With the release of BeiDou Interface Control Document (ICD) on December 27, 2012, detailed information of the BeiDou B1I open service signal became available to commercial and scientific research communities worldwide, leading to growing interest in BeiDou signals, applications, and multi-constellation integration and cooperation. It is well known that during strong ionospheric scintillations, the receiver carrier tracking loop is subject to increased error, cycle slips, and loss of lock. The objective of this thesis is to develop an algorithm that applies the vector tracking concept in conjunction with conventional scalar tracking using dual constellation signals from GPS and BeiDou satellites to improve robustness of the GNSS receiver tracking during strong ionosphere scintillations. Such improvement will increase the number of observables in space during space weather events and improve the spatial resolution of ionosphere tomography. This thesis work describes the integrated vector and scalar tracking algorithm and demonstrates its superior performance compared with that of the traditional stand-alone scalar tracking method using real dual constellation scintillation data collected on Ascension Island.
A Thesis

Submitted to the
Faculty of Miami University
in partial fulfillment of
the requirements for the degree of
Master of Science
Department of Electrical & Computer Engineering
by
Dongyang Xu
Miami University
Oxford, Ohio
2014
# Table of Contents

Table of Contents ................................................................................................................ ii
List of Tables ......................................................................................................................... iv
List of Figures ......................................................................................................................... v
List of Abbreviations ............................................................................................................. vi
Acknowledgements ................................................................................................................ vii
Chapter 1 Introduction and Background ............................................................................. 1
  1.1 BeiDou Navigation Satellite System Overview ........................................................ 1
       1.1.1 Space Constellation ..................................................................................... 1
       1.1.2 Coordinate and Time System ...................................................................... 3
       1.1.3 Signal Specifications .................................................................................. 3
  1.2 Ionospheric Scintillation ........................................................................................... 6
       1.2.1 Ionosphere Scintillation indexes .................................................................. 6
       1.2.2 Ionospheric Scintillation impacts on GNSS receivers ................................. 7
  1.3 Prior Research ........................................................................................................... 8
  1.4 Goals of Thesis Research ........................................................................................ 10
  1.5 Overview ................................................................................................................. 11
Chapter 2 System and Methodology ................................................................................. 12
  2.1 GNSS Receiver Overview ...................................................................................... 12
  2.2 Scalar Tracking Loop ............................................................................................. 13
       2.2.1 Correlator ................................................................................................... 14
       2.2.2 Phase Lock Loop ....................................................................................... 16
       2.2.3 DLL ............................................................................................................ 18
  2.3 Vector Tracking Loop ............................................................................................. 19
List of Tables

Table 3.1 STL-based Tracking Configuration for BeiDou B1I signals............................ 31
Table 3.2 All PRNs observed on March 7 through 10...................................................... 32
Table 3.3 Number of times of loss of lock under different PLL bandwidths ................. 38
Table 4.1 Summarized Statistics of Tracked Result Differences between Different VTL
Approaches .......................................................................................................................... 51
List of Figures

Figure 1.1 BeiDou satellites world map at 15:41:43 on Nov 2, 2013(UTC) ...................... 2
Figure 1.2 BeiDou satellites 24-hour sky view over Ascension Island .............................. 2
Figure 1.3 Current frequency allocation of GPS, BeiDou, and Galileo ............................. 4
Figure 1.4 Signal structures of B1 I channel on MEO/IGSO and GEO satellites .............. 5
Figure 2.1 A fundamental SDR GPS receiver illustration ............................................ 12
Figure 2.2 STL-based receiver architecture ................................................................... 13
Figure 2.3 A conventional STL-based receiver channel block diagram ....................... 14
Figure 2.4 Block diagram of a traditional PLL .............................................................. 16
Figure 2.5 Block diagram of a second-order PLL loop filter ......................................... 18
Figure 2.6 Relationship between DLL discriminator output and $\delta_{r,\rho}$ (d=0.5) .......... 19
Figure 2.7 VTL assisted STL architecture ...................................................................... 23
Figure 2.8 A VTL-assisted-STL based receiver channel block diagram ...................... 23
Figure 2.9 Code phase prediction scenario of the VTL ................................................ 25
Figure 2.10 Illustration of $\Delta t_2$ solving procedure ................................................ 26
Figure 3.1 Data collection system configuration .......................................................... 31
Figure 3.2 Software tracking loop output computed C/$N_0$ results on .......................... 34
Figure 3.3 $S_4$ and $\sigma_\phi$ results processed from SDR and PolaRxS on ....................... 37
Figure 3.4 Sky views of the BeiDou satellites color mapped w.r.t. $S_4$ and $\sigma_\phi$ ........ 40
Figure 4.1 Comparisons between VTL and STL performance during signal outage ....... 43
Figure 4.2 Difference of tracked Doppler and C/$N_0$ between STL and stand-alone VTL 44
Figure 4.3 Comparison between the de-trended phase results of STL and stand-alone VTL ................................................................................................................................... 45
Figure 4.4 VTL tracked C/$N_0$ of satellites with strong scintillation over Ascension Island ........................................................................................................................................... 47
Figure 4.5 Comparison between STL and VTL scintillation tracking results of .......... 48
Figure 4.6 Sky view of the visible satellites in scintillation data .................................... 49
Figure 4.7 Pseudorange and C/$N_0$ difference using different VTL approaches .......... 50
Figure 4.8 De-trended phase, BD, and Doppler difference of different VTL approaches 50
# List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>ADC</td>
<td>Analog-to-Digital Convertor</td>
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<tr>
<td>AKF</td>
<td>Adaptive Kalman Filter</td>
</tr>
<tr>
<td>C/N&lt;sub&gt;0&lt;/sub&gt;</td>
<td>Carrier to Noise density ratio</td>
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<tr>
<td>CGCS2000</td>
<td>China Geodetic Coordinate System 2000</td>
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<tr>
<td>CSNO</td>
<td>China Satellite Navigation Office</td>
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<tr>
<td>CSRS</td>
<td>Canadian Spatial Reference System</td>
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<tr>
<td>EKF</td>
<td>Extended Kalman Filter</td>
</tr>
<tr>
<td>FLL</td>
<td>Frequency Lock Loop</td>
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<tr>
<td>GEO</td>
<td>Geostationary Earth Orbit</td>
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<tr>
<td>ICD</td>
<td>Interface Control Document</td>
</tr>
<tr>
<td>IF</td>
<td>Intermediate Frequency</td>
</tr>
<tr>
<td>IGSO</td>
<td>Inclined Geosynchronous Satellite Orbit</td>
</tr>
<tr>
<td>ISM</td>
<td>Ionosphere Scintillation Monitoring</td>
</tr>
<tr>
<td>LOS</td>
<td>Line-of-sight</td>
</tr>
<tr>
<td>MEO</td>
<td>Medium Earth Orbit</td>
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<tr>
<td>NCO</td>
<td>Numerical Controlled Oscillator</td>
</tr>
<tr>
<td>NH</td>
<td>Neumann-Hoffman</td>
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<tr>
<td>PCM</td>
<td>Position Comparison Method</td>
</tr>
<tr>
<td>PLL</td>
<td>Phase Lock Loop</td>
</tr>
<tr>
<td>PPP</td>
<td>Precise Point Positioning</td>
</tr>
<tr>
<td>PVT</td>
<td>Position, Velocity and Time</td>
</tr>
<tr>
<td>QPSK</td>
<td>Quadrature Phase Shift Keying</td>
</tr>
<tr>
<td>RAIM</td>
<td>Receiver Autonomous Integrity Monitoring</td>
</tr>
<tr>
<td>RCM</td>
<td>Range Comparison Method</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>SDR</td>
<td>Software Defined Receiver</td>
</tr>
<tr>
<td>SI</td>
<td>International System of Units</td>
</tr>
<tr>
<td>STL</td>
<td>Scalar Tracking Loop</td>
</tr>
<tr>
<td>UTC</td>
<td>Coordinated Universal Time</td>
</tr>
<tr>
<td>USRP</td>
<td>Universal Software Radio Peripheral</td>
</tr>
<tr>
<td>VDFLL</td>
<td>Vector DLL and FLL</td>
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<tr>
<td>VDLL</td>
<td>Vector Delay Lock Loop</td>
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<td>VTL</td>
<td>Vector Tracking Loop</td>
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Acknowledgements

I would like to express my sincere gratitude to my advisor, Dr. Yu (Jade) Morton for her constant support and guidance. The work in this thesis would have been impossible without her patient help and encouragement. I would also like to extend my thanks to Drs. Qihou Zhou and Chi-Hao Cheng from Miami University for their kind guidance on my curriculum studies and fulfillment of the TA duties; to my student colleagues Steve Taylor, for his kindness and patience for providing the data used in this project, and to Jun Wang, Yu Jiao, Hang Yin, and Harrison Bourne for their comradeship, time and effort; and to Professor Donald Ucci, Dr. Eric Vinande, and Dr. Jeffrey Hebert for their constructive inputs to my thesis work.
Chapter 1 Introduction and Background

1.1 BeiDou Navigation Satellite System Overview
Ever since China established the BeiDou navigation satellite test system in 2000, BeiDou has become an important member of the international global navigation satellite systems (GNSS) family with a fast growing number of satellites in orbit. Today, there are a total of 15 satellites in three types of orbits covering the globe. With the release of the BeiDou ICD on December 27, 2012, detailed information of the BeiDou B1I open service signal became available to commercial and scientific research communities worldwide, leading to growing interest in BeiDou signals, applications, and multi-constellation integration and cooperation.

