High Data Rate Global Positioning System Receiver Performance Analysis For Ionospheric Monitoring Within the Canadian High Arctic Region

by

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Abstract

The Canadian High Arctic Ionospheric Network (CHAIN) has recently begun an expansion of Global Positioning System (GPS) receiver stations within the Canadian auroral and high latitude regions which will be used to monitor the ionosphere. The stations included in this expansion will utilize the Septentrio PolaRxS Pro Global Navigation Satellite System (GNSS) receiver. This receiver is new to the CHAIN network and work regarding its performance as well as newly obtainable data thanks to its improved specifications, specifically the increased sampling rate of 100 Hz, must be analyzed.

One method of high arctic ionospheric monitoring in which the receiver will take part involves the calculation of GPS-derived total electron content (TEC). The accuracy of GPS-derived TEC relies heavily on the accurate estimation of the instrumental biases, known as the differential code bias (DCB). The most appropriate methods of estimating the DCBs for the Septentrio PolaRxS Pro receivers are determined and tested. These include two variations of the minimization of standard deviations method as well as two variations of bias estimation through the comparison of station-derived TEC and TEC maps provided by the International GNSS Service (IGS). Biases obtained using the minimization of standard deviations methods range from -9.81 TECU to 9.36 TECU. Methods involving the comparison of station-derived TEC and TEC maps return bias values ranging from -4.01 TECU to 18.05 TECU.
and -8.84 TECU to 11.57 TECU for a least squares comparison and a direct, per
epoch, comparison method, respectively.

Another method of ionospheric monitoring in which the receiver will be used involves
the logging and analysis of signal intensity and phase scintillation. The PolaRxS Pro
is capable of sampling GPS carrier signal intensity and phase at a maximum rate
of 100 Hz, double that of previous receivers. The characteristics of the amplitude
and phase scintillation spectra at 100 Hz sampling rates are described. Results are
obtained specifically within the auroral region during May 24th through 31st 2013.
Wavelet and Fourier transform methods of analysis are described for a qualitative
and quantitative comparison of the higher frequency spectral range with the current
theoretical predictions.

Higher frequency amplitude spectra shows an abrupt deviation from theoretical pre-
dictions. Temporal analysis shows no dominant characteristics during the scintil-
ation event in the higher frequency region where static analysis shows a near zero
spectral slope before, during and after the event. This constant spectrum in the high
frequency amplitude alludes to noise in the region.

Phase spectral analysis shows a more subtle deviation from theoretical predictions in
the higher frequency regime. In the lower frequency portion, up to about 20 Hz, the
expected behavior based on previous work is observed, a power law behavior with
a mean spectral slope around -2. In the higher frequencies the mean spectral slope
becomes increasingly more positive up to a value of -0.4394 seen in the 40 Hz to 50
Hz range.
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# Table of Contents

Abstract ii

Acknowledgments iv

Table of Contents vii

List of Tables viii

List of Figures xi

Abbreviations xii

1 Introduction and Thesis Outline 1
   1.1 Introduction .............................................. 1
   1.2 Total Electron Content (TEC) ............................ 2
   1.3 Ionospheric Scintillation ................................. 4
   1.4 Thesis Outline ............................................. 5

2 Ionosphere 9
   2.1 Introduction .............................................. 9
   2.2 Composition of the Ionosphere ........................... 10
   2.3 Geographical Differences in the Ionosphere ............ 13
   2.4 Ionospheric Effects on Electromagnetic Waves .......... 16

3 Global Positioning System 20
# Table of Contents

3.1 Introduction .................................................. 20
3.2 Signal Structure and Tracking .............................. 21
3.3 Positioning .................................................... 22
   3.3.1 Pseudorange ............................................. 23
   3.3.2 Phase Range ............................................. 24

4 Analysis Of Septentrio PolaRxS Pro Data ................. 27
   4.1 Introduction ............................................... 27
   4.2 Raw Data Logging and Structure ....................... 28
   4.3 Data Extraction .......................................... 30

5 Total Electron Content ........................................ 33
   5.1 Measuring Total Electron Content Using GPS Observables .......................... 33
      5.1.1 Phase Leveling ...................................... 35
      5.1.2 Vertical Total Electron Content (VTEC) .................. 36
   5.2 Electron Density Effects on Positioning ................ 37

6 Septentrio PolaRxS Pro Receiver Biases .................... 39
   6.1 Receiver Differential Code Biases ........................ 39
   6.2 Methods ................................................... 41
      6.2.1 Minimization of Standard Deviations Method ........... 41
      6.2.2 IONEX Map Comparison Method ......................... 43
   6.3 Results and Discussion ................................... 46
   6.4 Conclusion ................................................. 50

7 Ionospheric Scintillation ..................................... 56
   7.1 Introduction ................................................. 56
   7.2 Electromagnetic Waves in a Random Medium ............. 58
   7.3 Theoretical Models of Scintillation ...................... 62
List of Tables

6.1 Septentrio PolaRxS Pro receiver locations .......................... 47
6.2 Average receiver biases .................................................. 48
6.3 Average receiver biases for minimization of variances method using
   both 350 km and 450 km shell heights and IONEX mean method ...... 49

8.1 Mean spectral slope values for given frequency ranges of phase spectra 93
List of Figures

2.1 Electron density profile of the ionosphere in the mid-latitude region
[Watson, (2011)]. ...................................................... 14

2.2 Image of auroral activity as seen from space. Courtesy: NASA .... 16

3.1 Representation of C/A and P code modulation onto L1 carrier signal
[Kulshrestha, (1997)]. .................................................. 26

4.1 Septentrio PolaRxS Pro receiver [“PolaRxS Product”, (2012)]. ... 28

5.1 Example of pseudorange-derived TEC (red), phase-derived TEC (green),
phase-leveled TEC (black), and vertical TEC (blue) [Watson, (2011)]. 36

5.2 Figure demonstrating the geometry of the single layer ionosphere
model [Themens (2013)] ............................................. 37

6.1 Example plot of VTEC derived at the Churchill station for May 24th
- 31st 2013 using the Septentrio PolaRxS Pro GPS receiver with a 350
km shell height in the mapping function. .......................... 41

6.2 Example plot of the sum of standard deviations for given test receiver
DCBs for Churchill, May 24th (black), 25th (red) and 26th (green)
2013. The minimum of each curve is taken to be the receiver bias for
the 24 Hr period. ...................................................... 43

6.3 VTEC derived from the IONEX maps corresponding to the CHAIN
Churchill station for May 24th - 31st 2013. ......................... 45
6.4 Section of IGS network map illustrating the low number of stations located within the Canadian high arctic [Takasu, (2014)].

6.5 Comparison of VTEC using sum-of-variances-derived DCB and IONEX-derived VTEC.

7.1 Example of high rate GPS amplitude scintillation.

7.2 Example of high rate GPS carrier phase scintillation.

7.3 Illustrative example of GPS amplitude and phase spectra predicted by theoretical models.

7.4 Example of Detrended Signal Intensity and $S_4$

7.5 GPS signal intensity undergoing weak scintillation (4:29 UTC) and strong scintillation (4:55 UTC).

8.1 Examples of amplitude (blue) and phase (black) spectra during scintillation events at Cambridge Bay (top) and Iqaluit (bottom) using a 50 Hz sampling rate [Mushini, (2013)].

8.2 Illustrative example of multipath.

8.3 Detrended signal intensity and corresponding $S_4$ during multipath events for three consecutive days, May 25th to 27th 2013 on PRN 5.

8.4 Mean $S_4$ (a) for May 25th and 27th 2013 and modified $S_4$ (b) for May 26th 2013 on PRN 5.

8.5 Example signal intensity spectra using the STFT method.

8.6 Example carrier phase spectra using the STFT method.

8.7 Illustrative demonstration of the scintillation window (red) of the time series and the windows taken before and after the scintillation event (green).
8.8 Histogram of the power law deviation frequency for all signal intensity scintillation events. ........................................ 84
8.9 Histogram of slope values for the power law deviation region in all signal intensity scintillation events. ........................................ 85
8.10 Histogram of slope values for the signal intensity spectra power law deviation region before (a) and after (b) the scintillation event. ........ 86
8.11 Scatter plot between Fresnel frequency (a), $S_4$ (b), and spectral slope (c) and power law deviation. ........................................ 88
8.12 Example wavelet scaleogram for signal intensity scintillation event. . . 90
8.13 Example wavelet scaleogram for signal intensity scintillation event constrained to power law deviation frequency range. ................. 91
8.14 Example wavelet scaleogram for carrier phase scintillation event. . . . 92
8.15 Histograms displaying spectral slope for all phase events within a given frequency range. .................................................... 96
Abbreviations

CHAIN  Canadian High Arctic Ionospheric Network
DCB    Differential Code Bias
DPB    Differential Phase Biases
DOY    Day Of Year
EM     Electromagnetic
EUV    Extreme Ultraviolet
GNSS   Global Navigation Satellite System
GPS    Global Positioning System
IDL    Interactive Data Language
IGS    International GNSS Service
IMF    Interplanetary Magnetic Field
IONEX  Ionospheric Exchange Format
OCXO   Oven-Controlled Crystal Oscillator
PLL    Phase Lock Loop
PRN    Pseudo Random Noise
RINEX  Receiver Independent Exchange Format
SBF    Septentrio Binary File
SI     Signal Intensity
STFT   Short Time Fourier Transform
TEC    Total Electron Content
TECU   Total Electron Content Unit
UTC    Coordinated Universal Time
VTEC   Vertical Total Electron Content
Chapter 1

Introduction and Thesis Outline

1.1 Introduction

Since the first satellite launch in 1978, the Global Positioning System (GPS) has become extremely useful for use among many industrial, military, and civilian applications. In certain applications the accuracy in measurements taken from the transmitted GPS signals is very important [Leick, (2004)]. However GPS signals, and all other electromagnetic signals, can be degraded due to interactions with the Earth’s atmosphere. Different sections of the atmosphere affect these signals differently. A major atmospheric region which can have profound effects is known as the ionosphere. In this region of the atmosphere the neutral atoms and molecules become ionized, predominantly through photoionization, caused by an interaction with solar extreme ultra violet (EUV), hard X-ray, and Lyman-α radiation. This creates a layer of ionized plasma within an approximate height of 60 km to beyond 1000 km above the Earth’s surface. This layer has an impact on trans-atmospheric electromagnetic waves, which can cause the wave to undergo dispersion, refraction, or diffraction. These effects can cause degradation in the signal which can lower the accuracy of the measurements obtained from it, and in more extreme cases the
signal can become so degraded that it cannot be tracked. This loss in accuracy creates a need to thoroughly study and understand the ionosphere in order to lessen or even mitigate the effects seen on GPS signals and all radio communication [Langley, (1998)].

The Canadian High Arctic Ionospheric Network (CHAIN) has undergone an expansion and continues to expand to include a number of new Canadian high latitude and auroral region ionospheric monitoring stations [Jayachandran et al., (2009)]. These stations utilize the Septentrio PolaRxS Pro GPS receiver, a recently introduced receiver to not only CHAIN but the ionospheric monitoring community as a whole. The PolaRxS Pro boasts many useful features. Most important to this study is the capability of sampling GPS signal intensity and phase at a maximum rate of 100 Hz, where previous ionospheric monitoring receivers are only capable of rates as high as 50 Hz. Spectral analysis of this data allows for the study of frequency components up to 50 Hz, a range which was previously impossible in past GPS scintillation studies. Access to this increased frequency range allows for a more robust comparison of experimental data with current theoretical scintillation models. The introduction of the new Septentrio PolaRxS Pro receiver stations will also be used in ionospheric total electron content (TEC) monitoring. Before accurate TEC measurements can be obtained, an accurate method for estimating the receiver differential code bias (DCB) must be established.

1.2 Total Electron Content (TEC)

As GPS signals travel through the ionosphere they experience a group delay and phase advance. These delays and advances are caused by the interaction of the signal with the ionospheric plasma. In the use of GPS for accurate positioning the
group delay and phase advance will cause a timing error in the measurements which can lead to positioning errors. It can be shown that the delay and advance of the signal is proportional to the integrated electron density, TEC, of the ionospheric plasma [Leick, (2004)]. Knowledge of the ionospheric TEC can be used to remove these positioning errors, to first order, in the positioning measurements.

With the availability of at least two simultaneously transmitted signals of different frequencies and knowledge of the dispersive nature of the ionosphere the TEC can be calculated. The basis for TEC calculations lies in the differences in the delay of the signal’s group speeds and the advances in the signal’s phases. These observables are realized through the GPS parameters known as pseudorange and carrier phase respectively. Precise and up-to-date availability of ionospheric TEC is vital in understanding and remedying limitations within radio communication and navigation systems which stem from ionospheric propagation. The constant spatial and temporal availability of GPS allows for a comprehensive and cost efficient method of monitoring the TEC of the ionosphere. TEC monitoring is also a key factor in thoroughly understanding the structure and dynamics of the ionosphere.

An inherent bias lies within the calculation of GPS-derived ionospheric TEC. This bias stems from the hardware used to track the GPS signals (i.e. the GPS receiver, cables, antenna etc) and is likely to vary between receiver setups [Schaer & Dach, (2010)]. There is also a bias associated with the hardware used to transmit the GPS signals, fortunately these biases are estimated and provided by the University of Bern. To obtain accurate TEC this bias, known as the receiver differential code bias (DCB), must be estimated and removed [Garner et al., (2008)]. Many methods of estimating the receiver bias have been proposed through the years, however not all are suitable for all situations. Certain methods require the use of external equipment
aside from the typical GPS receiver setup which is not a feasible approach for many TEC monitoring stations. Other estimation methods rely on assumptions which do not translate to specific geographical areas, such as the Canadian high latitude and auroral regions [Themens (2013)]. Current methods, which can be used, must be examined and the best of which must be determined to ensure an accurate bias is obtained for use with each TEC monitoring station.

