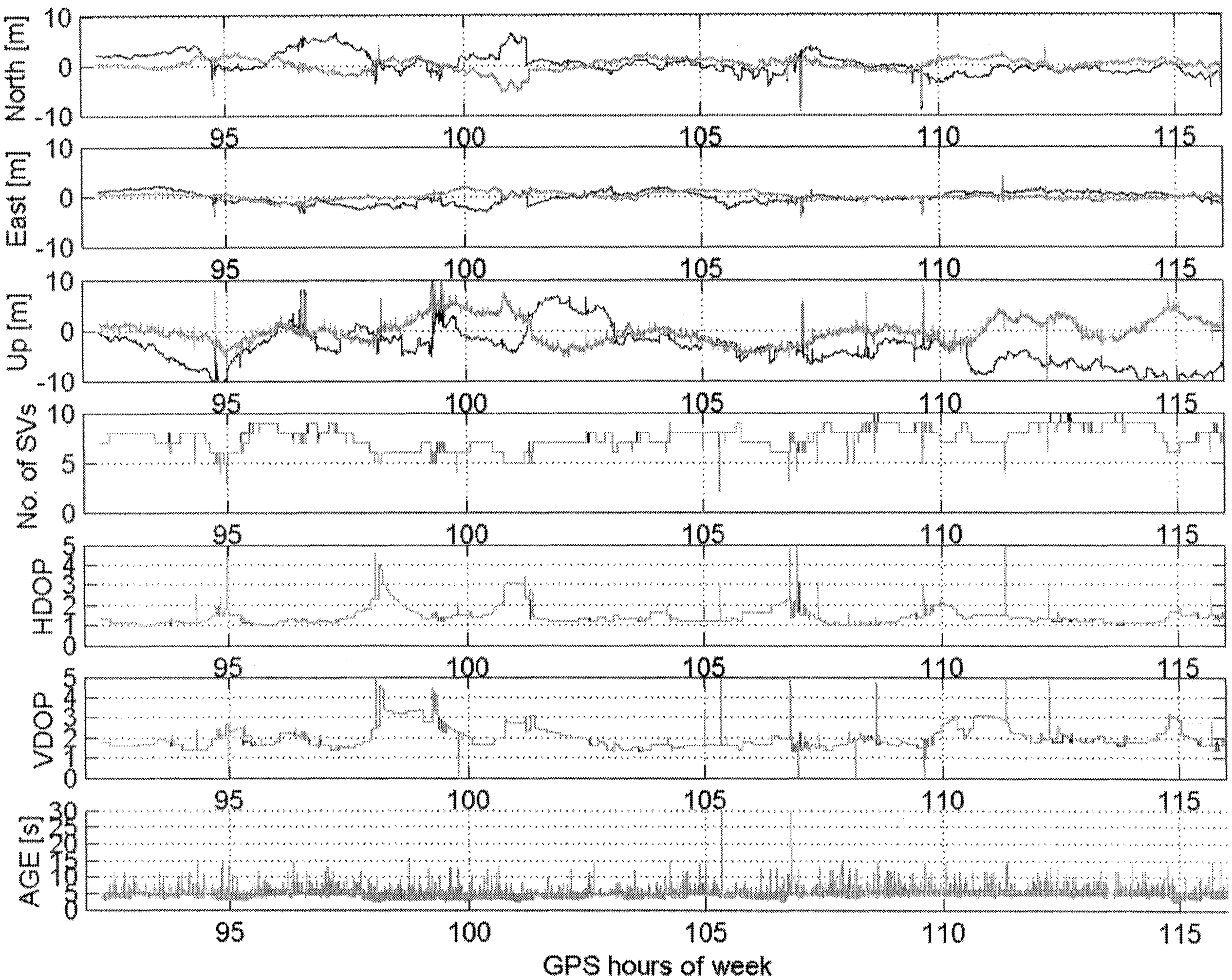


Figure 3.19: Standalone GPS (blue) vs. Beacon DGPS-corrected (green) solution comparison

CHAPTER 4

WIDE AREA DIFFERENTIAL GPS

Conventional DGPS works well for meter-level navigation over 100 km distances [Loomis, 1991]. However, it has a serious limitation: the achievable accuracy degrades with the growing separation distance between user and base station. The rate of degradation depends on the current state of the atmosphere, the transmission links used, etc. As a rule of thumb we can say that single-station DGPS accuracy degrades with approximately 1m every 100 km separation distance. Therefore to cover large areas with reasonable corrections a huge number of stations needs to be deployed.

Another approach to supplying the user community with differential corrections is more complex than single-station DGPS but it also provides better results. Networked DGPS (NDGPS) was invented to overcome the spatial decorrelation of GPS measurement errors. NDGPS makes it possible to cover wide areas with highly accurate corrections applying a minimum number of base stations.

4.1 Networked DGPS Background

4.1.1 NDGPS Classification

Networked DGPS systems can be classified in different ways. According to their coverage area size, there are three types: **Local Network**, **Regional Network**, and **World-Wide Network.** The smallest, the Local Network, assumes that the rover receiver will only use satellites visible to all reference stations. If the rover is allowed to use low-elevation angle satellites the network area becomes very limited. The other two types both provide corrections for wide areas: Regional Networks cover areas comparable in size to the United States or Western Europe, whereas World-Wide Networks estimate corrections for all satellites continuously. These two network types are also generally called Wide Area DGPS Networks.

Based on the applied correction-generating algorithm we also distinguish three different types: networks using **Measurement Domain-**, **Position Domain-**, and **State-Space Domain Algorithms**. Measurement domain algorithms are relatively simple algorithms providing corrections as the weighted mean of the various DGPS reference station corrections. They make use of the fact that averaging multiple sets of corrections has an error compensation effect. The drawback of this network solution is the degradation of correction accuracy with the distance from the network centroid. Usually local (or common-view) networks use measurement domain algorithms, but there are examples of it in all kinds of networked DGPS systems. Position domain algorithms follow a similar approach; they also deal relatively simply with the multiple-corrections.

These algorithms compute separate position solutions applying the individual reference stations' PRCs and RRCs, then weight and average the separate position solutions. The difference between the two aforementioned algorithms is that the first is applied in the measurement domain, before calculating the position fixes; the second is executed after position calculations are completed. The State-Space domain algorithm family is the most complex, but it provides the most accurate solution, independent of the baseline length. State-space domain algorithms model (estimate) the individual differential GPS error sources separately. Wide area networks apply these algorithms (e.g. WAAS, GPS·C).

4.1.2 Network Elements

Basically all networked DGPS/WADGPS systems are made up of 5 components:

1. A network of **Reference Stations** (RSs)
2. **Master Station**(s) (MS)
3. **Integrity Monitor Station**(s) (IMS)
4. **User Segment**
5. **Communications Links** between the individual components

(6.) In some cases **Virtual Reference Stations** (VRS) are also part of the system.

Reference stations are located at carefully chosen sites, with clear view to the horizon, minimal multipath, and very accurately determined position. They are equipped with high-performance GPS receivers and communication devices. RSs calculate pseudorange (and optionally carrier phase) corrections real-time and transmit those in real time to the Master Station(s) via terrestrial communication links (usually leased telephone lines) or satellite links. The incoming multi-reference DGPS corrections are processed at the Master Station(s) with sophisticated algorithms, which generate one single set of WADGPS corrections. The algorithms' task is to account and compensate for spatial decorrelation of GPS error sources. Finally the data is broadcast to users via any convenient communications link, such as geosynchronous communications satellite, (wireless) Internet, LF/MF radiobroadcast, etc. Integrity Monitor Station(s) check system integrity simulating network users. These are located at surveyed stations, usually at critical points of the network, equipped with GPS receiver(s) and communications system. IMS(s) are connected online to the MS(s), continuously reporting the "goodness" of the corrections. If, for any reason, an IMS detects intolerable system performance (e.g., latency of received corrections exceeds tolerance, position solution becomes worse than tolerance) it immediately reports the anomaly to the Master Station. The system then alerts users not to apply corrections. Users are equipped with GPS receivers and they are capable of receiving and decoding differential corrections.

Another type of NDGPS follows a slightly different idea. Multi-reference corrections are quality checked at the Master Station and are broadcast to Virtual Reference Stations, where the network algorithm computes the local set of corrections. The VRSs are reference stations without GPS receivers but they behave like real reference stations located in the vicinity of the users. They transmit local corrections usually in standard RTCM-format via a terrestrial radio link (e.g., FM-subcarrier). Even though this system is a bit more complex it has advantages over regular NDGPS. VRSs provide local corrections anywhere within the network that are easy to handle for the user receivers.

The bandwidth of a VHF/UHF radiobroadcast is typically much wider than that of a simple L-band communications satellite transmission giving opportunity for value-added resellers to attach any type of additional information (e.g., located commercial information) to the corrections. Furthermore, the PRC latency can also be reduced by this technique because the data link between the Master Station and VRSs should not necessarily be communications satellite-based. It can be a leased telephone connection, Internet or some other link.

Since the following part of the thesis is based on the investigation of Regional and World-Wide Networks the "WADGPS" term has been used instead of the more generic "NDGPS".

4.1.3 WADGPS Algorithms

The heart of a networked DGPS system is the algorithm that calculates a single set of corrections from multi-reference DGPS corrections. How do these algorithms work?

All algorithms share basic functions:

Received corrections are not synchronized, PRCs (and RRCs) arrive at the Master Station at slightly different epochs. Therefore the WADGPS algorithm's first task is to **extrapolate corrections to a single processing epoch**. The common processing epoch should be that of the latest arrived correction. The equation of extrapolation is then:

$$PRC_i^j\big|t_0 = PRC_i^j\big|t_k + RRC_i^j\big|t_k \cdot (t_0 - t_k) \tag{4.1}$$

where the pseudorange correction $PRC_i^j\big|t_k$ generated at reference station i for satellite j at time t_k is extrapolated to time t_0 [Abousalem, 1996].

In short baseline differential applications, the **atmospheric effects** are very similar at both reference and rover stations. In wide area applications this is not true, the reference station atmospheric delays are not valid for the rovers, therefore they **must be removed** and the atmosphere-free corrections must be transmitted to the Master Stations. (Or the raw data is sent from the RSs and all computations are performed at the Master Station). Atmospheric delays are functions of satellite elevation angle, therefore in order to remove the delays from each set of corrections arriving from the respective Reference Stations the position of the individual satellites have to be determined. To compute satellite coordinates, WADGPS algorithms use the broadcast ephemerides.

Tropospheric error can be removed by using tropospheric models. There are a number of models available, all providing good results. Saastamoinen zenith delay expressions in combination with the Niell mapping functions provide superior performance to the other models.

Reference stations are usually equipped with dual frequency GPS receivers so ionospheric delay can be computed directly from measurements. If dual frequency measurements are not available the algorithms apply ionospheric models (e.g. Klobuchar [1986] standard broadcast model).

Differential corrections include the **Reference Station's clock bias and drift**. In single-reference GPS, the rover receiver clock terms implicitly estimate the reference receiver clock effects. In a WADGPS network, corrections generated by various reference stations contain different clock terms. It is impossible to estimate all reference receiver clock bias and drift by the rover receiver. The solution is to choose a single reference station clock and use it as a "reference clock" for all the others. All multiple-PRCs should be normalized to this single clock and the user receiver is then able to solve for the single clock effect. In practice the MS is usually chosen as the "reference clock" station.

The normalized, atmospheric error free corrections are then weighted. PRC weight is computed as a combination of three factors: distance of the respective Reference Station from the Master Station, satellite elevation angles at the Reference Station, and the age of corrections. Abousalem [1996] applied a direct exponential model for **distance weighting**:

$$w_d = e^{-(2\times d)/4000} \tag{4.2}$$

where w_d is the distance weight.

He used 4000 km correlation (separation) distance as a maximum, and 400 km as a minimum; distances exceeding 4000 km were set to 4000, distances below 400 km were set to 400. It is necessary to set minimum and maximum values not to over- or underweight RSs located very close or very far from the user. These are empirical numbers. In another regional network e.g., in Europe, the correlation values are different (smaller) since the RSs are closer and more in number. Abousalem used 12 Canadian Active Control Stations (see Figure 4.1) as Reference Stations in a continent-size country.

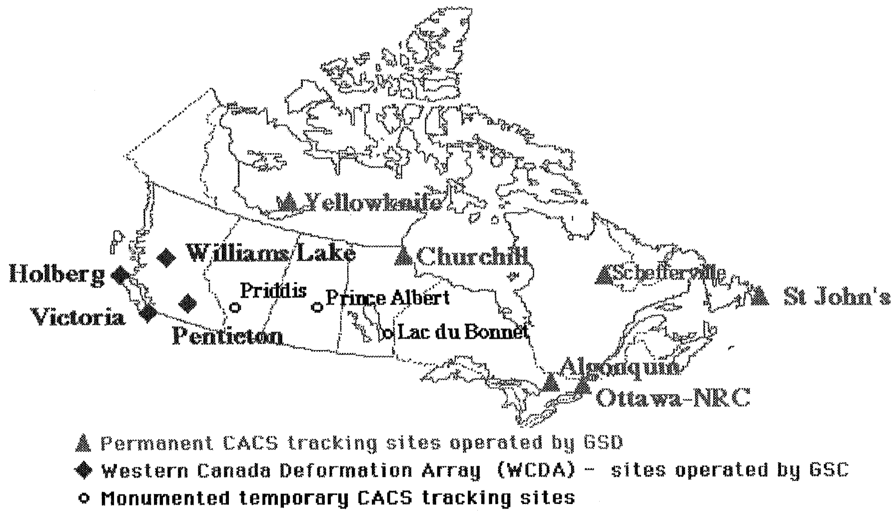


Figure 4.1: The Canadian Active Control System Network Configuration

(The network currently includes 25 stations but they are not all relaying their data in real-time.) [NRCan, 2001]

On the contrary, the European permanent network is made up of 118 Reference Stations (see Figure 4.2) reducing the correlation distance under 1000 km.

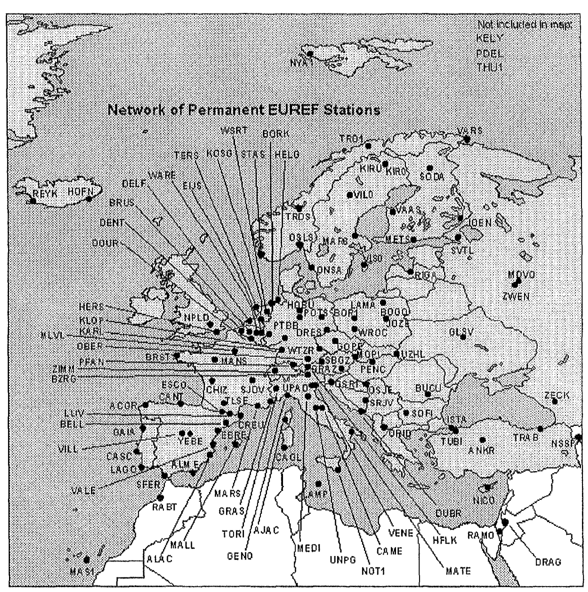


Figure 4.2: Network of Permanent EUREF Stations [EUREF, 2001]

Elevation angle weighting

The higher the elevation angle the less the atmospheric effect on the measurements is. The signal to noise density ratio (C/N_0) is also lower for low elevation angle satellites. Therefore corrections referring to higher elevation angle satellites should get more weight.

Age weighting

The RS that provides lower latency corrections gets more weight.

Different algorithms have different approaches in **generating a single set of corrections** from the weighted multi-RS PRCs and RRCs.

Measurement Domain Algorithms simply compute the mean of the multiple-station corrections for each satellite:

$$PRC^{j}_{mean} = \frac{\sum_{i=1}^{n}\left(w^{j}_{PRC_i} \cdot PRC^{j}_{i}\right)}{\sum_{i=1}^{n} w^{j}_{PRC_i}} \tag{4.3}$$

[Abousalem, 1996],

where w^{j}_{PRCi} is the total weight (combination of the three weight components).

State-Space Domain Algorithms model individual error sources in a least squares estimation, where "observations" are the multi-RS pseudorange and range rate corrections, and "unknown parameters" are the PRC and RRC correction components: three orbital offsets, three orbital error rates, a clock offset and a clock error rate for each satellite in view plus one receiver clock offset and one receiver clock drift for each participating RS [after Abousalem, 1996]. The resulting single set of corrections goes through **statistical tests and filtering** to detect and exclude outliers.

First the corrections are applied to the broadcast orbit and clock and then the user receiver computes an accurate position. If using Virtual Reference Stations, state space corrections are converted to localized range and range rate corrections, which are applied by the user before computing an accurate position.

Generation of **local ionospheric corrections** is usually based on a thin shell iono model. The WADGPS corrections contain vertical delay values for selected ionospheric grid points (IGPs), which are lattice points of a virtual grid of lines of constant latitude and longitude intervals at the height of the shell (usually 350~400 km). The iono correction related to the location of the receiver is a result of an interpolation process within the correction grid done by the receiver. The receiver knows the satellite positions (elevation angle, azimuth) from the navigation message, it calculates the pierce points of the signal path on the iono shell and interpolates delay values to these points (see Figure 4.3).

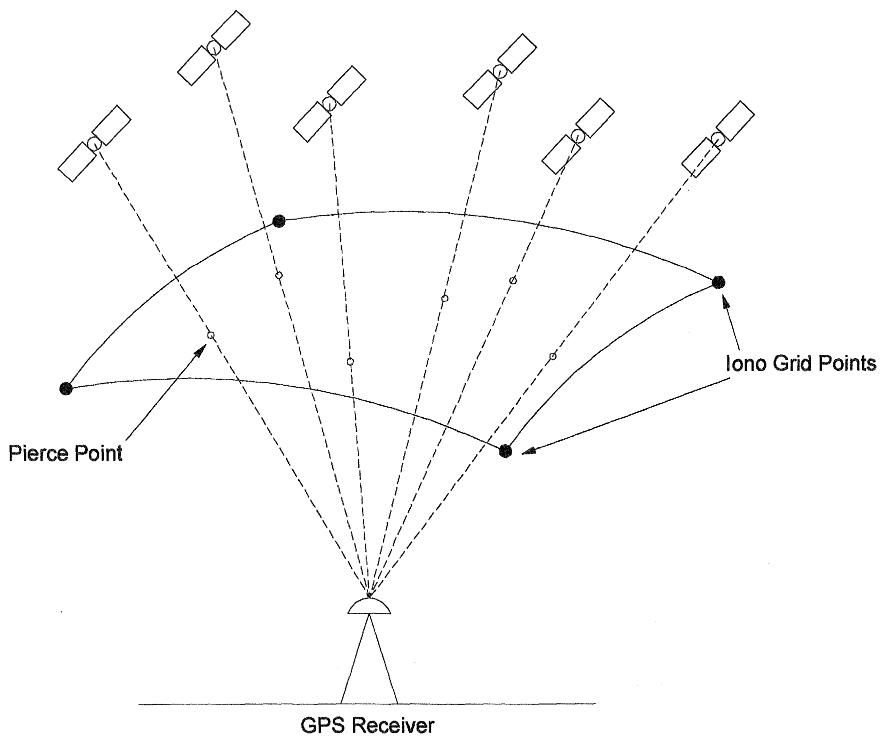


Figure 4.3: Applying ionospheric corrections

Usually **tropospheric corrections** are not generated but the receivers apply tropo models. If using Virtual Reference Stations, the tropospheric delay can be estimated and involved into the local corrections based on ground meteorological measurements or a climatological database.

The message before transmission must be standardized to RTCM or RTCA format.

CHAPTER 5

OPERATIONAL WADGPS SYSTEMS

After the general WADGPS overview, this chapter provides specific information on a number of operational systems. Three of them (WAAS, EGNOS, and GPS·C) have been extensively investigated through a series of test measurements. Results indicating their performance are presented here.

5.1 Wide Area Augmentation System (WAAS)

5.1.1 WAAS Background

The Wide Area Augmentation System is one of the two Satellite Based Augmentation Systems (SBASs) currently being tested around the world. These are safety-critical navigation systems, which provide high quality positioning information that enables GPS to meet air navigation performance requirements. Besides WAAS there is a similar system in Europe, the EGNOS (European Geostationary Navigation Overlay System). Japan is also building its system, the MSAS (MTSAT Satellite Augmentation System). The MSAS schedule was delayed because of a geostationary satellite launch failure. WAAS, EGNOS and MSAS when fully operational, will be interoperable resulting in seamless worldwide coverage.

The Wide Area Augmentation System is operated by the United States Federal Aviation Administration (FAA) and supplies the entire United States, parts of Canada, Mexico and the Caribbean with differential corrections. WAAS is basically an aviation community service; its primary mission is to support en route, terminal, nonprecision and precision approach (Category I) phases of flight in the U.S. National Airspace System. A navigation system permitting a precision approach provides both lateral (horizontal) and vertical guidance to a decision altitude/height (DA/H). If the required visual references, such as approach lights or the runway environment, are not in view at the DA/H, a pilot must execute a missed approach – that is, a specified, controlled routing away from the runway [Dewar, 1999]. Category I approaches can be used when the pilot sees the runway at no less than 60 m above the ground (DA/H) when there is at least a 800 m visibility.