1.1.1 Space Constellation
The current BeiDou space constellation consists of 5 Geostationary Earth Orbit (GEO) satellites (G1, G3~G6), 4 operational Medium Earth Orbit (MEO) satellites in orbits having an inclination of 55° to the equatorial plane (M3~M6), and 5 Inclined Geosynchronous Satellite Orbit (IGSO) satellites positioned at 58.75°E, 80°E, 110.5°E, 140°E, 160°E, (IG1~IG5) [BeiDou ICD, 2012]. While IGSO and GEO satellites are more localized over the Asian continent and neighboring ocean areas with latitudes from 60° to 160°E, MEO satellites operate in orbits that cover vast areas around the globe. The BeiDou satellites world map at 15:41:43 Coordinated Universal Time (UTC) on Nov 2, 2013 and a 24-hour sky view over Ascension Island (7.9°S, 14.4°W) starting from 00:00:00 UTC Nov 3, 2013 are shown in Figure 1.1 and Figure 1.2, respectively.
Figure 1.1 BeiDou satellites world map at 15:41:43 on Nov 2, 2013 (UTC)

Figure 1.2 BeiDou satellites 24-hour sky view over Ascension Island
1.1.2 Coordinate and Time System

The BeiDou system has its own coordinate and timing system: China Geodetic Coordinate System 2000 (CGCS2000) and BeiDou navigation satellite system Time (BDT). Both CGCS2000 and WGS-84 which have been adopted by GPS are ECEF right handed coordinate systems. They share nearly the same definitions for parameters of the Earth ellipsoid model, although their definitions of XYZ axes are different. A simple coordinate conversion needs to be performed between WGS-84 and CGCS2000 in a dual constellation receiver.

BDT adopts the International System of Units (SI) seconds, as the basic unit for continuous accumulation. The starting epoch of BDT was 00:00:00 on January 1, 2006 of UTC, and it is counted in weeks and seconds of a week with an offset controlled within 100ns with respect to the UTC. The time offset between BDT and GPST will result in a slowly varying bias between GPS and BeiDou measurements in a combined navigation solution. In the paper by Moudrak and Konovaltsey (2004), a method of solving GPS and Galileo system time offsets by introducing a fifth unknown into the positioning solution is presented, which can be used for GPS and BeiDou dual system as well.

1.1.3 Signal Specifications

The BeiDou system is currently broadcasting signals on three bands that overlap with Galileo: B1 (centered at 1561.098MHz in E2), B2 (centered at 1207.14MHz in E5b), and B3 (centered at 1268.52MHz in E6). According to BeiDou ICD Version 2 released on Dec 27, 2013, the signals on B1 and B2 bands are both Quadrature Phase Shift Keying (QPSK(2)) modulated, consisting of two carrier components, the I and Q channels. The ICD only revealed detailed information of the I channel of both bands. There has been no information released by the China Satellite Navigation Office (CSNO) on B3 signals. But soon after BeiDou M1 was launched on April 14, 2007 (local time), researchers discovered that a BPSK(10) modulated signal was broadcast on the B3 band by M1, and unveiled the spread spectrum code [Gao et al., 2007; Grelier et al., 2007]. In this project, only the signals from the B1 I channel are used, because the B1 band is very close to GPS L1 and should experience more closely similar ionospheric scintillation effects than the other two signals that are centered at much lower center frequencies. Signals from a much
more comprehensive combination of constellations and bands will be studied in future work. The current frequency allocation of GPS, BeiDou, and Galileo is depicted in Figure 1.3.

![Figure 1.3: Current frequency allocation of GPS, BeiDou, and Galileo](image)

The B1 signal for an arbitrary satellite \( j \) is expressed as follows:

\[
 s^I(t) = A_I C_I^j(t) D_I^j(t) \cos(2\pi f_{B1} t + \phi^I) + A_Q C_Q^j(t) D_Q^j(t) \sin(2\pi f_{B1} t + \phi^I)
\]  

(1-1)

where, the subscripts \( I \) and \( Q \) represent the I channel and Q channel, respectively; \( A, C, \) and \( D \) are the signal amplitude, ranging code, and navigation message, respectively; \( f_{B1} \) is the carrier frequency for B1; and \( \phi \) is the initial carrier phase.

Equation (1-1) shows that the Beidou B1 signal structure is very similar to that of the GPS L1 signal. The ICD only contains the information of the components of the B1 I channel, which is presented below. The ranging code on the B1 I channel is also a Gold code with a period of 1ms. However, the B1 I channel ranging code has a chipping rate of 2.046 Mcps and a length of 2046 chips, both of which are twice that of the GPS L1 C/A signal. The navigation message modulated on IGSO and MEO satellite signals is formatted as a D1 NAV message and is different from the D2 NAV message on GEO satellites. A block diagram illustrating the signal structures of the B1 I channel on MEO/IGSO and GEO satellites is depicted in Figure 1.4.
As shown in Figure 1.4, the D1 NAV message bit rate is 50bps and is secondarily modulated with a Neumann-Hoffman (NH) code [BeiDou ICD, 2012]. The length and chip width of the NH code are 20bits and 1ms, respectively, which are the same as those of the NH code modulated on the GPS L5 Q channel. The NH code is described as a synchronization sequence in the Interface Specification Document for GPS L5 [GPS ICD 705], since each chip is synchronized with every period of ranging code and every code period is synchronized with one bit of NAV message. The D2 NAV message is not modulated with any secondary code, and its bit rate is 500bps.
1.2 Ionospheric Scintillation

The ionosphere is a region of ionized gases in the upper atmosphere that extends from 50km to 1000km altitude [Misra and Enge, 2001]. Plasma irregularities in the ionosphere can cause amplitude and phase fluctuations intraversing GNSS radio signals, collectively referred to as ionosphere scintillation, which can impact GNSS receiver carrier tracking performance.

1.2.1 Ionosphere Scintillation indexes

The $S_4$ index and $\sigma_\phi$ are generally used as amplitude and phase scintillation indicators, respectively. The $S_4$ index is the standard deviation of the received signal power, normalized by the average signal power, which is given in Equation (1-2) below. $\sigma_\phi$ is the standard deviation of the de-trended signal carrier phase and is given in Equation (1-3), also below:

\[
S_4 = \sqrt{\frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}} \tag{1-2}
\]

\[
\sigma_\phi = \sqrt{\langle \phi^2 \rangle - \langle \phi \rangle^2} \tag{1-3}
\]

where <> represents the average value over the interval of interest, which is traditionally taken as a 60s period, $I$ is the de-trended signal intensity, and $\phi$ is the de-trended carrier phase.

As a normalized index, $S_4$ typically falls into the range of 0 to 1, with values greater than 0.6 defined as strong scintillation. The baseline $\sigma_\phi$ value is dominated by receiver oscillator phase jitter and environmental multipath, and a typical value is around 0.01 rad. The range of de-trended $\phi$ is limited by the receiver’s carrier tracking pull-in range. For scintillations that cause phase fluctuations beyond this range, the receiver will very likely experience cycle slips or even lose signal lock; the resulting $\sigma_\phi$ will either need to be repaired or discarded.
1.2.2 Ionospheric Scintillation impacts on GNSS receivers

Ionosphere scintillation most frequently occurs at high latitudes and equatorial areas, especially during solar maximum when it tends to be more intense [Basu et al., 2002]. The scintillation characteristics are also different between these two regions. In the equatorial region, amplitude and phase fluctuations are usually jointly observed, while, in high latitudes, phase fluctuations occur more frequently than amplitude fluctuations. Deep signal fades were also observed during strong scintillation events over equatorial regions. In Zhang et al. (2010), the carrier to noise density ratio (C/N0) of a received GPS signal collected in Ascension Island during a strong scintillation period of the last solar maximum (2001) showed deep signal fading of more than 25dB, which can also be seen in the results presented in Chapter 3.

Due to deep signal fading and large phase fluctuations that accompany strong scintillation events, the receiver carrier tracking loop is subjected to increased error, cycle slips, and loss of lock [Seo et al., 2009]. If the plasma irregularities causing strong scintillation cover a large area of the sky, the receiver may experience loss of lock in more than one satellite simultaneously. Because receiver positioning requires simultaneous tracking of a minimum of 4 satellites with a reasonable geometric distribution over the entire sky, and because the accuracy of the navigation solution is related to the redundancy of satellite observables [Misra and Enge, 2001], losing multiple satellites at the same time will degrade or cease to produce navigation solutions.

In recent years, GPS receivers have gained popularity as an effective and distributed means to monitor ionosphere and space weather [Muella et al., 2011; Mitchell and Spencer, 2003]. Numerous studies have been conducted on using GPS receivers to monitor ionosphere activities [Van Dierendonck and Klobuchar, 1993; Zhang and Morton, 2009; Van Dierendonck, 2005; Jiao et al, 2013]. However, there are very few studies on using GLONASS [Shanmugam and Macleod, 2013; Taylor et al., 2013], Galileo [Kassabianm and Morton, 2013] and BeiDou signals for Ionosphere Scintillation Monitoring (ISM) studies. Having a large number of signals in space will allow better spatial resolution of ionosphere tomography and more accurate and robust GNSS solutions. However, in order to gain a better understanding of the source and mechanism
behind ionosphere scintillation, receivers that can maintain lock during severe scintillation events and provide intact measurements need to be developed. In Jiao et al. (2014), GPS Intermediate Frequency (IF) data of triple-frequency signals (L1, L2C, L5) collected at Ascension Island during strong scintillation are processed to characterize signal fading, showing that the duration of signal C/N₀ on L1 falling under 30 dB-Hz is statistically around 1s and the duration of that falling under 25dB-Hz is around 0.7s. Therefore, the major requirements for an Ionosphere Scintillation Monitoring (ISM) receiver are to maintain lock during this time window and keep recording uninterrupted signal parameter measurements.

1.3 Prior Research

The performance of a GPS single frequency receiver in the presence of ionosphere scintillation using a Scalar Tracking Loop (STL) is evaluated in Zhang et al. (2010). In the paper, three different carrier tracking loops have been evaluated: a conventional Phase Lock Loop (PLL), a Frequency Lock Loop (FLL) assisted PLL, and a Kalman Filter-based PLL. The comparison between different carrier tracking loops in terms of steady-state error and tracking robustness are conducted based on real Radio Frequency (RF) data collect from Ascension Island. The results showed that the FLL-assisted PLL outperformed the other two. However, the performance of a STL is limited by its need for careful selection of loop parameters, which makes compromises between dynamic performance and tracking sensitivity. A STL, by definition, operates solely on information available from each individual satellite. It does not make use of information from other satellites or receiver positions, making it vulnerable to scintillation, interference, or momentary signal blockage. A Vector Tracking Loop (VTL), on the contrary, makes use of the additional information to improve the tracking performance under such conditions.