1.3 Ionospheric Scintillation

The ionospheric electron content can be spatially and temporally inhomogeneous, forming electron density irregularities and gradients. As radio signals, such as those transmitted by GPS satellites, travel through the ionosphere their wavefront can become distorted through refractive and diffractive interactions with these irregularities. This interaction can cause rapid fluctuations in the signal’s amplitude and phase. The occurrence of these fluctuations are referred to as scintillation. Positioning measurements obtained from signals effected by scintillation will have significant errors associated with them. In the most extreme cases of GPS signal scintillation, GPS receivers can lose their lock on the signal which may cause periods of time in which positioning measurements cannot be obtained. The study of ionospheric scintillation and the characteristics of the irregularities which cause it is an important step towards a fully realized understanding of the ionosphere. Scintillation studies can improve our grasp on the underlying dynamics of the ionosphere and the processes which create these irregularities. Greater insight into ionospheric scintillation can also aid in the advancement of GPS and other radio communication equipment, leading to technological advances which can lessen the impact of scintillation induced error [Strangeways, (2009)], [Secan et al., (1997)].
Spectral analysis of scintillating radio waves has been an area of interest in the past few decades, beginning with the use of radio stellar objects as electromagnetic wave sources [Yeh & Liu, (1982)]; [Crane, (1976)], and more recently scintillation events using GPS. Unfortunately, due to hardware limitations, the extent to which this topic can be investigated is limited. Recent studies have had access to GPS amplitude and phase measurements sampled at a maximum rate of 50 Hz, allowing for spectral analysis of the signal below 25 Hz. The Septentrio PolaRxS Pro receiver allows for signal intensity and phase spectra analysis of frequencies up to 50 Hz, granting the ability to analyze a frequency range previously inaccessible to GPS ionospheric scintillation research.

1.4 Thesis Outline

Chapter 2 discusses the ionosphere, its formation and its composition. The three distinct layers seen in the ionosphere, labeled as the D, E and F layers are each discussed in detail, including the formation and recombination of the ionospheric plasma, the main constituents of the respective layers and the main chemical reactions. There are a few geographical regions in which the ionosphere and its formation processes are distinct. These regions include the polar region, the auroral region (both of which are within the high latitude region) and the equatorial region. These regions and their unique phenomena are discussed. This thesis is concerned predominantly with the high latitude region of the ionosphere as it is the region where all data has been obtained for this study. The effects of electromagnetic wave propagation through the ionospheric medium are derived, with a focus primarily on waves of frequencies coinciding with those transmitted by GPS satellites. The derivation of these effects begins with the Appleton-Hartree equation describing the refractive index for an EM wave propagating through an ionized medium within a magnetic field. The group
and phase refractive indices are derived and their reliance upon the ionosphere's electron content and signal frequency are shown.

Chapter 3 examines the beginnings of GPS with a brief introduction to the system as well as its history. The structure of the signals transmitted by the GPS satellites are detailed, specifically the structure of the signals of interest for this study, i.e the L1 and L2 signals modulated by the coarse acquisition and precision codes. A concise introduction to the method used in GPS positioning is examined followed by the introduction of the two important GPS observables used in positioning: pseudorange and carrier phase. Pseudorange and carrier phase are also the observables of interest in GPS TEC monitoring, which is discussed in the chapter 5.

Chapter 4 describes the Septentrio PolaRxS Pro GNSS receiver. The PolaRxS Pro has recently been introduced into the CHAIN network and plans to install the receiver at additional CHAIN stations are currently underway. The benefits of this receiver compared with the previous ionospheric monitoring receivers are discussed. The structure of the raw binary files produced by the PolaRxS Pro are explained. The knowledge of the structure was used in the creation of software unique to the CHAIN network capable of extracting the relevant data from the raw files used within this study. Details regarding the data extraction are discussed.

Chapter 5 derives the method in which ionospheric TEC is calculated using GPS observables. Utilizing previous derivations the TEC is shown to be proportional to the differences between the pseudoranges and carrier phases on two separate carrier frequencies. The concepts of slant TEC, vertical TEC and the technique of phase-leveled TEC are discussed. The effect ionospheric TEC has on GPS positioning as well as methods of removing this effect are briefly introduced.
Chapter 6 explains the receiver differential code biases plaguing GPS-derived TEC. The three methods used in this study in an effort to obtain an accurate bias for the Septentrio PolaRxS Pros located in the auroral region are explained. These methods include the minimization of standard deviations method as well as two methods involving the comparison of station-derived TEC and TEC obtained from global TEC maps published by the International GNSS Service (IGS). The resulting biases obtained using the aforementioned methods as well as an analysis of the methods is then discussed followed by a conclusion and discussion of the results.

Chapter 7 discusses ionospheric scintillations and their effect on GPS signals. The importance of monitoring and studying ionospheric scintillation from a scientific and industrial view is then discussed. The standard method of quantizing ionospheric scintillation intensity is described in the next section. The effect ionospheric scintillation has on GPS-derived positioning is discussed next. Currently there are a few respected theoretical models which predict the spectra of the amplitude and phase of a GPS signal undergoing scintillation. These models include the phase screen theory and the Rytov approximation which are discussed from a qualitative standpoint for use in comparison with the experimentally obtained signal intensity and phase spectra seen in chapter 8.

Chapter 8 discusses the spectral analysis of the high rate GPS signal intensity and phase. First the methods used in performing the analysis are explained. These methods include short-time Fourier and wavelet transforms which allow for the calculation of the amplitude and phase spectra. Both methods can be used for a temporal analysis of the spectra while the Fourier transform also allowed for a static view. The results obtained from the aforementioned methods are shown and discussed. This is followed by the conclusion and discussion of the results, summarizing the important
results as well as what impact they will have on future analysis.

Chapter 9 concludes the thesis, summarizing the important results seen within the previous sections as well as the influential aspects and their effects on future analysis. Results of importance include the varied receiver biases seen between the PolaRxS pro receivers, the inaccurate values seen within the global TEC maps specifically within the high latitude and auroral regions, the high frequency noise floor seen within the spectral analysis of GPS signal intensity during ionospheric scintillation events and the high frequency deviation from theoretical predictions seen in the phase spectral analysis. This leads to a plan for future work which stems from the knowledge obtained from the analysis seen in this thesis.
Chapter 2

Ionosphere

2.1 Introduction

The history of the ionosphere dates back to initial predictions of electrified layers within the atmosphere in the nineteenth century. However the definitive beginnings lie with Marconi’s famous transatlantic communication experiment in 1901. The successful radio communication from Cornwall to Newfoundland led to hypotheses that an ionized layer of atmosphere must exist for the reflection of the radio waves as it would be impossible for the waves to travel directly from Cornwall to Newfoundland due to the curvature of the Earth [Hunsucker & Hargreaves, (2003)].

The ionosphere is a subsection of the Earth’s atmosphere where the neutral atoms and molecules have become ionized, creating a shell of plasma. The ionosphere in its entirety is typically defined to lie in the region from 60 km to beyond 1000 km above the Earth’s surface, however the boundaries are not well defined. Ionization of the atmospheric layer is done predominantly through photoionization, where high frequency photons emitted by the sun interact with the neutral atoms and molecules in the atmospheric gas. This interaction causes the ejection of an electron from
the atom or molecule, leaving the negative free electron and a positively charged ion [Hunsucker & Hargreaves, (2003)]. The dominant neutral atoms and molecules which undergo the photoionization process in the ionosphere are oxygen (O₂ and O), diatomic nitrogen (N₂) and nitric oxide (NO). Specific conditions are needed to allow for the ionization process of these atoms, conditions which include altitude, time of day, season and solar activity. The ionization of the ionosphere can also be affected by the precipitation of electrons and protons through the “open” magnetic field lines seen in the high latitude regions.

2.2 Composition of the Ionosphere

The composition of the ionosphere consists of three distinct layers classified as the D, E and F layers while the F layer can typically be seen to split into two sublayers, F1 and F2. These layers do not have defined edges and their heights and thicknesses can change based on varied conditions. The layers are uniquely based on the ionization processes of the main neutral species which reside within the layers and the methods by which electron recombination can occur.

The D region is typically classified as lying between 60 km to 90 km, the lowest ionospheric layer, with an average electron density of 10⁸ – 10¹⁰ e/m³. The wavelengths of radiation capable of penetrating into the D region and ionizing the neutral constituents are the Lyman-α radiation with a wavelength of 121.1nm, extreme ultraviolet (EUV) lying in the wavelength range of 102.7 nm - 111.8 nm and hard X-rays within the range of 0.1 nm - 1 nm. However, the hard x-rays are more likely to be seen only during moderate to high solar activity. The Lyman-α radiation is capable of ionizing the NO molecules within the layer, while the EUV radiation ionizes molecular oxygen (O₂). The hard X-rays can ionize almost all the constituents
of the layer, the most common being \(N_2\) and \(O_2\). Therefore the main ions seen in the D layer are \(\text{NO}^+\), \(N_2^+\) and \(O_2^+\). However the \(N_2^+\) are quickly converted:

\[
N_2^+ + O_2 \rightarrow O_2^+ + N_2
\]  

leaving the \(\text{NO}^+\) and \(O_2^+\) ions. Ionization may also occur through the interaction with cosmic rays, more prominently at lower altitudes. Since there is no diurnal dependence on the cosmic rays they are free to ionize the constituents continuously. However their effect is minimal compared to the other ionization processes.

The main ionization reactions occur during daytime hours while the sun’s radiation is capable of interacting with the atmosphere. Since the reaction only occurs during direct interaction with the solar radiation there is a higher electron density during the day compared to the night time. In fact the D layer can almost completely disappear through recombination during the night. The main source of recombination in the D layer is dissociative recombination. In the lower altitudes of the D layer the molecules can become hydrated due to the higher concentration of water vapor. These hydrates have a much higher molecular weight and therefore have much higher recombination rates [Hunsucker & Hargreaves, (2003)].

The E region is labeled as lying between 90 km to 120 km in height with an average electron density of \(10^{11}\) e/m\(^-3\). EUV radiation within the wavelength range of 80 nm - 102.7 nm is capable of penetrating into the layer and ionizing the \(O_2\) molecules. X-rays lying within the 1 nm - 10 nm range also have an effect on the layer, being capable of ionizing almost all constituents. The commonly seen ions in this layer are \(\text{NO}^+\), \(N_2^+\) and \(O_2^+\). However, the \(N_2^+\) are rapidly converted in the same reaction seen in the D layer.
Recombination in the E layer is done through two main reactions: radiative recombination of the type:

\[ X^+ + e \rightarrow X + hv \] (2.2)

and dissociative recombination:

\[ XY^+ + e \rightarrow X + Y \] (2.3)

where dissociative recombination has a much higher recombination rate and is the main driving force of electron loss in the region. Unlike the D region, the free electrons and ions do not completely recombine during night-time in this region, but the electron density decreases significantly. A possible cause of the persistent ionization throughout the night could be meteoric ionization [Hunsucker & Hargreaves, (2003)].

The F region is typically located above 120 km, stretching to the lower side of the plasmasphere. The F layer consists of the bulk of the total ionospheric plasma with a typical density of about \(10^{11} - 10^{12} \, \text{e/m}^3\) [Hunsucker & Hargreaves, (2003)]. Also unlike the lower regions, the F region can split into two, the F1 and F2 regions. This split will depend on different factors, such as the time of day, and the geographical location. Depending on these conditions it is possible that the F1 layer may not exist at all.

The smaller F1 layer typically lies within the 120 km to 200 km region. This region is not always seen, such as during the night time hours due to the lack of solar radiation and is most noticeable during the day, summer, and solar minimum time frames. Radiation within the 20 nm to 90 nm wavelength range interacts with the neutral constituents of the F1 layer creating the common ions within the layer: \(\text{O}_2^+\),
$N_2^+$, $O^+$, He$^+$, and N$^+$. However successive reactions leave NO$^+$ and O$_2^+$ as the most common ions, similar to the lower layers. Like the E layer, the main source of electron loss is through dissociative recombination reactions.

The F2 layer exists above the F1 layer and extends into the plasmasphere. The peak density of the ionosphere typically lies within the F2 region, around 200 - 400 km in the high latitude regions. The maximum density of the layer typically peaks around 1400 hrs local time with a minimum density directly preceding sunrise. Electron loss in the F2 layer occurs mostly through the following reaction

\[
O^+ + N_2 \rightarrow NO^+ + N \\
NO^+ + e \rightarrow N + O
\]

where O$^+$ is the common ion in this region. Due to the molecular weight of N$_2$ compared to the O atoms there is a decreased density of the N$_2$ in this layer. This creates a faster rate of electron production compared to electron recombination. The higher density of O atoms compared to the molecular constituents combined with vertical diffusion through pressure gradients and gravitation effects is also the reason for the formation of the ionospheric peak density within the F2 layer. Below the peak the density of the molecular constituents will be enough to cause the O$^+$ to begin recombination reactions while above the peak the O$^+$ density will decrease due to gravitational effects.

### 2.3 Geographical Differences in the Ionosphere

Figure 2.1 shows a typical electron density profile of the ionosphere during both day and night for maximum and minimum solar cycles in the mid-latitude region. The
several layers discussed above can be seen very clearly, also showing a distinct peak in density in the F region. The density and height of this peak varies diurnally as well as geographically. In low latitude regions the F peak shows an increase in height during the evening hours, typically reaching a maximum height of about 500 km [Davies, (1969)], compared to a peak height of about 200 km to 400 km in the high latitude regions [Hunsucker & Hargreaves, (2003)]. This is due to an eastward electric field in the E layer caused by ionospheric plasma drift by tidal winds. These winds are a result of dayside heating and nightside cooling of the Earth. A subsequent ExB force is created by this electric field and the near parallel magnetic field in the region.
This effect combined with the impact of gravity and pressure gradients forces the plasma from the heightened F2 layer downwards where it settles around 15° to 20° of either side of the geomagnetic equator. These regions of increased electron density are known as the Equatorial Anomaly [Knight, (2000)].