Precision aviation is not the only benefit of WAAS; it can also serve a large part of the terrestrial and marine GPS user community. It could help boaters, precision agriculture, crop dusters, surveyors, cell phone 911 emergency services, recreational users, and so on, and so forth. Providing wide area differential corrections, WAAS improves the accuracy of the basic GPS service to better than 7 metres (2σ) vertically and horizontally (CAT I requires 7.6 m). After S/A was turned off, the most significant advantage of WAAS is not the improved accuracy but the very high level of integrity, availability and continuity that is not provided by standard GPS.

The system is based on a network of 25 Wide Area Ground Reference Stations (WRSs), deployed throughout the U.S. to measure pseudoranges and carrier phases on both L1 and L2 frequencies. WRSs send their GPS and meteorological measurement data to one of the two Wide area Master Stations (WMSs) (see Figure 5.1). Here clock and ephemeris correction vectors are computed for each satellite. Ionospheric corrections (vertical delays) are also calculated for selected ionospheric grid points. Tropospheric corrections are not generated. The need for higher accuracy by WAAS was satisfied by implementing a new tropospheric model into the user receivers. The new model is based on UNB3, a model developed at the University of New Brunswick which uses the Saastamoinen zenith delay model, the Niell mapping functions and a look-up table of meteorological data.

In the WMSs, incoming data go through a complex integrity check process. One WMS processor is responsible for the differential correction determination and verification; another, the safety processor, makes sure that the data generated by the first one are correct. This integrity monitoring function is used to detect out-of tolerance conditions. If the service is not satisfactory, the system alerts users not to apply WAAS for navigation.

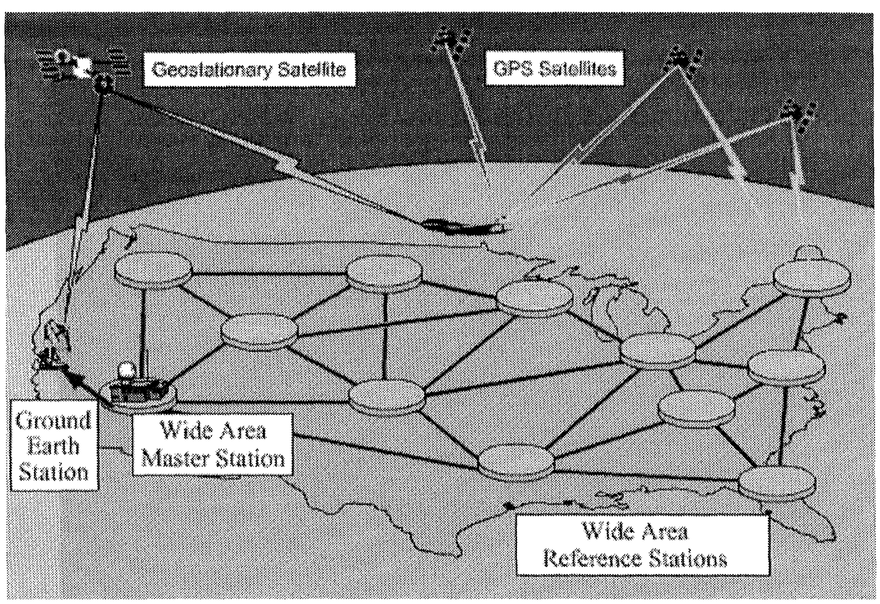


Figure 5.1: WAAS Architecture (simplified) [MITRE, 2001]

The integrity checked data are prepared and uploaded to the two geostationary communications satellites (GEOs) via the three ground earth stations (GESs). The two GEOs are Inmarsat 3, AOR-W (Atlantic Ocean Region-West; PRN 122) located at 54°W, and POR (Pacific Ocean Region; PRN 134) located at 178°E. On Figure 5.2 footprints of SBAS GEOs are represented. Besides the two WAAS satellites, AOR-E (Atlantic Ocean Region-East; PRN120) and IOR (Indian Ocean Region; PRN 131) are also printed here. These two, together with European Space Agency's ARTEMIS satellite serve EGNOS.

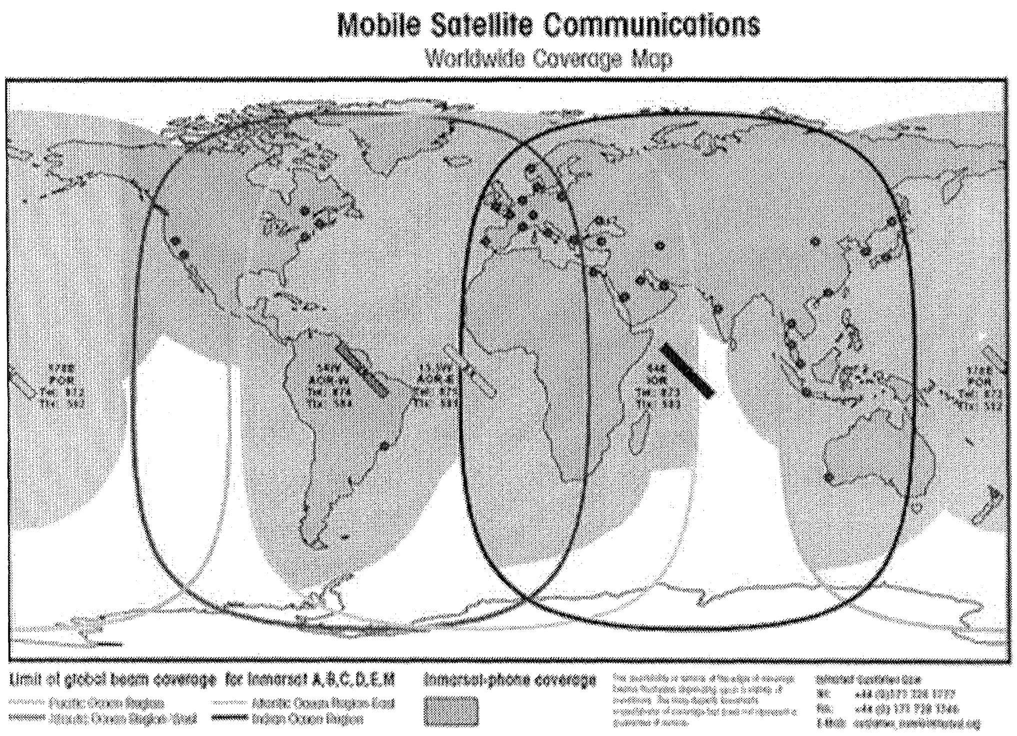


Figure 5.2: Footprints of Inmarsat GEOs [Yeazel, 2001]

The message is then broadcast on the same frequency as GPS (L1, 1575.42 MHz) to receivers, which are located within the broadcast coverage area of WAAS. The communications satellites also act as additional navigation satellites, providing additional signals for position determination [FAA, 2001] (in the UNB test measurements these extra signals have not been used). The user avionics apply the corrections to their pseudorange measurements to improve the accuracy of their position estimates.

5.1.2 Test Measurements at UNB

The goal of the test measurements was to compare the accuracy of WAAS corrected positioning to standalone GPS positioning, demonstrating the improvement made by a wide area DGPS system. For the test measurements, high performance GPS receivers were used to reduce possible receiver-related errors. NavCom NCT-2000D, according to the NavCom website [NavCom, 2000] is the most accurate GPS receiver on the market today, that operates either in single frequency or dual frequency mode, and offers two WAAS channels besides ten GPS channels. To verify reported WAAS performance, receivers were used in single frequency mode providing a carrier-smoothed code solution. The system architecture (see Figure 5.3) was very similar to the one used in the beacon-DGPS tests. A single GPS antenna (AreoAntenna Technology Inc. AT 2775-42) supplied both receivers.

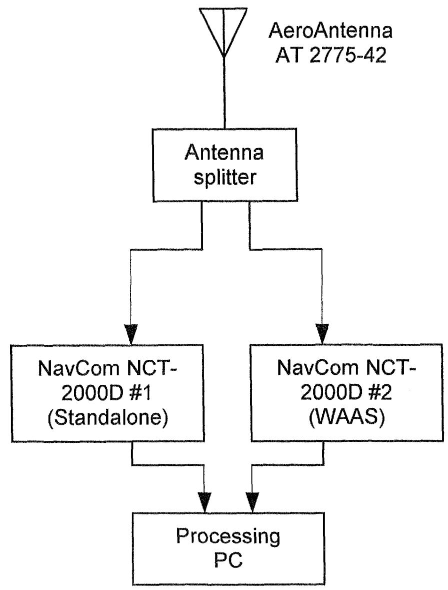


Figure 5.3: WAAS test architecture

In NavCom's GPS software (StarUtil) there is an option to switch WAAS reception on or off. On one of the receivers, WAAS was turned off. The position solution provided by the receivers was logged on a Pentium III PC. The position data was output on one of the receiver's communications ports in standard NMEA-0183 (National Marine Electronics Association) format. There are a number of NMEA messages provided by the NCT-2000D: ALM, GGA, GLL, GSA, GSV, RMC, VTG, and ZDA. These are ASCII messages that make it quite easy to retrieve the useful information, which, in this case were the latitude, longitude, and height values for every position fix. These numbers are contained in the GGA message:

GPGGA Global Position System Fix Data

Time, position and fix-related data of the GPS receiver.

Structure:

$GPGGA	utc	lat	lat dir	lon	lon dir	GPS qual	# sats	hdop	alt	units

hog	units	age	stn ID	*xx	[CR][LF]

Field	Structure	Field Description	Symbol	Example
1	$GPGGA	Log header		$GPGGA
2	utc	UTC time of position(hours/minutes/seconds/ decimal seconds)	hhmmss.s s	220147.50
3	lat	Latitude (DDmm.mm)	llll.ll	5106.7194489
4	lat dir	Latitude direction (N = North, S = South)	a	N
5	lon	Longitude (DDDmm.mm)	yyyyy.yy	11402.3589020
6	lon dir	Longitude direction (E = East, W = West)	a	W
7	GPS qual	GPS Quality indicator 0 = fix not available or invalid 1 = GPS fix 2 = Differential GPS fix	x	1
8	# sats	Number of satellites in use (00-12). May be different to the number in view	xx	08
9	hdop	Horizontal dilution of precision	x.x	0.9
10	alt	Antenna altitude above/below mean sea level (geoid)	x.x	1080.406
11	units	Units of antenna altitude (M = metres)	M	M
12	hog	Height of geoid (mean sea level) above WGS84 ellipsoid	x.x	46.9
13	units	Units of geoidal separation (M = metres)	M	M
14	age	Age of Differential GPS data (in seconds)	xx	,,
15	stn ID	Differential reference station ID, 0000-1023	xxxx	,,
16	*xx	Checksum	*hh	*48
17	[CR][LF]	Sentence terminator		[CR][LF]

Table 5.1: NMEA GGA sentence structure

Example:

$GPGGA,220147.50,5106.7194489,N,11402.3589020,W,1,08,0.9,1080.406,M,,,,

*48[CR][LF]

Further analysis of the receiver performance is available by logging other types of NMEA sentences. Positioning accuracy changes in time as the number of visible satellites and the satellite geometry varies. Dilution of precision (DOP) values are good indicators of changes of precision. GSA NMEA message contains PDOP, HDOP, and VDOP numbers:

GPGSA GPS DOP and Active Satellites

GPS receiver operating mode, satellites used for navigation and DOP values.

Structure:

$GPGSA	mode MA	mode 123	prn	prn	prn	prn	prn	prn	prn	prn	prn

prn	prn	prn	pdop	hdop	vdop	*xx	[CR][LF]

Field	Structure	Field Description	Symbol	Example
1	$GPGSA	Log header		$GPGSA
2	mode MA	A = Automatic 2D/3D (not used by GPSCard) M = Manual, forced to operate in 2D or 3D	M	M
3	mode 123	Mode: 1 = Fix not available; 2 = 2D; 3 = 3D	x	3
4 - 15	prn	PRN numbers of satellites used in solution (null for unused fields), total of 12 fields	xx,xx,.....	18,03,13,25,16, 24,12,20,,,,,
16	pdop	Position dilution of precision	x.x	1.5
17	hdop	Horizontal position and time dilution of precision	x.x	0.9
18	vdop	Vertical dilution of precision	x.x	1.2
19	*xx	Checksum	*hh	*3F
20	[CR][LF]	Sentence terminator		[CR][LF]

Table 5.2: NMEA GSA sentence structure

Example:

$GPGSA,M,3,18,03,13,25,16,24,12,20,,,,,1.5,0.9,1.2*3F[CR][LF]

On 17-18 July 2001 24 hrs of data was logged at 1 Hz data rate. In the GGA NMEA message GPS quality indicator (Field 7) shows whether the receiver used DGPS (WAAS) corrections for computing position fixes or not. If this value is 2 that means WAAS corrections were applied, if it is 1 then the receiver was navigating, but only in standalone mode, and finally if the number is 0 that means no GPS fix at all. That happens if there are not 4 healthy satellites (at least) locked by the receiver.

In the WAAS corrected case, the above-mentioned value was 2 all time (86400 epochs/24 hr), that indicates very high-level system availability (See Appendix II).

With the help of my ConvertC.m Matlab program, geographical coordinates (latitudes, longitudes, heights) were transformed into topocentric easting, northing, and up values in order to have better understanding of the results. The known position of the reference point (zero in topocentric system) contains again the sub 10 cm bias because of using ITRF97 coordinates instead of WGS 84 (mentioned in Chapter 3.2). WAAS corrections are in the WGS 84 (G873) datum, therefore the position fixes output by the receiver are also in WGS 84.

Tables 5.3 and 5.4 show the positioning error statistics of standalone and WAAS solutions respectively.

	N error	E error	U error
Mean [m]	0.32	0.20	-1.12
Max (abs) [m]	9.15	3.89	9.40
2 std. dev. [m]	4.70	2.38	5.64
2 hor. std. dev. [m]	5.27		
2 r.m.s. [m]	4.75	2.41	6.08
2drms [m]	5.32		

Table 5.3: Standalone position solution

	N error	E error	U error
Mean [m]	0.03	-0.26	-0.85
Max (abs) [m]	8.37	3.61	6.79
2 std. dev. [m]	1.19	1.01	3.06
2 hor. std. dev. [m]	1.56		
2 r.m.s. [m]	1.19	1.14	3.50
2drms [m]	1.65		

Table 5.4: WAAS-corrected position solution

Root mean square (r.m.s.) is the indicator of positioning accuracy, which unlike the standard deviation contains the bias between the sample mean and the real value. 2r.m.s. (two times the r.m.s.) values for WAAS in each component are much smaller than the CAT I requirement. 2drms (twice the distance r.m.s.), which shows the horizontal accuracy, is below the 2-metre level. We can see more than 4 metres improvement in horizontal positioning (2drms). Mean values are close to the known point in both cases;

the big difference is not caused by biases. WAAS reduced the maximum errors especially in the height component. The distinctive difference happens in precision. Standard deviations in the WAAS case are reasonably small: horizontal components are close to the metre level. In 95 % of the time, our horizontal position solutions were within a 1.6 m circle, this accuracy satisfies the majority of real-time non-geodetic applications. These results are reasonable based on a WADGPS system, especially considering the strong multipath environment and the fact that Fredericton is located at the edge of the WAAS ionospheric grid.

A WAAS-corrected up component offset with several jumps is recognizable in Figure 5.4, whereas north and east errors are very constant except for a minimal number of spikes. The corrected data series are somewhat noisier especially in height compared to NavCom's standalone solution.

HDOP data show changes in satellite geometry. The anomalies between 65 and 70 hours (standalone receiver HDOP does not agree with WAAS receiver HDOP) are due to the different numbers of satellites used. The effect of poor standalone HDOP is reflected in the horizontal components (mainly in northings). The reason for few satellites available to the standalone receiver needs further analysis.

The 10 GPS channel receivers used 0-degree elevation mask, differences in the number of applied satellites came from the slightly different receiver electronics, WAAS provided corrections for all satellites in view.

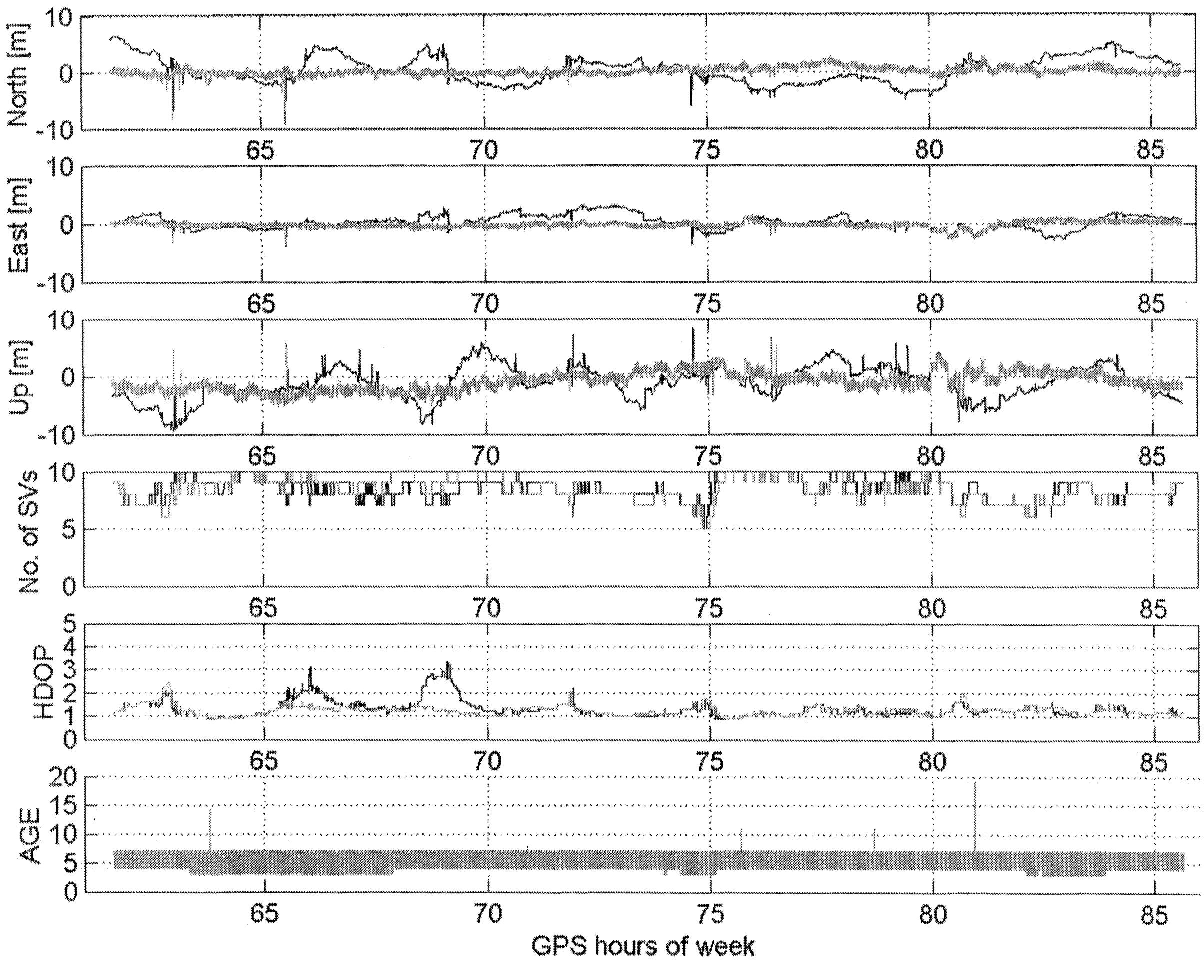


Figure 5.4: Standalone GPS (blue) vs. WAAS-corrected GPS (green) solution comparison

The age of corrections changes between 4 and 7 seconds during the whole data series, with a minimal number of outliers. A 35-second sample of the correction age data is shown in Figure 5.5:

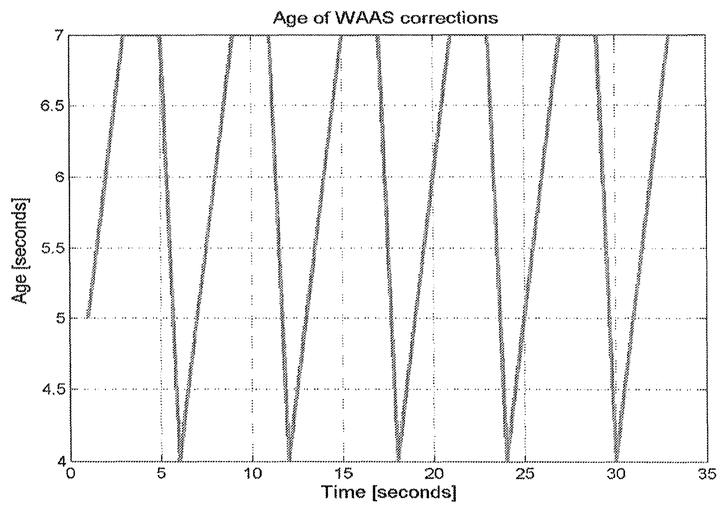


Figure 5.5: Age of WAAS correction

Figures 5.6 and 5.7 show accumulation of corrected position fixes around zero. The less than 30 cm offset in the east component is visible on Figure 5.6. The horizontal error distribution histograms (see Figures 5.8 and 5.9) and probability distribution functions (see Figure 5.10) show the widespread standalone position fixes and the concentrated WAAS-fixes. 95% of the errors are within ~ 1.5 metres if using corrections; the value is ~ 4.5 metres without WAAS.