The concept of VTL was first introduced by Parkinson and Spilker (1996). For conventional receivers, receiver signal processing and navigation signal processing are treated as independent systems. A VTL, however, makes use of the inherent relationship between a navigation solution and receiver-satellite relative motion-induced signal dynamics to form an integrated closed loop at the receiver signal processing stage. In Parkinson and Spilker (1996), a Vector Delay Lock Loop (VDLL) is proposed, which is
based on the fact that a position solution is intrinsically related to the code phase of the ranging code. With a Jacobian geometric matrix, a linearized relation can be established between the receiver position vector error and the pseudorange measurement vector, which are related to the code phases of visible satellites. This relationship represents the measurement model for an Extended Kalman Filter (EKF). The potential advantages of VDLL is also discussed in Parkinson and Spilker (1996): the power of signals from more than 4 visible satellites can be combined to aid VTL tracking of other weak signals, providing immunity to momentary blockage of one or more satellites and improving high dynamic performance.

Various implementations of different VTL architectures are presented in the literature for a stand-alone receiver in recent years [Lashley et al., 2009; Won et al., 2011; Peng et al., 2012]. In Lashley et al. (2009), an EKF is used to simultaneously estimate the user position and track GPS signals. The state estimations of the EKF are utilized to predict code phases and carrier frequencies of received signal through a Vector DLL and FLL (VDPLL). Residuals generated from discriminators are then used to correct the EKF’s states. The results showed that the VDFLL can maintain tracking of 5 satellite signals with up to 8G coordinated turns when C/N_0 falls to 19 dB-Hz, and 7 satellite signals with 4G turns when C/N_0 = 16 dB-Hz. This result demonstrates the VTL’s superior performance in handling highly sensitive and dynamic signals, a scenario commonly encountered during strong ionospheric scintillation. In Won et al. (2011), the results presented confirmed the VTL’s performance under momentary blockage of satellites. The disadvantage of such implementations is that errors experienced in a particular channel may affect tracking accuracy in other integrated channels, thereby degrading the overall receiver performance.

In Henkel et al. (2009), a multi-frequency least-square estimation-based VPLL is proposed. It utilizes multi-frequency signal measurements and the frequency dependency property of ionosphere delay, and incorporates the ionosphere and troposphere delay error into the receiver state vector. The estimation of the receiver state vector is based on the weighted least-square estimation. A multidimensional extension of the traditional scalar filter is used to filter the estimated receiver states to reduce the noise. The results
showed only a somewhat reduced carrier phase tracking error under moderate ionosphere scintillations. In Peng et al. (2012), the VTL is used to assist a compromised STL to enhance its tracking robustness instead of replacing the STL entirely, as in Lashley et al. (2009); Won et al. (2011). Furthermore, a Receiver Autonomous Integrity Monitoring (RAIM) algorithm is implemented to ensure that only those channels that are not compromised can be used to generate VTL outputs, thereby preventing errors from a degraded satellite signal contaminating other channels in the VTL.

Despite the differences between these VTL approaches in their implementations, their main idea of the VTL concept remains the same as in Parkinson and Spilker (1996). These approaches commonly utilize an EKF or Adaptive Kalman Filter (AKF) [Peng et al., 2012], in which the PVT information is used as feedback to update and estimate the parameters of all the tracked channels as a vector. Through this kind of vector tracking, the disturbed channels can be aided by other nominal channels and tracked more robustly. However, these algorithms are not ideal for stationary applications as ISM, in which receivers are deployed in fixed locations that can be surveyed beforehand. Furthermore, the other major concern for ISM receivers besides robustness is to preserve ionosphere effects on the signal from being removed or altered by extensive filtering and optimization during signal processing, so that the mechanisms of ionosphere turbulences can be fully studied. In this way robust receivers able to comprehensively confront severe scintillation can be developed [Yin et al., 2014].

1.4 Goals of Thesis Research
In this thesis, a dual constellation VTL-assisted STL implementation suitable for ISM receiver is presented and applied to dual constellation signals from GPS and Beidou satellites for ionosphere scintillation studies. Specifically, this thesis study leads to the following novel contributions:

- Implemented STL-based tracking algorithms in a Software Defined Receiver (SDR) for processing real BeiDou B1I and GPS L1 IF data collected over Ascension Island under ionosphere scintillation events. The performance of the STL-based tracking algorithms using different parameters were compared for future optimization of STL during scintillation.
- Developed a dual constellation SDR that simultaneously tracks the BeiDou B1I and GPS L1 signals and performs navigation message decoding on the two systems. The SDR navigation solution can be obtained when there are more than 4 satellites of either constellation or jointly 5 satellites of dual constellation.
- Implemented a VTL assisted STL algorithm in the SDR involving dual constellation signals and conducted performance evaluations using real data with artificially introduced signal outages.
- Applied the VTL-assisted STL algorithm to the real Ascension Island scintillation GPS L1 and Beidou B1I data. Compared the outputs with that of the STL-based implemented SDR and evaluated the performance of the VTL-assisted STL algorithm during strong ionosphere scintillation events.

1.5 Overview

This thesis contains five main parts. This Chapter introduces the BeiDou Navigation Satellite System and ionosphere scintillations, and then summarizes the previous research on the VTL. The methodology of the STL and VTL are described in Chapter 2. Chapter 3 presents the results obtained by tracking real BeiDou signals under strong scintillation with the STL, and discusses the STL performance using different parameters. Chapter 4 presents a dual constellation VTL tracking performance test using real data with artificial signal outages and real data under strong scintillation collected at Ascension Island. Chapter 5 summarizes the thesis and proposes directions for future work.
Chapter 2 System and Methodology

2.1 GNSS Receiver Overview

A basic GNSS SDR receiver block diagram is given in Figure 2.1. The RF signals transmitted from GNSS satellites are received by an antenna, and then amplified and down-converted to an IF signal through the RF chain. After being digitized by the Analog-to-Digital Convertor (ADC), the IF digital signal is processed by software, which consists of signal processing and navigation processing functions. In the signal processing function, the input signal is first acquired and tracked. After the tracking reaches a steady state, the navigation message can then be decoded from the navigation data bit transitions on the signals, and the ranging code phase and carrier frequency are estimated by the tracking loops. In the navigation processing function, the ephemeris and signal time stamps are obtained from the navigation message, the code phase estimate is converted to the pseudorange, and the carrier frequency estimate generates the pseudorange rate. If pseudoranges and pseudorange rates from more than 4 satellites are available, Position, Velocity and Time (PVT) solutions can be computed from them [Tsui, 2004].

As pointed out in Parkinson and Spilker (1996), not all GNSS receivers perform the traditional navigation processing. Often, navigation processing is integrated into specific applications such as time and frequency transfer, static and kinematic surveying, ionosphere remote sensing and scintillation monitoring, differential systems, and GPS
satellite signal integrity monitoring. For these special purposes receivers, the structure and implementation of the signal processing function may vary and the interaction between the signal processing function and the application processing function may be different, depending on the specific application of the receiver.

### 2.2 Scalar Tracking Loop

In the signal processing function of a conventional receiver, the tracking of different satellite signals is typically performed in several parallel STLs that operate independently. A STL comprises a DLL and a carrier tracking loop. The carrier tracking loop can be a PLL, FLL, or a combination of both. The PLL tracks the carrier phase and frequency with high accuracy, while the FLL only tracks the carrier frequency. On the other hand, a FLL has a better dynamic performance in handling interference than the same order PLL. The PLL is usually implemented with a higher order filter than the DLL, because the carrier has a much higher frequency compared to the code and is more susceptible to the impact of dynamics. The DLL tracks the code phase and sometimes makes use of the PLL outputs as an aid to lower the dynamic impact and increase the accuracy, as the accumulated carrier phase is less noisy [Parkinson and Spilker, 1996].

The architecture and detailed channel block diagram of a STL-based receiver are given in Figure 2.2 and Figure 2.3, respectively.
2.2.1 Correlator

In Figure 2.3, all the components and flow paths that share a light green color constitute the correlator. First, the IF signal carrier is wiped off by in-phase (I) and quadra-phase (Q) replica carriers generated by the carrier generator with a frequency of the sum of IF and Doppler, and then the two channels of signals are correlated with the early (E), prompt (P), and late (L) code replicas that are generated by code generator to wipe the code off of the signal. A total of six correlator products ($I_E$, $I_P$, $I_L$, $Q_E$, $Q_P$, $Q_L$) are generated after the correlation function. The E and L code replicas are separated in phase by a spacing of typically 0.5 to 1 chip, with P in the middle.

Ignoring the cross-correlation from signals of other satellites and the impact that the limited pre-detection bandwidth has on the autocorrelation of the ranging code, the six correlation products over one code period (1ms for BeiDou B1I and GPS L1 signals) can be expressed as follows:
\[ I_E = A \cdot N \cdot D \cdot \frac{\sin(\pi \delta_f \cdot T)}{\pi \delta_f \cdot T} \cdot R(\delta_{\tau, p} - d) \cdot \cos(\delta_\phi) + \text{noise}_{I,E}; \]
\[ Q_E = A \cdot N \cdot D \cdot \frac{\sin(\pi \delta_f \cdot T)}{\pi \delta_f \cdot T} \cdot R(\delta_{\tau, p} - d) \cdot \sin(\delta_\phi) + \text{noise}_{Q,E}; \]
\[ I_p = A \cdot N \cdot D \cdot \frac{\sin(\pi \delta_f \cdot T)}{\pi \delta_f \cdot T} \cdot R(\delta_{\tau, p}) \cdot \cos(\delta_\phi) + \text{noise}_{I,p}; \]
\[ Q_p = A \cdot N \cdot D \cdot \frac{\sin(\pi \delta_f \cdot T)}{\pi \delta_f \cdot T} \cdot R(\delta_{\tau, p}) \cdot \sin(\delta_\phi) + \text{noise}_{Q,p}; \]
\[ I_L = A \cdot N \cdot D \cdot \frac{\sin(\pi \delta_f \cdot T)}{\pi \delta_f \cdot T} \cdot R(\delta_{\tau, p} + d) \cdot \cos(\delta_\phi) + \text{noise}_{I,L}; \]
\[ Q_L = A \cdot N \cdot D \cdot \frac{\sin(\pi \delta_f \cdot T)}{\pi \delta_f \cdot T} \cdot R(\delta_{\tau, p} + d) \cdot \sin(\delta_\phi) + \text{noise}_{Q,L}; \]

where \( A \) is signal amplitude, \( N \) is the number of samples within \( T \) ms pre-detection time, \( D \) is the current message bit (+1 or -1), \( \delta_f \) is the Doppler frequency error, \( T \) is pre-detection time, \( \delta_{\tau, p} \) is code phase error of prompt replica code, \( d \) is the phase spacing that separates E, P, and L, \( R(\cdot) \) is the autocorrelation function of ranging code, and \( \delta_\phi \) is the phase error.