The structure and dynamics of the ionosphere in the high latitude and auroral regions differs greatly from the lower latitudes. In this region the magnetic field lines connect to the outer magnetosphere making it susceptible to particle emissions from the solar wind, unlike in the equatorial region. The outer magnetosphere’s interaction with the solar wind is the main source of activity in the high latitude ionosphere, causing this region of the ionosphere to be extremely dynamic. This region of the ionosphere can be split into two sections, the auroral region and the polar region. These regions can be seen in Figure 2.2.

The auroral region is a ring around the Earth’s geomagnetic poles, residing in the area between the “open” and closed field lines of the Earth’s magnetic field. Typically this is where the auroras (Borealis and Australis) can be seen. These auroral events are caused by an influx of particles originating from solar wind which travel along the Earth’s magnetic field into the atmosphere. The collision of these particles with the neutral species of the atmosphere can cause the neutral species to become ionized, releasing photons with wavelengths which can lie within the visible spectrum.

The polar region is the area contained within the auroral regions, an area which has a close interaction with the Earth’s “open” magnetic field lines. Due to the “open” field lines connection with the inter-planetary magnetic field (IMF) this region is highly susceptible to space weather. Interactions between the conductive magnetospheric plasma passing through the magnetic field within the IMF creates an electric potential through a dynamo action. The resulting electric field will point in the dawn
to dusk direction. This potential appears across the open field lines and has been shown to increase the rate of plasma transport into the polar region [Hunsucker & Hargreaves, (2003)].

### 2.4 Ionospheric Effects on Electromagnetic Waves

The ionosphere is a refractive, dispersive and birefringent medium. To begin looking at the effects of the ionosphere on electromagnetic (EM) waves (specifically GPS signals) we start with the Appleton-Hartree equation, used to describe the refractive index of an EM wave propagating through an ionized medium within a magnetic field [Davies, (1969)].

\[
 n^2 = 1 - \frac{X}{1 - iZ - \frac{\frac{1}{4} Y_s^2}{1 - X - iZ} \pm \frac{1}{1 - X - iZ} \left(\frac{1}{4} Y_s^4 + Y_c^2 (1 - X - iZ)^2\right)^{1/2}}
\]

(2.4)

where:

- \( n \) = The complex refractive index.
- \( X = \frac{\omega^2}{\omega_p^2} \)
- \( Y_s = \frac{\omega \mu}{\omega} \sin \theta \)
- \( Y_c = \frac{\omega \mu}{\omega} \cos \theta \)
\( Z = \frac{\nu}{\omega} \)

\( \nu = \) The electron collision frequency of the medium.

\( \omega = \) The angular frequency of the wave.

\( \omega_p = \) The plasma frequency of the medium.

\( \omega_B = \) The angular electron gyro frequency.

\( \theta = \) The angle between the wave vector and the magnetic field

As we are interested solely in the interaction of GPS signals with the ionosphere in this study, specific assumptions can be applied to the above equation. The frequency of GPS signals fall within the 1-2 GHz range, much larger than the collision frequency within the ionosphere, therefore we can take \( Z \) to be negligible. Making this assumption in (2.4) gives:

\[
n^2 = 1 - \frac{X}{1 - \frac{1}{2}Y^2 \pm \frac{1}{2} \left( \frac{1}{4}Y^4 + Y_c^2 \left( 1 - X \right)^2 \right)^{1/2}}
\]

(2.5)

Expanding the above equation about inverse frequency results in:

\[
n \approx 1 - \frac{1}{2}X \pm \frac{1}{2}XY|\cos \theta| - \frac{1}{8}X^2 - \frac{1}{4}XY^2(1 + \cos^2 \theta)
\]

(2.6)

Since the terms higher than first order become orders of magnitude smaller compared to the first order terms we can further approximate the expression to:

\[
n \approx 1 - \frac{1}{2}X
\]

(2.7)

Substituting in for \( X \):

\[
n \approx 1 - \frac{1}{2}\frac{\omega_p^2}{\omega^2}
\]

(2.8)
\[ \omega_p = \sqrt{\frac{Ne^2}{\epsilon_0 m}} \]  

(2.9)

where:

\( \epsilon_0 = \) The permittivity of free space.

\( e = \) electron charge.

\( m = \) electron mass.

\( N = \) The electron density in the ionosphere.

\[ n \approx 1 - \frac{40.3N}{f^2} \]  

(2.10)

This shows that the refractive index of the ionosphere depends upon the electron density as well as the frequency of the GPS signal, proving the ionosphere is a dispersive medium.

Since we are dealing with modulated waves there are two velocities of interest, phase velocity and group velocity. Equation (2.10) can be thought of as the phase refractive index of the carrier wave and we can derive a similar expression for the group refractive index.

First we define the phase velocity as [Davies, (1969)]:

\[ V_p = \frac{\omega}{k} \]  

(2.11)

and group velocity as:

\[ V_g = \frac{\partial \omega}{\partial k} \]  

(2.12)

where:

\[ k = \frac{2\pi}{\lambda} \]
The wavelength of the signal.

Assuming the dispersion is small, the group and phase velocity can be related by the following [Davies, (1969)]:

\[ V_g = V_p + k \frac{\partial V_p}{\partial k} \quad (2.13) \]

and we may define the group and phase refractive indices as:

\[ n_g = \frac{c}{V_g} \]
\[ n_p = \frac{c}{V_p} \quad (2.14) \]

Using (2.14) in (2.13) results in:

\[ n_g = n_p + f \frac{\partial n_p}{\partial f} \quad (2.15) \]

and using the above in conjunction with (2.10):

\[ n_g \approx 1 + \frac{40.3N}{f^2} \quad (2.16) \]

As with the phase refractive index we see a dependence on the ionospheric electron density and carrier frequency. The difference between the two refractive indices is the sign of the electron density dependent term, indicating an advance in the carrier's phase and a delay in the modulation. Due to the dependence on the electron density, the refractive indices will be highly variable through time and space [Langley, (1998)].
Chapter 3

Global Positioning System

3.1 Introduction

The Global Positioning System consists of a constellation of about 30 active satellites orbiting the Earth with an orbital period of 12 sidereal hours and an orbital altitude of about 20200 km ["Space Segment", (2014)]. Initiated in 1973 and deemed fully operational in 1995 ["Global Positioning", (1995)] the system was implemented as a space-based alternative to the current positioning and navigation systems being used at the time. The satellites transmit information on 3 carrier waves, L1, L2, and L5, with frequencies of 1.575 GHz, 1.228 GHz, and 1.176 GHz respectively ["New Civil Signals", (2014)]. The carrier signals are modulated through phase modulation to allow for the transmission of ranging codes and a navigation message from a satellite to a receiver. Traditionally there were two codes used, the coarse/acquisition code (C/A code) and the precision code (P code). The C/A code is used primarily for civilian use while the P code is an encrypted code reserved for military use. A newer code has recently been introduced, the civilian (C) code, which is transmitted on the L2 carrier. However, the civilian code and the new L5 carrier are of no interest in this particular study.
3.2 Signal Structure and Tracking

The C/A code is a 1023 binary digit pseudorandom noise (PRN) sequence which repeats every millisecond. Each binary digit, or chip, is a microsecond long, therefore 1.023 million binary chips are generated every second. Since the wave is traveling, ideally, at the speed of light the length of each chip can be calculated, which turns out to be about 300 m. This can be thought of as the wavelength of the C/A code. Due to the quickly repeated code a receiver can lock onto a signal very quickly, allowing for quick positioning.

The P code, also a PRN code, generates 10.23 million chips a second, 10 times faster than the C/A code. Therefore the wavelength of the P code is 10 time shorter, about 30 m. The P code is much longer than the C/A code, having a length of \(2.35 \times 10^{14}\) chips, a length of 266 days. Each satellite is only assigned a unique 7 day section of the P code.

A receiver has knowledge of the C/A codes which it uses to track the signals. These PRN codes are uniquely transmitted from each satellite. This allows for the receiver to distinguish between different satellite signals. The receiver replicates the signal and code and attempts to correlate it with the received signal. Through knowledge of the code and the transmission time of the signal the travel time and therefore the travel distance can be computed. An image representation of the modulation of the C/A and P codes onto the L1 carrier can be seen in Figure 3.1.

As well as the ranging codes there is a navigation message which is superimposed onto the signal. This message contains the satellite's ephemeris information, the satellite's clock offset to GPS time and information regarding the satellite's health and anticipated accuracy. Less accurate information regarding the position of the
other satellites within the constellation is also transmitted within the navigation message. This allows for a receiver to quickly acquire other satellites within view after an initial signal is successfully tracked.

Originally the L2 carrier transmitted only the P code while the L1 signal transmitted both the C/A code and P code. To allow for this the satellite transmits two L1 carrier signals which have a phase shift of 90° between them. One would then carry the C/A code while the other carries the P code [Langley, (1998)].

Recently the new civilian (C) code was introduced. This the new code is modulated onto the L2 carrier signal along with the current P code. This new civilian code will allow for greater accuracy for civilian positioning when used in conjunction with the course acquisition code [Leveson, (2006)].

The L5 signal has also recently been introduced with the launch of the Block IIF satellites in 2010 [“New Civil Signals”, (2014)]. This new signal is designed for safety-of-life services, specifically aviation safety services. L5 boasts higher power and greater bandwidth making it a much better option than the previous signals. This will allow for improved accuracy regarding ionospheric corrections when used in combination with the L1 C/A code.

### 3.3 Positioning

GPS positioning is done, in the most basic sense, through trilateration. A given GPS receiver first requires a minimum of three satellites in view to perform the trilateration by calculating the distance between the receiver and each satellite which then allows for the calculation of the receiver location (latitude, longitude and height).
However the receiver also requires one more additional satellite to be in view at a
given time, creating the need for a minimum of four satellites. This additional
satellite is needed, in combination with the others, to estimate the offset between
the satellite clocks and receiver clock. The receiver to satellite distance is calculated
one of two ways, using either the ranging codes modulated to the GPS signal or the
phase offset of the carrier signal [Komjathy, (1997)].

3.3.1 Pseudorange

The first technique used in GPS positioning is through the calculation of the pseudor-
geange. The pseudorange is a measure of the pseudo distance between the transmitting
satellite and a receiver. Using the transmitted ranging codes (C/A, P or C) the re-
ceiver can calculate the lag between the received code and the transmitted code.
This is done by replicating the transmitted signal within the receiver and comparing
it with the signal being received. The lag between these codes corresponds to the
travel time of the code, and therefore the carrier wave. With the knowledge of the
travel time and the speed of the wave (the speed of light) the travel distance can
be computed. However, this calculated distance is an apparent distance between
satellite and receiver, as there are many errors involved, including ionospheric and
neutral atmospheric effects, instrumental delays, clock errors between receiver and
satellite and interference errors such as multipath [Leick, (2004)]. The pseudorange
for a given satellite \( (p) \), receiver \( (k) \), carrier signal \( (n) \) and ranging code \( (a) \) can be
represented by the following Equation [Leick, (2004)]:

\[
P^p_{k,n}(t_k) = \rho^p_k(t_p) + cdt_k - cdt^p + T^p_k(t_k) + \delta^p_{k,n,a} + \epsilon_{n,a} \tag{3.1}
\]

\[
\delta^p_{k,n,a} = d_{k,n,a}(t_k) + d^p_{k,n,a}(t_k) + d^p_{n,a}(t_k) \tag{3.2}
\]
where:
\[ \rho_k^p(t^p) = \text{The geometric distance between the receiver and satellite.} \]
\[ dt_k, dt^p = \text{The clock error in the receiver and the satellite respectively.} \]
\[ c = \text{The speed of light in a vacuum.} \]
\[ I_{k,n,a}(t_k) = \text{The ionospheric delay in code } a \text{ on carrier } n. \]
\[ T_k^p(t_k) = \text{The tropospheric delay on the signal.} \]
\[ d_{k,n,a}(t_k) = \text{The receiver hardware delay.} \]
\[ d_{k,n,a}^p(t_k) = \text{Multipath delay.} \]
\[ d_{n,a}^s(t_k) = \text{The satellite hardware delay.} \]
\[ \epsilon_{n,a} = \text{Measurement noise.} \]

### 3.3.2 Phase Range

Similar to the pseudorange, receiver to satellite distances can be calculated using a difference in the carrier phase between received and receiver generated signals. Note that the range measurement using the phase difference is an ambiguous result due to there being no knowledge of the number of complete cycles the signal has undergone between transmission and reception. The carrier phase can be represented for a given satellite \((p)\), receiver \((k)\) and carrier \((n)\) by the following equation:

\[
\Phi_{k,n}^p(t_k) = \frac{f_n}{c} \rho_k^p(t^p) - f_n dt_k + f_n dt^p - I_{k,n}^p(t_k) + \frac{f_n}{c} T_k^p(t_k) + \delta_{k,n}^p + \epsilon_n + N_k^p \tag{3.3}
\]

\[
\delta_{k,n}^p = d_{k,n}(t_k) + d_{k,n}^p(t_k) + d_{n}^s(t_k) \tag{3.4}
\]

where:
\[ f_n = \text{The carrier frequency} \]
\[ \rho_k^p(t^p) = \text{The geometric distance between the receiver and satellite.} \]
The clock error in the receiver and the satellite respectively.

$c$ = The speed of light in a vacuum.

$I_{k,n}^p(t_k)$ = The ionospheric phase advance on carrier $n$.

$T_{k}^p(t_k)$ = The tropospheric delay on the signal.

$d_{k,n,a}(t_k)$ = The receiver hardware delay.

$d_{k,n,a}^p(t_k)$ = Multipath delay.

$d_n^p(t_k)$ = The satellite hardware delay.

$\epsilon_n$ = Measurement noise.

$N_{k,n}^p$ = The integer ambiguity.

The above equation is in units of cycles and can be converted to distance (meters) by multiplying by the wavelength of the carrier ($\lambda_n = \frac{c}{f_n}$). Note the change in sign in the ionospheric term compared to the pseudorange equation. This is due to the phase advance/group delay discussed in Chapter 2.