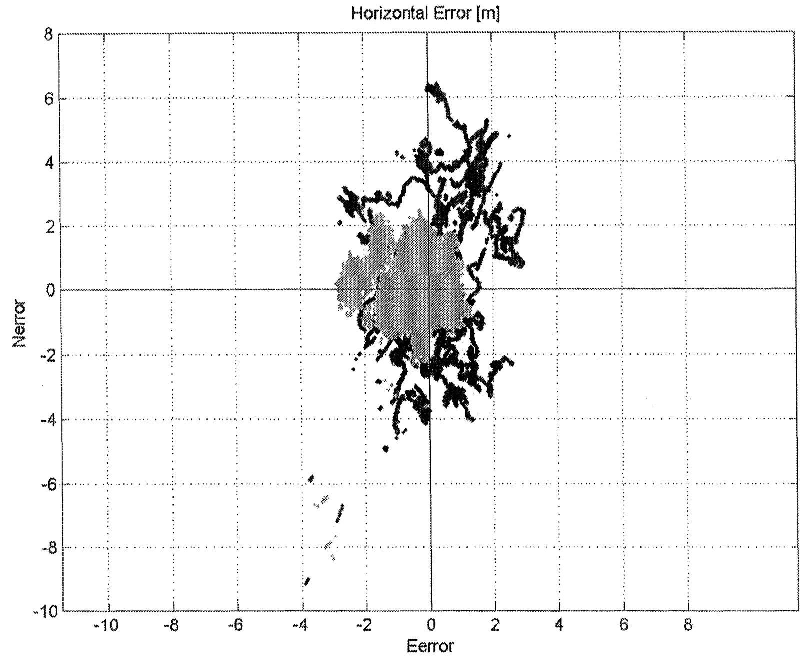


Figure 5.6: Standalone GPS (blue) vs. WAAS-corrected (green) horizontal position errors

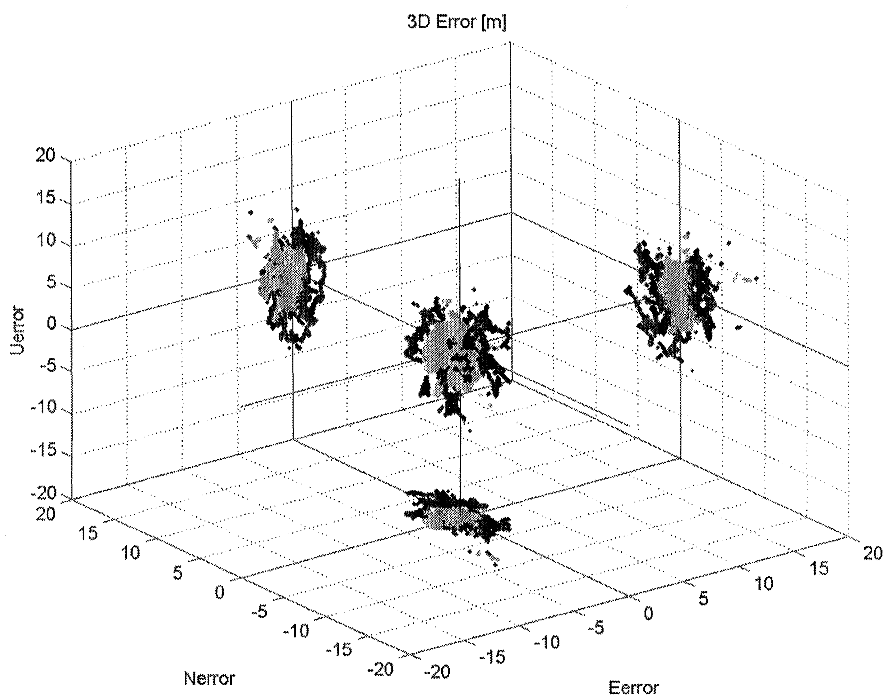


Figure 5.7: Standalone GPS (blue) vs. WAAS-corrected (green) 3D position errors

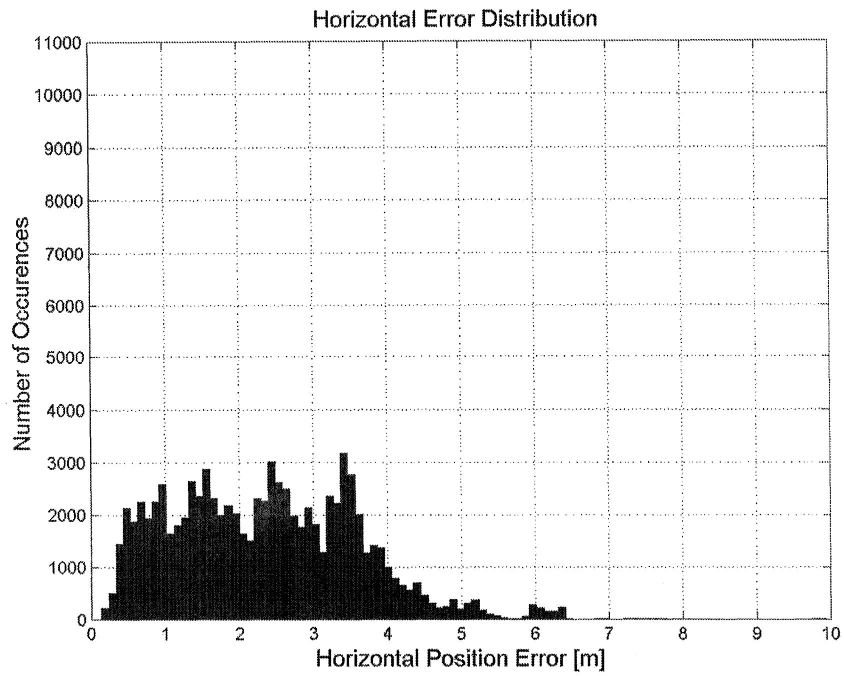


Figure 5.8: Horizontal error distribution of the standalone solution

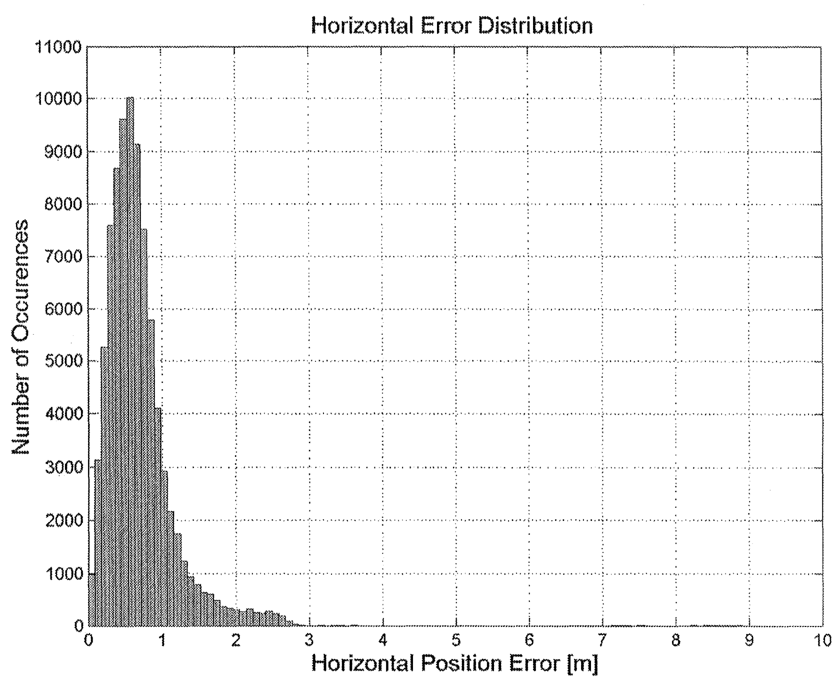


Figure 5.9: Horizontal error distribution of the WAAS-corrected solution

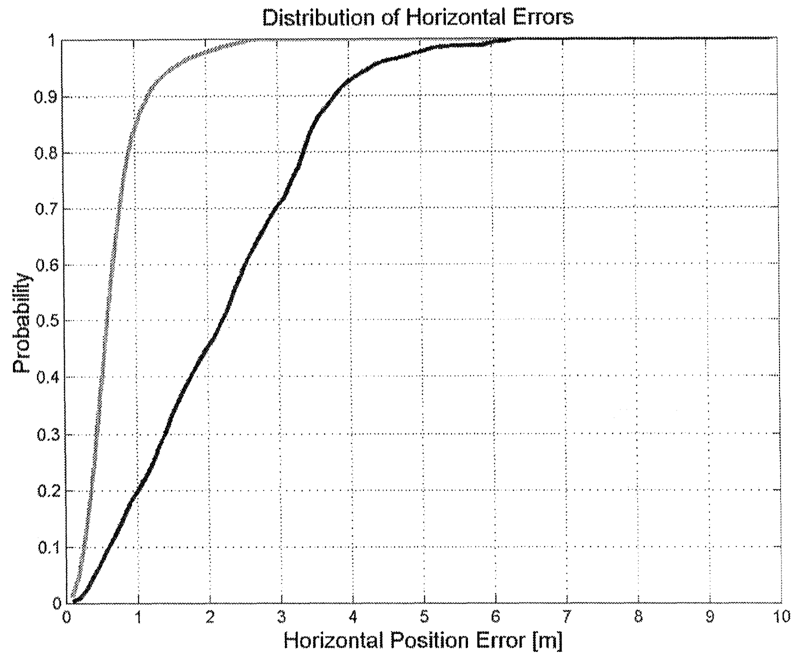


Figure 5.10: Horizontal error probability distribution functions

(Standalone-blue, WAAS corrected-green)

In Figures 5.6 and 5.7, the standalone solution shows significant difference in N-S and E-W directions. This phenomenon is recognizable on all standalone horizontal error plots throughout the report. GPS satellite geometry is responsible for the twice as large northing standard deviations as eastings. In the north direction on the northern hemisphere (e.g., Fredericton lat: 45° 57' N), since the inclination of the satellite orbits is 55 degrees, there are no satellites visible. On a skyplot (see Figure 5.11) generated in QuickPlot software (Trimble) the "hole" on the north side may explain why the standalone scatterogram is stretched in N-S direction.

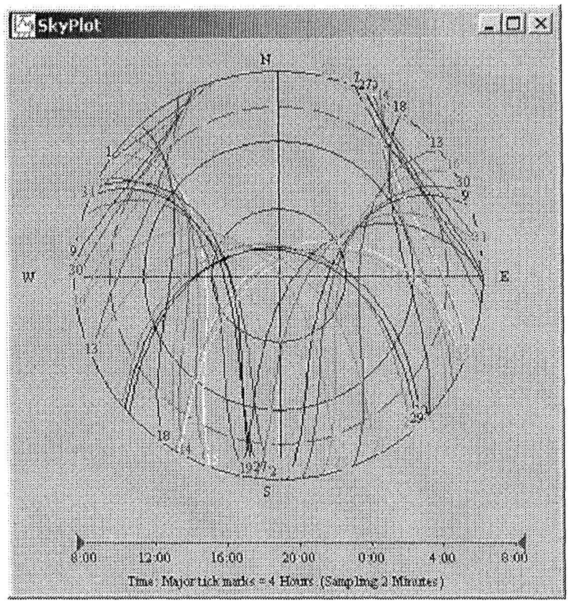


Figure 5.11: GPS satellite skyplot at Fredericton, Canada

As we go towards the equator (e.g., Kuala Lumpur lat: 3° 55' N) the hole will be smaller and smaller on the north side and another empty area appears by the South Pole (Figure 5.12). The scatterogram would be much more like a circle here. On the south (e.g., Sydney lat: 32° 56' S) basically the opposite happens as in Fredericton (Figure 5.13). The position plot would be N-S stretched there too.

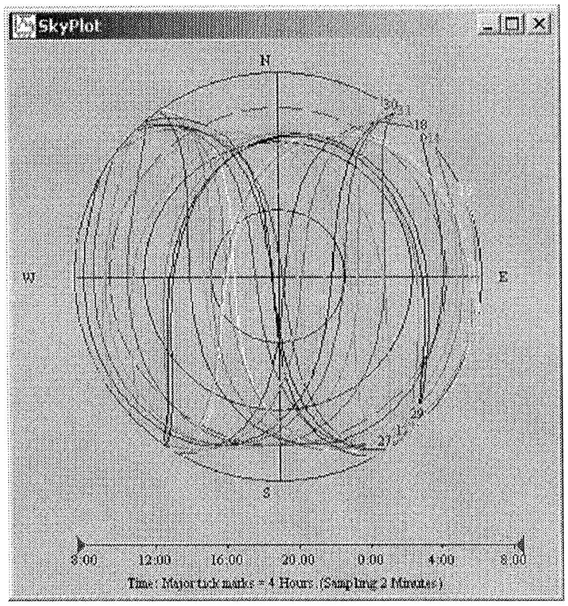


Figure 5.12: GPS satellite skyplot at Kuala Lumpur, Malaysia

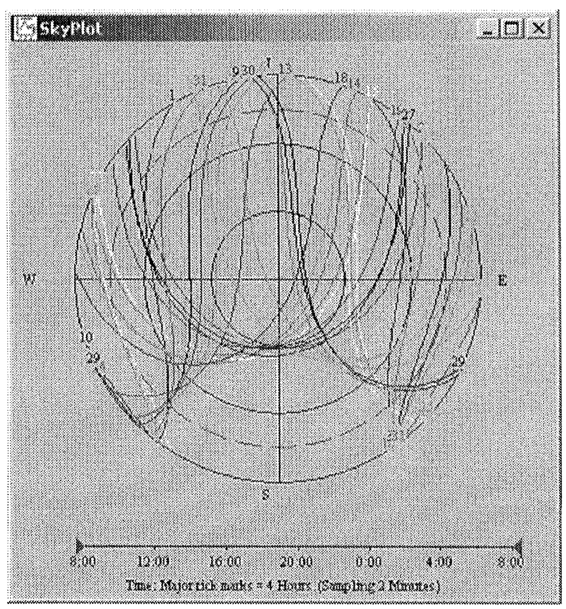


Figure 5.13: GPS satellite skyplot at Sydney, Australia

The effect of the "missing" satellites around the poles is similar to the phenomenon of bigger height errors in GPS positioning than horizontal. There are no satellites visible below the horizon. The horizontal position of the antenna is very well determined, on the other hand the vertical position is always less accurate because of the missing geometrical information from below (i.e. VDOP>HDOP).

5.2 European Geostationary Navigation Overlay System (EGNOS)

5.2.1 EGNOS Background

EGNOS, the European SBAS system is a joint program of the European Space Agency (ESA), the European Commission and Eurocontrol. In its final form it will be very similar to WAAS. Based on 34 reference stations scattered throughout Europe and other parts of the world (Figure 5.14), EGNOS will provide wide area differential corrections to the European user community.

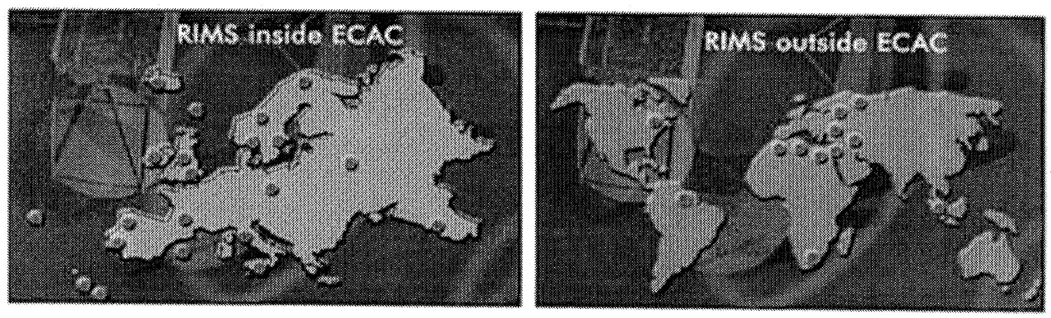


Figure 5.14: EGNOS reference station network

Four Master Control Stations will be implemented in EGNOS deployed in Italy, Spain, Great Britain and Germany. The correction feed will be uplinked from the seven Navigation Land Earth Stations. The space segment of EGNOS, as mentioned in the WAAS chapter, will consist of three geostaionary satellites: AOR-E, IOR and Artemis (Figure 5.15).

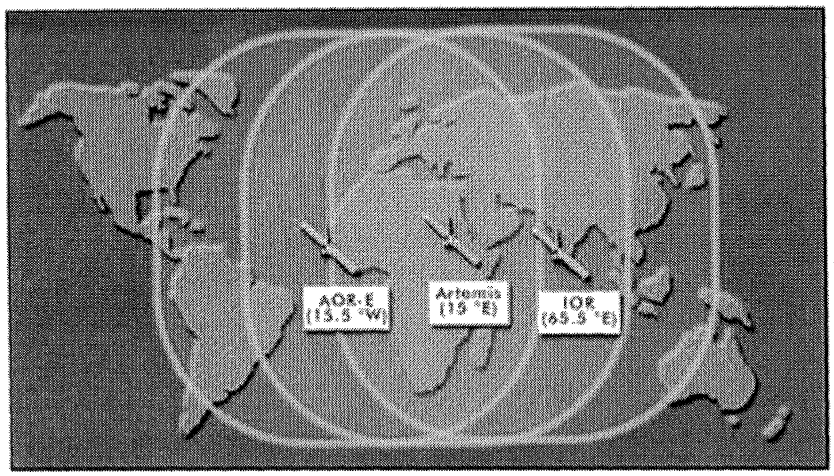


Figure 5.15: EGNOS space segment

The EGNOS implementation phase started in 1998; full operational readiness will be reached by 2003. The prototype version is already available since Feb. 2000. This pre-operational version is called the EGNOS System Test Bed (ESTB). The ESTB reference network is made up of 8 stations. At the moment, AOR-E is the only GEO that broadcasts ESTB messages. According to European test measurements, the achievable accuracy is better than 2.5 m horizontally and 4.5 m vertically 95% of the time. (Based on the EGNOS prototype Northern European Satellite Test Bed – NEST Bed – [Thales, 2001]) These results are close to the WAAS performance and will reach that level as the system develops. The footprint of AOR-E covers not only Europe but also Africa, the Middle East, South-America and the eastern parts of North America. This made it possible to test EGNOS (ESTB) in Canada.

Although the EGNOS message is available in parts of Canada, it is not complete: the ionospheric corrections are missing here. Now that S/A is gone, the ionosphere is probably the most significant source of positioning error. When using EGNOS outside the coverage area of the reference station network, the corrections do little to improve the accuracy, because there is no iono delay information available.

Ionospheric delay values are broadcast in the RTCA (Radio Technical Commission for Aeronautics) message type 26 (see Appendix III.1,3). Each line of the message refers to a grid point with the corresponding delay value. On Figure 5.16 red points represent ionospheric grid points for which AOR-E broadcasts corrections.

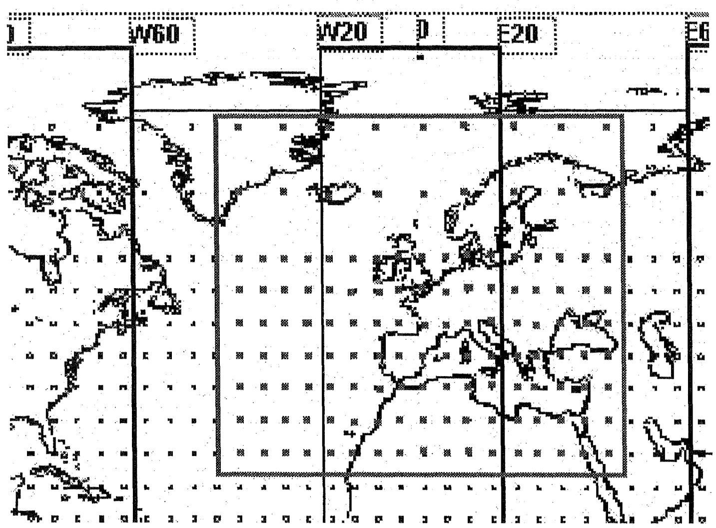


Figure 5.16: EGNOS ionospheric grid points

Canada is out of this range, therefore at UNB in Fredericton we received only ephemeris and clock corrections.

5.2.2 Test Measurements at UNB

WAAS and EGNOS-corrected positioning performance has been compared. The equipment used here was the same as in the WAAS test. One of the receivers used AOR-W (WAAS) signals, the other AOR-E (EGNOS) signals.

In the developmental phase, EGNOS does not broadcast messages all the time. When it is not operating, the RTCA message type 1 shows PRN 120 only, and all other message types do not contain information (see Appendix III.2).

ESA monitors EGNOS performance -ESTB Signal in Space status-, the results for every month are on their website [http://www.esa.int/EGNOS/pages/indexEST.htm].

At the time of the test measurement, in a 24-hour period on 1-2 August 2001, EGNOS was operating only for 5 hours 40 minutes. 0 degree elevation cut-off angle and 1 second data rate has been used. Results of EGNOS-corrected and WAAS-corrected positionings are shown on Tables 5.5 and 5.6 respectively.

	N error	E error	U error
Mean [m]	0.98	-0.05	0.19
Max (abs) [m]	23.97	14.11	65.45
2 std. dev. [m]	6.40	4.41	16.68
2 hor. std. dev. [m]	7.77		
2 r.m.s. [m]	6.69	4.42	16.68
2drms [m]	8.02		

Table 5.5: EGNOS-corrected position solution

	N error	E error	U error
Mean [m]	-0.21	-0.31	0.25
Max (abs) [m]	6.74	3.06	6.22
2 std. dev. [m]	1.48	1.09	1.69
2 hor. std. dev. [m]	1.84		
2 r.m.s. [m]	1.53	1.26	1.76
2drms [m]	1.98		

Table 5.6: WAAS-corrected position solution

The difference in WAAS results compared to Table 5.4 comes from the short observation period in this test. EGNOS results fulfil the expectations. The error in all components is huge due to the lack of iono corrections. Figure 5.17 shows the horizontal error scatterograms for the EGNOS test:

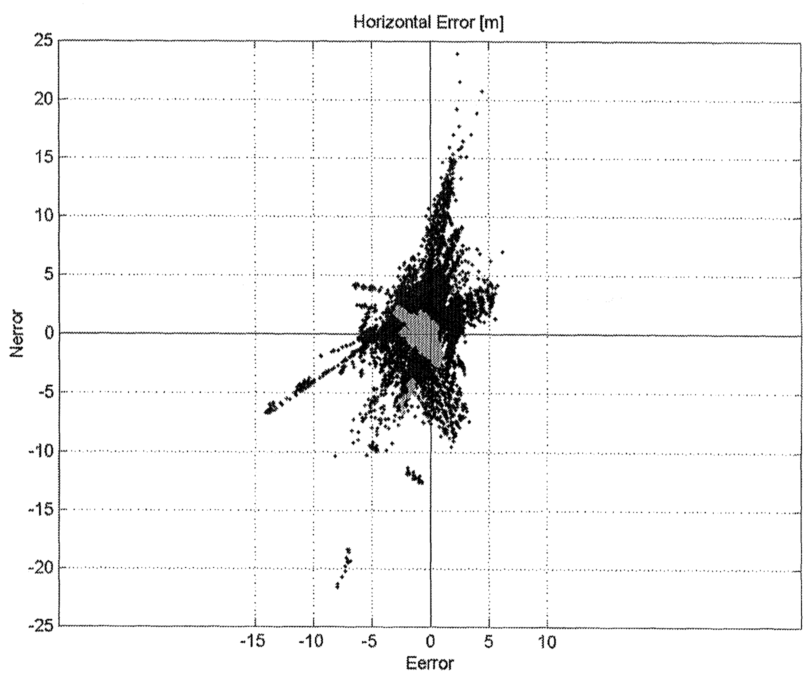


Figure 5.17: EGNOS- (blue) vs. WAAS-corrected (green) horizontal position errors

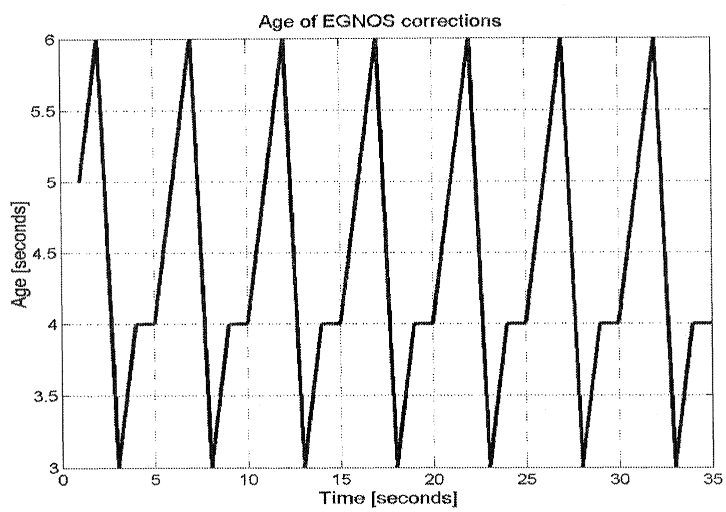


Figure 5.18: Age of EGNOS corrections

Maximum age of EGNOS corrections is 6 seconds, EGNOS correction delivery appears to be faster than that of WAAS (see Figure 5.18).

Further analysis of the dataset is not provided here, since these data do not reflect the real opportunities of EGNOS.

The only way to test if EGNOS orbit and clock corrections improve standalone GPS positioning accuracy would be to apply the standard ionospheric model (Klobuchar-model) replacing missing iono corrections. Unfortunately in the NavCom NCT-2000D when using WAAS corrections it is not possible to use the receiver's iono model.

5.3 Canada-wide Differential GPS (CDGPS)

5.3.1 CDGPS Background

Canada-wide Differential GPS (CDGPS) is a wide-area GPS correction delivery service that is currently under development (by the Canadian federal government and provincial government partners) and is scheduled to be operational by spring of 2002. CDGPS corrections will enable all Canadians (and beyond) to derive better (i.e. sub-metre to 3 metres at 95% confidence level) GPS-based positions than the autonomous GPS positions (i.e. up to 20 metres). CDGPS will deliver GPS·C RTCA corrections via a geostationary communications satellite MSAT broadcasting to all of Canada and territorial waters free of charge. A limited number of user "receivers" and a published broadcast specification are being developed. Future plans include the potential of accessing the corrections via the Internet. This service is not intended to serve commercial aviation as served by the Wide Area Augmentation System, nor is it intended to be guaranteed at levels deemed mission critical for public safety (i.e. no fault-tolerant architecture employed) [CDGPS, 2001].

GPS·C corrections are generated through a network of real-time GPS tracking stations (part of the Canadian Active Control System – CACS –) across Canada connected by high-speed communication links to computing facilities in Ottawa (see Figure 5.19). This infrastructure is developed, maintained and operated by Geodetic Survey Division (GSD), Natural Resources Canada.

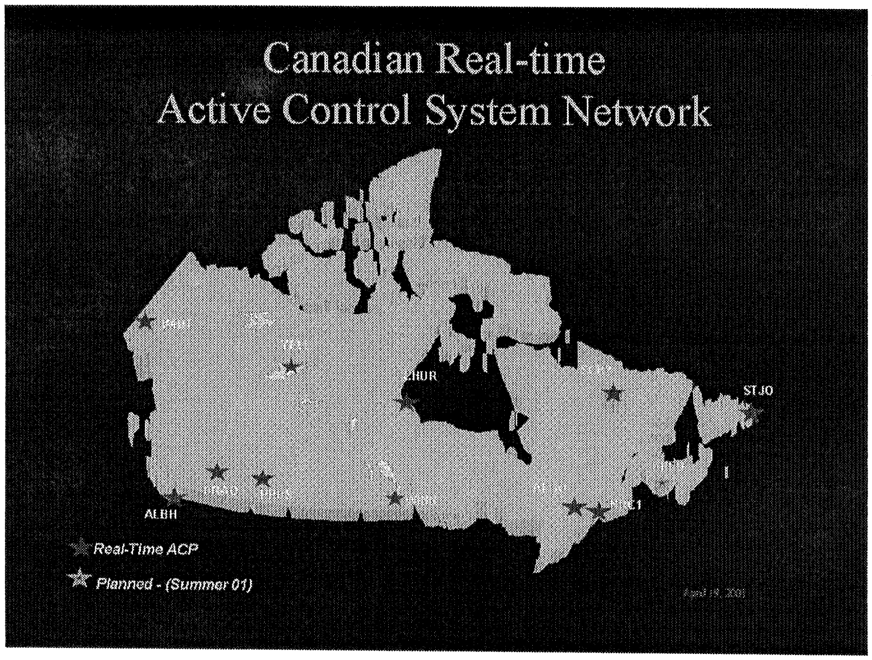


Figure 5.19: CDGPS reference stations

The Canadian Active Control System is made up of 14 reference stations (Real-Time Active Control Points or RTACPs):

Whitehorse, Yukon (WHIT)
Victoria, British Columbia (ALBH)
Penticton, British Columbia (DRAO)
Yellowknife, NWT (YELL)
Priddis, Alberta (PRDS)
Churchill, Manitoba (CHUR)
Winnipeg, Manitoba (WINN)
Algonquin Park, Ontario (ALGO)
National Research Council, Ontario (NRC1)
National Research Council, Ontario (NRC2)
Geodetic Survey Division 1, Ontario (GSD1)
Schefferville, Québec (SCH2)
St. John's, Newfoundland (STJO)
Washington, D.C., USA (partly operational)

Table 5.7: CDGPS Reference Stations in Canada

Later this year a new station will be deployed in Fredericton, New Brunswick to be able to provide more reliable service for Maritime Canada. A number of other RTACPs are also planned to put in southern USA.

At these stations continuous pseudorange and carrier phase measurements are recorded by high precision dual-frequency GPS receivers (TurboRogue) for all satellites in view. Meteorological data (temperature, pressure and humidity) are also collected at selected sites. The reference stations are equipped with atomic frequency standards (atomic clocks). The collected 1 Hz data is sent from each site to the Real-Time Master Active Control Station (RTMACS) in Ottawa. The master station is synchronized to GPS time and waits a certain amount of time to insure that a high percentage of the station data is received. The collected data is then verified and processed using predicted GPS orbits to generate broadcast orbit and satellite clock corrections and an ionospheric vertical delay grid. These corrections are then available to Virtual Active Control Points (VACP) and Integrity Monitoring Stations (IMS) within the wide area network via TCP/IP multicast service [CDGPS, 2001].

Data transfer is a crucial part of a DGPS network. To be sure that the same data is being received at the Master Station that was sent from the Control Points, CDGPS uses a Frame Relay Network for communication. Frame Relay by definition is a protocol oriented, packet-switched technology offered by telephone companies. "Packet switched" means that transmitted data are grouped in frames or packets, which have unique identification like an Internet address destination [Cutright and Girrard, 1994].

CDGPS differential corrections will be broadcast primarily via a communications satellite. The correction data stream arriving from the RTMACS is converted to L-Band satellite. The correction data stream arriving from the RTMACS is converted to L-Band signal at the TMI uplink facilities (TMI Hub) for transmission to MSAT-1, a Canadian geostationary satellite that orbits 36,000 kilometres above the Earth's surface.

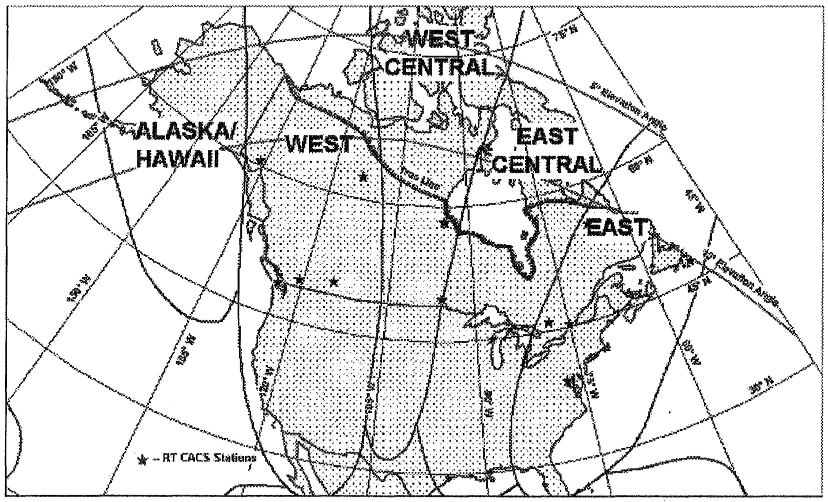


Figure 5.20: MSAT-1 coverage area

Figure 5.20 shows the footprint of MSAT-1 that covers Canada, USA, Caribbean and parts of Mexico. Users must be within line of sight to the satellite in order to obtain the GPS·C correction feed. There are few situations in which one may not be able to receive the signal. North-facing mountain slopes will likely be obstructed from MSAT-1. Receivers that operate under heavy tree canopy will also experience some degradation of reception to the signal. Finally, urban users may find obstruction from tall buildings. These obstructions altogether hinder obtaining corrections in 2-5% of Canada.

- In order to mitigate these effects a special coverage radio re-broadcast capability is incorporated into the design of CDGPS. The system will allow for local re-transmit (e.g., via VHF/UHF) capability in difficult terrain.

heavy forests. MSAT-1 power is optimized to have a very similar coverage to GPS. It is not beneficial to have better coverage of corrections than standard service, but it is essential to provide corrections everywhere, where GPS is available.

- In urban canyons cellular connection can be a solution for users willing to pay for a high performance service.

In British Columbia (western province of Canada) the provincial government together with a number of federal agencies, local governments, crown corporations and industry already started a real-time DGPS service in January 1998. Global Surveyor DGPS system is considered to be the test bed of CDGPS in a sense that it uses the same communication satellite and broadcast solution as CDGPS will. The system is based on two permanent GPS base stations. These are deployed at British Columbia Active Control System (BCACS) points, in Terrace and Williams Lake (Figure 5.21).

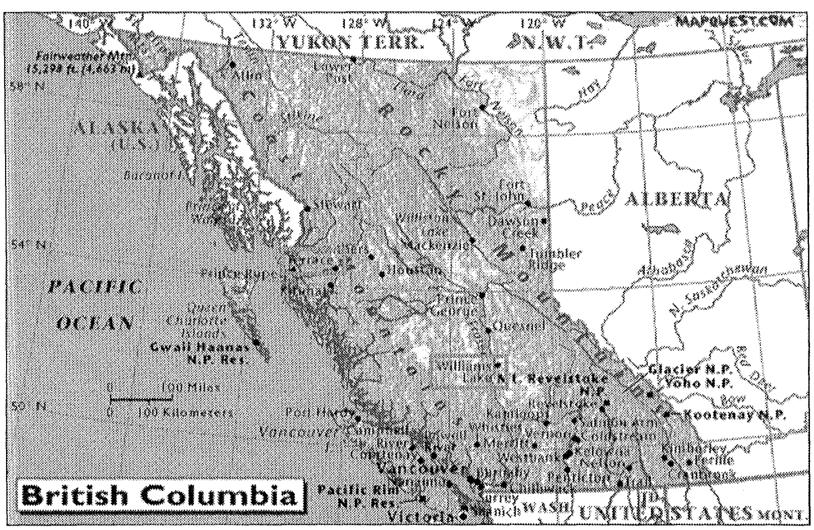


Figure 5.21: DGPS reference stations in British Columbia [http://www.mapquest.com]

Corrections computed at these control points are transmitted continuously to the MSAT control centre in RTCM format. The MSAT-1 broadcasts them using MSAT's western beam (Figure 5.20) which covers British Columbia, Alberta, Yukon and the Northwest Territories. Global Surveyor receivers pick up the DGPS data and feed it into the user's GPS receiver. This whole procedure is completed within 2-5 seconds.

It is the user's choice which base station's data will be applied. Since Global Surveyor does not provide network based wide area corrections, it is rather a conventional DGPS system using WADGPS communications technique, facing all the problems of single-station DGPS (spatial decorrelation of errors)[BCACS, 2001].

Besides communications satellite transmission, in the future the GPS·C correction feed or its localized version (i.e., RTCM corrections) will be available via the Internet. The use of the Internet as a way of transmitting corrections will be beneficial for value-added resellers. Forwarding companies could use this service in fleet tracking systems. Corrections will be available for users of WAP-enabled devices (e.g., cellular phones, radio transceivers). The appearance of GPRS (General Packet Radio Service) in mobile telecommunications provides even more opportunities for value-added cellular phone services (e.g., DGPS). Internet based corrections also provide a comfortable way to monitor and test GPS·C performance.

5.3.2 Test Measurements at UNB

As a pilot project, at UNB we were investigating this alternative data link before it may appear on the market as a commercial service. Access to the live GPS·C data stream is provided by the Geodetic Survey Division through a Virtual Private Network (VPN) over the Internet. VPN is a private network built atop a public network (i.e. Internet). Information flow within the VPN is encrypted. Hosts from outside the private network are excluded even if they are on the public network. The advantages of VPN are the higher security compared to the public network and lower costs compared to direct dial-up networking.

The Master Station computes corrections in RTCA-type format in 1 Hz data rate but broadcasts only every even seconds. In the after-S/A era, the loss of every odd second correction has no recognizable effect on the accuracy. The ancillary messages i.e. ionospheric grid values and mask, orbit and slow clocks, etc. are broadcast every 300 seconds. In Ottawa, a GSD computer receives the broadcast message and creates a 750 bps RTCA-like stream that arrives at UNB, via VPN. GSD supplied a PC to UNB, operating under the Linux OS, configured to access the private network, accept the GPS·C feed, localize the corrections to Fredericton and output a 9600 bps RTCM data stream to the serial port – becoming, in essence, a virtual reference station (see Figure 5.22).

The question again: how accurate is WADGPS-corrected GPS positioning? Since the GPS·C test is a pilot project of GSD and UNB, it is not easy to fully answer this question.

Working with the developmental phase GPS·C correction feed means a long-term investigation of all sorts of problems connected to the new wide area DGPS system and the alternative data transmission link. The real goal therefore was to carefully check the several software and hardware components involved and fix the preliminary problems. Accuracy tests were useful to monitor changes made on the system.

A networked reference station DGPS solution works well for users who are inside the network. The performance is worse at peripheral locations and degrades quickly moving away from the coverage area. Fredericton is located in Eastern Canada close to the Atlantic Ocean (Figure 5.19). Being on the periphery of the network, Fredericton results currently will not be as good as elsewhere in Canada. There are three base stations in the vicinity of Fredericton. Schefferville to the northwest, St. John's to the northeast and Ottawa to the southwest, but there is no station to the southeast (see Figure 5.19). Therefore corrections for SVs on the southeastern sky over the Atlantic are missing. There is a definite need for a new reference station to resolve this outage. The Washington, D.C. reference station's data are not yet fully involved in the computations because there are no ionospheric measurements provided from this station. That is the reason for having a lot of empty cells southeast of Fredericton in the iono grid. Once the Washington site is used, the grid should be more complete.

Furthermore the system is configured that corrections are provided only if the SV is visible from at least two sites. Much better results are expected throughout the Maritimes when the new Fredericton station will be operational sometime this fall.

Internet based service delivery is another source of possible difficulties. Although the connection between Ottawa and Fredericton is stable, there are network outages from time-to-time. The reaction of the correction generator software is vital in this aspect.

Originally the software shut down after ten seconds of missing transmission and needed manual restart. We found that the 10-second standby time was not enough so this period was raised first to 100 seconds and later to 10 minutes. Even with this 10-minute "keep alive" time, checking the connection every minute, there were times when the localizer finally shut down after 10 minutes. The final solution for this problem was to set up a "watch dog" that periodically tests the connection and restarts the application automatically if the network is back.

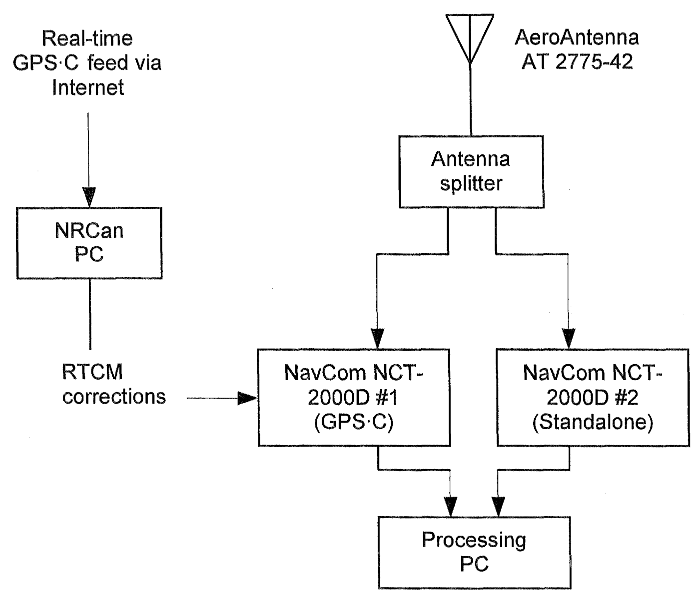


Figure 5.22: GPS·C test at UNB

Data were collected repeatedly from late June to be able to monitor all the changes to system algorithms and software. The test measurement described here was carried out on 13-14 August 2001. Figure 5.22 shows the system architecture used. Both GPS receivers were working in single frequency mode, the RTCM corrections were directly fed into one of the NCT-2000Ds. 24 hours of data were collected with 1-second data interval, using

10-degree elevation mask. GGA and GSV NMEA messages were logged, which provide position solution information and DOP values. GPS·C corrections significantly improved standalone positioning accuracy (see Tables 5.8 and 5.9). The bias between the mean position and the known coordinates became smaller. The corrected north mean value is still offset with more than half a metre that should be reduced. The more than 3 metres improvement in 2 times standard deviations results in horizontal accuracy close to the 2-metre level. The height error has been reduced by 5 metres.

	N error	E error	U error
Mean [m]	-0.70	-0.58	-0.97
Max (abs) [m]	8.15	5.23	12.96
2 std. dev. [m]	4.44	3.30	8.09
2 hor. std. dev. [m]	5.53		
2 r.m.s. [m]	4.65	3.50	8.32
2drms [m]	5.82		

Table 5.8: Standalone position solution

	N error	E error	U error
Mean [m]	-0.66	-0.07	-0.66
Max (abs) [m]	5.03	1.83	10.90
2 std. dev. [m]	1.76	0.94	3.14
2 hor. std. dev. [m]	1.99		
2 r.m.s. [m]	2.20	0.95	3.40
2drms [m]	2.39		

Table 5.9: GPS·C-corrected position solution

One of the major problems of the current CDGPS is that it delivers corrections for fewer satellites than the receiver views. GSD transmits only full corrections; they do not provide ephemeris and clock corrections for a satellite if the iono corrections are not available. After the Washington, D.C. station starts to provide iono data and therefore there will be no missing grid cells, the service will be a whole lot better. If the NavCom receiver is set to work in DGPS mode it will use only those satellites which are supplied with differential corrections.

To temporarily fix this problem, GSD altered their algorithm to provide iono corrections and therefore a complete correction set with only 1 grid point correction (vertical delay at Fredericton assumed to be the same as at the grid point). The drawback of altering the code in this way is the worse accuracy compared to the optimal situation.After resolving a number of other software problems and raising the cutoff angle from 0 to 10 degrees the number of SVs (Figure 5.23, fourth plot) became the same in both standalone and corrected cases for the whole observation time. So, of course, did the DOP values. The error plots of developmental phase GPS·C are very similar to the fully operational WAAS. The jump in position errors around 41.5 hrs is not caused by the correction age outlier that we can see roughly at the same time on plot 7.

A 35-second segment of correction age data is shown on Figure 5.24 starting at 55 hrs. Most of the time the maximum correction age is 5.2 seconds. The whole data set is not constant, but none of the spikes have a significant effect on the positioning accuracy.

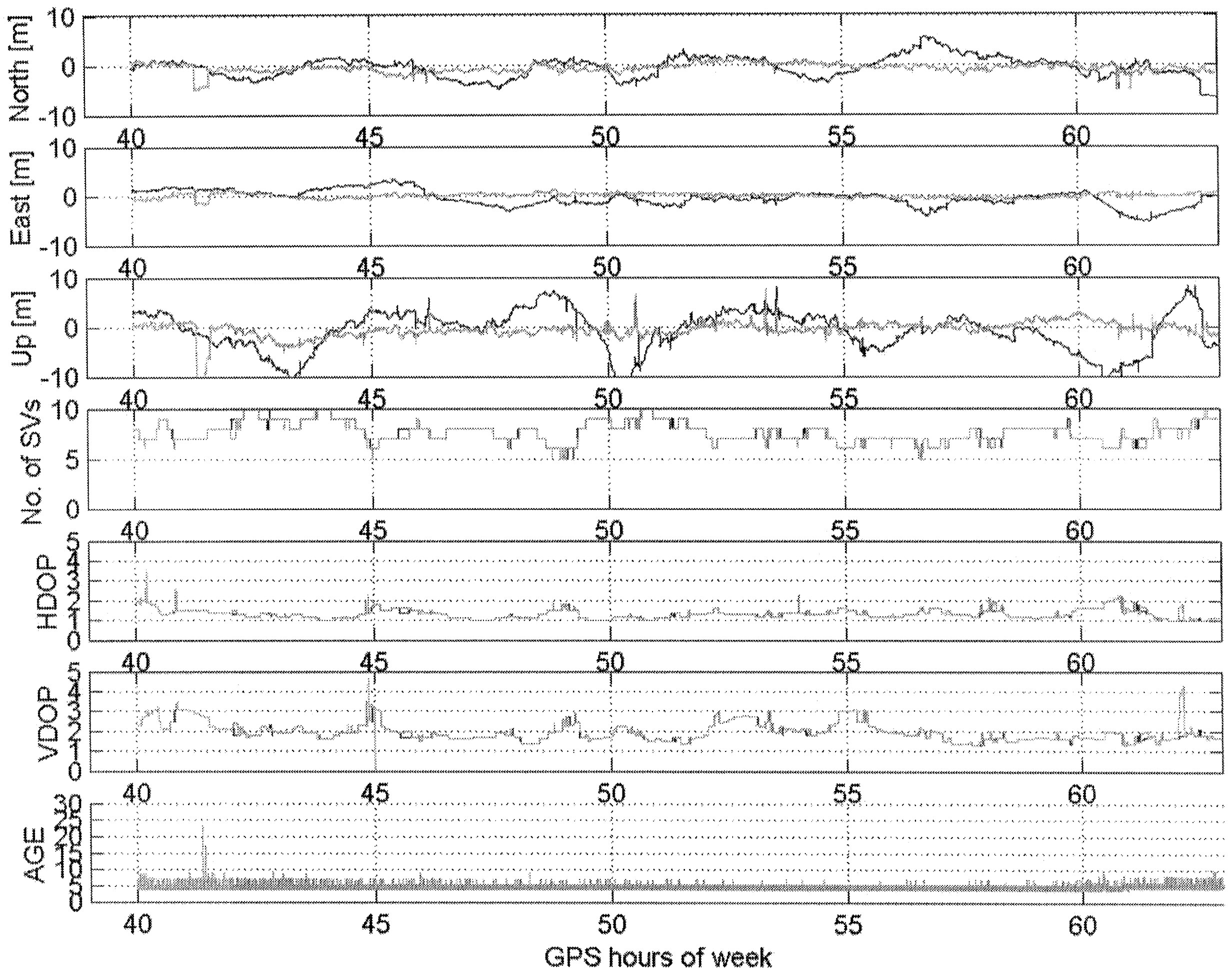


Figure 5.23: Standalone GPS (blue) vs. GPS·C-corrected (green) solution comparison

Corrected and uncorrected position fixes are plotted on Figures 5.25 and 5.26 (3D). Accumulation of corrected fixes around zero is clear. Histograms (see Figures 5.25 and 5.26) show the standard deviation reduction effect of GPS·C. When fully operational, CDGPS will be a potentially superior to WAAS.

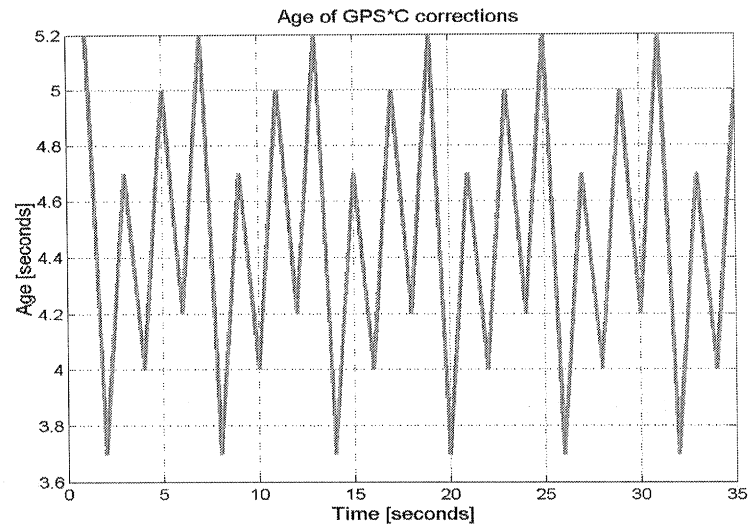


Figure 5.24: Age of GPS·C correction

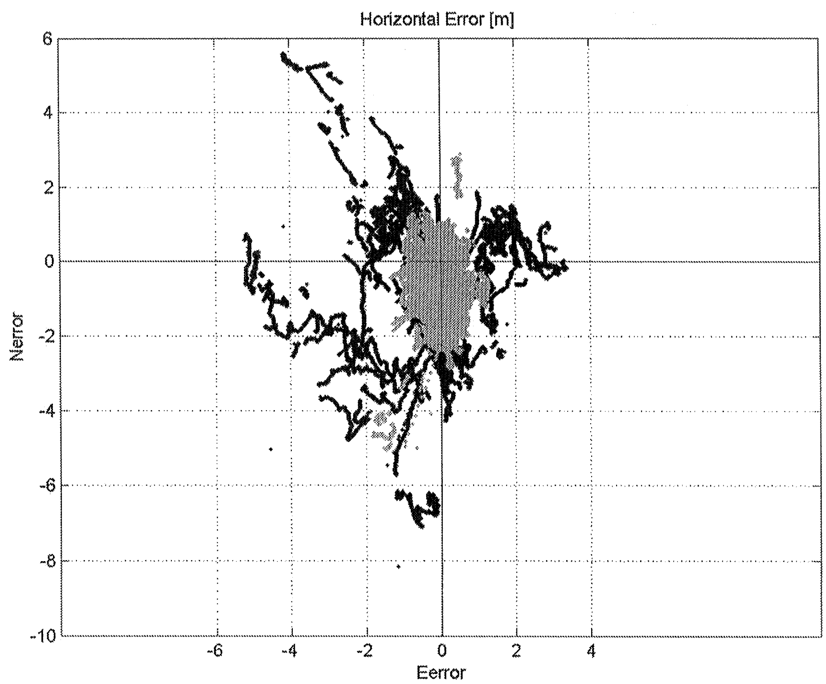


Figure 5.25: GPS·C-corrected (green) vs. Standalone (blue) position solution

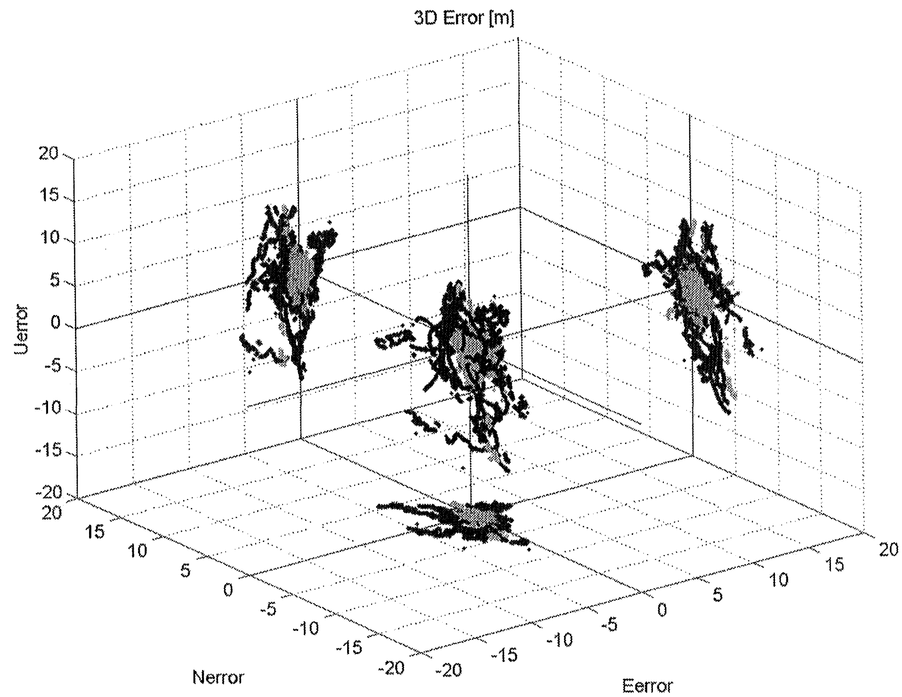


Figure 5.26: Standalone GPS (blue) vs. GPS·C -corrected (green) 3D position errors

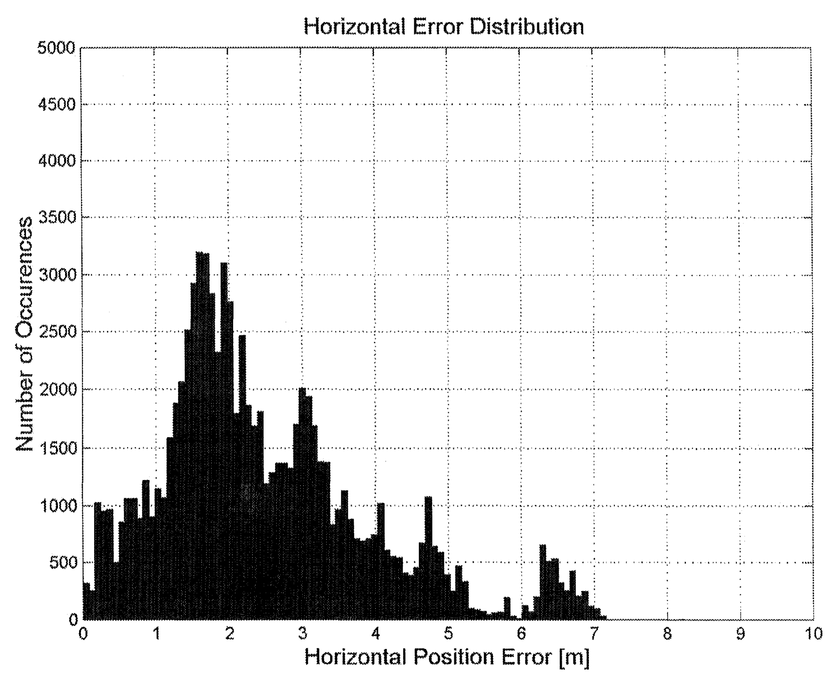


Figure 5.27: Horizontal error distribution of the standalone solution

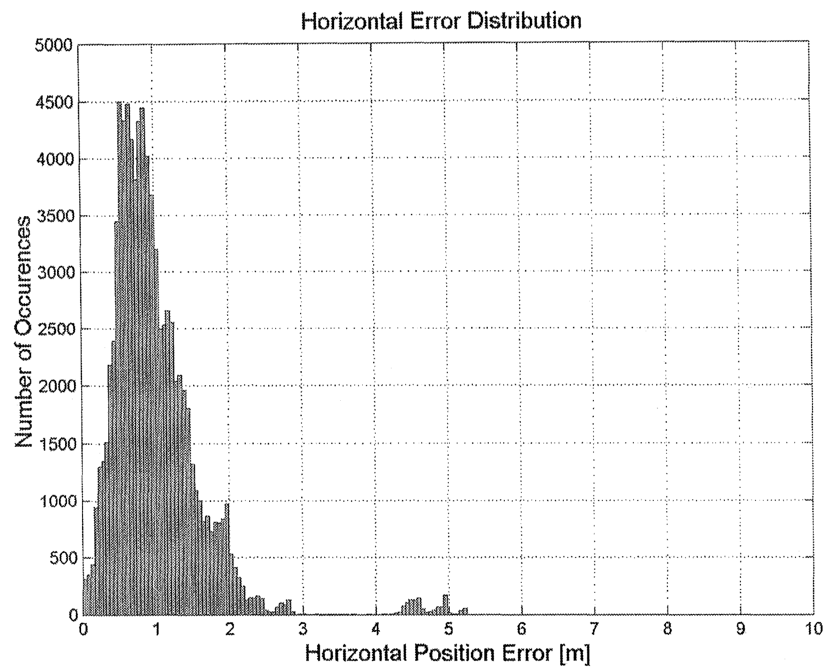


Figure 5.28: Horizontal error distribution of the GPS·C-corrected solution

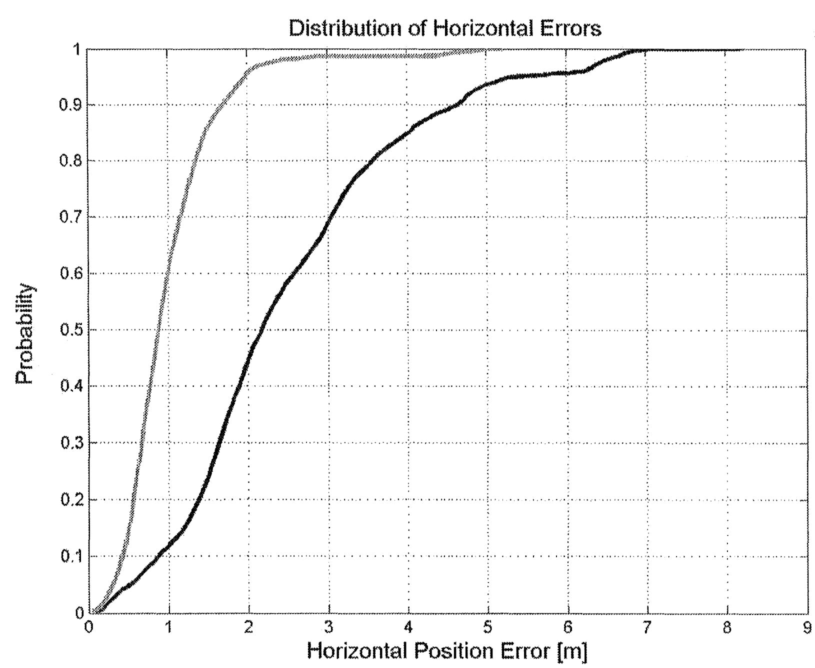


Figure 5.29: Horizontal error probability distribution functions

(Standalone-blue, GPS·C-corrected-green)

5.4 Other Operational Wide Area DGPS Systems

The objective of this chapter is to review other WADGPS systems operational worldwide to provide information on their performance, advantages and disadvantages. The list is not at all complete – there are a lot of systems not mentioned here. The provided information is mainly based on limited system descriptions available on the Internet.

5.4.1 OmniSTAR

Based on http://www.omnistar.com

OmniSTAR, developed and maintained by the Fugro Group of Companies, is a worldwide system providing WADGPS services. The system has proven positioning results accurate to the metre level in different locations over maximum baseline distances of 1000 kilometres [Abousalem, 1996].

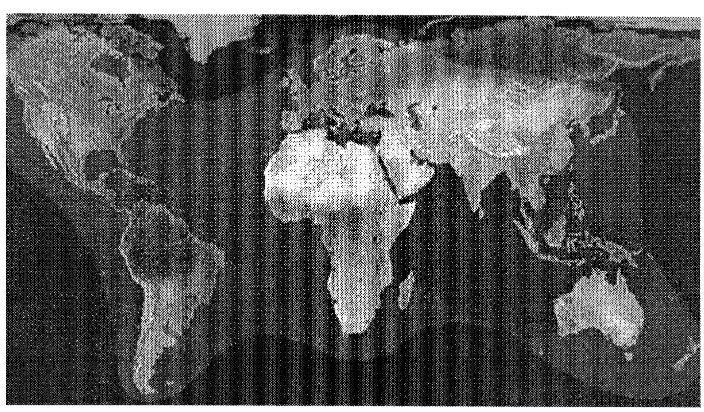


Figure 5.30: OmniSTAR worldwide coverage

The system consists of 86 ground Reference Stations around the world, 3 Network Control Centres (Master Stations) located in the USA, Europe and Australia. OmniSTAR currently uses six geostationary L-band satellites; they provide coverage for most of the world's land areas (Figure 5.30).

The system utilizes a measurement domain WADGPS algorithm. The Reference Stations track all GPS satellites above five degrees elevation angle and compute differential corrections every 600 millisecond in RTCM SC-104 V2 format. The data are sent to the Network Control Centres (NCCs) via leased wire lines. At the NCCs, the messages are checked, compressed, and formed into packets for transmission up to the OmniSTAR satellite transponders. This occurs approximately every 2 to 3 seconds. A packet will contain the latest corrections from each base station. The received data decoded and uncompressed by the user equipment will be the exact replica of the data as it was generated at the reference stations. These multiple data sets contain atmospheric corrections too as atmospheric errors are part of the total range error. The user set uses ionospheric and tropospheric models to compute and remove most of the atmospheric corrections from each Reference Station message, and generate a correction for its own location. Therefore it is essential to have a coarse approximation of the user's location. This information is provided by the inbuilt or external GPS receiver. After the OmniSTAR processor has taken care of the atmospheric corrections, it uses its location - versus the Reference Station locations, in an inverse distance-weighted least-squares solution. The output of that least-squares calculation is an RTCM-104 correction message that is optimized for the user's location. Thus there is no need for VACP network, the

Virtual Reference Station solution is computed at the user site, each OMNISTAR unit represents a mobile VACP station.

Summary of features:

Horizontal Accuracy (95%)	< 1 m
Frequency	L-band
Price Service (per year)/Receiver (CAD)	$1200/$7000
Message Protocol	RTCM SC-104 V2
Update rate	< 5 seconds

5.4.2 SkyFix

Based on http://www.thales-geosolutions.com/skyfix/

Thales Geosolutions (earlier RACAL) introduced the SkyFix DGPS system in 1990. SkyFix today broadcasts differential corrections worldwide. The ground network consists of more than 80 permanent Reference Stations and 2 Network Control Centres tied into the ITRF92 coordinate reference frame. Coordinate positions of Reference Station antennas are determined to an accuracy of better than 5 cm in each coordinate axis. The Reference Stations were originally equipped with 9-channel single frequency Trimble 4000 GPS receivers. All stations can be remotely controlled from the network centres. Corrections are generated at every station in RTCM SC-04 V2 format. The data is transmitted to the NCCs via a variety of links, which include leased lines, X·25 packet networks and VSAT systems. The two control centres in Singapore and Scotland perform system quality control and monitoring functions. Correction data is broadcast via two different types of satellite datalinks. The SkyFix system uses the low-power Inmarsat geostationary satellites, namely the AOR-W, AOR-E, IOR and POR, whereas SkyFix Spot system uses regional, high power spot beams on L-band communications satellites (see Figure 5.31). These regional services can be found in Australia & New Zealand, Europe, North America, Africa, The Middle East & CIS and in South America.

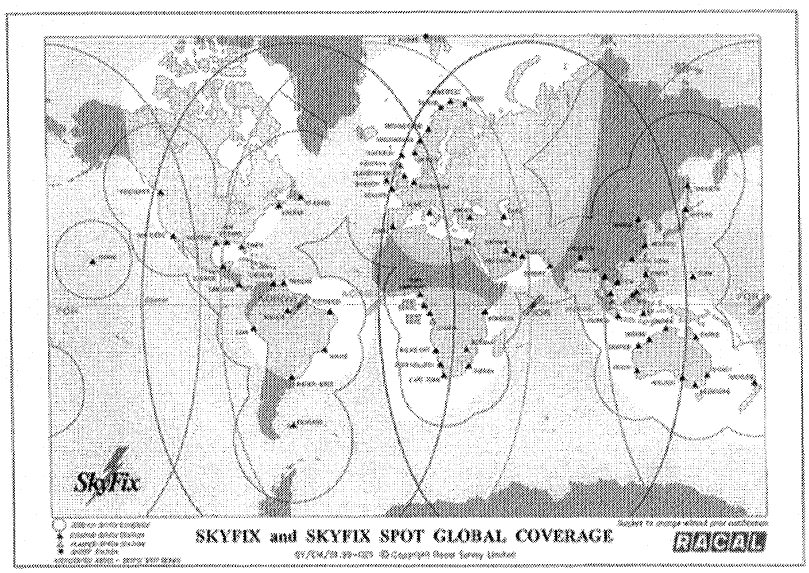


Figure 5.31: SkyFix and SkyFix Spot coverage

SkyFix, like other measurement domain WADGPS systems applies atmospheric models to remove Reference Station iono and tropo correction-components and replace them with local values. Measurement domain systems normally use the standard Klobuchar ionospheric correction model from the GPS broadcast messages. In 2001, around the 11-year Solar cycle peak, sunspot activity is greatly increased from that at sunspot minimum. In these conditions the Klobuchar model no longer sufficiently reflects the true ionospheric disturbances. SkyFix therefore introduced SkyFix Premier a totally reformed service. It offers improved performance by using dual-frequency DGPS systems at both the Reference Station and the user end. In the year 2000, 42 SkyFix Reference Stations in Africa, South America, Far East, Australia, Middle East and Europe have been upgraded with dual-frequency GPS receivers. The dual-frequency data is transmitted to the control centres where real-time Ionospheric Range Corrections (IRCs) are being generated. IRCs are broadcast as RTCM Type 55 messages. Local ionospheric range delays are calculated using the raw dual-frequency data from the user's receiver. RTCM corrections, including the SkyFix Premier Type 55 messages, are received from an Inmarsat or Spot satellite DGPS link. The local and Reference Stations' ionospheric range delay values are combined to eliminate the ionospheric differential delay errors for all satellites that are common in view. This allows for an iono-free DGPS solution to be derived. Due to dual-frequency receiver requirement on the user side, this solution is more expensive.

Summary of features (SkyFix Premier):

Horizontal Accuracy (95%)	< 2 m
Frequency	L-band
Price Service/Receiver (CAD)	?
Message Protocol	RTCM SC-104 V2
Update Rate	< 5 seconds

5.4.3 StarFire

Based on http://www.navcomtech.com/images/tech_archiv/StarFire%20System.pdf

NavCom Technology Inc., a wholly owned subsidiary of John Deere & Co., together with the Precision Farming Group of John Deere, have designed and implemented StarFire, a Wide Area Differential GPS system. The system, similarly to SkyFix Premier, is designed for dual-frequency operation. StarFire is based on a global network of Reference Stations equipped with NavCom NCT-2000D high-quality, dual-frequency GPS receivers. Location of the Reference Station antennas is determined to an accuracy of ±2 cm from network solutions based on the IGS worldwide control stations. Reference Stations send their 1 Hz raw measurements to the master stations where a WADGPS algorithm – Wide Area Correction Transform (WCT) – generates a single set of corrections. The data are then sent to the Land Earth Stations where they are uplinked to L-band Inmarsat geostationary satellites, which broadcast corrections throughout their wide service area.

Besides the reference receiver (and a redundant one of the same type as a backup) there is a production StarFire user equipment unit at every station, which serves as an independent monitor receiver. The monitor receivers apply the broadcast corrections and send their position solution results to the master stations. This multiple set of data is continuously monitored by an Alert Service processor to be aware of any service failures.

Both raw data and position solutions of the monitor receivers are transmitted to the Master Stations via frame relay private virtual circuits (backed up with ISDN dial up lines).

The WCT algorithm uses dual-frequency measurements to form smoothed iono-free pseudoranges. As a result of an extended dual frequency code-carrier smoothing, most of the multipath errors in the code pseudorange measurements are eliminated too. These multiple-PRCs are normalized to a single Reference Station clock (chosen as reference clock). The normalized sets of pseudoranges for each satellite are combined in a weighted average to form a single correction for that satellite. Range rate corrections are generated by differencing carrier phase measurements.

The rover receivers apply the same technique to remove the ionospheric effect and most of the multipath error.

The basic advantage of broadcasting only one set of corrections instead of multiple sets from each reference station is the narrowed bandwidth requirement on the GEO satellites. The price of leased satellite channels is proportional to the bandwidth used, so finally this means lower service costs for the user. Another great advantage of applying the WADGPS algorithm in the master station and not in the user equipment is flexibility. If upgrades are needed, the algorithm has to be changed only at the Master Station and not in every single rover receiver.

Summary of features:

Horizontal Accuracy (95%)	< 0.6 m
Frequency	L-band
Price Service (per year)/Receiver (CAD)	$1200/$10,000
Message Protocol	RTCM SC-104 V2
Update rate	< 5 seconds

5.4.4 IGDG

Based on http://gipsy.jpl.nasa.gov/igdg/system/index.html

Internet-based Global Differential GPS (IGDG) was developed by NASA's Jet Propulsion Laboratory (JPL). This service requires dual-frequency receivers at both the reference sites and at the user site and reportedly provides the highest achievable accuracy on the WADGPS market today (based on results issued by JPL). A dual-frequency system does not need ionospheric delay information transmitted, hence it requires fewer reference sites and offers higher accuracy compared to regular single-frequency systems. IGDG applies a state space domain algorithm that estimates the DGPS error components individually. After eliminating the ionospheric errors by using dual-frequency receivers there are three factors left to model: ephemeris errors, clock errors and the tropospheric effect.

JPL uses the Global Differential GPS (GDGPS) Reference Station network to acquire accurate ephemeris and clock corrections. IGDG also takes advantage of NASA's Global GPS Network (GGN). The two networks together consist of more than 70 stations around the world. 1 Hz raw measurement data are sent from these points to the Network Centre via the open Internet. IGDG's real-time orbit determination module, Real Time GIPSY (RTG) computes here precise GPS orbits and clocks parametres. Orbit and troposphere estimates are computed once per minute, clock estimates every second. These in the form of corrections to the broadcast ephemerides and broadcast clocks are transmitted to the users. The global differential corrections produced by RTG are packaged into a 560-bit/sec message, and are available on the open Internet via a TCP server running at JPL.

Due to the low bandwidth requirement of the correction message it can be easily broadcast over most communications channels, such as cellular telephony, radio modems, and geostationary relay satellites.

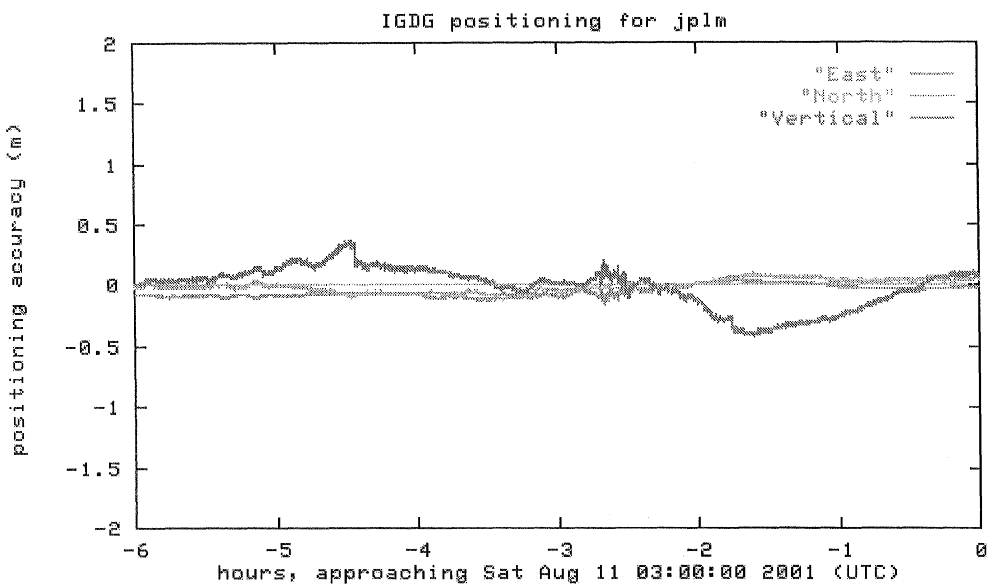


Figure 5.32: IGDG real-time positioning demonstration at JPL Mesa facility [http://gipsy.jpl.nasa.gov/igdg/demo/index.html]

Figure 5.32 shows a 6 hour session of IDGD-based real-time positioning at JPL Mesa facility, where zero is the surveyed position of the GPS antenna.

The 2 r.m.s. error values for the same period of time at this and 3 other stations are:

	N error [m]	E error [m]	U error [m]
JPL Mesa	0.10	0.12	0.34
Goldstone, California	0.26	0.16	0.54
Madrid, Spain	0.36	0.28	0.58
Tidbinbilla, Australia	0.16	0.10	0.14
Mean	**0.22**	**0.16**	**0.40**

Table 5.10: IGDG position solution [http://gipsy... ...igdg/all_demos/index.html]

The average of the 4 stations' results indicates the achievable IGDG accuracy, which, compared to other systems (e.g. WAAS) is superior. (These results show only 6 hours of data at sites selected by JPL, not providing information about multipath conditions.)

Summary of features:

Horizontal Accuracy (95%)	< 0.3 m
(Frequency)	Internet-based transmission
Price Service/Receiver (CAD)	?
Message Protocol	?
Update Rate	?

5.4.5 StarFire - IGDG

Based on http://www.navcomtech.com/press/010416.htm

In 16 April 2001 NavCom and JPL signed a contract on future collaboration. This means the union of JPL's IGDG software package and NavCom's StarFire network. The combination of the two state-of-the-art technologies will result in highly accurate real-time measurements globally. In the future NavCom will process data from NASA's worldwide network of reference sites along with data from NavCom's global network using IDGD.

CHAPTER 6

CARRIER PHASE DGPS AND PRECISE POINT POSITIONING

6.1 Carrier Phase DGPS

The RTCM SC-104 standard format for differential pseudorange corrections took hold fairly quickly and is currently in wide use. Users of Real-Time Kinematic (RTK) carrier phase positioning systems also have recognized the usefulness of such systems. Therefore new message types have been implemented in the RTCM standard (Version 2.1) in 1994. The new message pairs were message 18/19, which contain raw carrier phase and pseudorange measurement information, and message 20/21, which contain carrier phase and pseudorange corrections. The message types 18 and 19 pair is intended for use in double-differencing algorithms, whereas the 20 and 21 pair is meant for processing undifferenced data [Langley, 1998].

Carrier phase corrections (CFCs) as defined by Graczka [1999] are:

$$CFC_i = \Phi_i^{'} - FRAC(\frac{\rho_i}{N \cdot \lambda}) \tag{6.1}$$

where

$$N = INT(\frac{\rho_i}{\lambda}) \tag{6.2}$$

Φ_i' is the raw phase measurement at the base station,

N is the resolved ambiguity at the base station,

ρ is the corrected range at the base station,

λ is the wavelength.

The corrected phase at the rover station is:

$$\Phi_i = \Phi_i' + CFC_i \tag{6.3}$$

The rate of change of the phase corrections is:

$$RFC_i = CFC_i - CFC_{i-1} \tag{6.4}$$

The phase corrections at an arbitrary epoch t_i is:

$$CFC_i = CFC_{i-1} + RFC_i \cdot (t_i - t_{i-1}) \tag{6.5}$$

Applying CFCs is not as simple as applying PRCs. Using carrier phase corrections, the rover receiver has to resolve ambiguities too (on the fly ambiguity estimation).

Although message pair 18/19 is more prevalent than 20/21, there are advantages of using the corrections rather than the raw measurements. The advantages based on Wübbena *et al*. [1996] and Neumann *et al*. [1997] are:

1. Fewer bits are required for a correction than a raw measurement.
2. Corrections are less time sensitive than raw measurements.

3. This method can be more throughput efficient, or can at least offload some computational load from the rover receiver to the base station.
4. The transmitted base station position coordinates are not used to compute the rover's output position in a correction-based algorithm.
5. Corrections are less receiver-dependent than raw measurements. This simplifies the use of heterogeneous receiver equipment (base and rover receivers are not the same type).
6. Corrections may be derived from several receivers, which allows a network concept.

The first and main advantage is the narrower bandwidth requirement. According to Langley [1998], for RTK operations that carry out double differencing using message types 18 and 19, the data must be updated every 0.5-2 seconds. Therefore the data links for RTK use need data rates of at least 2,400 bps and preferably 9,600 or even 19,200 bps. Although the nominal data width of message types 20/21 is the same, the corrections contain more redundant data, which yields better compressibility. Geo++, a German GPS software company developed a standard data compression algorithm called RTCM++. This algorithm creates RTCM type 59 messages containing compressed corrections for a maximum of 12 satellites. The entire information fits into 2,400 bits compared to the 9,600 bits required for 18/19 messages or the uncompressed 20/21 pair. This allows data sending at 1Hz rate using 2,400 bps communication links, which is enough for most real-time kinematic applications [Wübbena *et al.*, 1996].

6.1.1 Networked Carrier Phase DGPS

Permanent GPS reference station networks have been operating around the world for many years. These networks have been used to serve a number of applications from crustal movement monitoring to data collection for Wide Area DGPS pseudorange-correction services. The use of reference stations in carrier phase-based GPS positioning is a relatively new idea, which supports precise navigation applications and surveying. The processing of carrier phase corrections from several reference stations in a multistation adjustment algorithm provides reduced distance dependent errors (iono, tropo and orbit errors) within the network. The basic idea of such an algorithm is to derive coefficients of an appropriate error model, which describes the distance dependent error situation in the working area [Wübbena *et al.*, 1996]. GNNET, a real-time multi reference station adjustment program developed by Geo++ estimates the DGPS corrections holding the coordinates of the reference stations fixed. It introduces a geometric model for the corrections, using the horizontal coordinates as parameteres (the mobile user knows his approximate position from standalone GPS). The coefficients of the model are estimated in an adjustment process. The geometric model can be a simple inclined plane (3-station network, see Figure 6.1) or a higher degree polynomial function (multistation network).

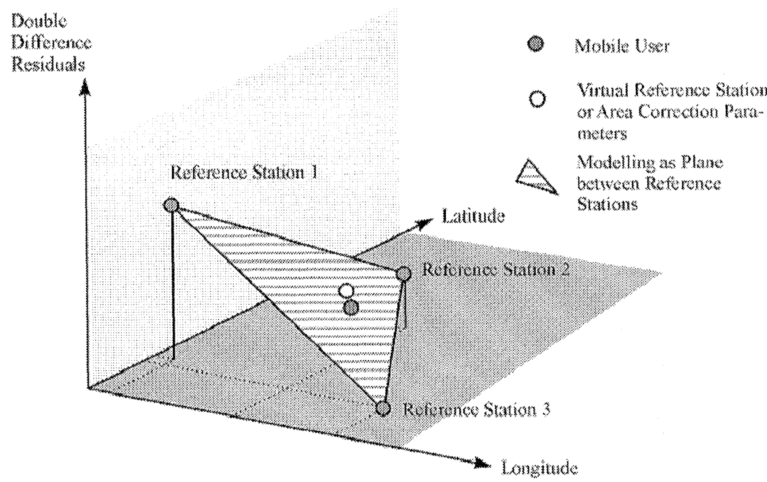


Figure 6.1: Geometric model for correction estimation

[Martin and Jahn, 2000]

The use of network-derived corrections not only improves the achievable accuracy, but also reduces the required time to fix the ambiguities at the rover station.

6.1.2 Long-Range RTK Positioning

Thales (Racal) developed a wide-area carrier phase-based DGPS system. This long-range real-time kinematic (LRTK) system is called GENESIS. The service is said to be capable of providing accuracies better than 20 centimetres in both horizontal position and height throughout the North Atlantic coverage area [Johnston, 2000]. According to the company, this is due to the system's ability to solve GPS integer wide lane ambiguities in a kinematic environment at more than 800 kilometres from a reference station - 20 times greater than other commercially available RTK solutions. Within the system, compressed proprietary LRTK messages are broadcast to the user by way of L-band satellite frequencies. Initially, four Reference Stations have been installed to optimize coverage in the North Sea and Norwegian Continental Shelf regions. Future plans include network extension in Europe [Thales-Geosolutions, 2000].

6.2 Real-Time Precise Point Positioning (PPP)

Real-time single point positioning using precise satellite ephemerides and clock corrections is one of the most promising fields of GPS research today. Precise orbits and clocks are computed by various organizations in North America including the International GPS Service (IGS) and the Geodetic Survey Division of National Resources Canada. Precise data are based on observations of a global tracking network. IGS currently collects pseudorange and carrier-phase measurements from up to 276 sites to generate precise orbit and clock information of various types [IGS, 2001] The most accurate - Final - orbital and clock information provided by IGS is produced with a delay of about 12 days (the Final orbits are usually available on the eleventh day after the last observation) and is updated weekly. The accuracy of the Final orbits is <5 cm r.m.s. and 0.1 ns (~3 cm) for satellite clocks. IGS also provides Rapid data, with 17-hour latency and daily update. Accuracy is 5 cm and 0.2 ns (~6 cm). Finally they produce Ultra-Rapid data delivered twice a day (at 0300 and 1500 UT) with 3-hour latency. Ultra-Rapid combinations contain 48 hours worth of orbits; the first 27 (estimated portion) are based on observations and the second 21 are a predicted orbit for real-time usage. The accuracy of the predicted orbits is ~25 cm and ~5 ns (~150 cm) for the clocks.

A communications link supplying real-time precise data can replace the less accurate broadcast GPS ephemerides. The main advantage of such a system is the ability of the user to perform precise absolute point positioning without the need for a base station or a network of stations. The achievable real-time accuracy using dual-frequency receivers is below the 20-centimetre (2RMS) level. JPL (→IGDG) and GSD who targeted this high level of accuracy do not use the standard Ultra-Rapid predicted orbits and clocks. Instead of predicting 21 hours they only predict half an hour or an hour of data, which will result in much higher accuracy. They can afford to do this because they are IGS Analysis Centres (ACs) so they possess some of the network data real-time and can update precise orbit and clock generation 24 times a day or more frequently.

A future step will be to unify the advantages of real-time precise point positioning with that of a WADGPS system. Already there are several realizations of such hybrid systems, although still in developmental phase. JPL signed a contract with NavCom to broadcast precise ephemeris- and clock-based corrections using the global coverage of the StarFire system (see Section 5.4.3). GSD is also enhancing the orbit and clock products of its real-time GPS Corrections (GPS·C) service by including Ultra-Rapid orbit predictions and processing carrier-phase data from a wide-area network [Héroux et al., 2001].

CHAPTER 7

GNSS MODERNIZATION

7.1 GPS Signal Modernization

The GPS signal structure has not changed much since the beginnings of satellite positioning. The currently operational 5 Block II, 18 Block IIA and 6 Block IIR satellites [USNO, 2001] transmit RF signals on two frequencies (L1 = 1575.42 MHz, L2 = 1227.60 MHz). Two types of pseudorandom noise (PRN) codes are superimposed onto the two carriers. C/A-code (Coarse/Acquisition-code) is modulated only upon L1 providing Standard Positioning Service (SPS) to civilian users. Encrypted P-code (Precision-code) reserved for the U.S. military is modulated on both carriers.

In May 2000 Selective Availability was turned off, which was a first step in a long-term modernization of the Global Positioning System. Introduction of new signals will reform GPS positioning techniques in the near future. A similar code to C/A will be added to the L2 signal (see Table 7.1) on the new Block IIR-M (modified) satellites to be launched starting in 2003.

Carrier Frequency	1 227.60 MHz
Power	2.3 dB less than L1 C/A
Chip Rate	1.023 MHz (511.5 kHz CM; 511.5 kHz CL)
Chip Length	~586 m (CM); ~586 m (CL)
Code Length	10 230 chips (CM = moderate length code) 767 250 chips (CL = long code)
Repetition Rate	20 msec (CM) 1.5 msec (CL)
Broadcast Bandwidth	20 MHz
Signal Structure (composite signal)	data channel (CM) (50% power) data-free channel (CL) (50% power)
Fully Available	~2011

Table 7.1: L2 Civil Signal Specifications [Fontana *et al.*, 2001]

A new military code (M-code) will also be added to both L1 and L2. And with the proposed launch of a new set of GPS satellites, the Block IIFs, a totally new signal - L5 = 1176.45MHz (see Table 7.2) - will appear, dedicated for civilian use. The first Block IIF satellites will be launched probably as early as 2005. The L5 will be in a portion of the spectrum that is allocated for aeronautical radionavigation services (ARNS). The ARNS allocation is required for any signal used in support of any aviation safety-of-life application [Shaw *et al.,* 2000].

Carrier Frequency	1 176.45 MHz
Power	3.7 dB more than L1 C/A
Chip Rate	10.23 MHz
Chip Length	~29.3 m
Code Length	10 230 chips (I5) 10 230 chips (Q5)
Repetition Rate	1 msec
Broadcast Bandwidth	24 MHz (20.46 MHz null-to-null)
Signal Structure (composite signal)	In-Phase (I5) = data channel (50% power) Quadraphase (Q5) = data-free channel (50% power)
Fully Available	~2015

Table 7.2: L5 Signal Specifications [Van Dierendonck, 2001]

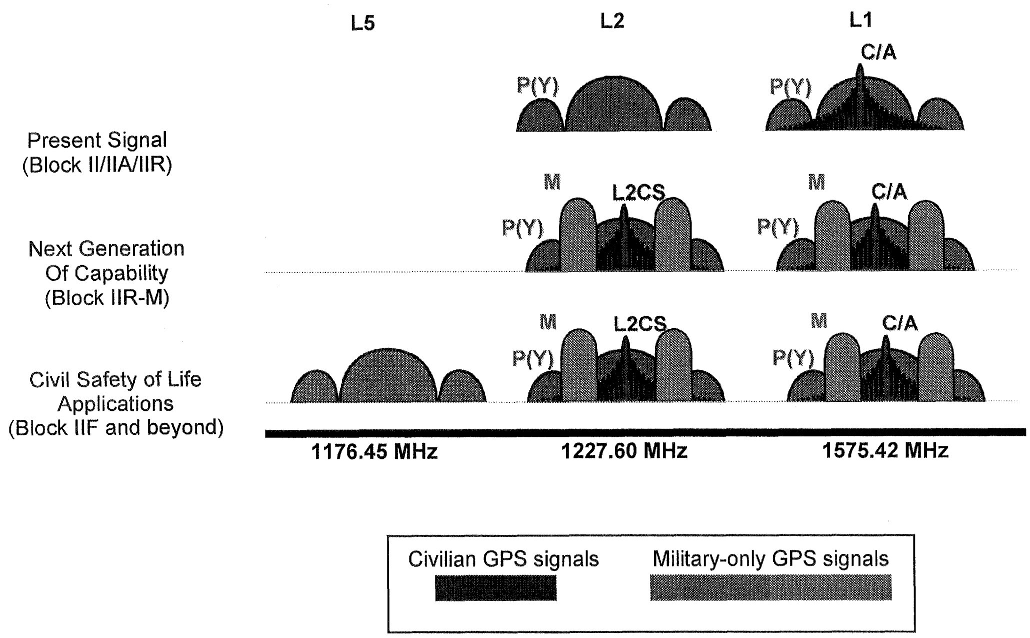


Figure 7.1: GPS signal modernization

[Novak, 2001]

Advantages of the new civil signals:

The second and third civil signals will provide signal redundancy, improve accuracy (see Table 7.3), availability, integrity and continuity of SPS, and improve resistance to radio frequency interference (protected band). Interference resistance (robustness) means that if interference causes the loss of a single frequency, applications continue with only a loss in performance not a loss in service. Also the ten-fold chip rate of the codes on L5 will result in lower noise and better measurement preceision.

Error Source	Range Error Magnitude (metres, 1σ) pessimistic values	
	SPS with SA set to zero	**SPS with two or more coded civil signals** (CS code on L2 and/or L5)
Selective Availability	0.0	0.0
Ionospheric Delay	7.0	0.1
Tropospheric Delay	0.2	0.2
Clock and Ephemeris Error	2.3	2.3
Receiver Noise	0.6	0.6
Multipath	1.5	1.5
Total User Equivalent Range Error (UERE)	7.5	2.8
Typical HDOP	1.5	1.5
Total Standalone Horizontal Accuracy, 95%	22.5	8.5

Table 7.3.: Comparing SPS accuracy before and after adding the new signals

[Shaw *et al.*, 2000]

Currently only the high-end GPS receivers (surveying instruments) have dual-frequency capability; the majority of the receivers on the market are cheap single-frequency devices. To determine and remove the ionospheric delay from our measurements, dual-frequency receivers have to be used. The introduction of the new civil signals only can improve accuracy if the manufacturers decide to implement L2CS or/and L5 capability in new receiver types.

The new signals will also result in higher achievable precision by differential techniques. Wide Area DGPS users will obviously benefit from the new signals in that they will be able to compensate for the ionospheric errors and will not need iono corrections any more. Carrier-phase DGPS users interested in achieving centimeter-level accuracies or better through ambiguity resolution will be greatly assisted by the new civil signals, which will improve wide-laning performance over that currently provided using semi-codeless receivers. Benefits will accrue mostly in terms of minimizing the time required for ambiguity resolution (including reacquisition) and maximizing the probability of correct resolution over short spans, especially over long baselines [MacDonald and Hegarty, 2000].

7.2 Galileo

Galileo, the European Global Navigational Satellite System will be the third independent satellite navigation system after GPS and GLONASS. Galileo is a joint project of the European Commission and the European Space Agency. According to current plans, the operational phase Galileo System will consist of 30 satellites in medium Earth orbit. (Detailed studies have been carried out to compare possible constellations. Another, latter discarded option was to launch 24-30 MEOs and 8 GEOs, but the achievable performance would not have been better and the estimated costs of this alternative constellation were higher.) The MEO satellites will be evenly distributed over 3 orbital planes at an altitude of about 23 000 km. Service is scheduled to start in 2005, and the system is expected to be fully operational by 2008 [Commission Communication, 2000].

The Galileo constellation should provide the best solution in terms of robustness and performance homogeneity including northern latitudes. The service plans recommend three different levels [Palacio, 2001]:

1. a basic service, free of charge, for applications intended for the public at large, in particular leisure activities.
2. a subscription service, with restricted access, for commercial and professional applications needing superior performance levels and a guarantee of service.
3. a very restricted, very high-level subscription service for applications which must not suffer any interruption or disturbance for reasons of security.

The great advantage of the new system lies in interoperability with the other existing systems. Galileo itself probably will not provide better service than GPS but with the raising number of redundant positional RF signals on air, accuracy, integrity, continuity and availability will increase for hybrid-system users.

Since the new GNSS architecture is not yet developed, and the future changes in the other two systems (e.g. GPS signal modernization) will indirectly affect Galileo's final structure, it is hard to predict the effects of Galileo on the European and global user community. There are rough estimates about the developing GNSS market in Europe: most likely the dominant sector will be the mobile telecommunication followed by another large segment, car navigation. Surveying, aviation, fleet management, leisure applications and others will also increasingly benefit from developing redundant GNSS systems.

CHAPTER 8

ARCHIVING RTCM PSEUDORANGE CORRECTIONS

RTCM corrections are designed to be applied in real-time. The idea of archiving corrections serves analytical goals. Archived RTCM corrections can be applied to an archived GPS data set from anywhere in Canada, such as one of the Canadian Active Control System stations. RinexCorr, a program developed in Matlab is able to archive RTCM Message Type 1 and 9 pseudorange corrections (Beacon DGPS, GPS·C) and apply them to RINEX observation files. The binary RTCM message is decoded by a commercial software (RTCMW, developed by Manfred Baeumker) that outputs an ASCII data stream and is able to save the data. RinexCorr's first subroutine (RinexC.m) reads the saved data and creates a RINEX observation file-looking correction file containing PRC and RRC values as observations (see Appendix IV.1). Then the main program (Endprog.m) takes this file and the original RINEX observation file and corrects C1 and P1 measurements with RTCM corrections (see Appendix IV.2). Using the UNB Virtual Reference Station, it is possible to generate GPS·C corrections for any other location in Canada so if there is no need for real-time positioning, UNB is capable of providing more accurate GPS data for any station using archived corrections localized to the specific location. We are also archiving WAAS messages at UNB. These, too, can provide site-specific corrections for any location in Canada. And so it is possible to compare GPS·C and WAAS accuracy for any site in Canada using correction data recorded at UNB.

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

Positioning accuracy of autonomous GPS significantly increased as Selective Availability was turned off in 2000. The improved performance definitely satisfies the needs of a large sector of GPS users. Whereas those applications, which require real-time accuracies around the metre level, are still depending on differential techniques. Differential GPS, originally developed to combat S/A, efficiently mitigates the effect of the numerous remaining measurement errors. Since the mid 1980s, a wide range of DGPS systems have been developed from the simplest single station systems to global WADGPS networks using precise ephemerides and clock corrections to provide highly accurate positions. In the report, the background theory of DGPS and WADGPS was discussed, several systems were studied, tested and analyzed.

According to the results of the test measurements real-time one-to-three metre horizontal positioning accuracy (2 σ) is achievable using WADGPS systems in Canada. The study showed that different receiver types have significantly different impact on the achievable accuracy. Multipath also greatly affects positioning performance. Since the test measurements were carried out in a relatively strong multipath environment, results provided in the study do not show the optimum performance of the respective systems. The results can be generally summarized as follows:

Single-station DGPS systems provide the least accurate service of all because these systems cannot cope with the spatially decorrelating behaviour of several GPS measurement errors. WADGPS systems based on Reference Station networks are able to mitigate the decorrelating effect. The achievable performance of such systems mainly depends on the applied algorithms, GPS measurements, and on the relative location of Reference and Rover Stations. Generally we can say that state-space domain algorithms, which estimate the individual error sources separately, have the most promising features and accuracy potential. Regional systems that provide corrections for continent-size coverage areas cannot guarantee the same level of accuracy everywhere within the network. Users close to the edge will probably not have as good position solutions as those in the middle of the coverage area. Global WADGPS nominally provides the same level of accuracy anywhere in the world. There is a trend to turn towards dual frequency WADGPS systems, which require dual frequency receivers on the user side too. These systems are more complex than the single frequency ones, but they also provide better accuracy for those willing to pay more for a higher quality service. The most promising technique is probably the precise orbit- and clock-based real-time positioning. This revolutionary technique has the potential to provide accuracies below the 0.5 metre level worldwide.

Since all the test measurements were carried out at the same location it would be important to test the performance of these systems in other environments. To have a better idea of the achievable accuracy, kinematic tests should also be done. Europe plays a leading role in the Differential GPS market, especially in the area of value added services. There are a lot of systems operating, which use different ways of correction transmission. These systems should be studied in order to determine which is the most convenient for all purposes.

REFERENCES

Abousalem, M.A. (1996). *Development and Analysis of Wide Area Differential GPS Algorithms*. UCGE Reports Number 20083, Department of Geomatics Engineering, The University of Calgary, Alberta, Canada.

BCACS (2001). British Columbia Active Control System Homepage *http://home.gdbc.gov.bc.ca/bcacs/* (last updated: 20 August, 2001).

Bisnath, S.B. and R.B. Langley (2001). "Pseudorange Multipath Mitigation By Means of Multipath Monitoring and De-Weighting." *Proceedings of the International Symposium on Kinematic Systems in Geodesy, Geomatics and Navigation* (KIS 2001), 5-8 June 2001, Banff, Alberta, Canada, pp. 392-400

Canadian Coast Guard (2001). "Canadian Marine Differential Global Positioning System (DGPS) Broadcast Standard" *http://www.ccg-gcc.gc.ca/dgps/dls/standard_e.pdf* (last updated: 8 August 2001).

CDGPS (2001). Canada-wide DGPS Service Homepage *http://www.cdgps.com/e/* (last updated: 26 July 2001).

Commission Communication to the European Parliament and the Council on GALILEO - 22 November 2000, Brussels, Belgium. *http://www.galileo-pgm.org/indexdp.htm.*

CSI (Communication Systems International Incorporated) (1996). *MBX-2 Beacon Receiver. User Manual.* Document Number 875-0005-007, Calgary, Alberta, Canada.

Cutright, P.J., K.M. Girrard (1994). "Frame Relay: an Analysis of the Technology" Eastern Oregon University *http://pierce.eosc.osshe.edu/frame.html.*

Dewar, G. (1999). "Aircraft Landings: The GPS Approach" *GPS World.* Vol 10, No. 6, pp. 68-74.

EGNOS (2001). Official Home Page *http://www.esa.int/EGNOS/.*

European Reference Frame (EUREF) (2001). "Euref Permanent Network, Tracking Network - Map" *http://www.epncb.oma.be/map.html* (last updated: 12 June 2001).

Federal Avionics Administration (FAA) (2001). "Wide Area Augmentation System" *http://gps.faa.gov/Programs/WAAS/waas.htm* (last updated: 24 March 2001).

Fontana, R.D., W. Cheung, P.M. Novak, and T.A. Stansell. (2001). "The New L2 Civil Signal." *Proceedings of the 14th International Technical Meeting of the Satellite Division of The Institute of Navigation*, Salt Lake City, Utah, U.S.A., 11-14 September, The Institute of Navigation, Alexandria, Virginia, U.S.A.

GPSCardTM (1994). *Command Descriptions Manual, Software Version 2.2/3.2* NovAtel Communications Limited, Calgary, Alberta, Canada.

Graczka, Gy. (1999). "Differential GPS" *Viewgraphs presented at the Civil GPS Interface Committee, International Information Subcommitee, European Meeting*, 2-3 December 1999 Prague, Czech Republic

Hansen, A. (2000). "Ionospheric Model." *http://waas.stanford.edu/~wwu/ahansen/papers/ionntm00/node3.html* (last updated: 21 September 2000).

Héroux, P., J. Kouba, P. Collins, and F. Lahaye (2001). "GPS Carrier-Phase Point Positioning with Precise Orbit Products".

Hofmann-Wellenhof, B., H. Lichtenegger, and J. Collins. (1997). *GPS Theory and Practice*. 4th Edition, Springer-Verlag, Wien, New York, 127 pp.

Hogan, M. (2001). *Wide Area Differential GPS (WADGPS) Introduction and Overview.* Presentation to UNB course GGE 6242, Department of Geodesy and Geomatics Engineering, University of New Brunswick, Fredericton, New Brunswick, Canada.

International GPS Service (IGS) (2001). "IGS Products" *http://igscb.jpl.nasa.gov/components/prods.html* (last updated: 22 May 2001).

ITRF (International Terrestrial Reference Frame) (1998). "Transformation parameters between ITRS and WGS84" *ftp://lareg.ensg.ign.fr/pub/itrf/WGS84.TXT* (last updated: 6 July 1998).

Johnston, G.T. (2000). "New Concepts in Long Range positioning" *http://iho.shom.fr/general/iisc9/johnston1.pdf.*

Langley, R.B. (1993). "Communication Links for DGPS" *GPS World.* Vol. 4, No. 5, pp. 47-51.

Langley, R.B. (1998). "RTK GPS" *GPS World.* Vol. 9, No. 9, pp. 70-76.

Langley, R.B., P.J.G. Teunissen, A. Kleusberg, Y. Bock, G. Beutler, and C.C. Goad. (1995). *GPS for Geodesy.* Netherlands Geodetic Commission, Delft, The Netherlands, pp. 3-33.

Loomis, P., L. Sheynblatt, T. Mueller (1991). "Differential GPS Network Design." *Proceedings of the 4th International Technical Meeting of the Satellite Division of The Institute of Navigation*, Albuquerque, New Mexico, U.S.A., 11-13 September, The Institute of Navigation, Alexandria, Virginia, U.S.A., pp.511-520.

Martin, S., C.H. Jahn (2000). "Experiences in Set-Up and Usage of a Geodetic Real-Time Differential Correction Network." *http://www.tu-bs.de/institute/iffl/publications/2000/EPS.pdf.*

McDonald, K.D. and C. Hegarty (2000). "Post-Modernization GPS Performance Capabilities" *http://www.poly-electronic.ch/dok-gps/gps-zukunft.pdf*.

Natural Resources Canada (NRCan) (2001). "About the Canadian Active Control System."*http://www.geod.nrcan.gc.ca/products/html-public/GSDproductsGuide/CACS/English/About_CACS.html* (last updated: 23 January 2001).

NavCom Technology Inc. (2000). "NCT-2000D™." http://www.navcomtech.com/prod_line/index.htm.

Neumann, J.B., K.J. Van Dierendonck, A. Manz, and T.J. Ford (1997). "Real-Time Carrier Phase Positioning Using the RTCM Standard Message Types 20/21 and 18/19." http://www.novatel.ca/Documents/Papers/File47.pdf.

Novak, P. (2001). "L2 and L5 Civil Signal Public Forum." *http://www.navcen.uscg.gov/gps/modernization/PublicForum29JunA-F.ppt.*

Palacio, L. de "General introduction" *http://www.galileo-pgm.org/indexdp.htm* (last update: 26 June 2001).

Parkinson, B.W., J.J. Spilker Jr. (1996). *Global Positioning System: Theory and Applications, Volume II.* American Institute of Aeronautics and Astronautics, Inc. 21 pp.

Rizos, C. (1999). "Multipath Disturbance & Signal Interference." Principles and Practice of GPS Surveying. The University of New South Wales, Sydney, Australia. *http://www.gmat.unsw.edu.au/snap/gps/gps_survey/chap6/6212.htm* (last updated: 18 January 2000).

Shaw, M., K. Sandhoo, and D. Turner (2000). "Modernization of the Global Positioning System" *GPS World.* Vol. 11, No. 9, pp. 36-44.

Takács, B. (2001). "The Accuracy of GPS Without SA" *Proceedings of the 3rd Symposium of Mobile Mapping Technology,* 3-5 January 2001, Cairo, Egypt.

Thales Avionics Ltd. (2001). "Thales Space Based Augmentation Systems - NEST Bed" *http://www.ravl.co.uk/gnss.html* (last updated: 10 January 2001).

Thales-Geosolutions (2000). "Racal Survey announces LRTK positioning service in Europe" *http://www.thales-geosolutions.com/press_releases.htm#05.*

The MITRE Corporation (2001). "Wide Area Augmentation System" *http://www.caasd.org/proj/satnav/waas.html* (last updated: 16 May 2001).

U.S. Naval Observatory (USNO) (2001). Current GPS Constellation *http://tycho.usno.navy.mil/gpscurr.html* (last updated: 13 September 2001).

Van Dierendonck, A.J. (2000). "The New L5 Civil GPS Signal." *GPS World.* Vol. 11, No. 9, pp. 64-71 *[www.gpsworld.com]*

Weill, L.R. (1997). "Conquering Multipath: The GPS Accuracy Battle." *GPS World.* Vol. 8, No. 4, pp. 59-66.

Wübbena, G., A. Bagge, G. Seeber, V. Böder, and P. Hankemeier (1996). "Reducing Distance Dependent Errors for Real-Time Precise DGPS Applications by Establishing Reference Station Networks." *http://www.geopp.de/download/kansas96.pdf*

Yeazel, J. (2001). "WAAS and its Relation to Enabled Hand-Held GPS Receivers" *http://www.gpsinformation.net/exe/waas.html* (last updated: 24 March 2001).

APPENDICES

APPENDIX I

BEACON DGPS REFERENCE STATIONS IN EUROPE

Figure I.1: Beacon DGPS reference stations in Europe (2000)

APPENDIX II

EXAMPLE OF NMEA GGA MESSAGE LOGGED BY NAVCOM NCT-2000D RECEIVER WORKING IN WAAS MODE

```
(...)
$GPGGA,134002.0,4557.01647,N,06638.53712,W,2,09,1.1,39.30,M,-21.01,M,,4.0,0000*5E
$GPGGA,134003.0,4557.01648,N,06638.53712,W,2,09,1.1,39.28,M,-21.01,M,,5.0,0000*58
$GPGGA,134004.0,4557.01649,N,06638.53713,W,2,09,1.1,39.25,M,-21.01,M,,6.0,0000*51
$GPGGA,134005.0,4557.01649,N,06638.53714,W,2,09,1.1,39.21,M,-21.01,M,,7.0,0000*52
$GPGGA,134006.0,4557.01637,N,06638.53703,W,2,09,1.1,38.86,M,-21.01,M,,7.0,0000*52
$GPGGA,134007.0,4557.01649,N,06638.53711,W,2,09,1.1,39.33,M,-21.01,M,,7.0,0000*56
$GPGGA,134008.0,4557.01642,N,06638.53704,W,2,09,1.1,39.52,M,-21.01,M,,4.0,0000*52
$GPGGA,134009.0,4557.01642,N,06638.53704,W,2,09,1.1,39.54,M,-21.01,M,,5.0,0000*54
$GPGGA,134010.0,4557.01642,N,06638.53703,W,2,09,1.1,39.57,M,-21.01,M,,6.0,0000*5B
$GPGGA,134011.0,4557.01642,N,06638.53703,W,2,09,1.1,39.60,M,-21.01,M,,7.0,0000*5F
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$GPGGA,134038.0,4557.01647,N,06638.53694,W,2,09,1.1,39.37,M,-21.01,M,,4.0,0000*5F
$GPGGA,134039.0,4557.01647,N,06638.53693,W,2,09,1.1,39.35,M,-21.01,M,,5.0,0000*5A
$GPGGA,134040.0,4557.01647,N,06638.53691,W,2,09,1.1,39.33,M,-21.01,M,,6.0,0000*53
$GPGGA,134041.0,4557.01646,N,06638.53690,W,2,09,1.1,39.30,M,-21.01,M,,7.0,0000*50
$GPGGA,134042.0,4557.01642,N,06638.53704,W,2,09,1.1,39.00,M,-21.01,M,,7.0,0000*58
$GPGGA,134043.0,4557.01654,N,06638.53715,W,2,09,1.1,39.49,M,-21.01,M,,7.0,0000*53
$GPGGA,134044.0,4557.01649,N,06638.53710,W,2,09,1.1,39.60,M,-21.01,M,,4.0,0000*55
$GPGGA,134045.0,4557.01649,N,06638.53711,W,2,09,1.1,39.63,M,-21.01,M,,5.0,0000*57
$GPGGA,134046.0,4557.01649,N,06638.53713,W,2,09,1.1,39.67,M,-21.01,M,,6.0,0000*51
$GPGGA,134047.0,4557.01650,N,06638.53714,W,2,09,1.1,39.70,M,-21.01,M,,7.0,0000*58
$GPGGA,134048.0,4557.01662,N,06638.53713,W,2,09,1.1,39.97,M,-21.01,M,,7.0,0000*58
$GPGGA,134049.0,4557.01650,N,06638.53705,W,2,09,1.1,39.48,M,-21.01,M,,7.0,0000*5D
$GPGGA,134050.0,4557.01655,N,06638.53710,W,2,09,1.1,39.35,M,-21.01,M,,4.0,0000*5D
$GPGGA,134051.0,4557.01656,N,06638.53710,W,2,09,1.1,39.31,M,-21.01,M,,5.0,0000*5A
$GPGGA,134052.0,4557.01657,N,06638.53711,W,2,09,1.1,39.29,M,-21.01,M,,6.0,0000*53
(...)
```

APPENDIX III

EXAMPLES OF WAAS & EGNOS RTCA MESSAGE

LOGGED BY NAVCOM NCT-2000D RECEIVER

DECODED BY ZDENEK LUKES (UNB)

III.1 WAAS Message (sample)

```
(...)
1 1125 405297 0 32 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 17 18 19 20 21
22 23 24 25 26 27 28 29 30 31 122 134
63 1125 405298
 3 14 1125 405299   0   0 0 0 0  255.875   0.000 14  0
 3 15 1125 405299   0   0 0 0 0    0.000   0.000  4  0
 3 17 1125 405299   0   0 0 0 0    0.000   0.000  3  0
 3 18 1125 405299   0   0 0 0 0   -0.125   0.000  5  0
 3 19 1125 405299   0   0 0 0 0  255.875   0.000 14  0
 3 20 1125 405299   0   0 0 0 0  255.875   0.000 14  0
 3 21 1125 405299   0   0 0 0 0   -0.625   0.000  7  0
 3 22 1125 405299   0   0 0 0 0  255.875   0.000 14  0
 3 23 1125 405299   0   0 0 0 0    0.375   0.000  3  0
 3 24 1125 405299   0   0 0 0 0  255.875   0.000 14  0
 3 25 1125 405299   0   0 0 0 0  255.875   0.000 14  0
 3 26 1125 405299   0   0 0 0 0   -0.125   0.000  3  0
 3 27 1125 405299   0   0 0 0 0    0.500   0.000 12  0
 2  1 1125 405300   0   0 1 0 1  255.875   0.000 14  0
 2  2 1125 405300   0   0 1 0 1  255.875   0.000 14  0
 2  3 1125 405300   0   0 1 0 1   -0.625   0.000  7  0
 2  4 1125 405300   0   0 1 0 1  255.875   0.000 14  0
 2  5 1125 405300   0   0 1 0 1  255.875   0.000 14  0
 2  6 1125 405300   0   0 1 0 1   -0.625   0.000  3  0
 2  7 1125 405300   0   0 1 0 1  255.875   0.000 14  0
 2  8 1125 405300   0   0 1 0 1   -0.375   0.000 11  0
 2  9 1125 405300   0   0 1 0 1    0.250   0.000  7  0
 2 10 1125 405300   0   0 1 0 1    0.250   0.000  5  0
 2 11 1125 405300   0   0 1 0 1  255.875   0.000 14  0
 2 12 1125 405300   0   0 1 0 1  255.875   0.000 14  0
 2 13 1125 405300   0   0 1 0 1  255.875   0.000 14  0
24  noupd
24 28 1125 405301   0   0 0 0 0  255.875   0.000 14  0
24 29 1125 405301   0   0 0 0 0  255.875   0.000 14  0
24 30 1125 405301   0   0 0 0 0  255.875   0.000 14  0
24 31 1125 405301   0   0 0 0 0    0.250   0.000 12  0
24 122 1125 405301   0   0 0 0 0  -24.500   0.000 12  0
24 134 1125 405301   0   0 0 0 0    2.750   0.000 13  0
28 1125 405302
63 1125 405303
62 1125 405304
(...)
24 1125 405325   25  217  1125 405344. 405325.  -19.   -1.500    2.500
1.500 0.0000000 -0.00048828  0.00000000 -0.00048828 0.0000000000
24 28 1125 405325   0   -6 1 0 1  255.875  255.875 14 14
24 29 1125 405325   0   -6 1 0 1  255.875  255.875 14 14
24 30 1125 405325   0   -6 1 0 1  255.875  255.875 14 14
24 31 1125 405325   0   -6 1 0 1    0.250    0.125 12 12
24 122 1125 405325   0   -6 1 0 1  -24.750  -24.500 12 12
24 134 1125 405325   0   -6 1 0 1    2.875    3.250 13 13
28 1125 405327
26 1125 405332 3.625 15 40 -140
```

```
26 1125 405332 3.375 15 45 -140
26 1125 405332 3.375 15 50 -140
26 1125 405332 3.125 4 55 -140
26 1125 405332 3.125 3 65 -140
26 1125 405332 2.125 15 75 -140
26 1125 405332 4.75 15 30 -135
26 1125 405332 4.5 15 35 -135
26 1125 405332 4 15 40 -135
26 1125 405332 3.375 15 45 -135
26 1125 405332 3.375 15 50 -135
26 1125 405332 3 4 55 -135
26 1125 405332 4 15 25 -130
26 1125 405332 5 15 30 -130
26 1125 405332 4.75 15 35 -130
28 1125 405333
26 1125 405334 4.375 15 20 -110
26 1125 405334 4.125 15 25 -110
26 1125 405334 4.5 15 30 -110
26 1125 405334 4.5 3 35 -110
26 1125 405334 4 4 40 -110
26 1125 405334 2.875 4 45 -110
26 1125 405334 2.25 15 50 -110
26 1125 405334 2.125 15 55 -110
26 1125 405334 5 15 20 -105
26 1125 405334 4.625 15 25 -105
26 1125 405334 4.5 3 30 -105
26 1125 405334 4.375 3 35 -105
26 1125 405334 3.875 4 40 -105
26 1125 405334 2.75 3 45 -105
26 1125 405334 2.375 4 50 -105
(...)
```

III.2 EGNOS Message (Sample) - No Corrections Broadcast

```
(...)
63 1126 68215
24  noupd
24  noupd
63 1126 68217
63 1126 68218
63 1126 68219
 2  noupd
63 1126 68221
24  noupd
24  noupd
63 1126 68223
63 1126 68224
63 1126 68225
 2  noupd
63 1126 68227
24  noupd
24  noupd
63 1126 68229
63 1126 68230
63 1126 68231
 2  noupd
63 1126 68233
24  noupd
24  noupd
63 1126 68235
63 1126 68236
63 1126 68237
 2  noupd
1 1126 68239 0 1 120
24  noupd
24  noupd
63 1126 68241
63 1126 68242
63 1126 68243
 2  noupd
63 1126 68245
24  noupd
24  noupd
63 1126 68247
63 1126 68248
63 1126 68249
 2  noupd
63 1126 68251
24  noupd
24  noupd
```

```
63 1126 68253
63 1126 68254
63 1126 68255
 2  noupd
9 1126 68257
24  noupd
24  noupd
(...)
```

III.3 EGNOS Message (Sample) - Healthy Operating

```
(...)
1 1125 405216 0 30 1 2 3 4 5 6 7 8 9 10 11 13 14 15 17 18 19 20 21 22 23 24 25
26 27 28 29 30 31 120
 2  4 1125 405217    0    0 2 0 2     0.000     0.000 14  0
 2  5 1125 405217    0    0 2 0 2     0.000     0.000 14  0
 2  6 1125 405217    0    0 2 0 2     0.000     0.000 14  0
 2  7 1125 405217    0    0 2 0 2     0.000     0.000 14  0
 2  8 1125 405217    0    0 2 0 2     1.000     0.000  3  0
 2  9 1125 405217    0    0 2 0 2     0.000     0.000 14  0
 2 10 1125 405217    0    0 2 0 2    -0.500     0.000  4  0
 2 11 1125 405217    0    0 2 0 2     0.000     0.000 14  0
 2 13 1125 405217    0    0 2 0 2     0.000     0.000 14  0
 2 14 1125 405217    0    0 2 0 2     0.000     0.000 14  0
 3 15 1125 405218    0    0 2 0 2     0.000     0.000 14  0
 3 17 1125 405218    0    0 2 0 2    -0.125     0.000  3  0
 3 18 1125 405218    0    0 2 0 2     0.000     0.000 14  0
 3 19 1125 405218    0    0 2 0 2     0.000     0.000 14  0
 3 20 1125 405218    0    0 2 0 2     0.000     0.000 14  0
 3 21 1125 405218    0    0 2 0 2     0.000     0.000 14  0
 3 22 1125 405218    0    0 2 0 2     0.000     0.000 14  0
 3 23 1125 405218    0    0 2 0 2     0.000     0.000 14  0
 3 24 1125 405218    0    0 2 0 2     0.000     0.000 14  0
 3 25 1125 405218    0    0 2 0 2     0.000     0.000 14  0
 3 26 1125 405218    0    0 2 0 2    -0.500     0.000  4  0
 3 27 1125 405218    0    0 2 0 2     1.875     0.000  5  0
 3 28 1125 405218    0    0 2 0 2    -3.750     0.000  4  0
 4 29 1125 405219    0    0 2 0 2     0.000     0.000 14  0
 4 30 1125 405219    0    0 2 0 2     0.000     0.000 14  0
 4 31 1125 405219    0    0 2 0 2     0.000     0.000 14  0
(...)
63 1125 405231
63 1125 405232
(...)
25 1125 405266   14    5  1125 405266. 405266.    0.     0.000     0.000     0.000
0.0000000
25 1125 405266   15    0  1125 405266. 405266.    0.     0.000     0.000     0.000
0.0000000
25 1125 405266   17  160  1125 405266. 405266.    0.     0.000     0.000     0.000
0.0000000
25 1125 405266   18    0  1125 405266. 405266.    0.     0.000     0.000     0.000
0.0000000
(...)
26 1125 405271 0 15 25 -40
26 1125 405271 0 15 30 -40
26 1125 405271 0 15 35 -40
26 1125 405271 0 15 40 -40
26 1125 405271 0 15 45 -40
26 1125 405271 0 15 50 -40
```

```
26 1125 405271 3.5 10 55 -40
26 1125 405271 3.5 6 65 -40
26 1125 405271 2.75 5 75 -40
26 1125 405271 8.125 13 25 -35
26 1125 405271 8.125 13 30 -35
26 1125 405271 0 15 35 -35
26 1125 405271 0 15 40 -35
26 1125 405271 0 15 45 -35
26 1125 405271 3.625 11 50 -35
(...)
```

APPENDIX IV

EXAMPLES OF RINEX-LOOKING CORRECTION- AND CORRECTED RINEX OBSERVATION FILES CREATED BY RINEXC.M AND ENDPROG.M MATLAB PROGRAMS

IV.1 RINEX-Looking Correction File (Sample)

```
     C                  CORRECTION DATA                        RINEX VERSION / TYPE
HTCORR 1.0              TAMAS HORVATH       23/ 9/2001  0:14: 6 PGM / RUN BY / DATE
TAMAS HORVATH           UNB GPSLAB                             OBSERVER / AGENCY
DATUM:NAD83(CSRS)                                              COMMENT
GILLIN-1                                                       MARKER NAME
1                                                              MARKER NUMBER
  1761243.6100  -4078248.8975   4561419.4551                   APPROX POSITION XYZ
        0.0000         0.0000         0.0000                   ANTENNA: DELTA H/E/N
     2    PRC    RRC                                           # / TYPES OF OBSERV
    ~2                                                         INTERVAL
  2001      9     20      0      0     0.000000                TIME OF FIRST OBS
                                                               END OF HEADER
  1  9 20  0  0  0.0000000  0  8 22  1 13  3 31 27 15  8
        -5.140          0.000
        -5.120          0.000
        -1.400          0.000
        -0.840          0.000
        -8.320          0.000
        -7.520          0.000
       -14.000          0.000
       -19.060          0.000
  1  9 20  0  0  1.8000000  0  8 22  1 13  3 31 27 15  8
        -5.140          0.000
        -5.140          0.000
        -1.400          0.000
        -0.840          0.000
        -8.340          0.000
        -7.540          0.000
       -14.000          0.000
       -19.040          0.000
  1  9 20  0  0  4.2000000  0  8 22  1 13  3 31 27 15  8
        -5.160          0.000
        -5.140          0.000
        -1.380          0.000
        -0.820          0.000
        -8.320          0.000
        -7.520          0.000
       -14.000          0.000
       -19.040          0.000
  1  9 20  0  0  6.0000000  0  8 22  1 13  3 31 27 15  8
        -5.160          0.000
        -5.140          0.000
        -1.380          0.000
        -0.820          0.000
        -8.320          0.000
        -7.540          0.000
       -14.000          0.000
       -19.020          0.000
  1  9 20  0  0  7.8000000  0  8 22  1 13  3 31 27 15  8
        -5.160          0.000
        -5.160          0.000
        -1.400          0.000
        -0.820          0.000
        -8.340          0.000
        -7.520          0.000
       -14.000          0.000
       -19.020          0.000
  1  9 20  0  0 10.2000000  0  8 22  1 13  3 31 27 15  8
(...)
```

IV.2 Corrected RINEX Observation File (Sample)

```
     RC            CORRECTED OBS. DATA    G (GPS)             RINEX VERSION / TYPE
RINEXC 1.0            TAMAS HORVATH       23/ 9/2001 11:33: 5 PGM / RUN BY / DATE
teqc  2000Jul20       ACS data            20010920 01:06:07UTCPGM / RUN BY / DATE
HP-UX 10.20|PA-RISC|cc A.10.32.03|=+|=|                       COMMENT
ALGO CACS-ACP   883160 ALGONQUIN PARK, ONT,  CANADA           MARKER NAME
40104M002                                                     MARKER NUMBER
-Unknown-             GEOD. SURVEY, NATURAL RESOURCES CANADA  OBSERVER / AGENCY
1103                  AOA BENCHMARK ACT   3.3.32.2N           REC # / TYPE / VERS
386                   AOAD/M_T                                ANT # / TYPE
   918130.0400 -4346072.6600  4561977.9300                    APPROX POSITION XYZ
        0.1000        0.0000        0.0000                    ANTENNA: DELTA H/E/N
     1     1                                                  WAVELENGTH FACT L1/2
     7    L1    L2    C1    P2    P1    S1    S2              # / TYPES OF OBSERV
                                                              COMMENT
                 C1    P1    CORRECTED!!!                     COMMENT
                                                              COMMENT
                   DATUM : NAD83(CSRS)                        COMMENT
                                                              COMMENT
    30.0000                                                   INTERVAL
L1 PHASE CENTRE 0.110m ABOVE ARP                              COMMENT
L2 PHASE CENTRE 0.128m ABOVE ARP                              COMMENT
where ARP is the Antenna Reference Point for HI measurement   COMMENT
Antenna mounted on roof of 615 Booth Street. Testing of       COMMENT
Benchmark ACT Receivers                                       COMMENT
    P1 =    P1  TurboRogue; =    Y1  Benchmark                COMMENT
    L1 = L1(CA)                                               COMMENT
    P2 =    P2  TurboRogue; =    Y2  Benchmark                COMMENT
    L2 = L2(P2) TurboRogue; = L2(Y2) Benchmark                COMMENT
 SNR is mapped to RINEX snr flag value [1,4-9]                COMMENT
    SNR:   >316  >100  >31.6  >10  >3.2    >0 bad=0           COMMENT
L1 & L2:      9     8     7     6     5     4     1           COMMENT
  2001     9    20     0     0    0.0000000     GPS           TIME OF FIRST OBS
                                                              END OF HEADER
 01  9 20  0  0  0.0000000  0  8G27G31G13G22G15G 8G 1G 3
 -14966225.689 6 -11661967.379 6  22261923.385    22261934.038    22261922.264
       123.000          88.000
 -19575055.722 9 -15253254.394 7  20845856.089    20845866.312    20845855.043
       254.000         157.000
 -17575125.916 9 -13694872.535 7  21316685.691    21316688.795    21316685.260
       217.000         149.000
 -10219340.438 5  -7963085.297 5  22488493.999    22488501.912    22488492.331
        76.000          52.000
  -2112988.581 4  -1646479.543 4  24168196.089    24168215.153    24168194.873
        16.000          10.000
  -1765037.760 4  -1375352.115 4  24121491.080    24121517.414    24121490.059
        16.000           8.000
 -13648786.662 6 -10635392.190 5  22165525.789    22165534.826    22165524.939
       104.000          68.000
 -20756581.339 9 -16173920.544 8  20673051.347    20673054.121    20673050.319
       290.000         197.000
 01  9 20  0  0 30.0000000  0  8G27G31G13G22G15G 8G 1G 3
 -15048781.831 6 -11726296.756 6  22246212.961    22246224.154    22246212.129
       125.000          92.000
 -19644233.260 9 -15307158.892 7  20832691.996    20832702.219    20832690.890
       254.000         161.000
 -17545490.774 9 -13671780.228 7  21322324.793    21322328.173    21322324.400
       217.000         149.000
 -10128613.365 5  -7892388.905 5  22505758.693    22505766.732    22505757.136
        77.000          50.000
```

```
 -2126305.562 4  -1656856.395 4  24165660.877    24165680.983    24165660.206
     19.000          11.000
 -1870274.675 4  -1457354.766 4  24101465.391    24101491.629    24101463.966
     11.000          12.000
-13559728.868 6 -10565996.563 5  22182473.694    22182482.414    22182472.446
    104.000          71.000
-20743948.788 9 -16164076.985 8  20675455.258    20675458.032    20675454.309
    295.000         199.000
01  9 20  0  1  0.0000000  0  8G27G31G13G22G15G 8G 1G 3
-15131155.963 7 -11790484.308 6  22230537.706    22230548.754    22230536.842
    134.000          96.000
-19712897.175 9 -15360663.160 7  20819625.609    20819635.855    20819624.605
    255.000         166.000
-17515266.866 8 -13648229.134 7  21328076.177    21328079.388    21328075.725
    211.000         144.000
-10037756.752 5  -7821591.576 5  22523048.201    22523055.931    22523046.638
     77.000          46.000
 -2139039.819 4  -1666779.149 4  24163238.608    24163257.540    24163237.520
     16.000           9.000
 -1975474.758 4  -1539328.757 4  24081445.794    24081471.925    24081445.033
     18.000           7.000
-13470331.652 6 -10496336.464 5  22199484.472    22199494.271    22199483.826
    106.000          71.000
-20730734.924 9 -16153780.459 8  20677969.738    20677972.506    20677968.816
    292.000         200.000
01  9 20  0  1 30.0000000  0  8G27G31G13G22G15G 8G 1G 3
-15213346.185 7 -11854528.570 6  22214897.432    22214908.386    22214896.572
    134.000          91.000
-19781045.667 9 -15413765.803 7  20806657.444    20806667.647    20806656.320
    253.000         167.000
-17484455.451 8 -13624220.244 7  21333939.363    21333942.573    21333939.008
    212.000         145.000
 -9946771.884 5  -7750694.304 5  22540361.374    22540369.894    22540360.178
     75.000          50.000
 -2151190.174 4  -1676246.936 4  24160925.975    24160945.399    24160925.097
     17.000          11.000
 -2080636.580 4  -1621272.927 4  24061434.694    24061460.318    24061433.616
     21.000           5.000
-13380597.558 6 -10426413.863 5  22216560.209    22216569.964    22216559.368
     98.000          66.000
-20716940.743 9 -16143031.734 8  20680594.935    20680597.454    20680593.884
    299.000         195.000
01  9 20  0  2  0.0000000  0  8G27G31G13G22G15G 8G 1G 3
-15295350.465 7 -11918427.943 6  22199292.437    22199303.471    22199291.610
    135.000         100.000
-19848676.692 9 -15466465.223 8  20793787.846    20793797.946    20793786.641
    254.000         171.000
-17453057.549 8 -13599754.354 7  21339913.916    21339917.463    21339913.709
    210.000         139.000
 -9855660.138 5  -7679698.166 5  22557699.324    22557707.859    22557697.954
     76.000          47.000
 -2162755.603 4  -1685258.937 4  24158724.799    24158744.605    24158724.199
     16.000          11.000
 -2185758.273 4  -1703185.854 4  24041430.719    24041456.674    24041429.603
     14.000          10.000
-13290529.282 6 -10356230.854 5  22233699.220    22233709.549    22233698.739
    102.000          70.000
-20702566.815 9 -16131831.259 8  20683329.981    20683332.593    20683328.977
    300.000         196.000
01  9 20  0  2 30.0000000  0  8G27G31G13G22G15G 8G 1G 3
-15377167.058 7 -11982181.066 6  22183723.359    22183734.241    22183722.416
    131.000          96.000
(...)
```

VITA

Candidate's full name: Tamás Horváth

Place and date of birth: Budapest, Hungary, 3 December 1976

Permanent Address: Béla király út 11/B
Budapest H-1125
Hungary

University attended: Budapest University of Technology and Economics

Publications:

Horvath, T. (1999). "Feasibility study of a Hungarian vehicle navigation system." Student Conference, Department of Geodesy and Surveying, Budapest University of Technology and Economics, 5 November, Budapest, Hungary (in Hungarian).

Horvath, T. (1999). "Opportunities offered by a vehicle navigation systerm." *Magyar Távközlés*, Vol. 10, No. 12, pp. 35-39 (in Hungarian).