As can be seen in Equation (2-1), the correlation process stripped the code and carrier modulations from the signal, leaving the accumulated signal amplitude over the correlation period, navigation data bits, factors due to the code phase error \( \delta_{\tau, p} \) and carrier phase error \( \delta_\phi \), and noise. The term \( \frac{\sin(\pi \delta_f \cdot T)}{\pi \delta_f \cdot T} \) can usually be considered as 1 for a small \( T \). The correlation products that contain the “raw” code and carrier phase error information are the inputs to the DLL and the PLL to keep tracking the signal.

Note that the D2 NAV message rate on GEO satellite signals is 500 bps, and the D1 NAV message on IGSO/MEO satellite signals is modulated with a NH code having a chip rate of 1 kcps. Therefore, the maximum coherent integration times are 2 ms and 1 ms for BeiDou GEO and IGSO/MEO signals, respectively, if the NH code phase has not been acquired in the acquisition stage. In order to perform a multi-code-period coherent
integration for B1I signals, the message bits need to be wiped off. It should be noted that in Equation (2-1), assuming the tracking loop is in steady state and $\delta_\phi$ is in the pull-in range of \([-\pi/2, +\pi/2]\) of a Costas discriminator, the sign of the message bit determines the sign of the correlator output in the I channel. A simple message strip-off method is implemented in the multi-code-period accumulation step: after every 1 ms integration, if $I_P$ is positive, then all six correlator outputs can be coherently integrated with their corresponding previous correlator outputs; if it is negative, then all of them will be multiplied by -1 before accumulation with their previous correlator outputs. The sign of $I_P$ can be recorded as a partial message bit for later bit synchronization and decoding. In this study, a maximum of 10-ms coherent integration time was allowed to accumulate signal power to compensate for the deep fades during strong scintillation.

2.2.2 Phase Lock Loop

In the context of GNSS receivers, a PLL consists of four components: a correlator, a phase discriminator, a loop filter, and a carrier reference generator. Figure 2.4 shows the block diagram of a traditional PLL for a GNSS receiver.

![Figure 2.4 Block diagram of a traditional PLL](image)

After correlation, the correlator outputs are first passed into a phase discriminator, where the carrier phase error $\delta_\phi$ between the carrier of the incoming signal and the local replica are estimated. There are a number of phase discriminators that can be applied to estimate the error. A Costas discriminator and a coherent discriminator are given in (2-2) and (2-3), respectively:

\[
\hat{\delta}_\phi = ATAN\left(\frac{Q_p}{I_p}\right), \quad (2-2)
\]

\[
\hat{\delta}_\phi = ATAN2\left(Q_p, I_p\right), \quad (2-3)
\]
The estimated carrier phase error $\hat{\delta}_\phi$ is affected mostly by thermal noise and dynamic stress on the carrier of the incoming signal. A carrier loop filter is needed to filter the noise and dynamics and adjust an estimate to be more closely related to the true phase error $\delta_\phi$ for the carrier generator.

The Costas discriminator has a pull-in range of $[-\pi/2, +\pi/2]$, making it insensitive to bit changes, while the coherent discriminator has a larger pull-in range of $[-\pi, +\pi]$. Here a Costas discriminator is chosen because the message bit wipe-off procedure in 2.2.1 has already wiped off the sign change in the two prompt correlation products, so the Costas discriminator and the coherent discriminator will have the same outputs. It has to be mentioned, however, that this kind of procedure will also wipe off the sign changes induced by ionospheric scintillation, which will then affect the accuracy of the phase scintillation estimation. In this thesis, the focus is on the methodology of STL and VTL, so the possible effect on scintillation analysis is ignored here. But future work will address the problem in two aspects: future available pilot signals from BeiDou, Galileo, and etc. will be used, which needs no such procedure. An alternative approach suitable for post-processing in Mao and Morton (2013) will be adopted, where navigation data bits on each satellite signal can be constructed from known navigation messages and removed from the input data streams. These two measures will then enable the use of a coherent phase discriminator, which has a larger pull-in range to accommodate larger phase variations during scintillation.

Typically, a second-order PLL filter is implemented in order to handle platforms expecting accelerations, resulting in a third-order PLL when taking the Numerical Controlled Oscillator (NCO) in the carrier generator into consideration. The block diagram of a second-order PLL filter is given in Figure 2.5, which outputs the filtered phase error $\hat{\delta}_\phi$. 

17
After incorporating the NCO, the transfer function of the resulting third-order PLL can be written as:

\[
H(s) = \frac{\beta \omega_0 s^2 + \alpha \omega_0^2 s + \omega_0^3}{s^3 + \beta \omega_0 s^2 + \alpha \omega_0^2 s + \omega_0^3},
\]

where \(\omega_0\) is the filter loop’s natural frequency. For a 3rd-order PLL, \(\omega_0\) is related to the loop equivalent noise bandwidth \(B_n\): \(\omega_0 = 1.2747 B_n\) [Zhang and Morton, 2011], and \(\alpha\) and \(\beta\) are additional filter coefficients which are typically set to 1.1 and 2.4, respectively [Tsui, 2004].

For the PLL, \(B_n\) is chosen as a compromise between the dynamics and the \(C/N_0\) of the incoming signal. A wider noise bandwidth can provide the PLL with a larger dynamic range, but will lower the tracking sensitivity, as the PLL will filter out less noise; a narrow bandwidth increases the PLL’s sensitivity but sacrifices the dynamics performance and requires a reference clock with high stability. In this thesis, four different PLL filter bandwidths were applied for STL tracking performance comparisons, which will be discussed in Chapter 3.

2.2.3 DLL

The DLL tracks the code phase, in a manner similar to the way the PLL tracks the carrier phase; thus, they share almost the same block diagram. Their main difference is the way they estimate the phase error. The code phase error \(\delta_{\tau,p}\) is estimated based on the
shape of the autocorrelation function of the ranging code, $R(\delta_{r,p})$. When $\delta_{r,p}$ is within the range of $(-1+d \text{ chip}, +1-d \text{ chip})$, there is a linear relationship between $\delta_{r,p}$ and $R(\delta_{r,p})$. A DLL discriminator is designed based on this linear relationship. For example, anormalized early minus late envelope discriminator is

$$\hat{\delta}_{r,p} = (1-d) \frac{E-L}{E+L}, \quad (2-5)$$

where $E=\sqrt{I_E^2+Q_E^2}, L=\sqrt{I_L^2+Q_L^2}$

The relationship between the output of a normalized early minus late envelope discriminator and $\delta_{r,p}$ ($d=0.5 \text{ chip}$) is depicted in Figure 2.6. The light yellow region is the stable region of the discriminator.

![Figure 2.6 Relationship between DLL discriminator output and $\delta_{r,p}$ ($d=0.5$)](image)

Typically, a first order DLL filter with a bandwidth much narrower than that of the PLL is implemented, as the code tracking is less vulnerable to dynamics and is much noisier.

### 2.3 Vector Tracking Loop

The STL tracks the code phase and carrier frequency of the signal from individual satellites independently, producing independent estimates for the pseudorange and the pseudorange-rate measurements for each satellite. These measurements are then used in the navigation solution function to solve the receiver’s PVT states. However, when there
are more than 4 satellites in view, giving more than 4 sets of available measurements, the system is over-determined. Moreover, the satellite-receiver paths generally prevent the measurements from being truly independent. The VTL makes use of the fact that the measurements from different satellites are actually dependent, and combines them in the signal processing stage, which makes it essentially different from the STL [Parkinson and Spilker, 1996].

The differential carrier phase and code pseudorange measurement models from a satellite \( j \) are given as:

\[
\rho^j = r^j + c(\delta t - \delta T^j) + I + T + MP^j + e_p; \quad (2-6)
\]

\[
\lambda \Phi^j = \dot{r}^j + c(\dot{\delta t} - \dot{\delta T^j}) - \dot{I} + \dot{T} + \dot{MC}^j + \dot{e}_c; \quad (2-7)
\]

where \( \rho \) and \( \Phi \) (for conciseness, the superscript \( j \) will be omitted) are the measured code phase pseudorange and differential carrier phase. \( \lambda \) is the carrier wavelength; \( r \) and \( \dot{r} \) are the geometric range and range rate from the receiver to the GPS satellite, respectively; \( c \) is the speed of light in a vacuum; \( \delta t \) and \( \delta T \) are the offsets of the receiver and satellite clocks from GPS Time, respectively; \( \dot{\delta t} \) and \( \dot{\delta T} \) are the clock drift rate of the receiver and satellite, respectively. \( I \) and \( \dot{I} \) are the ionosphere delay (in meters) and rate of change in delay (m/s); \( T \) and \( \dot{T} \) are the tropospheric delay (in meters) and rate of change in delay (m/s); \( MP \) represents the effect of multipath on the pseudorange. \( \dot{MC} \) represents the rate of change in multipath on the differential carrier phase.