With these equations in mind techniques can be created to measure or model the error terms and remove them from the positioning measurements to increase the positioning accuracy. For example, as was discussed earlier we have seen that the ionospheric effects on the signal are proportional to the ionospheric electron density therefore if knowledge of the density can be obtained during the time of a positioning measurement the ionospheric error term can be eliminated.
Figure 3.1: Representation of C/A and P code modulation onto L1 carrier signal [Kulshrestha, (1997)].
Chapter 4

Analysis Of Septentrio PolaRxS Pro Data

4.1 Introduction

The PolaRxS Pro multi constellation (GPS, GALILEO and GLONASS) and multi frequency (L1, L2, L5 and E5abAltBoc) receiver is a newly introduced receiver by Septentrio. Capable of stationary and kinematic positioning and ionospheric monitoring; the important aspect in regard to this study and the CHAIN network. The PolaRxS Pro allows sampling of parameters of interest, GPS signal amplitude and phase, at a maximum rate of 100 Hz, double that of the receivers currently used by CHAIN. The PolaRxS Pro also utilizes an ultra low noise oven-controlled crystal oscillator (OCXO) which allows for less noise in the carrier phase measurements, a necessity in ionospheric monitoring. Septentrio claims that their receiver provides data with a noise level unmatched by the receivers available at the time of release [“PolaRxS Pro”, (2014)]. This claim has yet to be tested by CHAIN.

The receiver houses 2 GB of internal storage for on-board data logging as well as
USB and Ethernet connections to log directly to a PC. The Ethernet availability also allows the unit to connect directly to a network, allowing for remote access and logging. A host of software is provided with the receiver allowing for multiple post processing and real time data analysis. The main software items of interest for the ionospheric community are those which allow for data format conversion (RINEX, ASCII, etc), ionospheric scintillation indices production, and TEC calculation. However for this study custom software was written to extract and produce the required data directly from the raw binary files logged by the receiver [“PolaRxS Application”, (2012)].

Figure 4.1: Septentrio PolaRxS Pro receiver [“PolaRxS Product”, (2012)].

4.2 Raw Data Logging and Structure

The PolaRxS Pro provides a graphical user interface (GUI) to allow for the customization of the data that will be recorded to the raw files, referred to as SBF (Septentrio binary file) files. The SBF files are structured by means of sequential blocks, where each block contains a predefined collection of observables. Theses blocks can be set to a given sampling rate ranging as high as 100 Hz [“PolaRxS
Application”, (2012)]. The blocks of interest in this study are as follows:

MeasEpoch: contains observables such as the pseudorange, carrier phase, Doppler, C/N\textsubscript{0} and the lock-time among others.

IQCorr: contains the I and Q correlation values as well as the carrier phase least significant byte (phaseLSB).

ChannelStatus: contains the satellite elevation angle and azimuth data.

A number of other blocks are logged through necessity however they do not contain data of interest to this study. They are:

MeasExtra: contains supplemental information associated with those obtained within the MeasEpoch block.

ReceiverStatus: contains general information of the status of the receiver.

ReceiverSetup: contains general information regarding the setup of the receiver.

GPSNav: contains the decoded navigation message for one GPS satellite at a time.

CHAIN currently logs the above blocks at the following sampling rates.

50 Hz: IQCorr

1 Hz: MeasEpoch, MeasExtra

0.1 Hz: ReceiverStatus, ChannelStatus, ReceiverSetup

OnChange: GPSNav

However the data used in the scintillation section of the thesis utilized a sampling rate of 100 Hz for the IQCorr block.
4.3 Data Extraction

The raw SBF files obtained from the receiver are, as the name suggests, in a binary format and must be decoded before the data can be used. Software capable of decoding and providing the observables of interest in a prompt and convenient manner was written using the Interactive Data Language (IDL) platform.

To decode the raw SBF files the program must sequentially read through the binary files until it reaches the 2-byte array [0x24, 0x40]. This array indicates the beginning of a block header. This header also contains a cyclic redundancy check (CRC) value which is used in ensuring the raw data of the block has not been modified in any way, an ID number which determines what type of block will follow, and a length value which indicates the length of the current block ["SBF Reference Manual", (2012)].

The header is followed by the GPS time of week and week number representing to the epoch which corresponds to the data contained within the block. This is followed by the observables or the values needed in computing the advertised observables.

A mapping of the blocks is provided by Septentrio which lists the block ID numbers as well as the location and type of each observable. An example of the information provided is as follows: after the header, and time stamps, 8 bytes into the MeasEpoch, block the satellite ID number is located. It is a 1 byte unsigned integer type. If the returned integer is 62 this indicates a problem with the data and it should not be used ["SBF Reference Manual", (2012)].

With some observables Septentrio has opted to employ compression techniques allowing for the logging of large number types while keeping relatively low file sizes and reducing CPU usage. For instance, in the MeasEpoch block the values known
as CodeLSB and CodeMSB are provided. With these two values the pseudorange can be calculated with the following expression:

\[
P = (\text{CodeMSB} \times 4294967296 + \text{CodeLSB}) \times 0.001 \quad (4.1)
\]

The compression techniques are typically only seen within a single block, however with the extraction of the high rate carrier phase a combination of values within the MeasEpoch and IQCorr blocks must be used. From the MeasEpoch block the low rate carrier phase is extracted. This can be used in conjunction with the Doppler frequency observable as well as the phaseLSB, a value provided within the high rate IQCorr block. Using these observables the high rate carrier phase can be constructed with the following [Taylor et al., (2013)]:

\[
\phi_{e_i} = \phi_{r_{i-1}} - f_d \cdot 0.01 \\
k = \left\lfloor \frac{\phi_{e_i} - \phi_{LSB_i}}{65.536} \right\rfloor \\
\phi_{r_i} = k \cdot 65.536 + \phi_{LSB_i} \quad (4.2)
\]

Where:

\( i \) represents the epoch of interest.
\( \phi_r \) is the reconstructed phase.
\( f_d \) is the Doppler frequency.
\( \phi_{LSB} \) is the phaseLSB value.

Note that \( k \) is an integer and must be rounded accordingly. The reconstruction of the carrier phase must be done for all epochs which lie between the phase values logged within the MeasEpoch block. Comparison between the reconstructed phase utilizing the phaseLSB value and carrier phase obtained through the MeasEpoch block with
an increased sampling rate show excellent agreement [Taylor et al., (2013)].

As stated earlier the IQCorr block also contains the I (in-phase) and Q (quadrature) correlation values. These values can be used to get the signal intensity through the following:

\[ SI = I^2 + Q^2 \]  \hspace{1cm} (4.3)

The quartz clocks which are used in GPS receivers are much less accurate and precise than the atomic clocks used on board the satellites. This inaccuracy causes the receiver clock to slowly drift from GPS time if left unattended. Many GPS receivers utilize a clock steering mechanism to ensure the on board clock does not drift too far from GPS Time [Taylor et al., (2013)]; however the Septentrio PolaRxS Pro does not. The PolaRxS Pro instead allows the clock to drift until the error between the receiver and satellite clocks reaches 500 µs at which point the receiver shifts the clocks time by 1 ms. This abrupt change in the receiver clock, typically referred to as a clock jump, can be seen in the pseudorange and carrier phase measurements and must be corrected. The corrected pseudorange (\(\rho_c\)) and carrier phase (\(\phi_c\)) after a clock jump can be obtained from the following [Taylor et al., (2013)]:

\[ \phi_c = \phi - (Nf_s + f_d)0.001 \]  \hspace{1cm} (4.4)

\[ \rho_c = \rho - Nc \]  \hspace{1cm} (4.5)

where \(\phi\) and \(\rho\) are the uncorrected carrier phase and pseudorange respectively, \(N\) is the number of clock jumps that have occurred since logging began, \(f_s\) is the carrier frequency, \(f_d\) is the doppler frequency and \(c\) is the speed of light.
Chapter 5

Total Electron Content

5.1 Measuring Total Electron Content Using GPS Observables

TEC measurements are calculated using the GPS observables pseudorange and carrier phase. The time difference between the receiver and satellite clock, combined with the ionospheric and hardware biases of the satellite and receiver, contribute to the pseudorange value. These values, as well as the carrier phase, are calculated for both the L1 and L2 carrier. The expressions for the pseudorange and carrier phase, in meters, are:

\[
P_1 = \rho_k^P + c(dt^P - dt_k) + I^p_{k,1,P} + T_k^p + c(d_{k,1} + d_1^P) \tag{5.1}
\]

\[
P_2 = \rho_k^P + c(dt^P - dt_k) + I^p_{k,2,P} + T_k^p + c(d_{k,2} + d_2^P) \tag{5.2}
\]

\[
L_1 = \rho_k^P + c(dt^P - dt_k) + I^p_{k,1,L} + T_k^p + c(\phi_{k,1} + \phi^P_1) + \lambda_1 N_{k,1}^p \tag{5.3}
\]

\[
L_2 = \rho_k^P + c(dt^P - dt_k) + I^p_{k,2,L} + T_k^p + c(\phi_{k,2} + \phi^P_2) + \lambda_2 N_{k,2}^p \tag{5.4}
\]

as described in [Leick, (2004)]. Where:
$P_f$ is the pseudorange on carrier $f$.

$L_f$ is the carrier phase on carrier $f$.

$P_k^p$ is the geometric distance between satellite $p$ and receiver $k$.

d$t^p$ and $d t_k$ are the clock errors associated with the satellite and the receiver respectively.

$I_{k,f,P}^p$ and $I_{k,f,L}^p$ are the ionospheric code delay and phase advance associated with signal $f$ respectively.

$T_k^p$ is the tropospheric delay, $d_{k,f}$ and $d_k^p$ are the hardware delays associated with the satellite and the receiver respectively.

$\lambda_f$ is the wavelength of the carrier signal.

$N_{k,f}^p$ is the integer ambiguity in carrier, and the factor $c$ is the speed of light.

For simplicity, measurement noise and multipath have not been included in the above equations.

Taking the difference between observables leaves only the frequency-dependent factors:

$$P_k^p = P_2 - P_1 = I_{k,2,P}^p - I_{k,1,P}^p - c(DCB^p + DCB_k)$$

(5.5)

$$L_k^p = L_1 - L_2 = I_{k,1,L}^p - I_{k,2,L}^p - c(DPB^p + DPB_k) + \Delta N_k^p$$

(5.6)

where:

$DCB^p = \delta_1^p - \delta_2^p$ and $DCB_k = d_{k,1} - d_{k,2}$ are the differential code bias resulting from the satellite and receiver respectively.

$DPB^p = \phi_1^p - \phi_2^p$ and $DPB_k = \phi_{k,1} - \phi_{k,2}$ are the satellite and receiver differential phase bias respectively.

$\Delta N_k^p = \lambda_1 N_{k,1}^p - \lambda_2 N_{k,2}^p$. 

34
The geometry free linear combination equations can be related to slant TEC (sTEC) using the ensuing approximation [Leick, (2004)], derived by integrating equation (2.10) along the ray path:

\[ I_{k,f,P} = -I_{k,f,L} \approx A \frac{sTEC_{k}^{p}}{f^2} \]  

where \( A = 40.3m^3/s^2 \), \( sTEC_{k}^{p} \) is the total electron content (in TECU) along the slanted ray path between satellite \( p \) and receiver \( k \) using a signal of frequency \( f \) (in MHz).

Using the above approximation in combination with 5.5 and 5.6 relationships between sTEC and GPS observables can be generated:

\[ P_k^p = A \left( \frac{f_1^2 - f_2^2}{f_1^2 f_2^2} \right) sTEC_k^p - c(DBP^p - DCB_k) \]  

\[ L_k^p = A \left( \frac{f_1^2 - f_2^2}{f_1^2 f_2^2} \right) sTEC_k^p - c(DPB^p - DPB_k) \]

### 5.1.1 Phase Leveling

The sTEC derived from the carrier phase is extremely precise based on the much higher bit-rate but contains an ambiguity term. The sTEC derived from the pseudorange does not contain an ambiguity but can be extremely noisy. A method of eliminating the ambiguity term must be established to make use of the precision in the phase-based sTEC measurements. The method used in this paper to eliminate this ambiguity is that of [Themens (2013)]:

\[ sTEC_k^p = \frac{1}{A} \left( \frac{f_1^2 - f_2^2}{f_1^2 f_2^2} \right) (L_k^p + W + cDCB_k) \]  

where \( W \) is the leveling constant proposed by [Themens (2013)]. The leveling con-
stant is obtained by finding the mean pseudorange-derived sTEC value within a 20° elevation range at the peak of the satellite of interest’s arc. Notice that the above expression is independent of both the DPB and $\Delta N_p$ terms; thus only DCBs need to be evaluated. Figure 5.1 shows an example of pseudorange-derived TEC (red), phase-derived TEC (green), phase leveled TEC (black), and vertical TEC (blue) which is described in the next section.

![Graph showing pseudorange-derived TEC, phase-derived TEC, phase leveled TEC, and vertical TEC](image)

Figure 5.1: Example of pseudorange-derived TEC (red), phase-derived TEC (green), phase-leveled TEC (black), and vertical TEC (blue) [Watson, (2011)].