The receiver-to-satellite geometric range equation is given as:

\[
r^j = \sqrt{(x^j - x_r)^2 + (y^j - y_r)^2 + (z^j - z_r)^2}
\]

As can be seen in Equations (2-6), (2-7), and (2-8), the differential carrier phase and code pseudorange measurements from different satellites are scalar measurements separated by the nonlinearity of the geometric range equation.

In the navigation processing stage, after linearizing Equation (2-8), the differential carrier phase and code measurements are combined in two matrix equations to solve the receiver position, velocity, and time, which are given in Misra and Enge (2010) as:
\[ \Delta \rho = G \cdot \Delta \mathbf{X} + \mathbf{\epsilon}_\rho; \]  
(2-9)  
\[ \lambda \Delta \Phi = G \cdot \Delta \mathbf{X} + \dot{\mathbf{\epsilon}}_\epsilon; \]  
(2-10)  

where, \( \Delta \mathbf{X} \) and \( \Delta \dot{\mathbf{X}} \) are the error vector of receiver position and velocity, respectively:  
\[ \Delta \mathbf{X} = \Delta [x_r, y_r, z_r, \delta t], \quad \Delta \dot{\mathbf{X}} = \Delta [\dot{x}_r, \dot{y}_r, \dot{z}_r, \dot{\delta t}]. \]

\([x_r, y_r, z_r, \delta t] \) and \([\dot{x}_r, \dot{y}_r, \dot{z}_r, \dot{\delta t}] \) are the receiver position and velocity in ECEF, respectively. \( \Delta \rho \) and \( \Delta \Phi \) are the error vectors of the code pseudorange and carrier-phase rate, respectively. \( \mathbf{\epsilon}_\rho \) and \( \dot{\mathbf{\epsilon}}_\epsilon \) are the noise and error source vectors of the two measurements. \( G \) is the geometric matrix linearized from Equation (2-8), given as:

\[
G = \begin{pmatrix}
h_x^1 & h_y^1 & h_z^1 & -1 \\
\vdots & \vdots & \vdots & \vdots \\
h_x^N & h_y^N & h_z^N & -1 \\
\end{pmatrix}_{N \times 4}
\]

(2-11)

where \( N \) is the number of satellite in view, and

\[
h_x^j = (x_r - x^j) / r^j \\
h_y^j = (y_r - y^j) / r^j \quad \text{for} \ j = 1 \ \text{to} \ N. \\
h_z^j = (z_r - z^j) / r^j \\
\]

By solving Equations (2-9) and (2-10), the PVT solution of the receiver is obtained based on the measurements from no less than 4 satellites. The essential difference between a STL-based receiver and a traditional VTL-based receiver lies in the fact that, in addition to solving the receiver PVT using Equations (2-9) and (2-10), the VTL-based receiver makes use of them in reverse, namely using \( \Delta \mathbf{X} \) and \( \Delta \dot{\mathbf{X}} \) to estimate and predict the code phase in a VDLL and carrier frequency in a VFLL for signal tracking. When more than 4 satellites are in view, the additional satellite signals will help to improve the accuracy of position estimation and hence the code phase and carrier frequency estimation, thereby contributing to the tracking of the compromised signals.

For a traditional VTL-based receiver, an EKF is typically chosen over the conventional least squares approach to estimate the PVT solutions in order to improve the estimation
accuracy. Through the linearized geometric matrix, the PVT information can be treated as the states vector and the code pseudorange and carrier-phase pseudorange rate as the observation vector. After establishing the EKF state space model and observation model, the standard EKF updating and projecting procedure can be performed to keep tracking the signal and updating the navigation solutions, which can be found in Brown and Hwang (1992).

However, the traditional VTL is not ideal for ISM applications. Because the position of an ISM receiver is fixed and can be surveyed beforehand, the only receiver state that needs to be updated is the receiver time, so the PVT solution updating of the EKF is unnecessary. Furthermore, one of the major concerns of an ISM receiver is to preserve ionosphere effects on the signal from being removed or altered by extensive filtering and optimization during signal processing, so that the mechanisms of ionosphere turbulence can be fully studied and robust receivers capable of comprehensively confronting them can be developed [Yin et al., 2014].

2.3.1 ISM Vector Tracking Loop
The VTL approach presented in this thesis is designed specifically for an ISM receiver and is different from a traditional VTL in several aspects. First, instead of utilizing an EKF that increases the computational costs and introduces more filtering effects, the ISM VTL makes fully use of the assumption that the receiver is stationary and simplifies the estimation process of the code phase and carrier frequency. Second, rather than replacing the STL completely with VTL as in Lashley et al. (2009) and Won et al. (2011), a VTL assisted STL implementation is applied, where the STL is still used to track the nominal signals and the VTL is only used to aid the challenged channels during intermittent signal fades [Peng et al, 2012], which typically will return to a nominal value after around 1s [Jiao et al., 2014]. Furthermore, a RAIM algorithm is implemented to determine whether a channel is under stress and in need of aid from the VTL (vector aiding).

The architecture and the block diagram of the VTL assisted STL are given in Figure 2.7 and Figure 2.8, respectively.
Figure 2.7 VTL assisted STL architecture

Figure 2.8 A VTL-assisted-STL based receiver channel block diagram

23
In Figure 2.8, all the components and flow paths that share a blue color constitute the STL, which process the signals from all the nominal channels in parallel, providing message bit, code phase, and carrier frequency information for navigation data decoding and PVT calculation. The tracked code phase, carrier Doppler frequency, and calculated C/N₀ (C/N₀ is not implemented in this thesis, but will be applied in future work) will also be sent to integrity check to assess the STL tracking status of a channel. If the integrity check determines any channel as challenged, the Doppler and code phase updating will be handed over from STL to VTL. The VTL will then track the signal by estimating the code phase and the Doppler frequency.

Both the integrity check and the VTL tracking parameters estimation process utilize the receiver position information, which will be discussed in detail later. Depending on how this position information is obtained, the VTL implementation can be classified into two approaches:

Approach 1: The position is surveyed results generated beforehand by the Canadian Spatial Reference System (CSRS) on-line Precise Point Positioning (PPP) service. Therefore, in the PVT calculation procedure, the position variable will be fixed and set to the surveyed position, and only the time variable will be calculated and updated.

Approach 2: The position comes from the live dual constellation PVT solutions generated by the algorithm presented in this paper. Through this approach, the estimation process will be affected by the position error, but will be able to tolerate low receiver dynamics if using a relatively high updating rate.

Before going into the details of this implementation, three assumptions need to be clearly stated:

1. The receiver stays stationary;
2. The oscillator used is no worse than an Oven-Controlled Crystal Oscillator (OCXO), that has a rather stable frequency offset and can be treated as a constant for an hour period.
3. The receiver is already in steady-state tracking and has already achieved a valid position and receiver time solution before VTL can be performed.
Based on these three reasonable assumptions and the fact that the satellite position and velocity is accurately predictable using ephemeris, it is feasible to predict the code phase and Doppler of the next epoch a short amount of time away.

Figure 2.9 illustrates the scenario of the code phase prediction.

Assuming at current time $T$, the receiver received a signal transmitted from the satellite at time $T-\Delta t_1$, where $\Delta t_1$ is the signal propagation time delay and has been accurately computed by the code tracking loop. $S(T-\Delta t_1)$ is the satellite position at time $T-\Delta t_1$, and $U(T)$ is the receiver position at time $T$. After time $\Delta T$, the signal received by the receiver transmitted at time $T+\Delta T-\Delta t_2$, where $\Delta t_2$ is the signal propagation time delay at receiving time $T+\Delta T$ and is clearly not equal to $\Delta t_1$. $S(T+\Delta T-\Delta t_2)$ is the satellite position at time $T+\Delta T-\Delta t_2$, and $U(T+\Delta T)$ is the receiver position at time $T+\Delta T$. To predict the code phase at receiving time $T+\Delta T$, the value for $\Delta t_2$ needs to be determined.

If the time $\Delta T$ is small enough, the changes in pseudorange during the time period can be considered to have a linear dependency on $\Delta T$, and $\Delta t_2$ can then be obtained by a simple linear extrapolation. The approximation procedure is illustrated in Figure 2.10.
In Figure 2.10, all the highlighted text boxes indicate transmission times of the signal received at the corresponding receiving times marked on the horizontal axis. $T_x$ is the time when the signal transmitted at $T-\Delta t_1+\Delta T$ is received, and $\Delta t_x$ is the corresponding propagation time delay. The procedure can be broken down into a few steps:

1. Calculate the satellite position $S(T-\Delta t_1+\Delta T)$ using ephemeris;

2. $\Delta t_x = \|S(T-\Delta t_1+\Delta T)-U(T_x)\|/C$, where $U(T_x)=U(T)$ in the case of a stationary receiver. If $\Delta T$ is small enough (in this thesis, 0.2s is used) and the receiver is moving at a relatively low velocity as in most non-aviation applications, the approximation might still be valid for estimating $\Delta t_x$. But if the receiver is on a high dynamic platform, an INS will be needed in order to estimate $U(T_x)$.

3. $T_x = T-\Delta t_1+\Delta T+\Delta t_x$;

4. $\Delta t_2 = \Delta T \cdot (\Delta t_x-\Delta t_1)/(T_x-T)+\Delta t_1$.

After solving for $\Delta t_2$, the code phase at $T+\Delta T$ can be predicted and used to control the code generator.
As for the Doppler prediction, since $\Delta t_2$ is now known, the satellite velocity at receiver time $T+\Delta T$ can also be calculated using ephemeris, and then, the Doppler can be estimated as:

$$f^\text{d} = l^k \cdot (V^k - V)/\lambda + \hat{f}_\text{clock drift}$$

(2-12)

where $l^k$ is the unit direction vector from the receiver to the satellite $k$, $V^k$ is the velocity of satellite $k$, and $V$ is the receiver velocity, both of which are under the ECEF system; $\hat{f}_\text{clock drift}$ is the clock drift estimation. Based on assumption 2, $\hat{f}_\text{clock drift}$ can be considered as a constant and estimated beforehand by averaging the Doppler residual between the STL tracked Doppler frequency and $l^k \cdot (V^k - V)/\lambda$ during the quiet times to establish the baseline.

It should be noted that, Equation (2-12) doesn’t take into consideration other error sources in Equation (2-7) that will result in a gradual accumulation of phase errors, which makes this VTL approach infeasible for long-term tracking. However, for even the severe scintillation scenarios, where the deep fades last on average for around 1s with an average time separation of about 14s [Jiao et al., 2014], the error accumulation is within the pull-in range of the STL, so that the STL can lock back to the signal again without re-acquisition after the signal rebound from amplitude fades. The disruption in the measurements can also be avoided.

### 2.3.2 Receiver Autonomous Integrity Monitoring

Available RAIM methods can be generally categorized into two types: Range Comparison Method (RCM) and the Position Comparison Method (PCM) [Parkinson and Axelrad, 1988]. PCM calculates the differences between the position solution based on measurements from all satellites and the position solution based on measurements from a subset of satellites, while RCM makes use of the difference between the measured pseudorange and the one predicted by making use of the geometric Equation (2-8). A RCM is employed in this thesis for the RAIM, since the status of the tracking loop output is directly related to the pseudorange measurements.
In the RCM method, a range residual error is used as the indicator for detecting possible failure. The range residual error presented as a RAIM indicator in Parkinson and Axelrad (1988) is based on this predicted range, given as:

$$\hat{\epsilon} \equiv \rho_{\text{pred}} - \rho_{\text{meas}},$$

(2-13)

where $\rho_{\text{pred}}$ is the predicted range that is the geometric range vector between the predicted satellite position and the receiver position, and $\rho_{\text{meas}}$ is the measured pseudorange.

A threshold of 40m is used here, which is 10m lower than the threshold used in Peng et al. (2012) in order to make it more sensitive during severe scintillation and able to promptly detect the challenged channel before the tracking parameters has accumulated too much error due to lose of lock. If the $\hat{\epsilon}$ of a satellites is larger than 40m, the satellite will be determined as challenged.

Another index used for integrity check is the Doppler residual $\delta f$, which is defined as:

$$\delta f = \frac{1}{k} \cdot (V^k - V) / \lambda - \tilde{f}_d.$$

(2-14)

where $\tilde{f}_d$ is the estimated Doppler from STL tracking.

It should be mentioned that the $\delta f$ is biased with a clock drift introduced by the oscillator, but based on assumption 2, the clock drift can be considered as a constant and estimated beforehand, which can be done by averaging the Doppler residual during the quiet times and establishing the baseline.

In Equation (2-14), after obtaining the ephemeris, the satellite velocity $V^k$ at a given time can be easily and rather accurately calculated, and receiver velocity $V$ is 0 according to assumption 1. For a receiver on a moving platform, the estimated receiver velocity from the PVT solutions can be used, which includes estimation error effects. The impact of the estimation error effects will be the subject of future studies. The estimated Doppler provided by the STL tracking is typically quite accurate and is also very sensitive to the
phase fluctuations during ionosphere scintillation events. Therefore, the Doppler residual $\delta f$ can be conveniently obtained and used as another index for integrity check.

2.4 System Time Offset

For the VTL-assisted-STL tracking of BeiDou and GPS dual constellation signals, the system time offset between these two systems should be resolved before integrating the measurements of the two systems. Moudrak and Konovaltsey (2004) present a method of solving dual system time offset by introducing a fifth unknown into the positioning solution using measurements from 5 or more satellites. Since the system time offset can be considered a constant in a short amount of time, we only need to solve the system time offset before scintillation commences when all channels were operating in STL mode and use it to correct the measurements coming from BeiDou satellites during VTL-assisted tracking. The expanded positioning solution matrix equation is given as:

$$\Delta \rho = \tilde{G} \cdot \Delta \tilde{X} + \tilde{\epsilon}_p$$

(2-15)

where $\Delta \rho$ is the pseudorange measurement column vector that places the GPS measurements on the upper side, and the BeiDou measurements on the lower side. $\tilde{G}$ is the geometric matrix that combines BeiDou and GPS satellites line-of-sight unit vector, $\Delta \tilde{X}$ is the expanded receiver states with the fifth unknown as the system time offset, given as:

$$\tilde{G} = \begin{bmatrix}
h_{x,GPS}^1 & h_{y,GPS}^1 & h_{z,GPS}^1 & -1 & 0 \\
\cdots & \cdots & \cdots & \cdots & \cdots \\
h_{x, BDS}^N & h_{y, BDS}^N & h_{z, BDS}^N & -1 & 0 \\
h_{x, BDS}^1 & h_{y, BDS}^1 & h_{z, BDS}^1 & -1 & -1 \\
\cdots & \cdots & \cdots & \cdots & \cdots \\
h_{x, BDS}^M & h_{y, BDS}^M & h_{z, BDS}^M & -1 & -1 \\
\end{bmatrix}; \quad \Delta \tilde{X} = \begin{bmatrix}
\Delta x_r \\
\Delta y_r \\
\Delta z_r \\
\Delta \delta t_{GPS} \\
\Delta \delta t_{SYS}
\end{bmatrix},$$

(2-16)

where $\delta t_{SYS}$ denotes the system time offset, and BD is short for BeiDou.
Chapter 3 BeiDou STL Processing Results of Data During Ionosphere Scintillation

There have been numerous studies of the ionospheric scintillation impact on GPS signals and the use of GPS receivers to monitor ionosphere activities [Van Dierendonck et al., 1993; Zhang and Morton, 2009; Van Dierendonck, 2005; Jiao et al, 2013]. However, there has been no study on using BeiDou signals for ionosphere scintillation studies. As the number of global and regional navigation satellites increases, effective utilization of these signals for ionospheric scintillation monitoring will greatly improve spatial and temporal observability of ionosphere structures and dynamics. In this thesis, a BeiDou STL-based SDR was developed and applied to the BeiDou IF data under strong ionospheric scintillation as preliminary test for the development of a dual constellation SDR later on. The results of processing BeiDou B1I signals using STL is presented in this chapter. The techniques developed here will be applicable for later inclusion of other GNSS and RNSS signals.

3.1 Data Used

The BeiDou B1I data used in this study was collected in March 2013 from a multi-constellation GNSS data collection system consisting of a Septentrio PolaRxS receiver and five USRP-N210 based RF front ends. Figure 3.1 depicts the data collection system configuration. The Universal Software Radio Peripheral (USRP-N210) front ends are configured to record raw GPS L1, L2C, L5, Beidou B1, Galileo E5a/E5b, GLONASS L1 and L2 IF samples at zero IF frequency with different sampling rates (10MHz for BeiDou B1 and 25MHz for GPS L1) and 4-bit resolution. The PolaRxS receiver and the RF front ends all share inputs from the same Novatel 703-GGG wideband antenna and are driven by the same OCXO originating from the PolaRxS receiver. While the PolaRxS receiver continuously recorded data, the RF front ends were activated daily for five hours (UTC 20:00-01:00) on March 7 to 10, resulting in a total of 20 hours of data and measurements. Based on the processing results, very strong scintillation events with $S_4$ index beyond 1 and carrier phase sigma over 0.9 rad were observed. Some of these strong scintillation events lasted for more than 3 hours. The PolaRxS receiver had numerous cycle
slips and extended periods of loss of lock of signals during these strong scintillation events.

![Data collection system configuration](image)

**Figure 3.1 Data collection system configuration**

### 3.2 Tracking Results of the SDR

The configuration of the tracking loop in the SDR is given in Table 3.1. To maintain lock of signals during strong scintillations, several different PLL bandwidths were tested. The result demonstrated that a 2Hz PLL bandwidth is most optimal in maintaining lock of signals.

**Table 3.1 STL-based Tracking Configuration for BeiDou B1I signals**

<table>
<thead>
<tr>
<th>Tracking Loop Used</th>
<th>Order</th>
<th>Integration Time</th>
<th>Bandwidth</th>
<th>Discriminator</th>
</tr>
</thead>
<tbody>
<tr>
<td>DLL</td>
<td>2</td>
<td>10ms</td>
<td>0.25Hz</td>
<td>$(1-d) \frac{E-L}{E+L}$</td>
</tr>
<tr>
<td>PLL</td>
<td>3</td>
<td>10ms</td>
<td>2Hz</td>
<td>$ATAN\left(\frac{Q_p}{I_p}\right)$</td>
</tr>
</tbody>
</table>

A maximum of five BeiDou satellites was observed through March 7 to 10, one GEO satellite (BeiDou PRN 05, denoted later as B5) and four MEO satellites (B11, B12, B14,
Table 3.2 lists the PRN numbers along with their maximum $S_4$ index and $\sigma_\phi$ values observed on all four days from March 7 to 10. It should be mentioned that due to the satellite clock problem of rapid frequency offset variations with B30 [Hauschild et al., 2011], the tracking loop experienced numerous losses of lock and the measurement quality was greatly damaged; therefore, the PRN 30 $S_4$ index and $\sigma_\phi$ values are not presented in Table 3.2.

Table 3.2 All PRNs observed on March 7 through 10

<table>
<thead>
<tr>
<th>Date</th>
<th>PRN</th>
<th>Max $S_4$</th>
<th>Time (UTC)</th>
<th>Max $\sigma_\phi$ (cycles)</th>
<th>Time (UTC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/7</td>
<td>B5</td>
<td>&gt;1</td>
<td>23:05</td>
<td>0.18</td>
<td>23:05</td>
</tr>
<tr>
<td></td>
<td>B11</td>
<td>0.65</td>
<td>23:24</td>
<td>0.1</td>
<td>23:24</td>
</tr>
<tr>
<td></td>
<td>B12</td>
<td>&gt;1</td>
<td>22:51</td>
<td>0.23</td>
<td>22:51</td>
</tr>
<tr>
<td></td>
<td>B14</td>
<td>0.96</td>
<td>22:21</td>
<td>0.035</td>
<td>22:21</td>
</tr>
<tr>
<td>3/8</td>
<td>B5</td>
<td>0.99</td>
<td>21:47</td>
<td>0.2</td>
<td>21:47</td>
</tr>
<tr>
<td></td>
<td>B11</td>
<td>&gt;1</td>
<td>23:42</td>
<td>0.2</td>
<td>23:42</td>
</tr>
<tr>
<td></td>
<td>B12</td>
<td>&gt;1</td>
<td>23:15</td>
<td>0.17</td>
<td>23:15</td>
</tr>
<tr>
<td>3/9</td>
<td>B5</td>
<td>&gt;1</td>
<td>21:16</td>
<td>0.077</td>
<td>21:16</td>
</tr>
<tr>
<td></td>
<td>B12</td>
<td>1.0</td>
<td>00:44</td>
<td>0.068</td>
<td>00:44</td>
</tr>
<tr>
<td>3/10</td>
<td>B5</td>
<td>&gt;1</td>
<td>21:21</td>
<td>0.21</td>
<td>21:21</td>
</tr>
<tr>
<td></td>
<td>B30</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

As can be seen in Table 3.2, all of the satellites experienced strong ionosphere scintillation with a $S_4$ exceeding 1 and $\sigma_\phi$ exceeding 0.2 cycles, and the maximum values of $S_4$ index and $\sigma_\phi$ all happened at the same time. The tracked C/N$_0$ results during the entire 5 hour period are given in Figure 3.2 (a)-(d).
As can be seen in Figure 3.2 (a), all the 4 satellites started to experience signal fading from 22:00 UTC time on March 7. Figure 3.2(b) shows signal fading of up to 25 dB-Hz on B5 lasting for almost 3 hours on March 8. In (a)-(d), the C/N₀ of all the MEO satellites (B11, B12, B4) show variations of quasi-sinusoid at times, which suggests multipath effects, while in the GEO satellite (B5) no such variations can be seen. This is because, for the GEO satellite, there is hardly any relative motion between the receiver and the satellite, the multipath effect will not vary that much.
The $S_4$ and $\sigma_\phi$ results computed from the SDR tracking loops are compared with those generated by the PolaRxS receiver and shown in Figure 3.3 (a)-(d).
As can be seen in Figure 3.3, the $\sigma_\phi$ and $S_4$ both showed scintillation at the same time, which matches with the time span of the fluctuations and deep drops of the C/N$_0$. The $\sigma_\phi$ results of the PolaRxS receiver showed multiple long gaps during the scintillation which is the sign of loss of track or cycle slips in the carrier phase measurements during tracking. In (d), only results from the SDR are presented for B30 because the PolaRxS receiver was not programmed to track it at that point. The results show small spikes on $\sigma_\phi$ all the time, which is consistent with the Doppler spikes observed on B30 in Sleewaegen (2010).

### 3.3 Comparisons under Different PLL Bandwidths

To maintain lock of signals during strong scintillations, several different PLL bandwidths were tested. The results show that a 2Hz PLL bandwidth is optimal in maintaining lock of signals. The results presented in section 3.1 are based on the 2Hz PLL bandwidth.

The amount of time during which the receiver lost lock of a signal is one indicator of the tracking performances of different PLL bandwidths under scintillation. Table 3.3 shows comparisons of the times when loss of track occurred under different PLL bandwidths (2Hz, 5Hz, 8Hz, and 15Hz). To track the times of loss of lock, it is necessary to detect
when the receiver started to lose lock and when it reacquired the signal. Doppler frequency is used to determine whether the receiver has lost lock since, for a stationary receiver, the approximate Doppler of a given time can be calculated through the almanac or ephemeris in post-processing, and a loss of lock can be determined whenever the PLL output frequency is off by a certain threshold, which is set to 30Hz in this project.

Table 3.3 Number of times of loss of lock under different PLL bandwidths

<table>
<thead>
<tr>
<th>Date</th>
<th>PRN number</th>
<th>Times of loss of lock</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2Hz</td>
</tr>
<tr>
<td>3/7</td>
<td>B5</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>B11</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>B12</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>B14</td>
<td>0</td>
</tr>
<tr>
<td>3/8</td>
<td>B5</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>B11</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>B12</td>
<td>0</td>
</tr>
<tr>
<td>3/9</td>
<td>B5</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>B12</td>
<td>0</td>
</tr>
<tr>
<td>3/10</td>
<td>B5</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>B30</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 3.3 shows that a larger PLL bandwidth is more likely to lose lock during the scintillation. On March 10, B5 experienced up to 90 times loss of lock during the 5 hour period. The tracked C/N₀ of B5 on March 10 given in Figure 3.2(d) showed prolonged deep signal fading for almost 3 hours.

The ability to maintain lock using a small PLL bandwidth indicated that the scintillation signal is dominated by deep fading without large phase dynamics.

Although the STL presented here with narrow PLL bandwidth is capable of maintaining lock of all signals experiencing deep fading, such a design is not highly desirable for
several reasons. First, the use of a narrow PLL bandwidth is only possible when a quality local oscillator is used in the receiver front end. This is because oscillator-induced phase jitter typically increases with lower bandwidth. Second, the data used in this study was collected on a stationary platform. If a receiver is on a dynamic platform, the narrow PLL bandwidth will not be able to maintain tracking of the platform-induced signal dynamics unless additional sensors, such as an INS, is used to aid the tracking loop. Finally, the extensive filtering associated with the narrow PLL bandwidth may smooth out scintillation-induced signal dynamics, thereby masking real physical features needed by scientists studying the scintillation phenomena.

3.4 Sky views of the BeiDou Satellites
The sky views of the BeiDou satellites color-mapped according to their $S_4$ index and $\sigma_\phi$ values over the 4 days are given in Figure 3.4:
Figure 3.4 Sky views of the BeiDou satellites color mapped w.r.t. $S_4$ and $\sigma_\phi$. 
As can be seen in Figure 3.4 (a), (b), (c),(d), the MEO satellites paths are different during the same time of day for the four days. We note, however, that the GEO satellite stays at the same spot every day, which makes it perfect as a reference station for ionosphere remote sensing. Moreover, the fact that the GEO satellite stays stationary makes its multipath variation very slow and, in fact, negligible (due to imperfection of the orbit and other forces, it is not completely geo-stationary). Additionally, we do not have to be concerned with the satellite signal ionosphere piercing point scan velocity due to satellite motion. Therefore, the GEO satellite is ideal for ionosphere studies. Many ionosphere studies have been carried on using geo-stationary satellites in the past [Van Dierendonck and Arbesser-Rastburg, 2004]. Although the BeiDou constellation has only 14 satellites in space at this point, an aggressive launching schedule is planned in the next few years. With the fast growing number and the diversity of satellites, the BeiDou constellation will be able to cover the globe with a more dense distribution, which will greatly benefit ionosphere monitoring and space weather studies with its additional new open source signals. Combining Beidou and GPS constellations will dramatically increase the number of observables during space weather events and improve the spatial resolution of ionosphere tomography, which is especially needed during space weather events when there are plasma structures in the otherwise relatively smoothly distributed ionosphere.
Chapter 4 Dual Constellation VTL-assisted-STL Performance Test and Evaluation

In this Chapter, the dual constellation VTL-assisted-STL receiver is tested with two types of data, and its tracking performance is compared with that of the STL. The first is real data collected locally in Oxford, Ohio during quiet times of the ionosphere. Artificial signal outages were added into the data to test the VTL-assisted-STL tracking performance during short signal outages. The same data is also used to evaluate the stand-alone VTL tracking performance in terms of the tracking error accumulation. The second type of data is the same real IF data discussed in Chapter 3, to evaluate the VTL tracking performances under scintillation. During these tests, the same configuration described in Table 3.1 is applied to both the stand-alone STL and the one used in the VTL-assisted-STL implementation with the PLL bandwidth changed into a less demanding value of 15Hz, if not otherwise specifically stated. The VTL approach 1 is used as the default approach during these tests and the comparisons with STL. The comparison between different VTL approaches will also be presented here.

4.1 Locally Collected Data

The first data used was collected locally in Oxford, OH on the Miami University campus with a 5MHz sampling frequency using a USRP N210 board, at 9AM UTC on June 11th, 2014. Up to 7 GPS satellites and 2 BeiDou satellites can be tracked in the data.

4.1.1 Artificial Signal Outages Data Test

For measurement purposes, 10s of signal outage was artificially performed on GPS PRN14 (denoted as G14) and BeiDou PRN 11 (denoted as B11). The C/N0 and Doppler tracked using both algorithms are shown in Figure 4.1.
In Figure 4.1, the highlighted area shows the signal outage duration, the missing C/N₀ data points are due to limitations of the C/N₀ calculation involving extremely low C/N₀ values. We can see that the VTL showed successful tracking on both PRNs during this signal outage, and no signal re-acquisition is needed, while the STL showed immediate loss of lock.
4.1.2 Stand-alone VTL Tracking Performance Test

As discussed in 2.3.1, phase errors will gradually accumulate when using stand-alone VTL for long-term tracking. In this section, the same IF data are used to conduct a stand-alone VTL tracking performance test, in order to obtain preliminary quantitative understanding of the error accumulation. More comprehensive analysis will be delivered in future work.

During the test, a stand-alone VTL was used to continuously track the signals of B11 and G14, while signals from the other satellites were still tracked by an STL. The differences of tracked Doppler and C/N₀ between the two implementations (STL results minus VTL results) are given in Figure 4.2. The comparison between the de-trended phase results of the STL and the VTL is given in Figure 4.3, as well as its zoomed-in version.

![Figure 4.2 Difference of tracked Doppler and C/N₀ between STL and stand-alone VTL](image-url)

Figure 4.2 Difference of tracked Doppler and C/N₀ between STL and stand-alone VTL
Figure 4.3 Comparison between the de-trended phase results of STL and stand-alone VTL.
In Figure 4.2, we can see that the Doppler difference slightly increases on G14 to around 0.2Hz, and the C/N$_0$ difference shows gradual decreasing of the VTL tracked C/N$_0$ on both satellites, indicating the accumulation of tracking error. In Figure 4.3, the VTL tracked de-trended phase shows multiple cycle slips, which is the sign of phase error accumulation. The zoomed-in version shows the de-trended phase experienced a sudden jump at 13.18s on G14 and at around 11.88s on B11. This is because the VTL tracking phase error kept increasing from the beginning and eventually exceeded the PLL discriminator range of ±90 degrees, which then resulted in cycle slips in the carrier phase measurements. Therefore, an upper bound of around 10s can be inferred on the applicable duration of the stand-alone ISM VTL tracking. Fortunately, this duration is long enough for the receiver to maintain lock and keep the measurements intact through the deep fading, which will be confirmed in the results of the scintillation data tests presented later.