### 5.1.2 Vertical Total Electron Content (VTEC)

In the methods described later, vertical TEC (VTEC) is used instead of sTEC. A conversion from sTEC to VTEC is done using a geometric mapping function derived from the single-layer ionosphere model. The mapping function is as follow

$$M(\varepsilon) = \cos(\chi) = \sqrt{1 - \left(\frac{R \cos(\varepsilon)}{R + h}\right)^2}$$  \hspace{1cm} (5.11)
where \( e \) is the elevation angle of the satellite, \( R \) is the mean radius of the Earth, \( \chi \) is the ray’s zenith angle at the intersection with the ionospheric shell, and \( h \) is the height of the thin shell ionosphere, see Figure 5.2. Using this relationship, VTEC is just:

\[
VTEC = sTEC \cdot M(e)
\] (5.12)

![Figure 5.2: Figure demonstrating the geometry of the single layer ionosphere model [Themens (2013)]](image)

5.2 Electron Density Effects on Positioning

As was discussed the ionospheric effect on the positioning parameters is directly proportional to the electron density. However with the availability of two carrier signals a linear combination of the observables of interest can be used to remove the ionospheric effects to first order. Estimation of ionospheric delay to first order is typically accurate on the order of a couple centimeters [Langley, (1998)]. This approach assumes the carrier signals follow the same path through the ionosphere, and therefore encounter the same electron density or TEC. This isn’t entirely true
and under times of intense electron density can cause problems [Langley, (1998)]. If single frequency positioning is being used then the ionospheric effect cannot be differenced out. A few options exist in these situations: the ionospheric effect can be ignored, which is not an ideal option, or a technique of differencing simultaneous measurements between separate, but closely located, stations. This has inherent problems due to the difference in location and elevation and in turn the signal will travel a slightly different ionospheric path to get to each receiver. The last option is to use a model of the ionospheric electron content and remove the effects accordingly. Examples include the worldwide total electron content maps provide by the International GNSS Service [Hernandez-Pajares et al., (2009)] as well as CHAIN for the Canadian high latitude and auroral regions [Jayachandran et al., (2009)].
Chapter 6

Septentrio PolaRxs Pro Receiver Biases

6.1 Receiver Differential Code Biases

The constant availability of the GPS signals allows for a comprehensive and cost efficient method of monitoring the TEC of the ionosphere. Precise and up-to-date availability of ionospheric total electron content is vital in understanding and remediing limitations or problems within radio communication and navigation systems. TEC is also a key factor in understanding the structure and dynamics of the ionosphere. GPS is an invaluable resource in calculating TEC; although with the GPS system, there lies an inherent bias which must be calculated and removed from TEC measurements. This bias stems from the nature of the hardware used to track the GPS signals (i.e. the GPS receiver, antenna, cables, etc.) and can vary between receivers of the same model [Schaer & Dach, (2010)].

The CHAIN network is dedicated to understanding the physics of the ionosphere within the Canadian polar cap and auroral oval regions. CHAIN uses a collection
of radio instruments throughout this region, including GPS data, to monitor the ionosphere and provides near real time TEC data. In an effort to provide more accurate data, CHAIN is adding more GPS receiver stations to its high latitude network. The receivers used in these stations are the Septentrio PolaRxS Pro; new receivers to CHAIN, as well as the ionospheric monitoring community. Due to the recent release of this receiver, little work has been published; therefore work has to be done before accurate ionospheric data can be generated.

In this study the receiver DCB for 6 Septentrio PolaRxS Pro receivers set up at 6 CHAIN stations are determined. Common methods for determining the receiver DCB have been shown to be inaccurate for high latitude regions [Themens (2013)], such as the least squares fit method [Lanyi & Roth, (1988)], due to assumptions unsuited for the high latitude region. Common methods include comparing the TEC measurements generated from GPS receivers with TEC derived from other instruments, using external equipment such as a GPS signal simulator, or by making the assumption that TEC is never negative and simply shifting the TEC positively until the nighttime values are within a few TECU of the positive side of zero [Kao et al., (2013)]. The simple method of shifting the TEC to align the nighttime values close to zero is not appropriate for high latitude regions due to appreciable nighttime plasma transported by an anti-sunward ExB drift [MacDougall & Jayachandran, (2007)]. The new CHAIN stations do not have other instruments accompanying the GPS receivers, further limiting the possible methods that can be used.

In the high latitude regions it is also common to compare GPS-derived TEC with TEC maps generated from data obtained at much lower latitudes though it is suspected that this method can lack the desired accuracy. As was shown in [Themens (2013)] the most accurate method, without other equipment for comparison, is the
minimization of standard deviations method. Another method that could be useful but needs further investigation is using IONEX maps for use as a comparison. Due to these findings the methods used in this study are the minimization of standard deviations method and the IONEX comparison method.

![Station VTEC](image.png)

Figure 6.1: Example plot of VTEC derived at the Churchill station for May 24th - 31st 2013 using the Septentrio PolaRxS Pro GPS receiver with a 350 km shell height in the mapping function.

### 6.2 Methods

#### 6.2.1 Minimization of Standard Deviations Method

The Minimization of standard deviations method, as proposed by [Ma & Maruyama, (2003)], is based on the basic principles of VTEC projection in the horizontally homogeneous ionosphere. In this way, the VTEC from measurements along different ray paths is assumed to be the same, if correctly calibrated. In reality the ionosphere
has horizontal gradients and a vertical structure but assuming these gradients are minimal, all VTEC measurements at a given time can be approximated as equal after removing all biases. More realistically, however, it can be taken that the variance between all VTEC measurements at a given time will be at a minimum after removing all biases; therefore, a range of possible biases can be employed and the bias attributed to the lowest variation in VTEC measurements can be considered the receiver bias. An elevation cutoff angle of 30° was used to minimize the possible effects of signal noise and multipath, although according to [Komjathy & Langley, (1996)] the cutoff angle should not affect the results. Satellite and test receiver biases are removed before converting to VTEC. Satellite biases are taken from the University of Bern’s FTP database at ftp://ftp.unibe.ch/aiub/CODE/. Monthly P1-P2 biases were used. The test receiver biases used ranged from -25 to 25 TECU in increments of 0.1 TECU. The standard deviation of VTECs is calculated as

\[
\sigma_k^b(t) = \sqrt{\frac{1}{P-1} \sum_{p=0}^{P} (VTEC_k^p(t) - \bar{VTEC}_k(t))^2}
\] (6.1)

Where \(\sigma_k^b\) is the standard deviation for a given bias \(b\) and receiver \(k\), and \(P\) is the number of satellites in view at time \(t\) [Ma & Maruyama, (2003)]. The standard deviations are then summed over the chosen test period

\[
\sigma_{k,\text{total}}^b = \sum_{t=t_0}^{T} \sigma_k^b(t)
\] (6.2)

Where \(\sigma_{k,\text{total}}^b\) is the total of all standard deviations during the interval \(t_0\) to \(T\), which was chosen to be 24 hours. This length of time was chosen arbitrarily however longer times were susceptible to problems caused by computational limitations. The minimum total standard deviation is determined and the accompanied test bias is chosen as the daily receiver bias, see Figure 6.2. In this part of the study a shell height of 350 km is chosen, based on the GPS-SCINDA software currently being used.
within the CHAIN network [Carrano, (2007)].

In an effort to keep true to statistical principles a sum of variances rather than standard deviations has been proposed as an improvement on this method [Themens (2013)]. This would modify Equation 6.1 into:

\[ \sigma_k^2(t) = \frac{1}{P-1} \sum_{p=0}^{P} (VTEC_k^p(t) - \overline{VTEC}_k(t))^2 \]  

(6.3)

6.2.2 IONEX Map Comparison Method

IONEX (Ionosphere Map Exchange Format) is a file format used within the IGS community to provide snapshots of the TEC around the globe [Schaer et al., (1998)]. The IONEX files contain VTEC values at 2 hour intervals and in spatial increments
of 2.5° latitudinally and 5° longitudinally. To determine a VTEC value within the grid a simple linear interpolation is performed. The values provided within the maps have all biases removed, where DCBs are typically estimated using network or polynomial fitting techniques [Mannucci et al., (1998)]. This allows for a comparison between the VTEC values found by a given receiver and those obtained from the IONEX maps. This comparison results in

\[ VTEC_I = (sTEC^p_k + DCB^p_k) \cdot M(e) \]

\[ DCB^p_k = \frac{VTEC_I}{M(e)} - sTEC^p_k \]  \hspace{1cm} (6.4)

where the IONEX VTEC is taken as the true VTEC and \( sTEC^p_k \) and \( DCB^p_k \) represent the sTEC and receiver bias, respectively, for a satellite \( p \) and receiver \( k \) and \( M(e) \) is the mapping function.

A shell height of 450 km is used when calculating the mapping function in this method as it is the most commonly used value among the IGS analysis centers when computing the IONEX maps. For a given day upwards of 18 IONEX maps were available from the IGS global data center (ftp://cddis.gsfc.nasa.gov/gps/products/ionex). Due to different techniques used among the analysis centers the IONEX maps can produce slightly different results. With no reason to believe certain analysis centers provide more accurate results for the region than other an average of all available maps were taken. These values are represented as the \( VTEC_I \) used in Equation 6.4.

To compare with the IONEX maps, sTEC is calculated for all satellites for the 24 hour period at a given receiver, \( k \), coinciding with the times in the IONEX maps \( t \). The sTEC used in relationship 6.4 is a 1 minute boxcar average taken around \( t \). The receiver DCB is then calculated from the following:
Figure 6.3: VTEC derived from the IONEX maps corresponding to the CHAIN Churchill station for May 24th - 31st 2013.

\[
DCB_{k,t} = \frac{1}{P} \sum_{p=0}^{P} \frac{VTEC_I}{M(e)} - sTEC_t^p
\]

\[
DCB_k = \frac{1}{T} \sum_{t=1}^{T} DCB_{k,t}
\]

(6.5)

where \(DCB_{k,t}\) is the receiver bias at the bi-hourly epoch \(t\), \(P\) is the number of satellites in view at time \(t\), \(DCB_k\) is the daily receiver bias and \(T\) is the total number of bi-hourly biases [McCaffrey & Jayachandran (2013)].

A second method of retrieving the bias from the IONEX data is by performing a linear regression between the station-derived sTEC and the IONEX-derived VTEC converted to sTEC, as is shown Equation 6.4, over all data available [McCaffrey & Jayachandran (2013)]. This method is also performed and compared with the
previous methods.

Due to the low temporal resolution of the IONEX maps as well as an underwhelming amount of stations in the Canadian high latitude region contributing to the IGS there could be inconsistencies between the IONEX data and the station-derived data. A section of map illustrating the locations of IGS stations is shown in Figure 6.4. The calculation of the receiver biases using the IONEX data will double as an initial test into the validity of the data in this region.

![Figure 6.4: Section of IGS network map illustrating the low number of stations located within the Canadian high arctic [Takasu, (2014)].](image)

### 6.3 Results and Discussion

Six Septentrio PolaRxS Pro receivers located at six different stations within the CHAIN network were used in the receiver DCB calculations. The locations of these stations is outlined in Table 6.1. Due to the recent setup of these receivers, a limited amount of data was available for analysis, ranging from 8 to 22 days of data for a given station. The available data for the stations of interest include day of year (DOY) 144-151, 2013 for Churchill and Gillam, DOY 207-225, 2013 for Kuglutuk.
and DOY 204-225, 2013 for the remaining stations.

<table>
<thead>
<tr>
<th>Location</th>
<th>Code</th>
<th>Latitude (N°)</th>
<th>Longitude (E°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Churchill</td>
<td>Chuc</td>
<td>58.759</td>
<td>265.92</td>
</tr>
<tr>
<td>Gillam</td>
<td>Gile</td>
<td>56.337</td>
<td>265.36</td>
</tr>
<tr>
<td>Edmonton</td>
<td>Edmc</td>
<td>53.357</td>
<td>247.03</td>
</tr>
<tr>
<td>Fort Simpson</td>
<td>Fsic</td>
<td>61.757</td>
<td>238.77</td>
</tr>
<tr>
<td>Fort Smith</td>
<td>Fsmc</td>
<td>60.026</td>
<td>248.05</td>
</tr>
<tr>
<td>Kuglutuk</td>
<td>Kugc</td>
<td>67.818</td>
<td>244.20</td>
</tr>
</tbody>
</table>

Table 6.1: Septentrio PolaRxS Pro receiver locations

The receiver biases averaged over the span of data availability are listed in Table 6.2 where $DCB_{Var}$ and $DCB_{Std}$ represent the receiver bias calculated using the minimization of variances and standard deviations, respectively, while $DCB_{I,Avg}$ and $DCB_{I,Reg}$ represent the receiver bias calculated from the IONEX mean method and IONEX regression method, respectively. Errors are taken as the standard deviation between all daily biases obtained using the respective methods; error in the linear regression method is taken as the standard error in the regression. It can be seen by the standard deviations that the receiver bias varies between daily periods while it should remain constant without any change in hardware. This is believed to be due to problems with the assumptions used in the methods as they describe ideal conditions. However, the daily variations appear to be fairly low based on the standard deviations obtained.

The receiver DCBs calculated using the minimization of standard deviation and variations, as expected, consistently agree within $1\sigma$, where errors do not exceed 1.1 TECU and differences are all within 0.31 TECU. The $DCB_{Std}$ is consistently lower than $DCB_{Var}$, this may point towards systematic underestimation in the receiver DCBs when using the minimization of standard deviations method assuming the
Table 6.2: Average receiver biases

minimization of variances is more statistically accurate.

The minimization of variations method is a more appropriate approach statistically and therefore is chosen as truth for comparisons with the rest of the results. The DCBs obtained from the IONEX methods do not always agree with their minimization of variances counterparts. The biases obtained using the IONEX linear regression show large disagreement with the minimization methods, while the IONEX mean method biases show overlap within 1σ for all stations except Fort Simpson and Kuglutuk. The IONEX-derived biases typically show lower errors than those found with the minimization methods, this can be attributed to the inherent smoothing of the IONEX data itself and stability of IGS stations DCBs.

Note that the two stations whose biases do not agree between the sum of variances and IONEX method are located at the highest latitudes within the stations of interest. The biases obtained from the IONEX method for these higher latitude stations also suggest an overestimation of the IONEX data in this region, which is consistent with the results in [Themens (2013)].
The most noticeable difference between the IONEX and the minimization methods is the shell height used for the mapping function, recalling that the minimization method used a 350 km height where the IONEX data used 450 km. This led to the next step of reevaluating the minimization of variances method using a shell height of 450 km. The results are shown in Table 3.

<table>
<thead>
<tr>
<th>Location</th>
<th>( DCB_{\text{Var}350} ) (TECU)</th>
<th>( DCB_{\text{Var}450} ) (TECU)</th>
<th>( DCB_{f,\text{Avg}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chuc</td>
<td>-5.01</td>
<td>-3.97</td>
<td>-3.33</td>
</tr>
<tr>
<td></td>
<td>( \pm 1.09 )</td>
<td>( \pm 1.20 )</td>
<td>( \pm 0.87 )</td>
</tr>
<tr>
<td>Gilc</td>
<td>-9.75</td>
<td>-8.69</td>
<td>-8.84</td>
</tr>
<tr>
<td></td>
<td>( \pm 0.99 )</td>
<td>( \pm 1.10 )</td>
<td>( \pm 0.90 )</td>
</tr>
<tr>
<td>Edmc</td>
<td>-1.25</td>
<td>-0.36</td>
<td>-0.03</td>
</tr>
<tr>
<td></td>
<td>( \pm 0.68 )</td>
<td>( \pm 0.70 )</td>
<td>( \pm 0.58 )</td>
</tr>
<tr>
<td>Fsic</td>
<td>-6.30</td>
<td>-5.46</td>
<td>-3.20</td>
</tr>
<tr>
<td></td>
<td>( \pm 1.10 )</td>
<td>( \pm 1.16 )</td>
<td>( \pm 0.65 )</td>
</tr>
<tr>
<td>Fsmc</td>
<td>2.03</td>
<td>3.01</td>
<td>1.91</td>
</tr>
<tr>
<td></td>
<td>( \pm 0.97 )</td>
<td>( \pm 1.03 )</td>
<td>( \pm 0.73 )</td>
</tr>
<tr>
<td>Kugc</td>
<td>9.36</td>
<td>10.27</td>
<td>11.57</td>
</tr>
<tr>
<td></td>
<td>( \pm 0.75 )</td>
<td>( \pm 0.77 )</td>
<td>( \pm 0.63 )</td>
</tr>
</tbody>
</table>

Table 6.3: Average receiver biases for minimization of variances method using both 350 km and 450 km shell heights and IONEX mean method.

The biases resulting from the modified shell height show a systematic change on the order of 1 TECU. This systematic increase in bias causes a closer agreement between the minimization of variances and the IONEX mean methods, in turn causing the Kugluktuk station to now agree within uncertainty. This result is in agreement for all stations except Fort Simpson.

VTEC calculated by applying the 450 km shell height and using the biases obtained from the minimization of variances method is compared with the VTEC obtained from the IONEX maps, and presented in Figure 6.5. Each plot shows a three day portion of the data available for each station, DOY 147-149, 2013 were used for Churchill and Gillam while DOY 213-215, 2013 were used for the remaining four
stations. The red curve represents the station-derived VTEC and the black curve represents the IONEX-derived VTEC, measured in TECU and hours UTC.

The IONEX data seems to show a compressed diurnal variability compared to the data obtained from the respective stations. This trend could explain the behavior of the biases obtained from the IONEX methods. The IONEX mean method relies on the overestimation and underestimation of a 24 hour period being cancelled out when the mean is taken. Examining Figure 6.5d shows very little overestimation during the day-time hours for Fort Simpson, therefore the resulting bias does not agree with its minimization method counterpart, as seen in Table 6.2. This lack of diurnal compatibility could also explain the disagreement seen in the IONEX regression technique, $D\!CB_{1,\text{Reg}}$, seen earlier in Table 6.2. It was suggested by [Themens (2013)] that the linear regression should not be effected by the diurnal variations and therefore does not display the effects of the overestimation and underestimation cancellation, resulting in much more inaccurate biases.

### 6.4 Conclusion

The biases obtained show a difference between receivers on the order of 19 TECU. Based on work done by [Schaer & Dach, (2010)] a spread of 19 TECU = 6.66 ns is well within the reasonable limit of biases between receivers of the same model; therefore a single bias cannot be used for all PolaRxS Pros, and biases must be calculated on a receiver by receiver basis.

The biases obtained from the minimization methods lie within $1\sigma$ of one another and therefore it can be said that, with the current accuracy of the measurements, there is no difference between using a sum of variances and using a sum of standard
Figure 6.5: Comparison of VTEC using sum-of-variances-derived DCB and IONEX-derived VTEC
deviations. An increase in shell height from 350 km to 450 km showed a systematic increase in receiver biases of roughly 1 TECU. Work performed by [Komjathy, (1997)] shows that the effect of varied shell height choice on VTEC is no more than 2 TECU, therefore it is assumed that shell height should not significantly affect DCB calculations. Results obtained by [Mushini et al., (2009)] shows that shell heights varying from 250 km to 450 km can result in a shift in VTEC less than 1 TECU. This is consistent with the results seen in this study.

Using the IONEX VTEC to calculate receiver biases may be a viable approach in the region of study. Using a linear regression shows a large overestimation of the bias compared to those obtained from the minimization methods. However, taking the mean of biases obtained using the relationship between IONEX VTEC and station-derived sTEC appears to be a possible method of calculating the receiver bias but may not be reliable. Taking the mean relies on averaging out the decreased diurnal variability shown by the IONEX data. Without longer data sets the validity of this method cannot be determined with certainty. The decrease in diurnal variability shown by the IONEX data is believed to be due, at least in part, to the inherent smoothing caused by the low temporal resolution, as well as a lack of IGS stations in the high latitude region.

Increased solar activity could have been an issue with the data used in the study. Due to the lack of data available, solar activity could skew the results. A sudden commencement storm occurred on DOY 144 with increased activity lasting until DOY 148. Kp values exceeding 4.0 were also observed between DOY 206 and DOY 215. The Kp indices were obtained from the Indices of Global Geomagnetic Activity FTP site, ftp://ftp.gfz-potsdam.de/pub/home/obs/kp-ap/. However, reasonable errors in receiver DCB throughout these high activity days indicate that any effect the
solar activity has had on the receiver DCB calculations are likely to be acceptable.
Chapter 7

Ionospheric Scintillation

7.1 Introduction

In 1946, while monitoring the radio-frequency radiation from the stellar radio source Cygnus, irregular fluctuations were seen in the signal \cite{Yeh & Liu, 1982}. Further investigation showed high correlation of these short-period fluctuations between monitoring stations separated by short distances and showed no correlation with stations with large separation \cite{Smith, 1950}. This indicated that the source of the fluctuations was local and not a feature of the stellar source. Following these results it was later concluded that the fluctuations were caused within the Earth’s atmosphere, resulting in the first observations of ionospheric scintillation \cite{Hartz, 1955}.

Since the launch of the first artificial satellite in 1957 \cite{Yeh & Liu, 1982} ionospheric scintillation has been of growing interest in the scientific community. The motivation for scintillation research comes from two main areas: first, the effects of scintillation on trans-ionospheric radio communication \cite{Yeh & Liu, 1982}; second, scintillation research leads to a better understanding of the dynamics and underlying physics of the ionosphere. With the modern GNSS constellations transmitting continuous,
multi-frequency signals, the study and monitoring of ionospheric scintillation can be performed thoroughly worldwide.

However, modern industrial applications have become reliant on accurate GPS and other radio communications. This creates a need to fully understand the processes which can cause the signal degradation. Ionospheric scintillation research helps further our understanding of the underlying dynamics of the ionosphere and the processes resulting in the irregularities which cause scintillation. As these processes become better understood, improved ionospheric models can be created [Secan et al., (1997)]. Improved models and understanding eventually lead to methods of limiting or eliminating the loss in accuracy seen in GPS and other radio communication due to scintillation [Strangeways, (2009)].

As discussed in Chapter 2, the formation of the ionosphere through ionization of the neutral atmospheric constituents, results in a plasma of positively charged ions and free electrons. The density of this plasma can be unstable and inhomogeneous especially in the higher latitude regions, causing density gradients and irregularities. As GPS signals travel through the ionosphere and interact with these irregularities they can cause interference within the signal. The signal’s wavefront will refract as it enters and exits the ionized medium and can diffract around the edges of the irregularities. This can cause the signal to interfere with itself which can cause large, short scale fluctuations in the signal’s amplitude and phase. These fluctuation events are what we refer to as scintillation. Examples of high rate GPS amplitude and phase scintillation can be seen in Figures 7.1 and 7.2 respectively.
7.2 Electromagnetic Waves in a Random Medium

To begin the study of GPS signals interaction with ionospheric irregularities we start with investigating the effects of electromagnetic waves in a random medium. First we recall Maxwell’s equations for the components of an EM wave:

\[ \nabla \times E = -\frac{1}{c} \frac{\partial B}{\partial t} \]  \hspace{1cm} (7.1)
\[ \nabla \times H = \frac{1}{c} \frac{\partial D}{\partial t} + \frac{4\pi}{c} J \]  \hspace{1cm} (7.2)
\[ \nabla \cdot D = 4\pi \rho_e \]  \hspace{1cm} (7.3)
\[ \nabla \cdot B = 0 \]  \hspace{1cm} (7.4)

where

\( E \) is the electric field.

\( B \) is the magnetic field.
Figure 7.2: Example of high rate GPS carrier phase scintillation.

$H$ is the induction field.

$D$ is the displacement field.

$J$ is the current density.

$\rho_e$ is the net charge density.

These four equations can be used to describe the formation and propagation of all electromagnetic waves [Wheelon, (2004)]. We can relate the magnetic and induction fields through:

$$B = \mu H$$  \hspace{1cm} (7.5)

where $\mu$ is the magnetic permeability. The electric and displacement field can also be related through:

$$D = \epsilon E$$  \hspace{1cm} (7.6)
where \( \epsilon \) is the dielectric constant, which contains the information needed to characterize wave propagation though a given medium. Due to the stochastic nature of the ionosphere we decompose \( \epsilon \) into:

\[
\epsilon(r, t) = \epsilon_0(r) + \Delta \epsilon(r, t)
\]  

(7.7)

where \( \epsilon_0 \) is defined as the average dielectric constant which is a function of position and \( \Delta \epsilon(r, t) \) is the fluctuating component which can vary with position and time.

To derive the electromagnetic field equation we must combine equations 7.1 and 7.2 while assuming that the region of interest has a current density equal to zero \((J = 0)\).

\[
\nabla \times \nabla \times E = -\frac{1}{c} \nabla \times \frac{\partial H}{\partial t} = -\frac{1}{c} \frac{\partial}{\partial t} (\nabla \times H) = -\frac{1}{c} \frac{\partial}{\partial t} \left( \frac{1}{c} \frac{\partial D}{\partial t} \right) = -\frac{1}{c^2} \frac{\partial^2}{\partial t^2} (\epsilon E)
\]  

(7.8)

(7.9)

(7.10)

We can simplify the double curl operation using the following:

\[
\nabla \times \nabla \times E = -\nabla^2 E + \nabla (\nabla \cdot E)
\]  

(7.11)

Using 7.3 and 7.6 while assuming that \( \rho_e = 0 \)

\[
\nabla \cdot D = 0
\]  

(7.12)

\[
\nabla \cdot \epsilon E = 0
\]  

(7.13)

\[
E \cdot \nabla \epsilon + \epsilon \cdot \nabla E = 0
\]  

(7.14)
therefore

\[ \nabla \cdot \mathbf{E} = -\mathbf{E} \cdot \nabla \log \epsilon \]  

(7.15)

where

\[ \nabla \log \epsilon = \frac{1}{\epsilon} \nabla \epsilon \]  

(7.16)

Combining 7.10, 7.11, and 7.15 results in:

\[ -\nabla^2 \mathbf{E} + \nabla(-\mathbf{E} \cdot \nabla \log \epsilon) = -\frac{1}{c^2} \frac{\partial^2}{\partial t^2}(\epsilon \mathbf{E}) \]  

(7.17)

We can approximate the \( \nabla(-\mathbf{E} \cdot \nabla \log \epsilon) \) term to be zero by assuming an isotropic medium. With the substitution of 7.7 this results in [Wheelan, (2004)]:

\[ \nabla^2 \mathbf{E} - \frac{1}{c^2} \frac{\partial^2}{\partial t^2}(1 + \Delta \epsilon) \mathbf{E} = 0 \]  

(7.18)

Substituting \( \mathbf{E}(\mathbf{r}, t) = \mathbf{E}(\mathbf{r})e^{\text{-jwt}} \)

\[ \nabla^2 \mathbf{E}(\mathbf{r})e^{\text{-jwt}} - \frac{1}{c^2} \frac{\partial^2}{\partial t^2}(1 + \Delta \epsilon) \mathbf{E}(\mathbf{r})e^{\text{-jwt}} = 0 \]  

(7.19)

We can modify Equation 7.19 to be written as scalar through the following assumptions [Yeh & Liu, (1982)]:

The scintillation causing irregularity is located at a given height above the receiver and has a thickness \( L \).

The size of the irregularity is much larger than the wave’s wavelength.

The variations within the irregularity in time are much smaller than the period of the wave of interest.
\[ \nabla^2 E(r) + k^2 (1 + \Delta \epsilon(t)) E(r) = 0 \]  \hspace{1cm} (7.20)

where \( k = \frac{2\pi}{\lambda} \). The solution to this wave equation forms the basis for scintillation theory.

### 7.3 Theoretical Models of Scintillation

Current ionospheric scintillation models, such as the Phase Screen Theory and the Rytov approximation, show good agreement with the lower frequency results previously investigated [Mushini, (2013)]. Phase Screen Theory is based on the idea of electromagnetic wave diffraction with a phase-changing irregular screen. The screen contains irregularity slabs acting as thin screens which alter the phase of the propagating wave through constructive and destructive interference. The theory is capable of predicting how the phase and amplitude of radio waves are affected when interacting with irregularities in the ionospheric electron density in the weak scintillation regime. The use of the Rytov approximation to expand on the Phase Screen Theory allows the prediction of radio waves during medium to strong scintillation ([Crane, (1976)], [Yeh & Liu, (1982)]).