4.2 Strong Scintillation Data

In the equatorial region, simultaneous amplitude and phase fluctuations are usually observed [Seo et al., 2009]. In this section, real scintillation data of dual constellation collected during the same experimental campaign in March 2013 was used to test the tracking performance of the VTL-assistedSTL under strong scintillation. The data collection system configuration can be found in 3.1. Among the 20-hour data over 4 days, a segment of the data collected on 0308 from 23:10PM to 12:30AM was selected as it contains strong scintillation events on three satellites (G31, B11, B12) with extended signal fading of over 25dB. A total of 9 satellites are visible in the data, and the VTL-assistedSTL receiver used the unaffected ones to aid these three satellites whenever the integrity check is triggered. The tracking results showed successful tracking on all these satellites. The tracked C/N$_0$ of the three satellites using VTL are given in Figure 4.4.
The BeiDou satellites tracking results using STL with a 15Hz PLL bandwidth have been shown in Table 3.3, indicating loss-of-lock on B11. The STL was also used to track G31, plotted here for comparison, and the results also showed loss of lock. Comparison of the STL and VTL-assisted STL tracking results of these two satellites are given in Figure 4.5.
Figure 4.5 Comparison between STL and VTL scintillation tracking results of (a) G31 (b) B11

Figure 4.5 shows the Doppler frequency and the de-trended phase for both satellites. We can see that the STL lost lock during the strong phase scintillation and deep fading when re-acquisition will also be difficult due to the low C/N$_0$, whereas the VTL-assisted STL successfully maintained lock.

4.2.1 Comparison Using Different VTL Approaches

In order to analyze the effect of positioning error, the VTL approach 2 was also applied to the implementation and to track the scintillation data. In addition, a modified version of approach 2 was applied here as approach 2s, which only makes use of a subset of all the visible satellites, for the purpose of assessing the effect of reduced GDOP and the benefit of having additional signals from BeiDou satellites:

Approach 2s: Approach 2s is essentially the same as approach 2, except that only a subset consisting of 6 satellites are used in the VTL algorithm. Two of the BeiDou satellites and one of the GPS satellites G14 were excluded, to demonstrate the effect of a reduced GDOP and of the limited number of available satellites from the un-augmented GPS system. The sky view of the satellites in sight is shown in Figure 4.6, in which the excluded three satellites are drawn in a light blue color and with dashed lines.
Approaches 2 and 2s both lead to successful tracking of the scintillation signals. The pseudorange difference and the C/N₀ difference during VTL tracking between the three approaches (approach 1 - approach 2 and approach 1 - approach2s) are given in Figure 4.7, where ‘AP’ is short for approach and the intermittent result spans during VTL tracking are plotted together. De-trended phase, de-trending carrier phase baseline difference (denoted as BD), and Doppler difference are also used to compare the tracking performance of the 3 different approaches, since the carrier tracking is more vulnerable to error accumulation. Furthermore, these three indices can also reflect the effects that the VTL tracking has on scintillation characterization. The comparison results are given in Figure 4.8. Since B11 are excluded in approach 2s, only the G31 results are given in both figures.
Figure 4.7: Pseudorange and $\Delta C/N_0$ difference using different VTL approaches.

Figure 4.8: De-trended phase, BD, and Doppler difference of different VTL approaches.
The two pseudorange differences in Figure 4.7 both showed multiple spikes and the ones from the AP1-AP2s difference tend to be larger, indicating the effect of positioning errors and reduced GDOP on pseudorange accuracies. The C/N₀ differences in Figure 4.7 showed that the tracked C/N₀ of the three approaches have no significant difference from each other except a couple of outliers, which might be due to the distortion of the C/N₀ calculation during extremely low C/N₀ [Mao and Morton, 2013]. In Figure 4.8, the detrended phase results of the three approaches also agree with each other except a few spikes, indicating the feasibility of the three approaches as far as the accuracy of the phase measurements during scintillation is concerned. In addition, by comparing the BD and Doppler differences, the AP1 and AP2 showed higher consistency than AP1 and AP2s, indicating that reduced GDOP has an adverse effect on carrier phase tracking accuracy.

The standard deviations (std), mean values, and maximum absolute values (max) of the three indexes (pseudorange difference, BD, and DD) are quantitatively summarized in Table 4.1 with the mean GDOP differences.

### Table 4.1 Summarized Statistics of Tracked Result Differences between Different VTL Approaches

<table>
<thead>
<tr>
<th></th>
<th>AP1 minus AP2</th>
<th>AP1 minus AP2s</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pseudorange Difference (m)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>std</td>
<td>2.18</td>
<td>3.24</td>
</tr>
<tr>
<td>mean</td>
<td>0.02</td>
<td>-0.01</td>
</tr>
<tr>
<td>max</td>
<td>30.13</td>
<td>49.55</td>
</tr>
<tr>
<td><strong>BD(cycle)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>std</td>
<td>0.25</td>
<td>0.38</td>
</tr>
<tr>
<td>mean</td>
<td>-0.17</td>
<td>0.61</td>
</tr>
<tr>
<td>max</td>
<td>0.59</td>
<td>1.7</td>
</tr>
<tr>
<td><strong>DD(Hz)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>std</td>
<td>4.75e-3</td>
<td>1.17e-2</td>
</tr>
<tr>
<td>mean</td>
<td>4.18e-4</td>
<td>6.37e-3</td>
</tr>
<tr>
<td>max</td>
<td>6.51e-2</td>
<td>2.46e-2</td>
</tr>
<tr>
<td>Mean GDOP difference</td>
<td>0</td>
<td>1.17</td>
</tr>
</tbody>
</table>

From Table 4.1, we can see that the AP1-AP2s difference has higher standard deviation and maximum values for all the three tracking measurements than the AP1-AP2. This
indicates a lower tracking accuracy of approach 2s in terms of code phase and carrier frequency due to a reduced GDOP.
Chapter 5 Conclusion and Future Work

In recent years, GNSS receivers have gained popularity as an effective and distributed means to remotely sense ionosphere and space weather. With the release of BeiDou ICD, 14 operational satellites have become available to the public. The ionosphere research community will benefit from the dramatically increased number of satellites. A larger number of satellite signals in space will improve the spatial resolution of ionosphere tomography which is especially needed during space weather events when there are plasma structures in the otherwise relatively smoothly distributed ionosphere. These plasma structures interfere with traversing GNSS radio signals and cause signal amplitude and phase fluctuations, collectively referred to as ionosphere scintillation. Due to deep signal fading and large phase fluctuations that accompany strong scintillation events, the receiver carrier tracking loop is subjected to increased error, cycle slips, and loss of lock. To gain a full understanding of the source and mechanism behind ionosphere scintillation, receivers that can maintain lock during severe scintillation events and provide intact measurements need to be developed.

In this thesis, STL-based tracking algorithms were first implemented in a SDR to process real BeiDou B1I and GPS L1 IF data collected over Ascension Island under ionospheric scintillation events. Tracking results and scintillation characterization of BeiDou ionosphere scintillation are presented here, because the GPS L1 scintillation of the same data has already been presented in Carroll (2014). A maximum of five satellites were observed, all showing prolonged strong ionosphere scintillation with $S_4$ exceeding 1, $\sigma_\phi$ exceeding 0.2 cycles, and deep fades of over 25dB. The performances of the STL-based tracking algorithms using different parameters were compared. Based on the comparison results, a narrower bandwidth is less susceptible to loss of lock during strong scintillation in equatorial regions, which in turn indicates that the scintillation signal is dominated by deep fading without large phase dynamics in equatorial regions.

A dual-constellation VTL-assisted-STL tracking algorithm suitable for ISM receiver is then developed and tested with two types of data. The first one is real data collected locally during quiet times of the ionosphere. Artificial signal outages were added into the data to test the VTL-assistedSTL tracking performance during short signal outages, and
the results showed that this implementation can successfully maintain lock during momentary signal blockage. The same data are also used to evaluate the stand-alone VTL tracking performance in terms of the tracking error accumulation. The stand-alone VTL tracking test showed that this VTL algorithm will accumulate the carrier phase tracking errors, resulting in cycle slips in carrier phase measurements about 10s later, which entails an upper bound on the applicable duration of the stand-alone ISM VTL tracking. Luckily, this applicable duration is long enough for the receiver to maintain lock and keep the measurements intact through the deep fading, which is confirmed in the test results presented using the second set of data. The second set of data is real IF data that contains strong scintillation events on three satellites over Ascension Island, and is used to evaluate the VTL tracking performances under strong scintillation. The test results showed successful tracking during severe scintillation events with deep fades of over 25dB.

Using three different approaches of the VTL, experiments were conducted to analyze the effect of navigation accuracy in VTL implementation on tracking performance during scintillation. Results confirmed the benefit of a larger number of visible satellites enabled by additional signals from the BeiDou system for the VTL tracking during scintillation events.

The future work can be summarized into a few aspects:

1. Apply the method in Mao and Morton (2013) so that an ATAN2 phase discriminator can be used in the STL tracking. The increased range will allow more severe phase fluctuations to be observed without distortion.
2. More extensive performance testing needs to be done on the VTL-assisted STL algorithm using data of diverse scenarios, including the phase error accumulation in long-term VTL tracking.
3. Improve the Doppler estimation of the VTL by applying more advanced algorithms to address the other error sources.
4. Further develop the VTL to be able to be incorporated with EKF and INS, and extend the application to dynamic scenarios.
Bibliography


measurements from SBAS geostationary satellite signals. *Proceedings of ION GNSS 17th technical meeting of the satellite division*, Long Beach, CA.