These theoretical models predict a power law relationship between power and inverse frequency, meaning the spectral power is proportional to \( f^{-p} \). Utilizing a log-log scale would show a linear decrease in power as frequency increases with a slope of magnitude \( p \), known as the spectral index, where \( p \) has been shown to vary between 1.5 to 4, approximately, depending on location, irregularity characteristics and ionospheric conditions [Mushini, (2013)], [Fang et al., (2012)]. The theoretical results show that different irregularity scales contribute to scintillation. It can be shown that in phase
scintillation all irregularity sizes can contribute to the scintillation while with amplitude scintillation irregularity sizes larger than the Fresnel distance are filtered out. Therefore the signal's amplitude displays a constant spectrum up to a given frequency followed by the power law structure. This frequency is referred to as the Fresnel frequency \cite{Yeh & Liu, (1982)}. An illustrative example of the theoretical predictions for GPS amplitude and phase scintillation can be seen in Figure 7.3.

![Illustrative example of GPS amplitude and phase spectra predicted by theoretical models.](image)

Figure 7.3: Illustrative example of GPS amplitude and phase spectra predicted by theoretical models.

### 7.4 Quantifying Scintillation

A typically used standard has been developed in the measurement and quantification of scintillation events known as $S_4$ and $\sigma_\phi$. The signal's amplitude time series are filtered using a high pass filter with a cutoff of 0.1 Hz. The effect of the filter is to remove the trend of the signal as well as the low frequency components of the signal originating from the slow varying receiver clock, multipath and satellite dynamics. The resultant time series can be used to calculate the $S_4$ and $\sigma_\phi$ indices, indices used to quantify the amplitude and phase scintillation respectively. $S_4$ is defined as the
normalized standard deviation of the amplitude (P):

$$S_4 = \sqrt{\frac{\langle P^2 \rangle - \langle P \rangle^2}{\langle P^2 \rangle}}$$

(7.21)

and $\sigma_\phi$ is defined as the standard deviation of the phase:

$$\sigma_\phi = \sqrt{\langle \phi^2 \rangle - \langle \phi \rangle^2}$$

(7.22)

Note that $\langle \rangle$ denotes a time average, typically taken over 1 minute intervals [Van Dierendonck et al., (1993)].

Figure 7.4 shows an example of detrended signal intensity with the corresponding $S_4$. Typically scintillation index values between 0.1 and 0.5 are considered weak scintillation events while values between 0.5 and 1 are considered moderate to high. Figure 7.5 shows an example of weak scintillation (seen around 4:29 UTC) and strong scintillation (seen around 4:55 UTC).

### 7.5 Scintillation Effects on Positioning

The rapid fluctuations caused by ionospheric scintillation can cause a degradation in GPS signals and in the most extreme cases it can cause the receiver to lose lock on a signal entirely. When scintillations affect the signal the carrier phase and signal intensity will rapidly fluctuate. The rapid fluctuations in the carrier phase causes
a Doppler shift in the signal. If the Doppler shift exceeds the bandwidth of the receiver’s phase lock loop (PLL) it will cause a loss of lock on the signal making it unable to record data for a period of time. However, increasing the PLL bandwidth to mitigate scintillation effects will increase measurement noise and is therefore not an ideal solution [Banville et al., (2010)]. If the receiver loses lock on the signal it will lose count of the carrier phase measurement which will have adverse effects in both ionospheric and position based measurements [Banville & Langley, (2013)].

Amplitude fluctuations caused by scintillation effects can also cause a receiver to lose lock. This occurs if the amplitude of the signal fades so heavily that it causes the signal-to-noise-ratio to drop below the receivers threshold [Skone et al., (2001)].
This is typically a rare occurrence among modern receivers as it would require severe scintillation to drop below the threshold [Leick, (2004)]. These occurrences of loss of lock are more likely to happen in receivers employing codeless or semi-codeless techniques, techniques used to gather information from the encrypted P code without having full knowledge of the code itself. Codeless and semi-codeless tracking loops undergo a loss of about 27-30 dB and 14-17 dB respectively, in respect to full code correlation, making them more susceptible to amplitude fading [Banville et al., (2010)].

The L2 PLL uses a smaller bandwidth, that of about 1 Hz compared to 15 Hz on L1, which makes it more susceptible to phase loss of lock in all receiver types [Skone et al., (2001)]. Due to its lower signal power, L2 is also more prone to having a loss of lock during scintillation activity therefore scintillation research is typically done using the L1 GPS carrier signal which is true for this study.
Chapter 8

100 Hz GPS Amplitude and Phase Scintillation Analysis

8.1 Ionospheric Scintillation Research

The study of ionospheric scintillation has an importance in both the scientific and commercial fields. From a scientific standpoint the study of scintillation can further our understanding of the processes that are the cause of ionospheric scintillation. This will help to supplement our knowledge of the ionosphere as a whole. With a better grasp on the ionospheric medium and the formation of the scintillation causing irregularities more accurate models can be created. Access to more accurate models and a greater understanding of the ionosphere naturally leads to more resilient technologies which are currently negatively affected by the ionosphere. Most prominent examples being those associated with GPS positioning, i.e. the creation of GPS receivers which can better withstand scintillation effects and models which can more accurately remove errors within positioning measurements.

Spectral analysis of ionospheric scintillation affecting GPS signals can be used in
study the specific characteristics of the irregularities which cause scintillation. These characteristics include the size and drift speed of the irregularity [Yeh & Liu, (1982)]. The spectral characteristics of the scintillating signal, such as the slope of the power law behavior, can be used in relating the processes causing scintillation to other physical systems. However spectral analysis of GPS signals is limited by the currently available technology. With the introduction of the Septentrio PolaRxS Pro a larger spectral range can be examined with the availability of 100 Hz sampled signal intensity and phase, double the previously available sampling rate [Mushini, (2013)]. Figure 8.1 shows an example of amplitude (blue) and phase (black) spectra during scintillation at Cambridge Bay (top) and Iqaluit (bottom) using a 50 Hz sampling rate [Mushini, (2013)].

This frequency range has not been available for GPS scintillation research in the past so the region must be examined to determine whether it can be of use to ionospheric scintillation spectral research. Previous work suggested that scintillation characteristics could not be seen in the higher frequency regions [Mushini, (2013)], however without access to this region it could not be fully determined. The PolaRxS Pro now allows for analysis of this realm to determine whether scintillation characteristics can be seen at higher frequencies and whether they are plagued by noise. The spectral analysis was chosen to be done through a temporal view of the spectra, showing how the power changes through time, as well as a static view. The temporal view was used to determine whether there are any dominant frequencies in the high frequency region during scintillation events effecting GPS signal intensity and phase. The static method was used for a statistical analysis of the high frequency range, used to begin determining whether the range contains useful scintillation information. Establishing the maximum frequency at which we can detect scintillation characteristics will allow the CHAIN network to adjust the in-field receivers to an
optimal sampling rate for observing GPS scintillation.

8.2 Data Analysis

High rate GPS signal intensity and phase was available for the Churchill and Gillam stations located within the CHAIN network for May 24th to 31st 2013, located at 58.759°N, 265.92°E and 56.337°N, 265.36°E respectively. The data is limited to two stations due to download bandwidth limitations. These limitations prevent the CHAIN network from logging and transferring continuous 100 Hz GPS signal intensity and phase at this time and therefore only continuous 50 Hz data can be obtained. The Churchill and Gillam stations were left to log a small set of 100 Hz data upon installation specifically for this study before being changed to the continuous 50 Hz.
To perform the statistical analysis on the scintillation events algorithms which are capable of determining scintillation events within the GPS signal intensity and phase time series were created to ensure a large number of events could be analyzed in a timely manner. To begin determining possible scintillation event candidates the algorithm examines one-hour segments of signal intensity and phase taken from the raw SBF files by calculating the corresponding scintillation indices. Note that the scintillation indices were chosen to be taken over a one second timed average as opposed to the typical one minute average [Van Dierendonck et al., (1993)]. Time series containing scintillation indices greater than 0.1 with elevations greater than 30° are considered possible candidates [Mushini, (2013)].

However, ionospheric scintillation is not the only cause of fluctuations in GPS signal intensity and phase. Therefore the algorithm must determine true scintillation events from false positives. The most common false positives can come from multipath. Multipath is the fluctuation in GPS signal intensity and phase caused by the signal reaching the receiver antenna by two or more paths. The signal can travel multiple paths by reflecting off nearby structures [Serrano et al., (2005)], [Leick, (2004)]. An illustrative example of multipath can be seen in Figure 8.2. These structures can be natural or man made and are typically permanent. Since GPS satellite complete their orbit approximately twice per sidereal day the effects of multipath should be repeated in the data at half sidereal day intervals. For simplicity full sidereal day intervals were chosen to be used. The offset of a sidereal day is -235.91 seconds from the 24 hour day.

After determining a possible scintillation event the algorithm will analysis the data from the same satellite for the two closest additional days. An example of multipath affecting the signal intensity for three consecutive days, May 25th – 27th 2013, can
be seen in Figure 8.3. In this example May 26th contains the possible scintillation event, at 6:44 UTC, so the day before and after has been obtained and shifted based on the sidereal day offset [McCaffrey & Jayachandran (2014)].

The scintillation indices for the three days are then calculated. The mean of the indices for the two offset days is then taken (Figure 8.4a). The mean is then subtracted from the scintillation indices of the possible event (Figure 8.4b). The resulting modified indices are then examined and the event is determined to be scintillation if it still contains indices greater than 0.1. Note that the true threshold for scintillation events is now slightly greater than 0.1 due to the baseline scintillation indices being subtracted out of the modified indices. In the modified $S_4$ example we see that the fluctuations seen around 6:30 UTC have been eliminated while the event at 6:44 UTC remains with indices greater than 0.1 indicating scintillation [McCaffrey & Jayachandran (2014)].
Figure 8.3: Detrended signal intensity and corresponding $S_4$ during multipath events for three consecutive days, May 25th to 27th 2013 on PRN 5.
Two methods were used in the spectral analysis of the GPS signal intensity and phase time series data, Fourier and wavelet transform. Wavelet transform is a fairly new technique in the study of GPS signals. The software used for the wavelet analysis was provided by [Torrence & Compo, (1998)] and has been investigated for GPS ionospheric scintillation studies, specifically in the high latitude region, by [Mushini, (2013)]. It has been shown that wavelet analysis provides a more robust alternative to the Fourier transform by allowing for an improved temporal look at the spectra compared to the Fourier transform techniques. However the Fourier transform provides a higher resolution of spectral data when performing a stationary analysis which was more important with this study.
Figure 8.4: Mean $S_4$ (a) for May 25$^{th}$ and 27$^{th}$ 2013 and modified $S_4$ (b) for May 26$^{th}$ 2013 on PRN 5.
A short-time Fourier transform (STFT) technique was also employed to examine the spectra of the signal intensity and phase. This is done by splitting the time series of interest into 1 minute, sequential windows and performing a Fourier transform on each window separately. The mean of the 1 minute transforms is then taken within a section surrounding the scintillation event. This section was taken to be 4 minutes, 2 minutes to either side of the peak of the event, where the peak is defined as the point of largest fluctuation in the time series. The window size and location have been chosen based on a quick analysis of a subset of events showing a satisfactory trade off between elimination of scintillation data and inclusion of noise. The transform can also be examined in a pseudo-temporal view of the spectra through a scintillation event by plotting the windows sequentially [McCaffrey & Jayachandran (2014)]. This technique was used as a comparison with the wavelet transforms in an effort to eliminate any artifacts which may have been caused by either technique.

8.3 Results and Discussion

Typical spectra computed from the 100 Hz GPS signal intensity using the STFT method can be seen in Figures 8.5. The low frequency range shows a smooth spectra followed by a power law structure beginning at the Fresnel frequency. The power law structure continues through the mid-frequency range. These are expected characteristics for the low to mid-frequency range based on the theoretical predictions as well as previous work. In Figure 8.5a the Fresnel frequency is located around 0.6 Hz. However at about 9 Hz we see a deviation from the power law into another section of smooth spectra, which does not conform to the current theoretical models. Note that the Fresnel frequency and power law deviation frequency can vary between events as can be seen in the other examples. Figures 8.6 show the spectra of the signal’s
carrier phase for the same scintillation events seen in the signal intensity examples. The phase spectra shows the expected power law characteristic through a larger frequency range than the signal intensity spectra. In the higher frequency range a much less abrupt deviation from the expected power law occurs. In this example the slope is seen to change above 10 Hz to a shallower value, slowly decreasing to a possibly flat spectra near the Nyquist frequency.

An algorithm was written to determine the deviation frequency for all events after they are confirmed to be scintillation. The technique involves determining the spectral slope for sequential, overlapping frequency ranges. This range is chosen to be 1 Hz based on testing which showed this range to produce the most accurate results. These 1 Hz windows are chosen to overlap by 0.5 Hz which results in 99 sequential slopes determined for each event. The algorithm then detects if and where an abrupt change in the spectral slope occurs and returns the corresponding frequency. The algorithm used to determine the power law deviation frequency is believed to be accurate to within a few Hz.
Analysis of the signal intensity scintillation events shows that the frequency at which the power law deviates is not constant. Figure 8.8 shows that this frequency can lie at any frequency less than 40 Hz. However, the majority of events begin to deviate below about 20 Hz.

Figure 8.9 shows the spectral slope values for the frequency range beyond the deviation frequency in the signal intensity spectra. It can be clearly seen that the slope is consistently very close to 0, alluding to a continuous spectra in the higher frequency range. The mean slope value for these events is -0.0353 with a standard deviation of 0.1668.

In an effort to determine if the higher frequency regime of the signal intensity scintillation events is noise or is in fact associated in some way with the scintillation
Figure 8.5: Example signal intensity spectra using the STFT method.
Churchill May 24 2013 PRN 7, time 21:54 UTC

Phase Power (dB/Hz)

Frequency (Hz)

(b)
Figure 8.6: Example carrier phase spectra using the STFT method.
event, the slope of this region was taken during a window just before and after the scintillation event occurs. As was stated in the previous section, when a scintillation event is found a four minute window of the time series data is taken for analysis. This window is determined by finding the peak in the scintillation intensity of the event and taking two minutes to either side of it. To determine the slope of the high frequency range before and after the event a four minute window is taken directly before and directly after the scintillation event window.
The high frequency region of interest is then determined by finding the deviation frequency during the scintillation event. Figures 8.10a and 8.10b show the histograms of these high frequency slopes before and after the scintillation events respectively. It can be seen that the mean slope value remains very close to zero for all three windows. The mean values are -0.0489 with a standard deviation of 0.2219 before the scintillation event and a mean of -0.0475 with a standard deviation of 0.1801 for after.

Figure 8.8: Histogram of the power law deviation frequency for all signal intensity scintillation events.

Figure 8.11 shows scatter plots between the power law deviation frequency and the associated Fresnel frequency, $S_4$ index, and spectral slope separately. Figure 8.11a shows a possible indication of decreased Fresnel frequency with an increase in power law deviation frequency. Figure 8.11b does not appear to show any correlation between $S_4$ and deviation frequency. Figure 8.11c seems to indicate an increase in spectral slope with increased power law deviation frequency. However there is no strong correlation between these parameters and the deviation frequency.
Wavelet scaleograms were used to analyze the spectra of the GPS signal intensity through time during all scintillation events. This method was originally used in an effort to determine whether any dominant frequencies were present in the high frequency signal intensity or phase during scintillation events. Scaleogram were computed for all events and analyzed manually. No dominant frequencies were conclusively found. The scaleogram where then used as an alternative view of the signal intensity deviation regime.

Figure 8.12 shows the detrended GPS signal signal intensity (upper plot) and an example scaleogram (lower plot) for May 24th 2013, PRN 22 at the Churchill station. The scintillation event can be seen between 12:36 and 12:45 UTC. During the scintillation event the peak power is seen at the lower frequency range with a decrease in power as the frequency increases, which is expected from what was seen with the Fourier transforms. The high frequency portion of the scaleogram shows little to no
Figure 8.10: Histogram of slope values for the signal intensity spectra power law deviation region before (a) and after (b) the scintillation event.
Figure 8.11: Scatter plot between Fresnel frequency (a), $S_4$ (b), and spectral slope (c) and power law deviation.
power during the scintillation event, this is due to the low frequency power overpowering the higher frequencies. To get a temporal look at the higher frequency portion, the approximate deviation frequency is determined from the STFT method and the scaleogram is trimmed to include only larger frequencies. This can be seen in Figure 8.13. During the scintillation event a slight high power feature can be seen at the lowest plotted frequencies, this is believed to be a portion of the lower frequency power law structure. Examining the higher frequency portion of the scaleogram for times before, after and during the scintillation event further imply that the higher frequency portion has a constant spectrum.

Figure 8.14 shows a typical wavelet scaleogram for a carrier phase scintillation event. Very little can be seen due to the power law behavior of the spectrum. The lowest frequencies show the highest power and therefore overwhelm the lower frequencies. The scaleogram examples shown are representative of the large majority of the events.

Figure 8.15 shows the spectral slopes of the phase spectra within different frequency ranges. The ranges chosen are 1 Hz to 10 Hz, 10 Hz to 20 Hz, 20 Hz to 30 Hz, 30 Hz to 40 Hz and 40 Hz to 50 Hz for Figures 8.15a through 8.15e respectively. Figure 8.15a, representing the 1 Hz to 10 Hz range, shows a peak in histogram density between the spectral slope range of -1.5 and -2. This is within the expected range of spectral slopes when performing GPS scintillation spectral analysis in the Canadian high latitude region, \(-1.75 \pm 0.25\), as seen in [Mushini, (2013)].

Figure 8.15b, showing the slopes within the 10 Hz to 20 Hz range shows similar results to Figure 8.15a, however the peak of the histogram has become less defined, showing a spread in the peak within the -1.5 to -2.5 range.

In the 20 Hz to 30 Hz range, Figure 8.15c, the histogram peak makes a clear shift
Figure 8.12: Example wavelet scaleogram for signal intensity scintillation event.
Figure 8.13: Example wavelet scaleogram for signal intensity scintillation event constrained to power law deviation frequency range.
Figure 8.14: Example wavelet scaleogram for carrier phase scintillation event.
much closer to a value of -1. Figure 8.15d, displaying the slopes within the 30 Hz to 40 Hz range, shows another shift in the peak, again shifting more positively to a value just below zero. Figure 8.15e, the 40 Hz to 50 Hz range, shows a clear mean slope very near zero.

Clearly there is a trend in mean spectral slope as higher frequencies are examined, showing that the phase spectral slope is gradually increasing. However the histograms for the higher frequencies, specifically the 30 Hz to 50 Hz range, have a large spread in spectra slopes, with possible extremes lying around -4 up to about 1. Table 8.1 shows the mean slope value and standard deviation for the respective frequency ranges. The increase in mean slope with increased frequency is clearly seen. However, an increase in standard deviation is seen as well. This increase in standard deviation may indicate that not all scintillation events show an increase in spectral slope at the same rate.

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>Mean Slope</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Hz - 10 Hz</td>
<td>-1.92</td>
<td>0.43</td>
</tr>
<tr>
<td>10 Hz - 20 Hz</td>
<td>-2.01</td>
<td>0.71</td>
</tr>
<tr>
<td>20 Hz - 30 Hz</td>
<td>-1.21</td>
<td>0.75</td>
</tr>
<tr>
<td>30 Hz - 40 Hz</td>
<td>-0.78</td>
<td>0.95</td>
</tr>
<tr>
<td>40 Hz - 50 Hz</td>
<td>-0.43</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Table 8.1: Mean spectral slope values for given frequency ranges of phase spectra

**8.4 Conclusion**

The characteristics of the high frequency components of GPS signal intensity and phase during ionospheric scintillation events were examined. The observed spectrum for the signal intensity and phase show a deviation from the qualitative predictions seen by the current theoretical models. In the signal intensity spectra an abrupt
Spectral Slope Between 1 Hz and 10 Hz

(a)

Spectral Slope Between 10 Hz and 20 Hz

(b)
Spectral Slope Between 20 Hz and 30 Hz

Spectral Slope Between 30 Hz and 40 Hz

(c)

(d)
Figure 8.15: Histograms displaying spectral slope for all phase events within a given frequency range.
deviation from the predicted power law behavior is observed. The frequency at
which this deviation occurs is not constant between events. However frequencies
below 20 Hz are favored.

Correlation between the power law deviation frequency and the Fresnel frequency,
spectral slope and scintillation index were examined. Possible correlation between
the decrease in Fresnel frequency and increase in deviation frequency as well as
increase in spectral slope with increased deviation frequency was noted, however the
correlation between these parameters is weak and must be further investigated.

The slope of the spectra within the frequency range greater than the deviation fre-
quency show a mean value very close to zero. The slope of this high frequency region
also appears to remain unchanged by a scintillation event. These results combined
with the temporal analysis of the signal intensity spectra during scintillation events
seem to indicate a constant spectrum within the higher frequency range. This can
be taken as a strong indication that the higher frequency region of the GPS sig-
nal intensity spectra is noise, at least up to 50 Hz, the highest frequency currently
accessible.

The phase spectra show a deviation from the qualitative theoretical predictions dis-
tinct from the signal intensity spectra. In the increasingly higher frequencies a
progressively shallower spectral slope is seen. The results indicate that the initial
deviation occurs most commonly around the 20 Hz range, showing a mean slope
increase from -1.92 to -1.21. Closer to the 30 Hz to 40 Hz range shows another
increase in mean spectral slope -0.78. The highest range observed, 40 Hz to 50 Hz,
shows a clear mean very near zero, -0.4349. This indicates that the spectral slope of
the signal’s phase during scintillation events slowly increase from their respectively
value to near zero. However despite the clear near zero mean, the slope values in the higher frequency range, 30 Hz to 50 Hz specifically, show a higher standard deviation possibly demonstrating that the spectral slope of all events are not increasing at the same rate. With the current data it can be hypothesized that all the phase spectral slopes will eventually reach zero. However a higher sampling rate is needed to confirm this.

With the currently available data it seems likely that the majority of GPS signal intensity events do not contain scintillation characteristics above 20 Hz. However GPS carrier phase shows the possibility of scintillation characteristics at frequencies up to, and possible beyond 50 Hz. These events also show a slowly changing spectral slope which does not agree with the current theories.

This shows that a sampling rate of 50 Hz should be sufficient for FPS signal intensity scintillation monitoring. For carrier phase scintillation monitoring, how to choose an optimal sampling rate is still unclear. The introduction of noise in the signal intensity at lower frequencies than the corresponding phase conforms with the methods used by the hardware at obtaining these observables. The methods used to obtain the signal intensity are expected to be much noisier than the phase thanks in part to the oven controlled crystal oscillator used by the PolaRxS Pro receiver.
Chapter 9

Conclusion And Future Work

9.1 Summary

9.1.1 Receiver Biases

The differential code biases were estimated for six auroral region PolaRxS Pro GPS receivers using four different methods. The resulting biases show a maximum difference on the order of 19 TECU between the six receivers with maximum errors on the order of 1 TECU. This difference ensures the need to calculate the DCBs for each receiver separately as it is incorporated into the CHAIN network. Receiver biases are assumed to be constant through time therefore the Septentrio biases should only need to be estimated once after they are installed in the network assuming there are no hardware changes after installation. The minimization of standard deviations method has been shown to be fairly reliable in the auroral region in past results therefore the values it produced were taken as the true bias values and were used to test the IONEX comparison methods. The two variations of the minimization of standard deviation method show nearly identical results.

The linear regression IONEX method results did not agree with the minimization
of standard deviation bias values. The linear regression values showed a consistent overestimation typically on the order of 5 TECU to 7 TECU. The IONEX mean method returned results which do agree within $1\sigma$ for four of the six stations. In an effort to obtain biases from the IONEX mean method that agree with the minimization methods for all stations the minimization method was performed using a modified ionospheric shell height, one that matches those used in the IONEX map creation. The DCBs obtained using the modified shell height of 450 km showed agreement for five of the six stations. The results indicate that the shell height used in bias estimation may have a significant impact.

Graphical comparison of the VTEC obtained from the IONEX maps and VTEC obtained from the CHAIN stations of interest showed interesting results. After removing the minimization of standard deviations derived biases from the CHAIN data the IONEX data was expected to agree with the five stations whose biases agreed. However the IONEX data showed consistently compressed diurnal variability. This would result in the mean VTEC over a daily multiple length of time agreeing between IONEX and CHAIN. However, the VTEC at a given epoch is likely to disagree. This may indicate that the agreement seen between minimization of standard deviation and IONEX comparison bias estimation is a coincidence. The compressed diurnal variability seen in the IONEX data is believed to be a byproduct of inherent smoothing due to low spatial and temporal availability of VTEC data in the Canadian high latitude and auroral regions.

### 9.1.2 Spectral Analysis

Spectral analysis of high rate GPS signal intensity and phase data during scintillation events between May 24th and May 31st 2013 were examined. The results showed deviations from the qualitative predictions obtained from currently accepted theories.
The signal intensity spectral results showed abrupt deviations from the expected power law behavior. The power law diverges to a constant spectrum at a frequency which was shown not to be consistent between scintillation events. Due to the constant nature of this section as well as the results confirming that this region shows no significant change during the scintillation the deviation was concluded to be noise. Since the frequency at which the scintillation characteristics begin to become overwhelmed by noise is not constant between events it should be determined and filtered accordingly before scintillation data is analyzed in future work. However the majority of frequencies at which the noise begins to become dominant fall below 20 Hz, suggesting a minimum sampling rate of 50 Hz, the currently used rate within the CHAIN network, should suffice for GPS signal intensity scintillation monitoring.

The deviation seen in the phase data does not follow the same characteristics seen in the signal intensity results. As the spectrum enters higher frequency ranges the slope of the power law was shown to slowly deviate to a more positive value. The rate at which the slope changes did not appear to be constant between events based on an increasing standard deviation in the mean slope. The high frequency region was not concluded to be noise as was the case with the signal intensity data. This conforms with our understanding of the methods used by GPS receivers to obtain the signal intensity and phase data. Due to the oven controlled oscillator used in sampling the signal’s phase it is expected to receive a much cleaner signal compared to the signal intensity. Results appear to indicate that the phase spectrum’s deviation asymptotically approaches a slope of zero near the 50 Hz region however without access to signal phase sampled at rates higher than 100 Hz this cannot be proven.
9.2 Future Work

The IONEX based receiver differential code bias estimation methods used in this study proved to be unacceptable in the high latitude and auroral regions. This is believed to be due to the compressed diurnal variability seen in the IONEX data. Work needs to be done to show why the compressed diurnal variability is seen. Once this is discovered work can be done to eradicate this error. Once this error is solved the IONEX based estimation methods can be tested again.

As more data becomes available at the PolaRxS Pro stations longer averages can be taken in an effort to lower the errors in the minimization of standard deviations methods and ensure that the results are not affected by increased solar activity. A larger spatial resolution which will become available with the installation of more PolaRxS Pro stations will allow for a more thorough look into the IONEX diurnal variability problem. If the compressed variability stems from the decreased temporal and spatiality resolution of data used in the IONEX maps then the degree to which the variability is inaccurate is likely to be dependent on location. Larger spatial availability of CHAIN data will allow for this hypothesis to be tested.

The work performed in this study regarding the spectral analysis of GPS signal intensity and phase sampled at 100 Hz during scintillation events has only scratched the surface of what can be done with this new data. The conclusion that the high frequency components of the signal intensity is noise should be used in future studies by determining the frequency at which the noise begins during the scintillation event and using a bandpass filter to remove the frequencies above that frequency. Past results could also be improved by utilizing this filtering method. The frequency at which the noise begins to overpower the scintillation characteristics should be examined more closely to determine whether there are any physical processes (i.e.
irregularity scale, drift speed, etc.) which have an effect. Data collected from different hardware should also be checked for an effect on the frequency at which the noise begins.

The high frequency components of the phase need to be examined more closely in an effort to confirm whether the slowly changing spectral slope is seen in all scintillation events. The cause of this change must also be determined. It was hypothesized in this study that the changing slope is not noise and is most likely a scintillation characteristic, however this idea needs to be proven.
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Conference Presentations:
