GNSS radio occultation technique for atmospheric refractivity profiling and planetary boundary layer height detection

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**NANYANG
TECHNOLOGICAL
UNIVERSITY**

SINGAPORE

**GNSS RADIO OCCULTATION TECHNIQUE
FOR ATMOSPHERIC REFRACTIVITY
PROFILING AND PLANETARY BOUNDARY
LAYER HEIGHT DETECTION**

**HAN BO
SCHOOL OF ELECTRICAL AND
ELECTRONIC ENGINEERING**

2018

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FOR ATMOSPHERIC REFRACTIVITY
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LAYER HEIGHT DETECTION**

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A thesis submitted to the Nanyang Technological University
in fulfillment of the requirements for the degree of
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2018

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution.

Date

HAN BO

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Summary

Global Navigation Satellite System (GNSS) Radio Occultation (RO) is an atmospheric remote sensing method attracting extensive attention with increasing number of RO missions. Valuable atmospheric parameters can be detected using this technique, providing crucial additions to current weather and climate studies. GNSS RO data have been assimilated into various weather data and models. During a RO event, the GNSS signals grazing the Earth's atmosphere are delayed and bent before picked up by the GNSS receivers. The excess Doppler frequency information measured by the receivers contains the Earth's atmospheric effect and is used to invert to atmospheric parameters such as refractivity profiles. This thesis covers several aspects in GNSS RO study. The GNSS tracking algorithms are first described which lays the groundwork for GNSS RO. Then, we study the RO inversion algorithms using the tracked GNSS signals to obtain the atmospheric refractivity profiles, and the error characteristics of the orbital errors' effect on the retrieved refractivity errors. Finally, the GNSS RO's application is extended to planetary boundary layer height (PBLH) detection.

The tracking algorithm in the thesis focuses on the open loop (OL) tracking algorithm which can track the GNSS signals to a lower altitude compared to the common closed loop (CL) algorithm. The OL algorithm is applied to the raw GPS data collected during a mountain-based RO (MRO) experiment. The RO inversion algorithms for both space-based and ground-based RO is described. For the space-

based RO, the Radio Occultation Processing Package (ROPP) provides more detailed inversion algorithms. The performance of ROPP is statistically evaluated for the Southeast Asia region by comparing with the co-located Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) and European Centre for Medium-Range Weather Forecasts (ECMWF) profiles. The ground-based RO algorithm is applied to the GNSS RO data collected during the MRO experiment. Vertical refractivity profiles below the receiver height near the MRO experiment site are retrieved. The refractivity profiles are further exploited to detect the PBLH using the common refractivity gradient method. An obvious GNSS signal amplitude drop-and-rise-back pattern is constantly observed in the collected data. Using the MRO geometry and the time when the GNSS signal's amplitude drops to the lowest, the PBLH can be directly detected using the signal's amplitude. This signal amplitude-based method is thus proposed for application on the collected MRO data and statistically verified. This method shows advantages such as easy to implement and avoids some of the assumptions and steps associated with the popular refractivity gradient-based method.

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Symbols and Acronyms

a	impact parameter.
$A(t)$	GPS baseband signal amplitude as a function of time.
$A(a)$	baseband signal amplitude as a function of impact parameter.
A^{rcv}	received signal amplitude (summed over 20 samples).
A_{L1}	amplitude for GPS L1 civil signal.
c	speed of light in vacuum.
C/N_0	carrier-to-noise density ratio.
C_{L1}	the ranging code for GPS L1 civil signal.
D_{L1}	the navigation data for GPS L1 civil signal.
$D(t)$	the navigation data bits in GPS baseband signal.
d_R	receiver altitude.
d_T	transmitter altitude.
e_R	unit vector of the signal path approaching to receiver.
e_T	unit vector of the signal path emitting from the transmitter.
$e(t)$	Gaussian noise in the GPS baseband signal composition.

$e_s(t)$	Gaussian noise after multiplied with the replica ranging code.
f_{carr}	carrier frequency.
f_{IF}	intermediate frequency.
f_d	Doppler frequency.
f_{edop}	excess Doppler frequency.
f_{dL1}	Doppler frequency for GPS L1 civil signal.
$\tilde{f}(t)$	Doppler frequency model.
i_n	in-phase correlation summation.
I	in-phase correlation summation (summed over 20 samples).
j	an index for calculation of I , Q , and Φ^{rcv} .
m	an index for refractivity-height profile.
n_i	an integer index.
n_{ref}	refractive index.
n_R	refractive index at receiver altitude.
n_T	refractive index at transmitter altitude.
N	refractivity.
N'_{rmg}	relative minimum gradient (RMG).
N'_{min}	the minimum refractivity gradient.
N'_{rms}	RMS value of the refractivity gradient.
$p(t)$	ranging code in GPS baseband signal.

P	pressure.
P_w	water vapor pressure.
q_n	quadrature correlation summation.
Q	quadrature correlation summation (summed over 20 samples).
r_0	tangent radius.
$\mathbf{r}_R$	position vector for receiver.
$\mathbf{r}_T$	position vector for transmitter.
s_{L1}	L1 civil signal.
T_I	integration period.
T	temperature.
$u(t)$	GPS baseband signal.
$u^i(t)$	in-phase component of the GPS baseband replica signal.
$u^q(t)$	quadrature component of the GPS baseband replica signal.
$u_s(t)$	GPS baseband signal multiplied with the replica ranging code.
u_T	length of $\mathbf{v}_T$.
$v(t)$	local replica signal without the ranging code.
$\mathbf{v}_R$	receiver velocity.
$\mathbf{v}_T$	transmitter velocity.
α	bending angle.
α_P	positive elevation bending angle.

α_N	negative elevation bending angle.
ϵ	unmodeled carrier phase measurement error.
ϵ_p	unmodeled position error.
ϵ_v	unmodeled velocity error.
η	angle between $\mathbf{r}_T$ and $\mathbf{v}_T$.
θ	angle between $\mathbf{r}_R$ and $\mathbf{r}_T$.
δt_u	receiver clock bias.
δt^s	satellite clock bias.
λ	wavelength of the carrier phase.
ϕ_R	angle between $\mathbf{e}_R$ and $-\mathbf{r}_R$.
ϕ_T	angle between $\mathbf{e}_T$ and $-\mathbf{r}_R$.
φ_C	carrier frequency phase.
φ^{rcv}	total receiver phase.
φ_G	geometric phase.
φ_E	excess phase.
φ_I	ionospheric delay effect on phase.
φ_T	tropospheric delay effect on phase.
φ_{L1}	carrier phase for GPS L1 civil signal.
$\Phi(t)$	GPS baseband signal phase.
$\Phi(a)$	baseband signal phase as a function of impact parameter.

Φ^{rcv}	total receiver phase (summed over 20 samples).
Φ_R	residual phase.
$\tilde{\Phi}(t)$	Doppler phase model.
Φ_0	the initial phase in GPS baseband signal.
ω	the Doppler angular frequency.
τ	the code delay in GPS baseband signal.
$\tilde{\tau}$	the estimated code delay in GPS baseband signal.
ABL	Atmospheric Boundary Layer
ADC	Analog-to-Digital Converter
ARM	Amplitude Relative Minimum
ASDC	NASA Atmospheric Science Data Center
BP	Back Propagation
CALIPSO	The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
CanX-2	Canadian Advanced Nanospace eXperiment
CDAAC	COSMIC Data Analysis and Archival Center
CHAMP	CHallenging Minisatellite Payload
CL	Closed Loop

COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate
COTS	Commercial-Off-The-Shelf
CT	Canonical Transform
DLL	Delay Lock Loop
ECMWF	European Centre for Medium-Range Weather Forecasts
FLL	Frequency Lock Loop
FSI	Full Spectrum Inversion
GNSS	Global Navigation Satellite System
GO	Geometric Optics
GPS	Global Positioning System
IF	Intermediate Frequency
IGS	International GNSS Service
IGRA	Integrated Global Radiosonde Archive
IGSO	Inclined Geosynchronous Orbit
LEO	Low Earth Orbit
MSISE-90	Mass Spectrometer Incoherent Scatter Radar extended model 1990
MRO	Mountain-based RO
NCAR	National Center for Atmospheric Research.

NCDC	National Climatic Data Center
NCO	Numerically Controlled Oscillator
NMC	National Meteorological Center
OL	Open Loop
PBL	Planetary Boundary Layer
PBLH	Planetary Boundary Layer Height
PLL	Phase Lock Loop
PRN	Pseudo-Random Noise
RO	Radio Occultation
ROM SAF	Radio Occultation Meteorology Satellite Application Facilities
ROPP	Radio Occultation Processing Package
RINEX	Receiver Independent Exchange Format
RMG	Relative Minimum Gradient
RMS	Root Mean Square
SDR	Software-Defined Radio
SNR	Signal-to-Noise Ratio
SS	Sliding Spectral
TEC	Total Electron Content
TOW	Time Of Week
TOGA	Tropical Ocean and Global Atmosphere

Chapter 1

Introduction

Global Navigation Satellite System (GNSS) radio occultation (RO) is an excellent remote sensing technique to measure the properties and characteristics of the Earth's atmosphere. It has been implemented in various satellite missions, providing meaningful additions to the existing methods to monitor the atmosphere (e.g., [1–13]). The products of RO, such as atmospheric refractivity, temperature, pressure, and humidity, are of great importance for weather studies, and can lead to essential parameters such as planetary boundary layer height (PBLH). An introduction to this thesis is given in this chapter. The motivation and objectives are presented in Section 1.1. The major contributions of the thesis are presented in Section 1.2. Section 1.3 discusses the thesis's organization.

1.1 Motivation and objectives

During the RO processing, the GNSS signals need to be tracked before RO data processing. The tracking algorithm of the GNSS receiver for RO adopts both close loop (CL) and open loop (OL) tracking. The latter proves to be more suitable for tracking lower altitude GNSS signals for both space-based and mountain-based RO (MRO) (e.g., [14–17]). The OL tracking algorithm requires knowledge of the

OL Doppler frequency model, whose construction requires precise knowledge of the transmitter's and receiver's orbit information. The orbital errors propagate to the final retrieved refractivity results under an OL tracking scenario RO and is explained in the following manner. Fig. 1.1 illustrates the orbital error propagation and shows the major steps in RO data processing.

The signal transmitted by the GNSS satellite satisfying the RO geometry propagates through the Earth's ionosphere and neutral atmosphere. The induced frequency shift, amplitude fading, signal delay, and signal bending can be measured from the GNSS receiver mounted on the low Earth orbit (LEO) satellite for space-based RO, or on mountaintops and airplanes for ground-based RO. The GNSS receiver tracks the signal and outputs observables such as the signal's Doppler frequency and amplitude. Combined with the transmitter's and the receiver's positions, the Doppler frequency shift and signal amplitude can be used to derive the atmospheric bending angle profiles. The bending angle profiles are then converted to the atmospheric refractivity profiles. Both the transmitter's and receiver's positions and velocities will affect the calculation of the OL Doppler frequency model. The transmitter's and receiver's position and velocity errors will propagate to other errors in the retrieved results such as bending angle and refractivity following the above RO processing chain.

Figure 1.1: RO error propagation chain. The transmitter's and receiver's orbit errors propagate to bending angle errors and refractivity errors.

In the RO processing chain mentioned above, errors occur at each step and propagate to the subsequent steps. The understanding of the error propagation characteristics is important in order to 1) provide the error assessment of the derived atmospheric physical data when the data are assimilated with other atmospheric measurement results; 2) provide the accuracy requirements on orbital determination errors and tracking errors when the total accuracy requirement on the RO results has been set. The issue of error assessment of RO processing chain has been visited by many researchers. Both [18] and [19] explained the error propagation from excess phase to bending angle, then to refractivity, temperature, and pressure. Georg Beyerle studied the GPS receiver induced error in RO by examining the OL and CL tracking algorithms [20]. Since the OL tracking algorithm is applied for low altitude GNSS RO signals, the study of the transmitters' and receivers' orbital errors' effect on RO in an OL scenario is important. The OL tracking algorithm requires the construction of an OL Doppler frequency model, which is affected by the accuracy of the transmitter's and receiver's positions and velocities. A combined study of the orbital errors' effect on the OL Doppler frequency model for OL tracking scenario is useful. Chapter 3 covers this topic.

An understanding of the transmitters' and receivers' orbital errors' effect on the RO retrieval accuracy helps define the positioning accuracy requirement for the RO inversion. To do RO inversion for real RO mission data, a software package named the Radio Occultation Processing Package (ROPP) provides an open source RO data processing tool. To better assess the performance of ROPP in the Southeast Asia region, statistical comparisons are carried out between the 2011 Southeast Asia Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) RO data processed using the updated software by the COSMIC Data Analysis and Archival Center (CDAAC) and using the ROPP, which is discussed in Chapter 4.

In addition to the space-based RO study in Chapter 3 and Chapter 4, a MRO experiment was carried out by the Colorado State University (CSU) GPS Lab on April 20–26, 2015 in Hawaii. As a ground experiment, MRO generally has fewer constraints compared to space-based RO experiments such as in terms of the power consumption, data storage, equipment weight, size, etc. The MRO experiment has a similar geometry to space-based RO and provides an excellent platform for verifying and developing the GNSS signal tracking algorithms and RO inversion algorithms. The collected raw data provide useful research resources for understanding the propagation of the GNSS signals in the lower troposphere. It also provides opportunities to study the vertical refractivity profiles below the receiver’s altitude for the nearby regions by inverting the excess Doppler frequency tracked by the GNSS receivers.

As stated earlier, the GNSS RO, both the space-based ones such as the COSMIC mission and the ground-based ones such as the MRO experiment, can be used to derive the atmospheric vertical refractivity profiles. These refractivity profiles can then be used for PBLH detection. PBLH is the height of the planetary boundary layer (PBL) and a crucial parameter for weather and climate studies. The PBL over the Hawaii MRO experiment region is characterized by a well-mixed, stratocumulus-topped atmospheric boundary layer (ABL) with a well-defined top [21]. Most previous applications of GNSS RO in PBLH detection generally lie within the space-based GPS-only RO (e.g., [21–32]). Here, we explore the potential of the GNSS MRO using the data collected in Hawaii. With the receiver located on the mountaintop instead of the satellites, the regional temporal and spatial resolutions are greatly increased. In addition, this experiment incorporates PBLH detection using GNSS constellations and regional services other than GPS such as GLONASS, Galileo, Beidou, and QZSS. Using them greatly increases the number of measurements.

The GNSS MRO inversion to obtain the refractivity profiles for PBLH detection needs both positive and negative elevation excess Doppler measurements, which is

not satisfied in some collected events. In addition, it also requires the inversion of the excess Doppler measurements to the refractivity profiles which complicates the procedure. To overcome these drawbacks, a PBLH detection method based on signal amplitude is proposed and applied to the MRO data in the thesis. In the collected GNSS signal, obvious carrier-to-noise (C/N_0) drop-and-rise-back patterns are often seen in the amplitude data. This C/N_0 drop-and-rise-back pattern is related to the sharp refractivity change that marks the PBL top and can be used for PBLH detection. The MRO experiment, PBLH detection, and the proposed signal amplitude method are discussed in Chapter 5.

The three topics mentioned above are the major chapters including simulation study of the effect of orbital errors on OL tracking algorithm in GPS RO, performance evaluation of ROPP in Southeast Asia, and PBLH detection using mountaintop-based GNSS RO signal amplitude. The structure of the thesis with chapter numbers is shown in Fig. 1.2. OL and/or CL tracking algorithms are used to track the GNSS signals. The tracked results including Doppler frequency, phase, and amplitude are used for further processing. On one hand, the Doppler frequency and phase are fed to the RO algorithms to derive the bending angle and refractivity profiles. The refractivity profiles are then used to determine the PBLH. On the other hand, the signal amplitude is also used for PBLH detection. Chapter 3 and Chapter 4 focus on the space-based RO inversion algorithms and the orbital error study for the OL tracking. Chapter 5 focuses on the mountain-based RO data processing, OL tracking of the MRO data, and PBLH detection.

The objectives of the thesis are as follows:

1. To derive the relationship between the orbital error and the refractivity error under an OL tracking scenario.

Figure 1.2: The structure of the thesis. The contents for different chapters are marked with different shades of grey.

2. To study and implement the RO inversion algorithms for both the space-based and ground-based scenarios. For the space-based scenario, the performance of the ROPP software (the software for space-based RO inversion mentioned earlier in this section) when applied to Southeast Asia RO data need to be verified by comparing with CDAAC processing results using the profiles generated by the European Centre for Medium-Range Weather Forecasts (ECMWF) as a benchmark. For the ground-based scenario, the RO inversion algorithm needs to be implemented for the MRO data collected in Hawaii.
3. To implement the OL tracking algorithm on the raw GPS signals collected during the MRO experiment, and compare the OL tracking results with those from the CL tracking algorithm. To study the effect of OL and CL algorithms on the PBLH detection.
4. To develop and verify the signal amplitude-based method for PBLH detection using the MRO data collected in the Hawaii experiment.

1.2 Major contributions of the Thesis

The major contributions of the thesis are summarized below:

1. A simulation loop is constructed to show the transmitter's and receiver's orbital errors' effect on the derived refractivity errors. Uniform, normal, and fixed orbit position errors of various error amounts are added to the simulation loop.
2. The performance of the software package ROPP is carefully examined for space-based RO data processing. The 2011 Southeast Asia COSMIC data are processed with ROPP and compared with the CDAAC output. Excellent consistency of the bending angle and refractivity retrieval results is found between

the processed results. In addition, co-located ECMWF profiles are used as references to further evaluate the CDAAC and ROPP processed results. Compared to ECMWF, both CDAAC and ROPP processed results have similar mean refractivity differences and standard deviation differences. A hypothesis testing based on the t-test is carried out to validate the results' statistical significance. A normalized error variance statistical test for refractivity is introduced and conducted. CDAAC and ROPP processing comparison shows that the differences in the adopted background bending angle models are the major reasons for the performance difference.

3. A method using MRO signal amplitude measurements and detecting the occurrence of minimum signal amplitude to derive PBLH is developed. The performance of this signal amplitude-based method for PBLH detection is verified by comparing the MRO data with the COSMIC data. This method is simple, easy to implement, and avoids some of the assumptions and steps associated with the common refractivity gradient-based method. Three additional data sources, COSMIC, Integrated Global Radiosonde Archive (IGRA), and Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), are used to demonstrate the feasibility, advantage, and validity of the signal amplitude-based method and its applicability to the MRO measurements.
4. Using the proposed signal amplitude-based method, we obtain PBLH measurements over the ocean (marine PBLH) using relatively low-cost equipment. GNSS data collected during the MRO experiment conducted on the summit of the Haleakala on the Hawaiian island of Maui from April 20–26, 2015 are used for the PBLH detection. The usage of all open signals on GPS, GLONASS, Galileo, Beidou, and QZSS provides much denser temporal and spatial PBLH measurements.

1.3 Organization of the Thesis

The thesis is organized as follows: Chapter 2 provides a literature review on the background knowledge. The detailed GNSS signal structure is introduced with a focus on GPS signal and OL tracking algorithm. Then the GNSS RO inversion techniques and PBLH detection using vertical refractivity profile are discussed. Chapter 3 studies the effect of orbital errors of the GPS and LEO satellites on the retrieved refractivity using simulations. Chapter 4 presents a statistical comparison between the ROPP and CDAAC. The entire COSMIC mission data for 2011 in Southeast Asia are used for the comparison. The ECMWF is used as a reference in the comparison. Chapter 5 discusses PBLH detection using the collected MRO data. The PBLH detection method based on the signal's amplitude is proposed and applied to the MRO data. The method is further verified using various other data sources. Chapter 6 concludes the thesis and recommends some research directions for future exploration.

Chapter 2

Literature Review of GNSS, GNSS RO, and PBLH Detection

This chapter reviews the fundamentals of GNSS, GNSS RO, and PBLH detection. The GNSS is introduced with a focus on the OL tracking algorithm for GPS signal. Then, the GNSS RO inversion algorithm is described including steps to invert the signal phase measurement to atmospheric bending angle and refractivity. Last, the PBLH detection is described as one of the many GNSS RO applications. The definition and importance of PBL and PBLH are first presented, followed by an introduction to the commonly used refractivity gradient method for PBLH determination. The current research status for space-based RO processing and PBLH detection are included.

2.1 GNSS and OL tracking algorithm for GPS signal

GNSS is widely used for navigation, surveying, mapping, timing, etc. In this section, the basic information of the GNSS is introduced with a focus on the GPS,

which is currently the most commonly used GNSS. The GPS signal structure is presented, followed by the GPS receiver's acquisition and tracking algorithms. The detailed OL tracking algorithm that is used for low altitude GPS RO signal tracking is described in detail. The advantages and disadvantages of the OL algorithm are discussed.

2.1.1 General introduction

GPS was developed by the US military and declared operational in 1995. It consists of the space segment, the control segment, and the user segment. The space segment is the GPS satellite constellation consisting of 31 operational satellites as of January 14, 2018 [33]. The satellites are split to 6 orbital planes with 4 to 6 satellites per plane. Their orbits' inclination angles are about 55° and the radii are approximately 26,560km. The control segment consists of 1 master control station and 12 other monitor stations [34]. The control segment monitors the satellites' orbit and health, maintains the GPS time, predicts the satellites' ephemeris and clock parameters, updates satellites' navigation message, and commands the satellites' maneuvers to maintain orbit [34]. The user segment is the GPS receivers found in smart phones, cell towers, and elsewhere.

In addition to the mostly widely used GPS, the Russia's GLONASS, European Union's Galileo, and China's Beidou Navigation Satellite System are treated as GNSS (e.g., [35]). There are other regional services and augmentation systems such as Japan's QZSS. The expanding number of GNSS, regional services, and augmentation systems are providing unprecedented opportunities for a variety of research and applications fields, such as precise navigation, timing, GNSS remote sensing, etc.

2.1.2 GPS signal structure

Different GNSS systems share similar characteristics and GPS is used as an example to show the GNSS signal structure. GPS satellites transmit L-band frequency signals known as L1 ($f_{L1}=1575.42$ MHz), L2 ($f_{L2}=1227.60$ MHz), and L5 ($f_{L5}=1176.45$ MHz) (e.g., [34] [36]). The frequencies in the brackets are the center frequencies for the three bands. Each GPS signal consists of the carrier, ranging code, and navigation data. The carrier is a sinusoidal signal with a frequency such as f_{L1} . The ranging code is a binary code called PRN (pseudo-random noise) code that is multiplied to the carrier. The navigation data is also a binary code that is further multiplied to the carrier. The navigation data contains the satellite ephemeris, health status, clock parameters, etc.

The L1 civil signal s_{L1} is the multiplication of the L1 carrier, CA code (ranging code) at 1.023MHz, and the navigation data message at 50Hz [34]:

$$s_{L1} = \sqrt{2}A_{L1}(t)C_{L1}(t)D_{L1}(t)\sin[2\pi(f_{L1} + f_{dL1})t + \varphi_{L1}], \quad (2.1)$$

where the parameters with subscript $L1$ are all for GPS L1 civil signal, A_{L1} is the amplitude, C_{L1} is the ranging code, D_{L1} is the navigation data, f_{dL1} is the Doppler frequency, φ_{L1} is the carrier phase, and t is the time. Fig. 2.1 shows the structure for GPS L1 signal.

2.1.3 GPS signal acquisition and tracking

The GPS signal baseband processing including acquisition and tracking is described in this subsection. After the GPS signal at carrier frequency is picked up by the antenna, the signal goes through filtering, amplification, and down-converted to

Figure 2.1: Main components of GPS L1 civil signal structure with the carrier, the CA code, and the navigation data message. Figure is not drawn to scale.

the intermediate frequency (IF). Then, the IF signal is digitized by an Analog-to-Digital converter (ADC) for receiver processing [34].

To synchronize with the incoming IF signal, the receiver creates a local replica of the received signal which changes with the incoming GPS signal's variations caused by the satellite motions. The local replica signal's ranging code shall closely match the incoming signal's ranging code, so that a correlation peak can occur. In addition, the replica signal's Doppler frequency shall be close to the incoming signal's Doppler frequency. The process to find the satisfying ranging code and Doppler frequency is known as acquisition. The output of acquisition contains the estimates of the signal's coarse ranging code phase and coarse IF Doppler frequency.

After acquisition, signal tracking is required to keep up with the changes in the incoming signal's code and Doppler frequency changes. GPS tracking is essentially building a narrow band filter whose center frequency changes with the frequency of

the incoming signal. In an actual tracking process, the small band filter may have a fixed center frequency but the local oscillator frequency changes instead [37].

There are various tracking methods. The more commonly used is the CL tracking, which utilizes a feedback loop to steer the local signal replica close to the incoming signal. Tracking loops are constructed to keep up with the code delay, phase, and frequency changes of the incoming signal. The corresponding tracking loops are referred to as delay lock loop (DLL), phase lock loop (PLL), and frequency lock loop (FLL), respectively. A description of the detailed CL algorithm can be found in [34] [37]. Commercial-off-the-shelf (COTS) receivers such as Novatel OEM615, OEM627, and Septentrio PolaRxS PRO utilize the CL tracking algorithm.

The tracking algorithm in GPS RO receivers generally uses the CL algorithm. When the GPS signals propagate in the lower atmosphere, large signal phase fluctuations and strong signal amplitude fading occur due to the scintillation and multipath propagation. Under these conditions, the CL algorithm encounters problems tracking the signals [15]. The tracking algorithm may operate in its non-linear region or even beyond its pull-in range, causing large refractivity bias in the lower troposphere measurements and early signal-loss-lock during an RO event. To overcome these drawbacks, researchers have proposed the OL tracking algorithm [14] [38]. The OL tracking algorithm does not use the feedback loop which is continuously minimizing the differences between the received signal and local replica. On the other hand, it uses an a-priori Doppler frequency model which is calculated based on GPS and LEO satellites' positions and velocities and meteorological information of the Earth's atmosphere such as refractivity. Currently, major GNSS RO missions switch to OL tracking when the GNSS signal propagates in the lower troposphere (e.g., [39–41]).

2.1.4 GPS OL tracking

The detailed OL algorithm is described in this subsection. Prior to the application of the OL tracking, the signal should be acquired and then tracked by the CL algorithm which can provide the basic ranging code phase and carrier Doppler frequency. The OL tracking algorithm first wipes off the modulated ranging code from the GPS IF signal. Then, the carrier is wiped off using a Doppler frequency model. Finally, the in-phase and quadrature-phase correlation sums are used to extract amplitude and residual phase (e.g., [20] [39] [42]). Fig. 2.2 shows a basic diagram of the OL tracking algorithm. The detailed Doppler frequency model construction is described in Section 5.2.1.

Figure 2.2: GPS OL carrier tracking signal flow diagram. The GPS IF signal goes through code and carrier wipe-off before the amplitude and residual phase are extracted. The Doppler frequency model is used for both code and carrier wipe-off procedures.

Code wipe-off

GPS signals are modulated with a ranging code, which needs to be wiped off before further processing. The initial code phase is directly obtained from the previous epoch's CL tracking results. The remaining code phases are then calculated using a Doppler frequency model.

The GPS IF signal can be represented as:

$$u(t) = A(t)p(t - \tau)D(t - \tau)e^{j[2\pi f_{IF}t + \Phi(t) + \Phi_0]} + e(t), \quad (2.2)$$

where $\Phi(t)$ is the time varying phase including the Doppler effect, Φ_0 is the initial phase at $t = 0$, f_{IF} is the intermediate frequency, τ is the code delay, $A(t)$ is the amplitude, $e(t)$ is the Gaussian noise, $p(t - \tau)$ is the ranging code with time delay, and $D(t - \tau)$ is the navigation data bits with time delay. A replica of the ranging code is computed based on the initial estimate of the code delay $\tilde{\tau}$ obtained from the CL tracking as $p(t - \tilde{\tau})$. The code wipe-off procedure can be written as:

$$u_s(t) = u(t)p(t - \tilde{\tau}). \quad (2.3)$$

Assuming that the estimated code phase delay is very close to the true code phase delay, the IF signal multiplied with the replica ranging code gives:

$$u_s(t) \approx A(t)D(t - \tau)e^{j[2\pi f_{IF}t + \Phi(t) + \Phi_0]} + e_s(t), \quad (2.4)$$

where $e_s(t)$ is the noise after multiplication.

Carrier Wipe-off

The signal with ranging code removed $u_s(t)$ is then further multiplied with the local signal replica generated using the Doppler frequency model. The local replica signal is:

$$v(t) = e^{-j[2\pi f_{IF}t + \tilde{\Phi}(t)]}, \quad (2.5)$$

where the Doppler phase model $\tilde{\Phi}(t)$ is constructed by integrating the Doppler frequency model $\tilde{f}(t)$: $\tilde{\Phi}(t) = 2\pi \int_0^t \tilde{f}(\tau) d(\tau)$.

In the implementation, $\tilde{f}(t)$ is updated every T_I integration period and approximated as a piecewise constant function for $(n_i - 1)T_I < t \leq n_i T_I$, where n_i is an integer index starting from 1. The Doppler phase model can be written as $\tilde{\Phi}(nT_I) = 2\pi T_I \sum_1^n \tilde{f}(n_i T_I)$, and will be simplified as $\tilde{\Phi}_n = 2\pi T_I \sum_1^n \tilde{f}(n_i)$.

The final correlation has in-phase and quadrature terms:

$$i_n = \frac{2}{T_I} \times \text{Re} \left[\int_{nT_I}^{(n+1)T_I} u_s(t) v(t) dt \right] \quad (2.6)$$

$$q_n = \frac{2}{T_I} \times \text{Im} \left[\int_{nT_I}^{(n+1)T_I} u_s(t) v(t) dt \right], \quad (2.7)$$

where Re and Im denote the real and imaginary part of the operands, respectively.

Extract Residual Phase and Amplitude

The residual phase Φ_n^R can be extracted using the previous correlation in-phase and quadrature terms i_n and q_n :

$$\Phi_{n+1}^R = \Lambda(n) + C_n, \quad (2.8)$$

where

$$C_n = \begin{cases} C_{n-1} + 2\pi & : \text{if } \Lambda(n) - \Lambda(n-1) < -\pi \\ C_{n-1} - 2\pi & : \text{if } \Lambda(n) - \Lambda(n-1) > \pi \\ C_{n-1} & : \text{otherwise.} \end{cases} \quad (2.9)$$

$\Lambda(n) \equiv \text{atan2}(q_n/D_n, i_n/D_n)$. D_n is the navigation data bit during the n th integration period and $C_1 = 0$. The total carrier phase φ_n^{rcv} is constructed by summing the estimated Doppler phase model $\tilde{\Phi}_n$ and residual phase Φ_n^R :

$$\varphi_n^{rcv} = \tilde{\Phi}_n + \Phi_n^R. \quad (2.10)$$

The in-phase and quadrature terms i_n and q_n , and the carrier phase φ_n^{rcv} are each summed over every $K = 20$ integration periods to obtain I , Q , and carrier phase Φ^{rcv} :

$$I_k = \sum_{j=K(k-1)+1}^{Kk} i_j \quad (2.11)$$

$$Q_k = \sum_{j=K(k-1)+1}^{Kk} q_j \quad (2.12)$$

$$\Phi_k^{rcv} = \frac{1}{K} \sum_{j=K(k-1)+1}^{Kk} \varphi_j^{rcv}, \quad (2.13)$$

where j is an index. The signal amplitude output is then calculated using I and Q :

$$A_k^{rcv} = \sqrt{I_k^2 + Q_k^2}. \quad (2.14)$$

2.2 GNSS RO

GNSS RO is an important atmospheric remote sensing technique. First, a general introduction to GNSS RO is provided including a brief history of the RO technique,

discussion on several major satellite missions, and some applications of GNSS RO. Then, the inversion algorithm using geometric optics (GO) for a space-based RO is introduced. Finally, the modified inversion algorithm for ground-based RO is presented.

2.2.1 General introduction

GNSS RO is a comparatively new atmospheric profiling technique that utilizes the GNSS signal traveling through the Earth's atmosphere [43]. As the GNSS signal grazes through the atmosphere, it experiences bending and delay caused by the atmosphere before reaching the GNSS receivers, as shown in Fig. 2.4 and 2.5 for both space-based and ground-based RO, respectively. By analyzing the received GNSS signal, the atmospheric parameters can be derived [14] [44] [45].

The concept of occultation was first applied to measure the ionosphere and atmosphere of planets and moons such as Venus, Mars, Jupiter, Saturn, Neptune, Titan, and Uranus in 1960–90s [46–54]. During these missions, S and X band signals were transmitted by spacecraft and received by an antenna on the Earth. At a certain geometry, the signal path is occulted by the planets' or moons' atmosphere or ionosphere. The occulted signal provides an opportunity to retrieve parameters such as electron number density, gas refractivity, pressure, temperature, molecular number density, dispersive radio frequency absorption, etc.

The first GPS RO mission for the Earth's atmosphere was the GPS/MET experiment from April 3, 1995 to March 1997 [1]. For the GPS/MET mission, a single low-gain antenna points towards the limb for both GPS occultation and positioning (see Fig. 5 in [55]). This design was not optimal, but this pioneering mission provided promising results with excellent measurement accuracy, resolution, and coverage [2–5]. Afterwards, a number of satellite missions were executed with evolving equipment such as the SAC-C in 2000 [6], the CHAMP in 2000 [9] [10], the

GRACE in 2001 [7] [8], the COSMIC in 2006 [11–13], etc.

COSMIC mission is a GPS RO mission with 6 LEO satellites at altitudes of about 800km [56]. COSMIC provides about 2,500 globally distributed profiles daily, greatly adding to the current weather and climate measurements [57]. The COSMIC data have been assimilated by a number of weather centers, such as the NOAA National Centers for Environmental Prediction (NCEP), the ECMWF, the Central Weather Bureau (CWB) of Taiwan, the United Kingdom Meteorological Office (UKMO), the Japan Meteorological Agency (JMA), the Air Force Weather Agency (AFWA) and others [41]. With the ongoing COSMIC-2 mission including 12 LEO satellites and the capability of receiving other GNSS signals such as Galileo and GLONASS, higher temporal resolution measurements at about 8,000 profiles daily are expected [58].

Both GNSS signal transmitter and receiver are required for GNSS RO. The operational GNSS satellites provide continuous signal sources and the GNSS receivers track these signals. The signal rays may travel through the Earth’s atmosphere at certain time periods due to the relative motions of the transmitters and receivers. The signal’s carrier phase, Doppler frequency, and amplitude can provide information about the Earth’s atmospheric propagation effect. The geometric Doppler frequency represents the Doppler caused by the relative motion between the transmitter and receiver. The excess Doppler frequency, which is the difference between the received Doppler frequency and the geometric Doppler frequency, corresponds to the effect of the Earth’s atmosphere and can be used to derive the bending angle and atmospheric refractivity profiles (e.g., [43] [44]).

Based on the different locations of the receivers, RO can be categorized into space-based RO and ground-based RO [59] [60]. For space-based RO, the receiver is typically mounted on LEO satellites. For ground-based RO, the receiver is located inside the Earth’s atmosphere, on airplanes, balloons, or mountaintops.

With advantages such as global coverage, high vertical resolution, high accuracy,

low cost in the long term, and long term stability, RO can provide useful data for weather and climate studies [43]. RO can profile and model the ionospheric total electron content (TEC), and monitor the ionospheric scintillation events (e.g., [61–63]). In the lower atmosphere, RO data are used to study water vapor and humidity (e.g., [64], [65]), cyclone and typhoon (e.g., [66], [67]), gravity wave (e.g., [68], [69]), tropical belt width (e.g., [70] [71]), and variations of precipitable water (e.g., [72]). In addition, RO is used to study the PBL (e.g., [21–24,26–32,73]). PBLH detection will be presented in Section 2.3 and Chapter 5.

2.2.2 Inversion algorithm for space-based RO

The inversion algorithm consists of the preparation of excess phase and excess Doppler frequency measurements, GO inversion to obtain the bending angle, and Abel transform to derive refractivity profile. The inversion algorithm for space-based RO is introduced in this section. Fig. 2.3 shows the processing chain described above. To improve the accuracy and robustness of the inversion algorithm, considerations other than those shown in the processing chain are needed in practical missions. These considerations includes filtering, quality control, ionospheric correction, etc., which are described in Section 4.2.

Figure 2.3: General RO processing chain. The GNSS signal is received by the receiver, and tracked Doppler frequency information is inverted to bending angle profiles through the inversion algorithm. Then, the refractivity profile is derived from the bending angle profiles using the Abel transform.

Currently, various centers have different RO data processing software and a study of the processing algorithms from six centers is covered in [74]. Among them, ROPP is an open source software package for space-based RO data processing. ROPP is used as the data processing tool for various space-based RO missions (e.g., [75]). It is also used to process the RO data from Nanyang Technological University's satellite mission: VELOX-CI [76]. In previous literature, comparative studies between CDAAC and ROPP processed results are published in [77] and [78] with focuses on 2009 and 2010 data, respectively. In Chapter 4, ROPP is evaluated for 2011 South-east Asian region using the latest (when the study was carried out) software version. In addition, the study also found that the climate model used by CDAAC plays a major role in improving ionospheric correction and bending angle estimation.

For a successful RO data processing, the precise orbit information of both the transmitter and receiver is needed. It is useful to quantify how much orbital errors affect the RO retrieval results. Both [18] and [19] explain the error propagation from excess phase to bending angle, refractivity, temperature, and pressure. [20] studied the GPS receiver induced error in RO. Compared to existing work [79] [80], the study in Chapter 3 includes the effect of an OL tracking algorithm and considers the RO retrieval performance degradation due to a compromised OL Doppler frequency model.

Excess phase and excess Doppler calculation

In general, the Earth's atmospheric refractivity exponentially decreases as the altitude increases. As the GNSS signal travels through the Earth's atmosphere, different atmospheric refractivities at different altitudes will refract and bend the signal. Since the signal propagates a longer distance than a straight line propagation, the receiver's tracking algorithm will output total phase that contains excess phase

delay. The time derivative of the excess phase is the excess Doppler frequency. The excess phase and excess Doppler frequency are due to the effect of the atmospheric bending and delay. The steps to process the direct GNSS receiver measurements to obtain the excess phase and excess Doppler frequency are described here. The excess phase and excess Doppler frequency are the immediate inputs to the RO inversion algorithm.

The total received carrier phase φ_C can be expressed as:

$$\varphi_C = \varphi_G + \varphi_I + \varphi_T + c\delta t_u - c\delta t^s + \epsilon, \quad (2.15)$$

where φ_G is the geometric straight line distance between the transmitter and receiver, φ_I is the ionospheric delay, φ_T is the tropospheric delay, δt_u and δt^s are the clock biases in the receiver and transmitter, respectively, c is the speed of light in vacuum, and ϵ is other errors including multipath, thermal noise, etc. The unit of φ_C is meter.

To obtain the excess phase, the first step is to eliminate the ionospheric error and clock biases. A simple method to remove the ionospheric error is using dual frequency measurements of the carrier phase [81]. For the transmitter clock bias, the control segment continuously monitors and broadcasts it in the navigation messages and are obtained from the International GNSS Service (IGS) website [82]. For the receiver clock bias, differencing techniques such as double differencing, single differencing, and zero differencing can be used [7] [83].

After the ionospheric bias and clock biases are eliminated, the remaining components in the phase measurement are the geometric distance φ_G , tropospheric delays φ_T , and other errors ϵ .

For OL tracking, the residual phase Φ^R calculated in (2.8) is just the excess phase φ_E [84]. The excess Doppler frequency is obtained by differentiating the excess

phase:

$$f_{edop} = \frac{d(\varphi_E)}{dt}. \quad (2.16)$$

For CL tracking, a tracking loop such as FLL outputs the total carrier phase φ_C . The geometric phase φ_G can be calculated based on the positions of the receiver and transmitter. The GNSS satellites' positions can be calculated using the broadcast ephemeris information. The receiver's position can be obtained using various positioning techniques. Then the excess phase φ_E is obtained as:

$$\varphi_E = \varphi_C - \varphi_G, \quad (2.17)$$

and the excess Doppler can be calculated using (2.16).

GO algorithm (space-based)

The excess Doppler frequency obtained earlier is inverted to derive the ray path's bending angle measurements. The most basic and intuitive inversion algorithm is the GO algorithm, which is applied to the GPS/MET experiment and has been proven adequate for deriving accurate atmospheric profiles [1] [4] [85]. The GO algorithm assumes that the GNSS signal path can be represented by a straight line. This simplification of the GNSS signal as a ray omits the diffraction effect. It is assumed that the Earth's atmosphere is spherically symmetric. Under this assumption, only one ray is observed at each time, uniquely defined by the impact parameter. This GO approximation is valid from Maxwell's equation under a limiting case where the signal's wavelength approximates to zero: $\lambda \rightarrow 0$ [85]. As the wavelength approaches zero, the electromagnetic waves shall propagate as straight rays. Under the GNSS RO scenario, the L-band signals' frequencies are in the range of 1.1GHz to 1.6GHz, which correspond to wavelengths in the range of 18cm to 27cm. Compared to the RO geometry dimension, the signals' wavelengths are relatively small, which makes

the electromagnetic ray approximation valid.

Fig. 2.4 shows the RO geometry. The signal path between the transmitter and the receiver is marked using a thicker line. The receiver and GNSS satellites are assumed to be located outside of the Earth's atmosphere. Under the assumption of local spherical symmetry, the impact parameters a illustrated in the figure are the same for both sides. Based on the relative motions between the transmitter and receiver, the relationship between the Doppler f_d and the velocities is given by the following equation:

$$f_d = \frac{f_{carr}}{c} \times (\mathbf{v}_R \cdot \mathbf{e}_R + \mathbf{v}_T \cdot \mathbf{e}_T), \quad (2.18)$$

where $\mathbf{v}_T$ and $\mathbf{v}_R$ are the velocity vectors for the transmitter and receiver, respectively; and $\mathbf{e}_T$ and $\mathbf{e}_R$ are the unit vectors of the signal rays as denoted in Fig. 2.4.

From the RO geometry in Fig. 2.4, the following equation relates bending angle α to ϕ_T and ϕ_R :

$$\alpha = \theta + \phi_R + \phi_T - \pi, \quad (2.19)$$

where ϕ_R and ϕ_T are angles denoted in Fig. 2.4. Using Snell's law, the impact parameter a can be expressed as:

$$a = d_T \sin \phi_T = d_R \sin \phi_R, \quad (2.20)$$

where d_T and d_R are the lengths of $\mathbf{r}_T$ and $\mathbf{r}_R$, respectively.

Using (2.18), (2.19) and (2.20), the bending angle and impact parameter pairs $\alpha(a)$ can be derived using an iterative procedure.

Figure 2.4: Space-based RO geometry. The signal travels from a transmitter (normally a GNSS satellite, denoted as a small circle) to a receiver (denoted as a star) following a bent path due to atmospheric refractivity. The total bending angle is denoted as α ; the impact parameter is denoted as a ; the transmitter's position vector and velocity vector are $\vec{r}_T$ and $\vec{v}_T$, respectively; the receiver's position vector and velocity vectors are $\vec{r}_R$ and $\vec{v}_R$, respectively; the unit vectors at the emitting and receiving ends are denoted as $\vec{e}_T$ and $\vec{e}_R$, respectively; the angle between $\vec{r}_T$ and $\vec{r}_R$ is denoted as θ . Figure is not drawn to scale.

Abel transform (space-based)

Under the assumption of spherical symmetric refractivity, the bending angle α is uniquely related to the refractive index as a function of radius. This relation can be derived from Bouguer's rule [48] [18]. The Abel transform is used to calculate the atmospheric refractivity using the bending angle profiles $\alpha(a)$ obtained in the previous section.

For a space-based RO, the Abel transform that relates the bending angle measurements $\alpha(a)$ to the refractive index as a function of impact parameter $n_{ref}(a_0)$ is given by [18]:

$$n_{ref}(a_0) = \exp \left[\frac{1}{\pi} \int_{a_0}^{\infty} \frac{\alpha(a) da}{\sqrt{a^2 - a_0^2}} \right]. \quad (2.21)$$

The tangent radius r_0 shown in Fig. 2.4 is related to the impact parameter a and the refractive index at the tangent radius $n_{ref}(r_0)$ by:

$$r_0 = \frac{a}{n_{ref}(r_0)}. \quad (2.22)$$

The refractivity N is related to the corresponding refractive index n_{ref} :

$$n_{ref} = 10^{-6}N + 1. \quad (2.23)$$

2.2.3 Inversion algorithm for ground-based RO

For a ground-based RO where the receiver is located inside the atmosphere, the GO algorithm is slightly different from the space-based RO described in Section 2.2.2. The steps for ground-based RO inversion are described in this section. More detailed discussions on the method can be found in the literature [86–90]. A MRO example with a stationary receiver located on a mountaintop is provided here.

The same RO processing chain as for space-based RO shown in Fig. 2.3 and

Section 2.2.2 applies here. The input GNSS signal's excess Doppler frequency is pre-processed to account for the ionospheric error, GPS satellite, receiver clock errors, etc. Then, the corrected excess Doppler frequency is used to calculate the bending angle profile using a modified GO method. Last, the refractivity profile is retrieved from the bending angle using a modified Abel transform. The geometry of a MRO event is the same as Fig. 2.4 except that the receiver is stationary ($\mathbf{v}_R = 0$) and located inside the atmosphere. Fig. 2.5 shows the MRO geometry with signal bending for a stationary receiver. The signal path between the transmitter and the receiver is marked using a thicker line.

Figure 2.5: Ground-based RO geometry. Similar to Fig. 2.4, except that $\mathbf{v}_R$ is zero and the receiver is located inside the Earth's atmosphere.

GO algorithm (ground-based)

The Doppler frequency f_d can be written as a function of the GNSS satellite velocity $\mathbf{v}_T$ and the unit ray vector $\mathbf{e}_T$:

$$f_d = \frac{f_L}{c} \times \mathbf{v}_T \cdot \mathbf{e}_T. \quad (2.24)$$

The GPS satellite orbit is known, hence the unit vector $\mathbf{e}_T$ can be determined. When expressed in scalar form, (2.24) is:

$$f_d = -\frac{1}{\lambda} \times u_T \cos(\phi_T - \eta) \quad (2.25)$$

for a setting RO event, and

$$f_d = -\frac{1}{\lambda} \times u_T \cos(\phi_T + \eta) \quad (2.26)$$

for a rising RO event. In (2.25) and (2.26), u_T is the length of $\mathbf{v}_T$, λ is the wavelength of the carrier phase, and η is the angle between $\mathbf{r}_T$ and $\mathbf{v}_T$.

Using (2.25) and (2.26), the angle ϕ_T can be determined. For a setting RO event:

$$\phi_{T_rising} = \eta \pm \arccos\left(-\lambda \times \frac{f_d}{u_T}\right). \quad (2.27)$$

For a rising RO event:

$$\phi_{T_rising} = -\phi_{T_setting}. \quad (2.28)$$

For ground-based RO, (2.20) shall be modified to consider the refractive index at the receiver's altitude, and becomes:

$$a = n_T d_T \sin \phi_T = n_R d_R \sin \phi_R, \quad (2.29)$$

where n_T is the refractive index at the transmitter side and can be approximated as 1, and n_R is the refractive index at the receiver's altitude.

In both rising and setting MRO events, a and ϕ_T both increase to a maximum and then decrease. Before calculating ϕ_R , the epoch where the a reaches a maximum needs to be identified. For a rising RO event, during the time before reaching the maximum a , $\phi_R = a \sin(a/n_R/d_R)$. During the time after reaching the maximum a , $\phi_R = \pi - a \sin(a/n_R/d_R)$. For a setting RO event, vice versa.

Using (2.19) and the known ϕ_R , ϕ_T , and θ (can be calculated based on transmitter and receiver positions), a can be derived, which shall always be smaller than $n_R d_R$. Also, we can derive the bending angle as a function of the impact parameter $\alpha(a)$.

Abel transform (ground-based)

As stated in the previous section, unlike the space-based RO scenario where the maximum a is either at the beginning or the end of a RO event, the a is a maximum somewhere in the middle of a MRO event. The bending angle $\alpha(a)$ can be classified into two groups: positive and negative elevation bending angle $\alpha_P(a)$ and $\alpha_N(a)$, with the maximum a serving as the separation point of the two groups. Definitions of these bending angles, the MRO geometry, and some relationships between the variables are introduced in this section.

Fig. 2.6 also shows a MRO event's geometry. The receiver is located inside the Earth's atmosphere and denoted as R . The Earth's center is denoted as O . The ray emitted from the GNSS satellite transmits through the Earth's atmosphere and is received by the receiver R . The rays at times t_+ , t_0 , and t_- are denoted in the figure. The impact parameters at these epochs are a_0 , a_{max} , and a_0 , respectively. Assume that this is a setting event where the GNSS satellite is descending. During the RO event, the impact parameter increases from a_0 to a_{max} , then decreases from a_{max} to a_0 . The time t_+ and t_- are selected as pairs with the same impact parameter a_0 .

Figure 2.6: A MRO geometry for explaining the positive (green), negative (red), partial (blue), and space (purple) bending angles. The impact parameters are denoted as a_0 and a_{max} . The rays at three epochs t_+ , t_0 , and t_0 are shown. The receiver is located at R . B is an imaginary point. The Earth's center is denoted as O .

The bending angle observed at receiver R during an entire RO event can be separated into positive elevation bending angles and negative elevation bending angles. For each positive elevation bending angle, there is a corresponding negative elevation bending angle that has the same impact parameter. At time t_+ , the bending angle is positive $\alpha_P(a)$ (the green segment), and at time t_- , the bending angle is negative $\alpha_N(a)$ (the red segment). Assuming that the atmosphere's refractivity is locally spherically symmetric, the following relations can be derived:

1. Extend the signal ray at t_+ to point A located outside the atmosphere, the bending angle for segment AR is equal to $\alpha_N(a)$. The space-based bending angle α (the purple segment) received at point A at t_+ equals the summation of bending angles:

$$\alpha(a) = \alpha_N(a) + \alpha_P(a); \quad (2.30)$$

2. Assuming there is an imaginary receiver B located at the same altitude as receiver R , the bending angle of the signal observed at receiver B at time t_- is the same with the bending angle of the signal observed at receiver R at time t_+ : $\alpha_P(a)$. Denote the bending angle for segment RB as the partial bending angle α' (the blue segment), then:

$$\alpha'(a) = \alpha_N(a) - \alpha_P(a). \quad (2.31)$$

After the bending angle profiles are obtained using the GO algorithm as described earlier in this section, they are grouped into positive and negative elevation bending angles. Then, the partial bending angle can be calculated using (2.31). For a ground-based RO, the Abel transform can retrieve the refractive index n_{ref} below

the receiver using the partial bending angle profiles $\alpha'(a)$:

$$n_{ref}(a_0) = n_R \exp \left[\frac{1}{\pi} \int_{a_0}^{n_R d_R} \frac{\alpha'(a) da}{\sqrt{a^2 - a_0^2}} \right]. \quad (2.32)$$

Compared to (2.21), the differences are that the receiver altitude's refractive index n_R is not 1, the upper integration limit is reduced from infinity to the receiver altitude d_R , and the integrand is the partial bending angle $\alpha'(a)$ instead of the total bending angle profile $\alpha(a)$.

2.3 PBLH determination

PBLH is an important parameter to characterize the lower troposphere. This section presents its definition, importance, and the commonly used refractivity gradient method to measure the PBLH.

2.3.1 General introduction

PBL, also known as the atmospheric boundary layer (ABL), is the lowest tropospheric region. This layer ranges from a few tens of meters to a few kilometers in height above the Earth's surface. Within the PBL, atmospheric parameters such as temperature and water vapor are strongly affected by the Earth's surface properties, responding to solar heating, convection, etc. The tropospheric region above the PBL is called the free troposphere. The PBL is the layer where the Earth's surface and the free troposphere exchange energy. It is important to model the PBL for weather and climate studies [91]. PBL affects various aspects such as air pollution, agricultural meteorology, mesoscale meteorology, etc [92].

PBLH (sometimes referred to as ABL depth, or PBL depth) is a crucial parameter for defining the structures of the PBL [24] [93]. Sharp changes in temperature and humidity occur at this height, marking the top edge of the PBL. The PBLH

is important for understanding the propagation environment in the lower troposphere [24] [94]. It affects various processes associated with the diurnal, synoptic, and climatological processes in the PBL, and characterizes the connection between the Earth's surface and the free atmosphere [28]. Moreover, PBLH is an important variable to predict critical climate parameters such as global cloudiness, precipitation, and surface winds [24] [93].

There are various methods to determine the PBLH over land, including using radiosondes, tower measurements, and field observations [91] [95] [96]. The marine PBLH determination results, however, are relatively sparse due to the difficulties in setting up equipment over the ocean. Several remote sensing techniques such as infrared and nadir-viewing passive microwave sounders are restricted in measuring the PBLH due to their inability to penetrate deep into the PBL and their coarse vertical resolution [24] [91].

GNSS RO has been shown to be a feasible PBLH detection technique without the drawbacks described above [91]. The GNSS RO derived atmospheric refractivity can be differentiated to obtain the refractivity gradient and used to detect the PBLH. Compared to other techniques, GNSS signals have the advantage of easy penetration through the atmosphere due to their L-band frequencies. GNSS can also achieve near-global coverage with the globally distributed GNSS satellites. The vertical resolution of the GNSS RO is fine enough to depict the PBL. Various authors have investigated space-based GNSS RO for detecting regional or global PBLH climatology, mainly using GPS (e.g., [21–32]).

Several recent studies on PBLH detection using RO mainly focuses on using space-based GPS RO mission results such as COSMIC and the refractivity gradient method (e.g., [31] [32] [97]). [30] studied and compared the marine boundary layer heights using the COSMIC, CALIOP, and radiosonde data. In Chapter 5, a 7-day MRO experiment is carried out and the collected GNSS data are used to

determine the PBLH. Compared to space-based RO, MRO generally is of low-cost and can achieve a high local spatial and temporal resolution. In addition, a novel method utilizing the signal amplitude instead of the refractivity gradient for PBLH detection is proposed. This signal amplitude methods avoids the stringent requirement on the collected data and ease the processing procedure. The usage of GNSS can increase the number of measurements. The detailed study will be covered in Chapter 5.

2.3.2 PBLH detection using refractivity gradient

This section describes the commonly used method to determine the PBLH using vertical refractivity profile's gradient. The neutral atmosphere refractivity of the microwave frequency signal is related to the temperature T , pressure P , and water vapor pressure P_w through the following equation:

$$N = k_1 \frac{P}{T} + k_2 \frac{P_w}{T^2}, \quad (2.33)$$

where $k_1 = 77.6 K \cdot hPa^{-1}$, $k_2 = 3.73 \times 10^5 K^2 \cdot hPa^{-1}$, and the unit of the refractivity is denoted as N-unit [98]. At the top of PBL, the temperature usually has a sharp increase and the water vapor has a sharp drop as altitude increases. As can be seen from the above equation, the abrupt changes of temperature and water vapor pressure both contribute to the decrease in refractivity as altitude increases. The refractivity gradient can be used to detect the PBLH (e.g., [27] [31] [32]). The height where the minimum refractivity gradient occurs is assumed to be the top of the PBL.

To allow for more accurate detection and filtering of outliers, the maximum and minimum height thresholds and refractivity gradient thresholds are defined. Not all RO profiles penetrate down to the lower troposphere, and the RO profiles that

cannot penetrate below the minimum height are discarded. For the profiles that pass the minimum height penetration criterion, the PBLH is determined as the height below the maximum height threshold and has the minimum corresponding refractivity gradient. The thresholds used in most literature are 0.5km, 3.5km, and -40 N-unit/km for the minimum height, maximum height, and refractivity gradient, respectively (e.g., [21] [32]).

With the refractivity gradient method, only a relatively sharp refractivity change indicates a clear PBL top. To quantify the sharpness of the refractivity gradient, a relative minimum gradient (RMG) used in [28] [32] is adopted in this study. The RMG (N'_{rmg}) is calculated using the following equations:

$$N'_{rmg} = -(N'_{min}/N'_{rms}) \quad (2.34)$$

$$N'_{rms} = \sqrt{\frac{N_1'^2 + N_2'^2 + \dots + N_m'^2}{m}}, \quad (2.35)$$

where m is the index for the refractivity-height profile; N' is the refractivity gradient; N'_{min} is the minimum refractivity gradient; and N'_{rms} is the root mean square (RMS) value of the refractivity gradient between the minimum (0.5km) and maximum (3.5km) threshold heights. A larger RMG value corresponds to a sharper refractivity gradient. Similar to [32], if a detected PBLH has a RMG value larger than 2, it is assumed to be a sharp inversion layer.

Fig. 2.7 shows the refractivity gradient as a function of tangent height from one radiosonde measurement at “HILO HI” Integrated Global Radiosonde Archive (IGRA) station from a balloon released on April 24, 2015 at 12:11:07 UTC. The height where the smallest refractivity gradient occurs is marked with a star. The height is 2.3km and the refractivity gradient is -333N-unit/km. The plot shows the results for the entire measurement range while the inside inset limits to 8km in tangent height.

Figure 2.7: An example profile of refractivity gradient profile as a function of tangent height obtained using a balloon-based radiosonde at the HILO HI IGRA station released on April 24, 2015 at 12:11:07 UTC. The star marks the detected PBLH at 2.3km and with a refractivity gradient of -333 N-unit/km. The inside inset is restricted to a tangent range of 8km for better visibility.

Chapter 3

Simulation Study of the Effect of Orbital Errors on OL Tracking Algorithm in GPS RO

GPS RO has recently attracted much attention for monitoring the Earth's atmosphere. To implement RO, we need the orbit information of both GPS satellites and GPS receivers, as well as the GPS signal received by the receiver. This chapter investigates GPS and LEO satellite orbit errors' effect on RO retrieval accuracy in an OL tracking scenario. Doppler model error and fractional refractivity error under different orbit error amounts are generalized in an OL tracking scenario.

GPS RO is a comparatively new technique to derive globally distributed profiles of the Earth's atmospheric parameters such as temperature, pressure, density, water vapor, geopotential heights, and winds. This chapter includes a simulation study of space-based RO, in which LEO satellites are used as platforms for GPS receivers. The 32 GPS satellites currently in operation provide continuous signal sources. The ray connecting the LEO satellite receiver and the GPS satellite transmitter propagates through the Earth's atmosphere. With the precise positions of the GPS and

LEO satellites, and by processing the received GPS signal, scientists can estimate some of the Earth's atmospheric parameters, which can then be assimilated into atmospheric models for the study of global weather and climate.

In the early years, the tracking algorithm in GPS receivers was generally the CL type where the receiver's tracking loop estimated carrier phase and Doppler frequency, and fed them back to drive the operation of the tracking loop. When there are large fluctuations in the signal dynamics due to atmospheric propagation or receiver-satellite range variations, the CL method may lose lock on the signals and cause large refractivity bias in the retrieval results. The OL algorithm is proposed to overcome these drawbacks by using an a-priori Doppler frequency model. In this chapter, we investigate how the accuracy of the GPS and LEO satellites' orbit positions and velocities affects the Doppler frequency model construction, and hence the performance of the OL tracking system. [43] used error propagation and studied the effect of orbit determination on the RO retrievals. The retrieval errors are derived for an orbital velocity error of 0.05mm/s. [79] mentioned that the orbital velocity error shall be smaller than 0.05mm/s for RO applications. It also showed that the COSMIC's orbits can be determined with 6cm and 0.02mm/s accuracies for position and velocity, respectively. [99] suggested that the COSMIC's cm-level orbital position accuracy is qualified for the RO study. [100] mentioned that the LEO orbits shall be determined with accuracies of 5cm and 0.05mm/s for position and velocity, respectively. This chapter investigates how the orbital position and velocity errors affect RO results in an OL tracking system.

This chapter uses simulations to carry out the study. First, through the inverse Abel transform and the inverse Full Spectrum Inversion (FSI), the refractivity profiles measured by high vertical resolution radiosondes are converted to simulated GPS signals. Second, we simulate OL tracking of the GPS signal. The OL Doppler frequency model is pre-determined based on the GPS and LEO satellite orbits and

high vertical resolution radiosonde measurements of atmospheric refractivity. During the tracking procedure, we alter the GPS and LEO satellite orbits by introducing controlled errors (discussed below) and incorporate the degraded Doppler frequency model into the OL algorithm. FSI and Abel transforms are then applied to tracking loop outputs to generate refractivity profiles. Finally, we compare the processed refractivity with the original input refractivity to compute fractional refractivity errors. The deviations from the input refractivity represent how the GPS and LEO satellite orbital position and velocity errors are translated into measurement errors in RO retrieval.

GPS satellite and LEO satellite orbital information is needed in the simulation study to calculate the OL Doppler frequency model. The GPS orbit information can be obtained from the broadcast ephemeris or the post-processed orbital data from the IGS website [34] [36]. The broadcast ephemeris data have a 3-dimensional (3D) RMS error of the order of 100cm, while the IGS data RMS error can be as small as 2.5cm [82]. The LEO satellite orbits are determined by the LEO satellite itself through precise orbit determination. The different position determination capabilities for different LEO satellites will lead to different orbital positioning errors. In the CanX-2 (Canadian Advanced Nanospace eXperiment) mission, the receiver 3D RMS position solution can be as high as 55m [80]. In the COSMIC mission, the satellites have 3D RMS positions of about 6cm [79]. These orbital positioning errors will affect the accuracy of the OL Doppler frequency model and impact the OL tracking performance.

Without losing generality, in this study we assign equal LEO and GPS satellite errors, and allow the 3D position RMS errors of the LEO satellite and GPS satellite to vary in the range of centimeters to decimeters. The orbit velocity error is chosen 0.05mm/s as this is mentioned as the requirement for the RO application and is studied in previous literature (e.g., [43]). It is also reflecting the actual orbit per-

formance of various LEO RO missions (e.g., [79]). Intuitively, larger orbital errors of GPS and LEO satellites will lead to poorer OL tracking performance, and hence worse RO retrieval results. This study uses simulations to investigate this hypothesis. Such quantitative relationships will identify the requirement on the accuracy of the satellite orbital information so as to ensure adequate tracking performance.

Section 3.1 describes the RO simulation loop, which includes the forward model, receiver simulation, and inversion methods. In Section 3.2, the RO simulations results under different types of orbit errors are described. Section 3.3 summarizes this chapter.

3.1 RO simulation loop

This chapter uses the simulation approaches described in [15] and [20]. The overall simulation schematic is shown in Fig. 3.1. The input refractivity is obtained from high resolution radiosonde data obtained from POLARSTERN cruise by Alfred Wegner Institute Helmholtz Center for Polar and Marine Research (<https://doi.pangaea.de/10.1594/PANGAEA.382988>). The occultation event is at August 1, 1999 09:39:00 (latitude: $79.9^\circ N$, longitude: $10.40^\circ W$). The average vertical resolution is 4.45m. Using the inverse Abel transform, bending angle profiles are derived from refractivity profiles. The bending angle profiles are then fed into the inverse FSI, which outputs the simulated GPS signals. In this simulation loop we use OL tracking. The tracked GPS signals then go through the FSI and Abel transforms to derive refractivity profiles. The comparison between the input refractivity and output refractivity can reveal how the tracking in the GPS receiver, and other factors, affect RO retrieval accuracy.

Figure 3.1: Schematic flow of the simulation loop. The comparison between the output refractivity and the input refractivity highlights the effect of orbital errors on the RO retrieval accuracy.

3.1.1 GPS and LEO satellites orbits and orbit errors

We first carry out the study under the assumption that both GPS and LEO satellites are counter-rotating in the same circular orbit with orbit radii of about 26,800km and 6,800km, respectively.

Theoretically, the GPS positioning error displays a normal distribution over the long term. In actual measurements, however, the positioning error may exhibit randomness due to various error sources [101] [102]. Without losing generality, we add the orbit position error in uniformly distributed, normally distributed, and fixed manners. The simulation first calculates the circular GPS and LEO orbits using the orbit radii and satellites' velocities. For uniformly distributed error, we add errors uniformly distributed between $-\epsilon_p$ to ϵ_p to the orbit's coordinates. For normally distributed error, we add errors normally distributed with mean 0 and standard deviation ϵ_p . For fixed error, we add ϵ_p error to the orbit coordinates. The ϵ_p is the orbit position error, which varies between 1cm and 50cm. For the orbit velocity error, we assign a fixed 0.05mm/s error to both GPS and LEO satellites. We use ϵ_v to denote the velocity error.

These ϵ_p and ϵ_v values are selected considering the general GPS satellite and LEO satellite positioning accuracies as mentioned at the beginning of this chapter.

3.1.2 Forward model

The forward model includes an inverse Abel transform and an inverse FSI. The inverse Abel transform relates the refractivity profiles to bending angle profiles, and the inverse FSI further converts bending angle profiles to simulated GPS signals. There are other methods similar to FSI, such as the canonical transform (CT) [15], sliding spectral (SS) [103], and back propagation (BP) [38] models. In this study we use FSI, which is a common method with acceptable computation complexity and accuracy [104].

Under the assumption of symmetric refractivity, the inverse Abel transform converts the atmospheric refractive index to signal's bending angle profiles as follows [105]:

$$\alpha(a) = -2a \int_{a_0}^{\infty} \frac{da}{\sqrt{a^2 - (a_0)^2}} \frac{d \ln[n_{ref}(a_0)]}{da}, \quad (3.1)$$

which is the inverse of (2.21).

The derived bending angle is a function of the impact parameter: $\alpha(a)$. Through the inverse FSI transform and with the knowledge of GPS and LEO positions and velocities, the simulated amplitude and phase at the LEO's location are derived. The detailed steps of inverse FSI are as follows.

1. Derive the satellite to satellite angle θ as a function of impact parameter a :

$$\theta(a) = \alpha(a) + \cos^{-1}\left(\frac{a}{d_R}\right) + \cos^{-1}\left(\frac{a}{d_T}\right). \quad (3.2)$$

2. Calculate the Doppler angular frequency ω as a function of impact parameter a :

$$\omega(a) = \frac{2\pi}{\lambda} \frac{d[\theta(t)]}{dt} a, \quad (3.3)$$

where $d[\theta(t)]/dt$ is the derivative of θ in the time domain.

3. The GPS signal amplitude and phase at the receiver's position in impact parameter space ($A(a)$ and $\Phi(a)$, respectively) are derived using the following equations:

$$A(a) = \sqrt{\frac{a}{d_T d_R \sin(\theta(a)) \sqrt{d_T^2 - a^2} \sqrt{d_R^2 - a^2}}} \quad (3.4)$$

$$\Phi(a) = - \int \omega(a) t(a) da, \quad (3.5)$$

where $t(a)$ is the time tag function in the impact parameter space.

4. The baseband GPS signal in the time domain is calculated using the Fourier transform:

$$u(t) = \mathcal{F}|U(a)| = \mathcal{F}|A(a)\exp(i\Phi(a))|, \quad (3.6)$$

and the signal amplitude $A(t)$ and phase $\Phi(t)$ are derived as:

$$A(t) = |u(t)| \quad (3.7)$$

$$\Phi(t) = \arg[u(t)], \quad (3.8)$$

where $\arg$ represents the calculation of the argument of a complex number.

3.1.3 OL tracking of the simulated GPS signal

After the inverse FSI, the simulated GPS signal is then fed to the OL tracking algorithm in the GPS receiver. OL tracking is the method to reproduce the GPS signal with knowledge of a Doppler frequency model as mentioned in Section 2.1.4. In the simulation here, some equations are slightly changed. To build the Doppler frequency model, one can use the inverse FSI and filter out the strongest signal components, or use the GO method that will be described later in Section 5.2.1.

In the OL tracking algorithm, the numerically controlled oscillator (NCO) frequency uses the Doppler frequency model's frequency [106]. The incoming GPS signal is correlated with a predicted signal whose Doppler frequency is just the Doppler model frequency. The predicted signal has in-phase and quadrature components as follows:

$$u^i(t) = \cos(\tilde{\Phi}(t)) \quad (3.9)$$

$$u^q(t) = -\sin(\tilde{\Phi}(t)), \quad (3.10)$$

where $\tilde{\Phi}(t)$ is the tracking loop model phase, and is updated every T_I period as

the integral of $\tilde{f}(t)$ with the initial phase at zero: $\tilde{\Phi}(t_0) = 0$. As described in Section 2.1.4, $\tilde{\Phi}(t)$ and $\tilde{f}(t)$ can be approximated as piecewise constant functions for $(n_i - 1)T_I < t \leq n_i T_I$ and simplified as $\tilde{\Phi}_n$ and $\tilde{f}_n$, respectively. The resulting in-phase and quadrature correlation sums are computed as follows:

$$i_n \approx D_n A_n \left(\frac{\sin(2\pi \Delta f_n T_I + \Delta \Phi_{n-1})}{2\pi \Delta f_n T_I} - \frac{\sin \Delta \Phi_{n-1}}{2\pi \Delta f_n T_I} \right) \quad (3.11)$$

$$q_n \approx D_n A_n \left(\frac{-\cos(2\pi \Delta f_n T_I + \Delta \Phi_{n-1})}{2\pi \Delta f_n T_I} + \frac{\cos \Delta \Phi_{n-1}}{2\pi \Delta f_n T_I} \right), \quad (3.12)$$

where D_n and A_n are the modulated data and signal amplitude, respectively; $\Delta f_n = f_n - \tilde{f}_n$ and $\Delta \Phi_n = \Phi_n - \tilde{\Phi}_n$ are the frequency and phase differences between the received signal and the Doppler model, respectively. Then the residual phase Φ_R , received phase Φ^{rcv} , and received amplitude A^{rcv} can be calculated using (2.8), (2.11), and (2.14).

3.1.4 Inversion methods and calculation of fractional refractivity error

The GPS signal after tracking is processed using the FSI to derive bending angle profiles. Then the Abel transform is used to calculate the refractivity from the bending angle profiles. Since the FSI and Abel transforms are essentially the opposite of the forward model described in previous section, the equations are not included here and can be found in [107]. The derived refractivity profiles are compared with the input refractivity to calculate the fractional refractivity difference:

$$\frac{\Delta N}{N} = \frac{N_{output} - N_{input}}{N_{input}}. \quad (3.13)$$

The fractional refractivity difference represents how well the refractivity result corresponds with the input, and reveals the effect of orbit errors on RO retrieval accuracy.

3.2 Simulation results

Using the schematics shown in Fig. 3.1, the simulation tests are described in this section. First, the effect of orbital errors on OL Doppler frequency model is examined. Then, the OL tracking with the OL Doppler frequency model is implemented and the fractional refractivity differences are calculated for different orbital errors.

3.2.1 Orbit errors' effect on Doppler frequency model

We calculate the RMS difference between the Doppler frequency model with and without adding the orbit positioning errors. Larger calculated Doppler frequency shift means the orbit positioning errors have more evident effect on the Doppler frequency model. The results are shown in Table 3.1. The uniform, normal, and fixed errors with ϵ_p ranging from 1cm to 50cm are calculated. The results show that the fixed orbit position error leads to the smallest Doppler frequency model shift, followed by uniformly distributed errors and normally distributed errors for the same orbit position error range. The Doppler frequency shift increases as the orbit position errors increases.

Table 3.1: Average Doppler frequency shift for different error (Hz).

$\epsilon_p(\text{cm})$	1	5	10	50
Error type				
Uniform	3.385	8.255	17.926	66.354
Normal	3.342	18.279	22.839	143.275
Fixed	0.035	0.181	0.360	1.347

For the orbit velocity error of 0.05mm/s, simulation results show that the average Doppler frequency shift is $3.1 \times 10^{-4} \text{Hz}$. Using Eq. (2.18), we can calculate that with velocity error of ϵ_v , the maximum Doppler frequency shift is $\sqrt{2}\epsilon_v/\lambda$. For GPS L1 with a wavelength of 19cm, this translates to Doppler frequency error of $3.7 \times 10^{-4} \text{Hz}$. The simulation results and equation derivation results agree with

each other.

3.2.2 Orbit errors' effect on fractional refractivity error

For uniformly and normally distributed orbit position error, 100 iterations are executed, resulting in 100 sets of fractional refractivity errors as shown in Fig. 3.2 and Fig. 3.3. The mean and standard deviation are calculated for the retrieval performance evaluations. In the figures on the left of Fig. 3.2 and Fig. 3.3, the mean fractional refractivity error is plotted in the center with the ± 1 standard deviations plotted on its left and right for a specific orbit position error ϵ_p . Due to the inversion errors caused by increased orbit position errors ϵ_p , the data volume decreases for increasing ϵ_p and for decreasing altitude as shown in the right planes of Fig. 3.2 and Fig. 3.3. The mean and standard deviation as well as the data numbers are plotted with respect to altitude. The plots show that while the mean fractional refractivity error is close to zero, the standard deviation increases as the orbit position error ϵ_p increases. Since the normal distribution orbit position error results in larger Doppler frequency shift as indicated in Table 3.1, the standard deviation of fractional refractivity errors with a normally distributed error is larger than that of a uniformly distributed error.

For the fixed orbit position errors, only one execution is plotted and the results are plotted in Fig. 3.4. Since the Doppler frequency shifts for fixed errors are small for the range of 1cm to 50cm, the resulting fractional refractivity errors are also small for 1cm to 50cm orbit position errors.

Figure 3.2: The left plane shows the mean and standard deviation of fractional refractivity errors for different uniformly distributed orbit position errors ϵ_p . The mean is plotted in the center with ± 1 standard deviations plotted on its left and right. The right plane shows the corresponding data volume used in the calculation. The solid line, dashed line, dotted line, and dash-dot line represent errors of 1cm, 5cm, 10cm, and 50cm, respectively. The left plane and right plane share the same legend.

Figure 3.3: The left plane shows the mean and standard deviation of fractional refractivity errors for different normally distributed orbit position errors ϵ_p . The mean is plotted in the center with ± 1 standard deviations plotted on its left and right. The right plane shows the corresponding data volume used in the calculation. The solid line, dashed line, dotted line, and dash-dot line represent errors of 1cm, 5cm, 10cm, and 50cm, respectively. The left plane and right plane share the same legend.

Figure 3.4: Plot of fractional refractivity errors for different fixed orbit position errors ϵ_p . The errors for (a), (b), (c), and (d) are 1cm, 5cm, 10cm, and 50cm, respectively.

For the fixed orbital velocity error $\epsilon_v = 0.05\text{mm/s}$, the result is plotted in Fig. 3.5. This result is comparable with the fractional refractivity error result shown in Fig. 9 of [43]. This indicates that for a velocity error of 0.05mm/s , the fractional refractivity error is 0.3% at around 25km and decreases as altitude decreases.

Figure 3.5: Plot of fractional refractivity errors for orbit velocity errors $\epsilon_v = 0.05\text{mm/s}$.

During the simulation, a specific radiosonde refractivity profile is used. The error propagation study focuses on the fractional refractivity error which considers the difference between the output refractivity and input refractivity profiles, and the shape of the refractivity profile shall have a limited impact on the error study. The assumption of the coplanar LEO and GPS orbit with opposite velocity directions is a worse-case of the geometry, where the maximum orbit position and velocity errors are projected onto the occultation plane. For the RO geometry in actual missions, specific orbit information can be input to the simulation loop for error study.

3.3 Summary

The effect of satellite orbit errors on the Doppler frequency model is investigated in this chapter. The study finds that the fixed orbit position error has the smallest impact on the Doppler frequency, while the normally distributed orbit error has the largest impact. A simulation study of orbit position and velocity errors' effect on fractional refractivity errors in RO is then presented, which shows the fractional refractivity errors for different orbit position errors and one orbit velocity error.

Chapter 4

Performance Evaluation of ROPP in Southeast Asia

There are several GNSS RO missions contributing to global weather forecasting, climate monitoring, and ionosphere studies. The COSMIC mission, a joint mission by Taiwan and US launched in the year 2006, consists of six LEO satellites orbiting at about 800km altitude (e.g., [12] [13]). To process the collected RO data, various centers have developed different software [74]. The processing software used by the CDAAC is continuously evolving and a set of newly reprocessed COSMIC RO data became available in October 2014 [108]. Another processing software package, the ROPP maintained by the Radio Occultation Meteorology Satellite Application Facilities (ROM SAF), provides an open source RO data processing tool that is adopted by many RO missions [109]. To better assess the performance of ROPP, investigations are carried out for the 2011 Southeast Asia COSMIC RO data processed using the updated CDAAC software and the ROPP in this chapter. Bending angle and refractivity results are compared. Co-located profiles generated using the ECMWF are used in the refractivity comparison as references. The choice of ECMWF as a reference is a common approach used in the literature (e.g., [6,15,77,97,110,111]). Both

the bending angle and refractivity differences between CDAAC and ROPP processed results exhibit relatively larger standard deviation below 10km. The mean bending angle and refractivity differences between the two processing software packages are relatively small, with the fractional differences of bending angle and refractivity being smaller than 2% and 1% below 40km, respectively. Comparison with the ECMWF profiles shows that the refractivity standard deviations between ROPP results and ECMWF are comparable to those between CDAAC results and ECMWF. The mean refractivity differences between their processing outputs and ECMWF are smaller than 1%. Normalized error covariance is calculated for the refractivity difference between CDAAC processed results and ECMWF profiles, and between ROPP processed results and ECMWF profiles. Results show that ROPP performance is slightly poorer than CDAAC at altitude above 30km, and slightly better at other altitudes.

As described in Section 2.2.2, RO data processing consists of three steps. First, the carrier phase measured by the GNSS receiver is converted to an excess phase measurement by eliminating the GNSS and LEO satellites' clock offsets and their relative range effect [112]. Second, the excess phase is converted to the bending angle profile of the neutral atmosphere using the geometric and/or wave optics method [105]. Finally, the bending angle profile is converted to a refractivity profile of the atmosphere. There are also other intermediate processing operations such as filtering of the signal, quality control, ionospheric correction, and optimization of bending angle estimates based on climatology information.

A comprehensive analysis of these detailed processing procedures at six processing centres can be found in [74]. Comparative studies between CDAAC and ROPP processed results are published in [77] and [78]. In [77], the study was carried out for 1,000 RO events on January 1, 2009 and 925 RO events on August 25, 2009. In [78], the comparison was made for RO data from 2010 in the Australian region. This

study investigates the latest (when the study was carried out) processing software used by CDAAC and ROPP maintained by the ROM SAF, with a focus on 2011 Southeast Asian region. One entire year's data have covered the seasonal effect and are considered enough for this study.

CDAAC provides users with access to unprocessed RO data for a number of RO missions, and services to process RO data and manipulate the processed results. The processing software itself, however, is not available for user modification. ROPP, on the other hand, is an open source software package, and it can process some recent RO missions' data and simulate RO data for research purposes (e.g., [75]). It is chosen to process the RO data collected by Nanyang Technological University's satellite mission: VELOX-CI [76]. The understanding of its performance is of importance to data users. The objective of this chapter is to provide an analysis of the accuracy of the ROPP software through comparison with CDAAC processing results and with profiles generated by ECMWF.

In addition, by quantifying and analyzing the difference between CDAAC and ROPP processing results, we hope that the study can offer suggestions to improve processing software for future development. Indeed, the study found that the climate model used by CDAAC plays a major role in improving ionospheric correction and bending angle estimation, thereby highlights the need for a better climate model in order to improve processing.

Section 4.1 introduces the data used and the data processing steps. Section 4.2 compares the detailed processing steps between CDAAC and ROPP. Section 4.3 presents the results of the comparison. Section 4.4 summarizes the findings of this chapter.

4.1 RO data processing

This section describes the COSMIC data, the ROPP software, and the ECMWF profiles used in this study. It also describes the error relationships between refractivity and derived temperature, pressure, and humidity.

4.1.1 COSMIC RO data selection

The RO data are downloaded from the COSMIC data archive website, CDAAC (<http://cdaac-www.cosmic.ucar.edu/cdaac/index.html>). An entire year of data from 2011 over Southeast Asia with a longitude and latitude range of $92^{\circ}E - 140^{\circ}E$, $10^{\circ}S - 24^{\circ}N$ are used. The location of Southeast Asia is marked as a rectangle in Fig. 4.1. The rationale for using Southeast Asian regional data for the comparison is twofold. First, there are few radiosonde stations in the Southern Hemisphere and over the oceans as observed in Fig. 4.1, which shows the geographic locations of the radiosonde stations taken from the IGRA database (<http://www.ncdc.noaa.gov/data-access/weather-balloon/integrated-global-radiosonde-archive>). Due to the lack of radiosonde observations, the application of RO will be particularly useful in the Southern Hemisphere. The second reason for selecting this region is that the tropical area has larger RO retrieval errors [40] [97], and therefore provides the worst-case study of the characteristics of the processing packages.

CDAAC stores the measurements from the COSMIC mission in the netCDF file format called atmPhs. For the selected time period and area, there are a total of 13,271 atmPhs netCDF files. The atmPhs files contain the excess phase and amplitude data as well as auxiliary data such as both LEO and GPS satellites' positions and velocities. The number of RO events per month are summarized in Fig. 4.2.

Figure 4.1: Distribution of the IGRA radiosonde stations.

Figure 4.2: Number of RO events for each month in 2011 for Southeast Asia with a longitude and latitude range of $92^{\circ}E - 140^{\circ}E$, $10^{\circ}S - 24^{\circ}N$.

CDAAC processes the data using its own processing software and publishes the processed results online. The processed data are stored as netCDF format files called atmPrf. Each RO event is associated with one atmPhs and one atmPrf file. The

latter contains the geographic location of the RO event, as well as the processed bending angle profile and refractivity profile. The bending angle profile relates the signal's total bending with the impact parameter, while the refractivity profile captures the atmosphere's refractivity versus the mean sea level altitude. For the above-mentioned time duration and area span, there are 13,271 atmPrf files. The ROPP processed results are evaluated against the CDAAC generated atmPrf data and the ECMWF profiles.

4.1.2 ROPP

ROPP is a software package maintained by ROM SAF and can be accessed from www.romsaf.org/software. The software version used in this study is ROPP-7.0. ROPP consists of five modules that process RO data, perform quality control, and assimilate data. The main module used in this study is the pre-processor module, ropp-pp. This module converts the excess phase and amplitude data into bending angle as well as refractivity corresponding to the LEO and GPS satellite's orbital positions and velocities. The ROPP processing tool is used to process the COSMIC excess phase and amplitude data contained in the atmPhs data files obtained from CDAAC.

4.1.3 ECMWF profiles

ECMWF is an independent intergovernmental organization. The ECMWF TOGA (Tropical Ocean and Global Atmosphere) 2.5 degree Global Upper Air Analysis stores atmospheric parameters such as temperature, humidity, and pressure. CDAAC routinely converts co-located gridded ECMWF profiles to netCDF files and compares them with RO measurements [113]. As a popular global weather analysis tool, ECMWF files are commonly used to evaluate the retrieved refractivity profiles from RO events. ECMWF is also used here as a reference data source, and both CDAAC

and ROPP processed results are compared with the co-located ECMWF profiles.

4.1.4 Intermediate data file generation

The atmPhs data obtained from the CDAAC website are in a CDAAC-defined netCDF format which cannot be processed by the ROPP software directly. A MATLAB conversion tool is developed in this study to convert the atmPhs data to an intermediate data structure, then to a netCDF file that can be read by ROPP. The ROPP package does contain a FORTRAN conversion function to convert the atmPhs data to the ROPP format. However, this function does not take into consideration the leap second difference between the GPS time and UTC; the former is adopted by CDAAC, while the latter is used by ROPP. GPS time leads UTC by 15 seconds in 2011. During the conversion of atmPhs file to the netCDF file that can be read by ROPP, the leap second will cause small errors in the GPS and LEO satellites' positions and velocities and is corrected prior to ROPP processing. After the atmPhs data are converted to files that can be accessed and processed by ROPP, ROPP is used to convert the excess phase and other auxiliary data into the bending angle and the refractivity profiles. As mentioned in Section 4.1.1, CDAAC provides the processed results, as atmPrf files, using its own processing software. The bending angle and refractivity profiles stored in the atmPrf file are then compared with the bending angle and refractivity profiles processed by ROPP. The same RO event's data processed by CDAAC and ROPP are then compared with the co-located ECMWF analysis. The processing steps are illustrated in Fig. 4.3.

Figure 4.3: Processing chain of the statistical comparison. The atmPhs data from CDAAC are processed to atmPrf data. In addition, the atmPhs data are also converted to ROPP format and processed by ROPP. The derived atmPrf data, ROPP data containing processed results, and the co-located ECMWF profiles are statistically compared.

4.1.5 Relationship of refractivity and temperature, pressure, and humidity errors

In the neutral atmosphere, the refractivity of a microwave frequency signal is related to temperature T , pressure P , and water vapor pressure P_w using (2.33). The refractivity error will affect the derived temperature, pressure, and water vapor pressure at a specific altitude. In [15], an example calculation is provided to demonstrate the dependency of errors in temperature, pressure, and water vapor pressure on refractivity error. The example shows that a -5% bias in refractivity will induce about +10 K error in temperature, or -5 hPa error in water vapor pressure at a near-surface altitude.

4.2 CDAAC and ROPP processing comparison

CDAAC and ROPP follow the same processing steps but with different implementations in ionospheric correction and bending angle estimation, and both processes rely on the use of climatological models. The difference between the climatological models used by the two software packages is one of the major reasons for the differences in the processed results. In this section, we describe the common processing steps of the two software packages and highlight the differences in their climatological models.

4.2.1 Assumptions

Both the CDAAC and ROPP algorithms assume that the refractivity is locally spherical symmetric. When using GO to calculate the bending angle profiles from the Doppler frequency measurements, both software assume single-ray propagations between the GPS and LEO satellites. This assumption is feasible at altitudes above the multipath region [74,114–116], and the multipath region means the altitude

regions where the atmospheric multipath is evident [117].

4.2.2 Pre-processing / filtering of L1 and L2 channel signal

Both CDAAC and ROPP uses radio holographic filtering from [118] to pre-process L1 and L2 channel signals [108] [116].

4.2.3 Quality control

Both CDAAC and ROPP have quality control procedures that can partially (truncation of data) or completely discard the entire RO data set (rejection of data). Truncation generally occurs in the lower altitude where the noise is prominent. The truncated data are denoted as null values in this study and are not used in the comparison. The rejection criteria for both CDAAC and ROPP are summarized below. The same set of RO events satisfying the CDAAC quality control criteria is used in the study.

In CDAAC, several quality control checks are implemented. If any of these quality checks fail, the entire file will be rejected and marked as “bad”. The criteria are as follows: mean difference between observational and standard bending angles between 60 and 80km should be smaller than 10^{-4} radian; maximal fractional difference between the retrieved and the standard refractivity should be smaller than 50%; bending angle error between 30km and 40km should be smaller than 0.1 radian; standard deviation of oscillations of the difference between observational and standard bending angles between 60km and 80km should be smaller than 1.5×10^{-4} radian; L1 signal-to-noise ratio (SNR) at 80km obtained by linear regression should be larger than 200.

In ROPP, if the fractional deviation from the co-located ECMWF profile exceeds 10% in the altitude range of 10km to 35km, the entire profile is discarded [74].

4.2.4 Derive bending angle using GO method

The same GO method from [43] is used by both CDAAC and ROPP to calculate the bending angle profiles iteratively from the Doppler frequency shift.

4.2.5 Derive bending angle using wave optics method

Both CDAAC and ROPP use the CT2 (Canonical Transform of Type 2) method presented in [119] by Gorbunov and Lauritsen [116] [120]. The CT2 method combines numerical efficiency of the FSI method [107] and accuracy of the phase matching method [121], which is known to provide the most accurate solution [111].

4.2.6 Ionospheric correction

Both CDAAC and ROPP carry out the ionospheric correction based on the linear combination of bending angles at a common impact parameter [122]. However, their implementations are different [74] [116].

In CDAAC, a threshold altitude is estimated for each RO event. Below this threshold altitude, the L2 signal is discarded while the L1 bending angle is corrected by the difference between the L1 and L2 bending angles extrapolated from above the threshold altitude [74] [105] [114].

ROPP uses the ionospheric correction algorithm described in [81]. An optimal linear combination between L1/L2 bending angle data and the model bending angle profiles from the MSISE-90 (Mass Spectrometer Incoherent Scatter Radar extended model 1990) climatological model is implemented. Using statistical optimization, the noise contribution to L1 and L2 bending angle measurements is reduced [116].

4.2.7 Optimal estimation of bending angle using background model/ initialization of bending angle

In CDAAC, the optimized bending angle is a combination of the measurements and fitted background bending angle model-inferred values with appropriate weight coefficients. The weight coefficients are determined based on the measurement estimations and background bending angle model errors. The background bending angle model used by CDAAC for processing COSMIC data is from NCAR (National Center for Atmospheric Research) plus a hydrostatic correction [74].

The same approach is adopted by ROPP. However, the background bending angle model used by ROPP is a search of the MSISE-90 climatological model based on months, latitude, longitude, and height (“global MSIS search” in [116]).

4.2.8 Derivation of refractivity

In CDAAC, the Abel transform is used to derive refractivity from the bending angle. If a RO event starts below 150km, the bending angle from climatology will be used to fill the gap. Exponential extrapolation is used if the climatologically derived bending angle is lower than 150km.

In ROPP, the same Abel transform is used. The optimized bending angle is extended above the highest measurement impact parameter using the climatological profile derived from the MSISE-90 model [116].

4.3 Results

Both bending angle and refractivity profiles processed by CDAAC and ROPP are compared against each other. Comparisons for different months as well as for different altitude ranges are made to study the deviation trends over time and altitude. The comparisons between ROPP processed results and ECMWF profiles, as well as

COSMIC data and ECMWF profiles, are also included.

4.3.1 Processing result comparison between CDAAC and ROPP

Fig. 4.4 compares the bending angle differences between ROPP and CDAAC processed results for Southeast Asia in 2011. An impact height grid is defined from the Earth's surface to 60km altitude with a 1km vertical interval. Since the two processing software packages use different vertical intervals, both data sets must be interpolated to this 1km vertical interval altitude grid. For some RO events, the signals penetrating the low atmosphere are truncated by the processing software because of large tracking errors [105]. As a result, some of the low atmosphere data are discarded by the CDAAC quality control algorithm. CDAAC also utilizes other quality check criteria to eliminate erroneous profiles. In this study, CDAAC has discarded 2,560 out of 13,271 RO events for the 2011 Southeast Asia data. ROPP implements less stringent quality control procedures, as mentioned in the previous section. To ensure a fair comparison, the same set of RO events that passed the CDAAC quality control check is used. As a result, the maximum number of data points in the right panel of Fig. 4.4 is 10,711. The mean and standard deviation of the processing result differences, fractional mean and fractional standard deviation, and the number of data points used in the calculation are plotted. The maximum bending angle standard deviation of about 2.3 micro radian occurs at an altitude of about 4km. The data number at 4km is 3,165 and is considered statistically large enough.

Fig. 4.5 shows the same statistical parameters as in Fig. 4.4 for the refractivity calculation. The maximum refractivity standard deviation of about 3 N-units occurs

Figure 4.4: Mean (solid) and standard deviation (dotted) of bending angle differences between ROPP and CDAAC processed data. (a): Bending angle difference between ROPP and CDAAC; (b): Fractional bending angle difference between ROPP and CDAAC; (c): Data points used in the graph.

at an altitude of about 4km. The same data number of 3,165 RO events as in Fig. 4.4 is found at 4km. The refractivity standard deviation decreases as the altitude increases.

Figure 4.5: Mean (solid) and standard deviation (dotted) of refractivity differences between ROPP and CDAAC processed data. (left): Refractivity difference between ROPP and CDAAC; (middle): Fractional refractivity difference between ROPP and CDAAC; (right): Data points used in the graph.

To clearly see the standard deviation variations of the bending angle and refractivity with respect to time, Fig. 4.6 and Fig. 4.7 are plotted to show the bending angle and refractivity deviations between the ROPP and CDAAC processed data over different months, respectively. The altitude is partitioned into 60 levels with vertical intervals of 1km per level. The value of mean standard deviation of each altitude bin is denoted by the color scheme shown in the figure's legend. White color indicates the low altitude ranges where there are no measurements. The data point numbers for plotting Fig. 4.6 and Fig. 4.7 are shown in Fig. 4.8. At the altitude range of 4km to 6km, the bending angle standard deviation is the largest being about 2 micro radian. At higher altitudes above 10km, the standard deviation decreases to below the 0.01 micro radian level.

Figure 4.6: Bending angle difference standard deviation (unit: 10^{-3} radian) between ROPP and CDAAC for every month.

Figure 4.7: Refractivity difference standard deviation (unit: N) between ROPP and CDAAC for every month.

Figure 4.8: Data points used for plotting Fig. 4.6 and Fig. 4.7.

For the monthly refractivity deviation variation result, the largest standard deviation of about 3 N-units can be found at an altitude of about 5km from January to March.

In [78], a similar study was carried out for the Australian region using the then available CDAAC and ROPP software package. A positive mean for bending angle difference was found. At altitudes below 5km, there was a negative fractional bending angle difference. From 5km to 35km, the authors found a positive fractional bending angle difference smaller than 3%. The results obtained from this study are similar, as shown in the left panel of Fig. 4.4, where there is a positive bending angle difference. In the middle panel of Fig. 4.4, it is shown that the fractional difference is positive. The largest fractional bending angle difference is found to be about 2%.

For the refractivity comparison results, [78] found that both the difference and fractional difference exhibited negative bias smaller than -1 N-unit and -3% from the surface to 35km, respectively. In this study, a very small positive bias for the difference and fractional difference below 50km is observed. Fig. 4.5 shows smaller bias values of the difference and fractional difference, where the largest values are 0.4 N-units and 0.2%, respectively.

Several factors may contribute to the differences observed. There is the difference in time and the region where the data are extracted. [78] uses the RO data in the Australian region in 2010, while this study selects data from Southeast Asia in 2011. The tropical areas usually have larger RO retrieval errors, and the larger refractivity differences is partially due to this fact. The processing software are also different. The CDAAC software package is v2010.2640 and v2013.3520, and the ROPP software package version is 6.0 and 7.0, respectively for the two studies. To better explain the difference, the same 2010 Australian region data used in [78] can be processed using the updated processing software package in a future study.

4.3.2 Comparison results with ECMWF

The above CDAAC and ROPP processed RO results are compared with co-located ECMWF profiles. The mean and standard deviation of the refractivity differences between CDAAC processed results and ECMWF profiles, as well as for ROPP processed results and ECMWF profiles are calculated for the entire data set and shown in Fig. 4.9. Since the ECMWF profiles have a maximum altitude of about 50km, only refractivity profiles below 50km are compared.

Figure 4.9: Mean (solid) and standard deviation (dotted) of refractivity differences between CDAAC processed results and ECMWF profiles (red), as well as for ROPP processed results and ECMWF profiles (black). (left): Refractivity difference; (middle): Fractional refractivity difference; (right): Data points used in the graph.

For the comparison between CDAAC processed results and ECMWF profiles, Fig. 4.9 shows that the refractivity difference between them (red) has a negative mean of less than 2.5 N-units and fractional difference mean of less than 1 % in the low altitude region (below 10km). The negative bias decreases as the altitude increases and becomes close to zero at above 12km. The overall mean of the fractional refractivity difference between CDAAC processed RO results and ECMWF profiles is

less than 7%. Their standard deviations can reach more than 5 N-units below 5km. At around 10km altitude, the standard deviation is about 1 N-unit.

The same comparison is performed between ROPP processed results and ECMWF profiles and the results are shown in black in Fig. 4.9. The difference between ROPP processed results and ECMWF profiles generally has a similar standard deviation than those between CDAAC and ECMWF. The standard deviations can also reach more than 5 N-units below 5km, and reduce to about 1 N-unit at 10km.

To better quantify the difference between CDAAC and ROPP processed results for different altitude ranges, the results from Fig. 4.9 are summarized in Table 4.1. The altitude range is divided into five intervals from the surface level to 50km. The mean and standard deviation are averaged for each 10km vertical altitude interval. The percentage in the table in brackets denotes the mean or standard deviation of the fractional refractivity differences. A larger standard deviation for one package means that this package's result is less consistent with the ECMWF profiles.

Table 4.1: The refractivity (N-unit) comparison between CDAAC and ROPP processed results.

Altitude (km)	COSMIC- ECMWF (mean)	COSMIC- ECMWF (s.d.)	ROPP- ECMWF (mean)	ROPP- ECMWF (s.d.)
0–10	-0.79 (-0.39%)	3.37 (1.60%)	-0.55 (-0.29%)	2.89 (1.41%)
10–20	-0.21 (-0.64%)	0.33 (0.75%)	-0.23 (-0.66%)	0.29 (0.67%)
20–30	-0.28 (-3.44%)	0.08 (0.80%)	-0.28 (-3.40%)	0.08 (0.82%)
30–40	-0.03 (-1.77%)	0.02 (1.14%)	-0.03 (-1.62%)	0.03 (1.42%)
40–50	-0.02 (-3.63%)	0.01 (2.34%)	-0.02 (-3.62%)	0.02 (3.51%)

Table 4.1 shows that ROPP processed results have a smaller mean refractivity difference for low altitude (below 10km), although the difference between the two software processing results is very small: -0.79 N-units for CDAAC and -0.55 N-units for ROPP. For altitudes above 10km, the difference between CDAAC and ROPP processed results is even smaller. Based on the calculation method described

in Section 4.1.5, a -0.39% fractional refractivity error can be translated to about +0.9 K in temperature or -0.4 hPa in water vapor pressure near the Earth's surface. The effect of the mean difference between the two processing packages is therefore negligible.

For the standard deviation results, the two software packages exhibit larger differences with ECMWF profiles at altitudes below 10km and from 30km to 50km. The refractivity error can be related to errors in the temperature and water vapor pressure. For example, the standard deviation between CDAAC results and ECMWF below 10km is 1.60%, which translates to a standard deviation of about -3.5 K in temperature or +1.5 hPa in water vapor pressure. The table also shows that the standard deviation of the ROPP processed result is comparable with that of CDAAC results. The fractional refractivity standard deviation between CDAAC results and ECMWF varies from 0.75% to 2.34%, while for ROPP the fractional refractivity standard deviation from ECMWF varies from 0.67% to 3.51% from the surface to 50km. This indicates that the both CDAAC and ROPP processed results are consistent with the ECMWF profiles. ECMWF has incorporated the COSMIC RO data since December 12, 2006, which means it is more favorable for CDAAC processed results than for ROPP processed results in any comparisons against ECMWF. The similar statistical results found between CDAAC and ROPP indicate that the ROPP processing algorithm is consistent with the CDAAC algorithm.

To verify the statistical significance of the results, a two-tail t-test is carried out. A significant level of 0.05 and the corresponding t-value thresholds are used. The research hypothesis is that the average refractivity difference between CDAAC and ECMWF significantly differ from the average refractivity difference between ROPP and ECMWF. The t-values for different altitudes are shown in Fig. 4.10. The results indicate that the research hypothesis can be accepted in most altitude regions except at 10km and 21–22km.

Figure 4.10: T-test result for average refractivity difference between CDAAC and ECMWF, and the average refractivity difference between ROPP and ECMWF. Thresholds of ± 1.962 are marked as dotted lines.

The standard deviation of the refractivity differences as presented above will increase if large variations exist in the CDAAC/ ROPP results or ECMWF results. To eliminate this effect, another statistical measure known as the normalized error variance [123], denoted by α , is adopted. The α -index better quantifies the correspondence between CDAAC/ ROPP results and ECMWF results. The expression for the α -index is as follows:

$$\alpha = \frac{\text{var}(A_1 - A_2)}{\text{var}(A_1) + \text{var}(A_2)}, \quad (4.1)$$

where in this context, A_2 is the set of ECMWF refractivity profiles, and A_1 is the set of refractivity profiles from either the CDAAC results or the ROPP results. “var” denotes the variance of the set. The α -index ranges from 0 to 2 and different values of the α -index have different implications as noted in [123]:

1. α -index close to 0 indicates that the two sets A_1 and A_2 vary similarly to each other, and only a small error pattern exists.
2. α -index close to 1 indicates that there are large pattern errors, and the two sets do not agree with each other. If A_1 is a random model independent of A_2 , α equals one.
3. α -index close to 2 indicates that the pattern errors are so large that the variations of the two sets tend to be opposite.

The plots of the α -indices for the comparisons between CDAAC processed refractivity results and ECMWF profiles, and between ROPP processed refractivity results and ECMWF profiles are shown in Fig. 4.11. ROPP processed results have a larger α -index than that of CDAAC processed results above about 30km. This indicates that the ROPP processed results are less consistent with ECMWF profiles compared to the CDAAC processed results for these altitudes, whereas the ROPP performs better at other altitude levels.

As can be seen from Fig. 4.11, the difference in α -index performance between CDAAC processed results and ROPP processed results is mainly above 30km altitude. A closer investigation of the two processing procedures reveals that this difference is largely due to the different models used in the process of initialization of bending angles [74]. The bending angle profiles calculated from excess phase are corrected for the ionospheric effect and optimally combined with a background model bending angle profile. At higher altitude, the contribution from the model bending angle increases and becomes the dominant portion of the output bending angle. The altitude at which the model bending angle overtakes the measured bending angle varies from one occultation event to another, and typically occurs

Figure 4.11: Alpha indices for the COSMIC-ECMWF refractivity (solid) and ROPP-ECMWF refractivity (dotted) statistical comparison.

between 30km and 60km altitude [105]. CDAAC and ROPP use different bending angle models: CDAAC uses the NCAR model plus a hydrostatic correction, while ROPP uses the MSISE-90 climatological model, which is primarily based on the tabulation of zonal average temperature and pressure, supplemented with averages from the National Meteorological Center (NMC) [124]. The NCAR model involves dynamical constraints on the atmospheric variables such as pressure, temperature, radiative heating, and vertical motion (which affect temperature through adiabatic compression/expansion). Hence the NCAR model provides a more realistic modeling of the upper atmosphere. The use of the NCAR model in the CDAAC is thus one major reason for its smaller α -index and hence better performance. Nevertheless, the ROPP's performance is still much better than a random model and is somewhat better than the CDAAC below about 20km where the measured bending angle has a larger contribution than the background model bending angle. Hence, the ROPP's measurements of the refractivity variations in the lower atmosphere are

slightly more reliable than the CDAAC's.

4.4 Summary

A comparative study of CDAAC processed results and ROPP processed results over Southeast Asia in 2011 is carried out. Excellent consistencies of bending angle and refractivity are found between the results. At about 4km, both the bending angle and refractivity standard deviation between the CDAAC and ROPP results are the largest, being about 2.3 micro radian and about 3 N-units, respectively. ECMWF profiles are used as references to evaluate the CDAAC and ROPP processed results. Both CDAAC and ROPP processed results have similar mean refractivity difference and standard deviation difference. A hypothesis testing based on the t-test is carried out to validate the results' statistical significance before a normalized error variance statistical test for refractivity is applied. The normalized error variance results show that the ROPP performs slightly poorer than the CDAAC at altitude above 30km, and slightly better at other altitude levels. CDAAC and ROPP processing comparison shows that the different background bending angle models used are the major reasons for this difference.

Chapter 5

PBLH Detection using Mountaintop-based GNSS RO Signal Amplitude

PBLH is a crucial parameter in modeling the troposphere. Space-based GNSS RO has been used for detecting the PBLH with receivers onboard LEO satellites. This chapter presents a method of PBLH detection using GNSS signal amplitude measured by a MRO system on the summit of Haleakala, Hawaii in April 2015. The data were recorded using both a commercial GNSS receiver and software-defined radios (SDR) connected to a high-gain antenna steered towards rising and setting GNSS satellites over the ocean surface. While the intent of the experiment was to collect raw wideband IF signals for characterization of strong scattered GNSS signals traversing the moist lower troposphere [125], this study focuses on using the data to derive PBLH. The commercial receiver processes the satellite signals using a traditional CL tracking algorithm, whereas the SDR outputs are processed with an OL tracking algorithm. The results from both the commercial receiver and the SDR are used to derive PBLH and demonstrate the feasibility of MRO for PBLH

detection. Although MRO lacks global coverage compared to the space-based RO, it offers dense regional temporal and spatial coverage at relatively low cost. The estimated PBLHs are comparable with those derived from space-based RO measurements, space-borne lidar, and local radiosonde profiles. Moreover, by experimenting with the raw IF data using various receiver algorithms and by analyzing the outcomes of the measurements, we gain insights into the nature of GNSS signal disturbances propagating through the PBL. Such insights are helpful in developing advanced technologies for future RO missions.

The second contribution of this study is the application of an easy-to-implement algorithm using signal amplitude for PBLH detection. The commonly used method to detect the PBLH using RO is the refractivity gradient method, which finds the height corresponding to the minimum refractivity gradient. Both space-based and ground-based RO produce vertical refractivity profiles through inversion, followed by differentiation of the refractivity to obtain refractivity gradients. The inversion for space-based and ground-based RO includes several steps such as the conversion from carrier phase to bending angle, then to refractivity profiles (e.g., [44] [59]). For ground-based RO, the requirements on the inversion are more stringent in that it requires one-to-one mapping of positive and negative elevation measurements as mentioned in Section 2.2.3 (e.g., [59] [86]). Some MRO events do not satisfy this requirement due to noisy or discontinued measurements in certain segments of positive elevation or negative elevation. The GNSS signal amplitude-based method described in this chapter does not have an inversion step and our results confirm that the method is effective for PBLH detection. With these advantages, the MRO-based signal amplitude method can be a useful addition to existing methods and could contribute to regional weather studies.

Section 5.1 describes the MRO data and data used for comparison purposes. Section 5.2 presents the detailed OL Doppler frequency model and tracking results. Sec-

tion 5.3 compares the refractivity gradient-based method and the signal amplitude-based method. Section 5.4 presents the PBLH values using the signal amplitude method and compares them with results obtained from different data sources and different detection methods. Section 5.5 summarizes the findings of this chapter. The OL tracking algorithm was described in Section 2.1.4.

5.1 Data used in this study

5.1.1 MRO data

A MRO experiment was carried out by the Colorado State University (CSU) GPS Lab on April 20–26, 2015 at the summit of the Haleakala volcanic edifice on the Hawaiian island of Maui (latitude: $20^{\circ}42'09''N$, longitude: $156^{\circ}15'24''W$, altitude: 3060m) [125]. A photo of the experiment setup is shown in Fig. 5.1 (photograph credit [125]). The antenna position is surveyed using the Precise Point Positioning service from Natural Resources Canada [126]. The test site was chosen to have minimal obstructions and cluttering from any nearby ground to allow the best reception of the occulting GNSS signals. During the experiment, a high-gain antenna was steered to follow rising or setting GNSS satellites in directions with no ground signal obstructions. The antenna is connected to a Septentrio PolaRxS PRO receiver (referred to as the PolaRxS in the rest of the study) and an array of SDRs. The PolaRxS outputs signal amplitude, carrier phase, Doppler frequency, along with other parameters for the following open signals:

- GPS L1 C/A, L2 CL, L5Q
- GLONASS L1 C/A, L2 C/A
- Galileo E1 C, E5a-Q, E5b-Q

- Beidou B1I, B2I
- QZSS L1 C/A, L2 CL, L5Q.

Figure 5.1: The 2015 Hawaii MRO experiment setup.

During the 7-day experiment, there were a total of 77 MRO events that show clear PBLH signatures. The GNSS satellites' positions and velocities are calculated from the Receiver Independent Exchange Format (RINEX) navigation files obtained from the IGS website [82].

The SDRs connected to the same antenna are used to record the raw IF data. The IF data enable the application of the OL tracking algorithm and other advanced signal processing techniques. In this study, however, the OL tracking of SDR data does not lead to superior performance in PBLH estimation when compared to the CL tracking by the PolaRxS receiver as shown in Section 5.3.2. This is demonstrated by applying the OL algorithm to the GPS L5 data-less pilot channel (GPS L5Q) and determining the PBLH. The OL algorithm was described in Section 2.1.4.

5.1.2 IGRA radiosonde data

The IGRA is a radiosonde data set available from the National Centers for Environmental Information (formerly the National Climatic Data Center (NCDC)) [127]. This archive hosts observations obtained with radiosondes and pilot balloons from more than 2,700 globally distributed stations. The measurements from the IGRA contain atmospheric pressure, geopotential height, temperature, dew point depression, wind direction, and wind speed. Refractivity profiles can be calculated from these measurements (see Section 2.3.2) and they are processed using the refractivity gradient method to validate the MRO results.

“LIHUE” and “HILO HI” are two radiosonde stations near the MRO experiment site and each station releases weather balloons twice a day. During the 7-day experiment, there are 28 refractivity profiles obtained from the two stations. Their refractivity profiles are used to detect the PBLH. The IGRA measurements’ vertical resolutions vary between stations and with time. For the 28 profiles used in the study, the average vertical resolution ranges from 115m to 415m over an altitude between 500m and 3.5km where the PBL top exists. The IGRA stations are rather sparse over the ocean compared to on land. The stations on or near the land are affected by the local terrain. As a result, there are few IGRA stations that can measure the marine PBLH.

5.1.3 CALIOP data

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) is a mission studying the global radiative effect of aerosols and clouds on climate. Launched on April 28, 2006, CALIPSO has been providing nearly continuous measurements of the vertical structure and optical properties of clouds and aerosols [128] [129]. Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) is the lidar payload onboard CALIPSO satellite. CALIOP sends laser pulses to-

wards the Earth's surface and the backscattered signals are collected by a telescope and subsequently converted to an electronic signal, from which vertical distribution of aerosols and clouds, cloud particle phase, and classification of aerosol size are derived [130].

In the subtropic and mid-latitude zones with a relatively cold sea surface temperature, the cloud top altitude is usually well defined by the PBLH [21] [30]. In [30], the cloud top altitude data from CALIOP measurements are assumed to be the PBLH, and is shown to be consistent with the spatial and temporal variations of that determined from the RO observations and the radiosondes. The estimated PBLH has a horizontal resolution of 1km and a vertical resolution of 60m [131]. The same methods used in [30] are applied to the level 2 cloud 1-km layer products (V4.01) ([132]) downloaded from the NASA Atmospheric Science Data Center (ASDC) to determine the PBLH in this study. We identified a set of CALIOP-derived PBLH data taken within 200km and within 2 hours of the MRO data's locations and times (see the CALIOP satellite path in Fig. 5.2) and this set of data is used in this study.

5.1.4 COSMIC data

The COSMIC mission, the CDAAC, and the atmPhs & atmPrf files were described in Section 4.1.1. There are 5 COSMIC RO profiles on April 20–26, 2015 in the area defined by latitude $17^{\circ}N - 23^{\circ}N$, longitude $160^{\circ}W - 155^{\circ}W$. Among them, two events passed the quality check described in Section 5.3.1. These two events are used to calculate PBLH with vertical refractivity profiles and the results are compared with the MRO measurements. A total of 30 COSMIC events from March, April, and May in 2014 and 2015 covering the same region were also downloaded. Their vertical refractivity profiles and signal amplitude profiles are both used to detect the PBLH in order to validate the signal amplitude-based method.

The tangent point is defined as the point along a ray path where the radius

vector from the center of curvature is normal to the ray. It is the closest point on the ray path to the Earth surface (e.g., [133]). In this study, a MRO event location is defined as the mid-point of the tangent point's ground track when the elevation of the incoming signal seen at the receiver is negative. Fig. 5.2 shows MRO GNSS receiver's location (Rcv.), MRO event locations (MRO), the IGRA radiosonde station locations (HILO HI and LIHUE), the 2 COSMIC RO events' locations (COSMIC), and the CALIOP determined PBLH locations (CALIOP). An example tangent point ground track is shown for one MRO event in the figure as the dashed line. The figure shows that MRO-detected PBLH results are much denser compared to the COSMIC events.

5.2 OL tracking Doppler frequency model and tracking results

Most space-based RO missions use OLs to track signals penetrating the lower troposphere. This is because the rapidly changing vertical refractivity gradients in the lower troposphere induce signal defocusing and result in deep signal amplitude fading at the receiver, which disrupts the feedback process of the CL carrier tracking loop of GNSS receivers [43] [134]. OL tracking does not rely on such a feedback mechanism and is therefore more robust (e.g., [14] [135]). OL tracking requires a Doppler frequency model to maintain lock on the signals. This section describes the Doppler frequency model and OL tracking results. The OL tracking algorithm was described in Section 2.1.4.

Figure 5.2: Relative locations where PBLH were detected using MRO (crosses), IGRA(circles), and COSMIC (diamonds) data on April 20–26, 2015 within the area defined by latitude $17^{\circ}N - 23^{\circ}N$, longitude $160^{\circ}W - 155^{\circ}W$. The CALIOP ground track containing measurements within 200km and 2 hour of the MRO data is plotted using the solid line. There are 2 COSMIC events and 77 GNSS MRO events. The triangle marks the location of the MRO receiver. The dashed line is the ground track of a MRO event.

5.2.1 Doppler frequency model

The Doppler frequency model is based on the relative motion between the transmitter and receiver and the vertical refractivity profiles. The calculation of the Doppler frequency model based on the bending angle profiles is the inverse of the GO algorithm presented in Section 2.2.2 [14] [135]. For convenience, the steps are described here again.

Fig. 2.5 shows the MRO geometry with signal bending for a stationary receiver. Under the assumption of locally symmetric refractivity, the following equations can be derived based on Snell's law and the geometry depicted:

$$n_R d_R \sin \phi_R = n_T d_T \sin \phi_T = a \quad (5.1)$$

$$\phi_R + \phi_T + \theta - \alpha - \pi = 0. \quad (5.2)$$

At the GPS satellite altitude, the refractive index n_T is approximately 1. The refractive index at the receiver n_R is calculated using measured temperature, pressure and humidity. These measurements are provided by the Institute for Astronomy at University of Hawaii for Haleakala Summit, where the receiver is located. The bending angle α is a function of impact parameter a and it can be obtained through Abel transformation using models of the atmospheric refractive index (e.g., NCEP T62 NWP model, U.S. Standard Atmosphere) or the average of nearby radiosonde measurements [14] [20]. The latter approach is used to create the Doppler frequency model. Using the above three equations and bending angle-impact parameter pairs $\alpha(a)$, the angles ϕ_R , ϕ_T , and the unit vectors $\vec{e}_R$, $\vec{e}_T$ can be calculated using an iterative method [14]. The Doppler frequency then can be calculated as [14]:

$$\tilde{f} = \frac{f_{carr}}{c} \times (\mathbf{v}_T \cdot \mathbf{e}_T). \quad (5.3)$$

5.2.2 OL tracking results

The OL tracking algorithm described in Section 2.1.4 is implemented to process the raw GPS L5 pilot channel IF data collected using the SDRs during the MRO experiment. An example of OL tracking of GPS PRN 26 signals is shown in Fig. 5.3. This event is recorded on April 24, 2015, starting at 12:26:00 UTC and is identified as event #1 in Section 5.4.1 and Table 5.1. The top panel shows the carrier-to-noise ratio (C/N_0) computed from the OL and CL tracking algorithms, and the bottom panel shows their C/N_0 difference. Also shown in the figure is the GPS satellite elevation. While both methods generated similar C/N_0 trends, the OL algorithm generates higher C/N_0 than the CL when the satellite is below about -3 degree elevation. This indicates that the OL can penetrate deeper into the lower troposphere.

Both CL and OL generated C/N_0 shows relatively high frequency fluctuations. Such fluctuations are most likely due to multipath reflections off the ocean surface. The OL C/N_0 has larger fluctuations than that from CL tracking. This is because compared to OL tracking, CL tracking has a small bandwidth which rejects more noise. If a signal has sufficient energy to remain above the CL tracking loop threshold, CL tracking will yield higher quality estimates. The high-gain antenna used in the MRO experiment lifted the deep fade in the signal above the CL tracking threshold, and therefore CL tracking is used in this study.

In addition to the multipath from signal reflections off the ocean surface, atmospheric multipath due to the sharp variations in refractivity may cause a bias in the retrieved refractivity profiles [15]. However, the bias does not impact the estimation of the height at which the sharp refractivity gradient occurs, and therefore will not impact PBLH estimation. This conclusion was validated in [15], which

Figure 5.3: GPS PRN26 L5Q signal C/N_0 comparison between CL and OL for MRO event #1. This event was recorded on April 24, 2015, starting at 12:26:00 UTC. The top inset shows the C/N_0 values of both CL and OL as well as the GPS satellite elevation. The bottom inset shows the C/N_0 difference between OL and CL (OL-CL).

processed simulated GPS signals with atmospheric multipath using both the GO and CT methods. The retrieved refractivity profiles using these two methods show nearly identical height of the sharp refractivity gradient.

However, for the signal amplitude-based method, the noisier measurements generated by the OL tracking will introduce larger errors in PBLH detection. Since the PolaRxS CL tracking can generate reliable outputs at altitude below the PBLH, the PBLH estimations using the amplitude-based method will be based on the PolaRxS measurements in the remaining study. The PolaRxS CL tracking results are adequate in this study because the MRO experiment used a high-gain antenna, which effectively lifted amplitude fade caused by strong defocusing in the moist lower troposphere. As a result, the PolaRxS receiver can maintain lock on the occulting signals at and below the PBLH.

Fig. 5.4 compares the Doppler frequency estimates generated by the OL and CL tracking methods. The Doppler frequency estimated by the OL has more fluctuations than the CL, although both results follow the same trend. CL method loses track of the signal and generates large Doppler errors when the satellite is below about -3 degree elevation.

5.3 PBLH detection method

5.3.1 Refractivity gradient method

The refractivity gradient method was introduced in Section 2.3.2. It was mentioned that threshold values are defined to filter the outliers, and the commonly used thresholds are 0.5km, 3.5km and -40N-unit/km for the minimum height, maximum height, and refractivity gradient, respectively. In this study, since our measurements are limited to a small area and within a time period with known PBLH median and

Figure 5.4: GPS PRN26 L5Q signal Doppler frequency comparison between CL and OL for the same event shown in Fig. 5.3.

standard deviation of $\sim 2\text{km}$ and $\sim 0.6\text{km}$ respectively (e.g., [21] [32]), we elevate the minimum height threshold to 1.4km .

5.3.2 PBLH detection using signal amplitude

A simpler approach to estimate PBLH is based on signal amplitude measurements. In [22], the altitude at which the GPS signal amplitude shows the strongest fading is used to determine the PBLH based on GPS RO data from CHAMP (CHAllenging Minisatellite Payload) satellite. Using the GNSS signal's amplitude fluctuations to detect PBLH was also suggested in [6] [11] [136]. Here we apply the signal amplitude-based method to the MRO measurements. For the MRO, GNSS signals reach the mountaintop receiver at about 3km above sea level in a limb-viewing geometry. As the GNSS signals travel through the PBL, the strong refractivity gradient introduces abrupt changes in the signal's phase and Doppler, and often a drop in C/N_0 followed by a quick recovery, as shown in Fig. 5.3. The stronger the gradient of the refractivity, the more abrupt the changes in the signal's phase and Doppler frequency. The most abrupt change in refractivity gradient occurs when the signal travels through the top of the PBL. This also causes the most abrupt changes in signal carrier phase and Doppler frequency, which often results in the receiver carrier tracking loop having a difficult time maintaining lock on the signal and leads to lower C/N_0 .

To compute the PBLH, the signal bending is first estimated using the methods described in Section 5.2.1. However, nearby radiosonde refractivity measurements are used without averaging as in Section 5.2.1. Instead, they are directly fitted with an exponential model to obtain the bending angle profiles, which define the geometry of the signal path. Based on the geometry of the transmitter and receiver, as well as the time when the lowest C/N_0 occurred, the PBLH can be calculated. Similar to the refractivity gradient method, thresholds are set to filter outliers. Based on

the receiver's location in this experiment, the elevation thresholds are set between -2.2 and 0 degree.

Atmospheric multipath in the lower atmosphere does not affect the signal amplitude method. The atmospheric multipath causes the signal amplitude to fluctuate, but the sharpest drop occurs at the top of the PBL where the sharpest change in the refractivity occurs. As a result, the time when the signal amplitude is the minimum reflects the top of the PBL. When estimating the signal bending and calculating PBLH using the time when the lowest C/N_0 occurs, the method used is the inverse of GO method, which has been verified in [15] to handle the atmospheric multipath, as mentioned in Section 5.2.2.

Factors such as receiver tracking error, local multipath, multipath reflections off the ocean surface, and ionosphere may cause the minimum signal amplitude to occur at different times for different frequencies and introduce errors in the detected PBLH. To reduce the error, GNSS signals at different frequencies transmitted from the same satellite are used to obtain average estimates as long as their measurements are available. Fig. 5.5 shows the example MRO event C/N_0 (the same event shown in Fig. 5.3 and Fig. 5.4) obtained using the PolaRxS receiver and the corresponding PBLH detection result. The C/N_0 for L1, L2 CL and L5Q signals, along with the GPS satellite elevation are plotted. The black dotted lines mark the elevation thresholds. The stars mark the time of week (TOW) when the PBLHs are detected using different frequencies. Based on the TOWs and the geometry of the transmitter and receiver, the PBLHs obtained using GPS L1, L2 CL, and L5Q are 2.20km, 2.33km, and 2.29km, respectively. The standard deviation of the three frequencies is 0.07km, and the mean PBLH is 2.27km.

Comparison of the PolaRxS outputs (Fig. 5.5) and the OL tracking results obtained from the SDR recorded IF data (Fig. 5.3) is consistent in their lowest C/N_0

Figure 5.5: MRO signal C/N_0 (PolaRxS output) for GPS L1, L2 CL, and L5Q and the PBLH detected using these signals. The MRO event is the same as the one shown in Fig. 5.3 and Fig. 5.4. The black dotted lines are the elevation thresholds. The stars mark the time when the lowest C/N_0 occurs. The numbers next to the stars indicate their corresponding TOWs.

estimates. Therefore, the PolaRxS measurements are adequate for the PBLH estimation. For the remaining analysis, the PolaRxS results will be used. Similar to the RMGs calculated in the refractivity gradient method, an amplitude relative minimum (ARM) can be defined and calculated for the signal amplitude method to represent the sharpness of the PBL. A larger ARM value corresponds to a sharper amplitude. Note that the ARM values cannot be compared directly to the RMGs defined earlier since they are derived from a completely different set of parameters. Similar to (2.34) in Section 2.3.2, the ARM (A_{rm}) is defined as:

$$A_{rm} = -(A_{min}/A_{rms}) \quad (5.4)$$

$$A_{rms} = \sqrt{\frac{A_1^2 + A_2^2 + \dots + A_\chi^2}{\chi}}, \quad (5.5)$$

where χ is the index for the amplitude-time profile; A is the amplitude; A_{min} is the minimum amplitude and A_{rms} is the RMS value of the amplitude gradient in the region (GPS satellite elevation between -2.2 and 0 degree). The ARM values for the MRO data are presented in Section 5.4.1.

Similar to the refractivity gradient method, there is the possibility of using the gradient of the signal amplitude instead of using the amplitude itself to determine PBLH. We found that due to the noisy amplitude measurements, the PBLH using the minimum amplitude gradient is easily affected by the noise. If we plot the signal amplitude gradient as a function of time, the minimum amplitude gradient is not standing out from the background for almost all events, unlike the case for refractivity gradient. The PBLH results are also not consistent with those using the minimum amplitude, and the disagreement between them is from -0.9 to 0.7km in this study. As a result, we use the minimum amplitude for PBLH detection and the ARM to represent the sharpness of the PBL top.

5.3.3 Comparison with the refractivity gradient method using MRO event

To further validate and to evaluate the performance of the signal amplitude method, the 77 MRO events are also processed using the refractivity gradient method. The method used for the inversion of the MRO data to obtain the vertical refractivity profiles and bending angle profiles based on the Doppler frequency measurements was described in Section 2.2.3. In (2.32), the atmospheric refractive index n_{ref} was obtained for an altitude below the receiver's altitude. The gradient of the refractive index n_{ref} can be used to determine the PBLH.

Fig. 5.6 shows the refractivity (black, bottom x-axis) and its gradient profile (red, top x-axis) for the GPS L5Q signal for the example MRO event shown in Fig. 5.3 and Fig. 5.4. Using the refractivity gradient method, the PBLH is 2.53km (marked by the star in Fig. 5.6). This result is 260m higher than the average PBLH (2.27km) obtained with the signal amplitude method applied to GPS L1, L2 CL and L5Q signals in Section 5.3.2.

In addition to the refractivity profile of the example MRO event shown in Fig. 5.6, the PolaRxS Doppler measurements for the 67 MRO events are also used to obtain refractivity profiles and to derive the PBLHs. There are an additional 10 MRO events without sufficient positive elevation Doppler measurements due to GNSS orbit configurations and possibly receiver tracking outages. These 10 events cannot be used to derive refractivity profiles and therefore no PBLH estimations were made using the refractivity gradient method, and no PBLH comparisons between the two methods are possible. For the 67 processed events, the PBLH difference between using the signal amplitude method and the refractivity gradient method is calculated. The mean and the standard deviation of the differences are 0.09km and 0.23km, re-

Figure 5.6: PBLH detection using the refractivity gradient method for the example MRO event (same event shown in Fig. 5.3 and Fig. 5.4). The bottom x-axis (black) indicates the refractivity profile inverted using GPS L5Q signal, and the top x-axis (red) shows the corresponding refractivity gradient. The star marks the PBLH height (2.53km) and the corresponding refractivity gradient (-81N-unit/km).

spectively. The results indicate good agreement between the two methods. Fig. 5.7 shows the PBLH difference results with the x-axis representing the event numbers. The MRO event numbers and PBLH results using the signal amplitude method are summarized in Section 5.4.1 and Table 5.1. This comparison also confirms the robustness of the signal amplitude method in that it does not require both positive and negative elevation measurements.

Figure 5.7: The PBLH differences obtained using the signal amplitude method and the refractivity gradient method for 67 MRO events. The mean and standard deviation of the differences are 0.09km and 0.23km, respectively. The event numbers for these 67 events are not from 1 to 67 and are summarized in Section 5.4.1 and Table 5.1.

5.3.4 Verification of the signal amplitude method using COSMIC data

The COSMIC data are used to further validate the signal amplitude method. The data are from March, April, and May (MAM) months (these are typically used, see [28] [31] [32]) in 2014 and 2015 covering latitude $17^{\circ}N - 23^{\circ}N$ and longitude $160^{\circ}W - 155^{\circ}W$. The PBLH results are obtained for each event using both the signal amplitude method (applied to the signal-to-noise ratio in the unit of dB in the atmPhs files) and the refractivity gradient method (applied to the corresponding refractivity profiles in the atmPrf files). There are 73 events in the data set, and 30 of them passed COSMIC's own quality check and the quality check described in Section 5.3.1 and Section 5.3.2. The geometry of the signal path is obtained using the refractivity and bending angle profiles contained in the atmPrf files without exponential fitting. The thresholds used in the signal amplitude method are set to corresponding to the same maximum and minimum altitude thresholds defined in Section 5.3.1: 3.5km and 1.4km, respectively. The differences between PBLHs obtained using the two methods for each event are plotted in Fig. 5.8. The mean difference is 0.10km and the standard deviation is 0.58km, indicating good agreement. The differences in the PBLH results are likely due to the noise in the measurements and errors in the inversion process.

5.4 PBLH detection results

The PBLH detection results from the IGRA radiosonde, COSMIC space-based RO, MRO and CALIOP lidar are summarized in this section.

Figure 5.8: The PBLH differences obtained using the signal amplitude method and the refractivity gradient method for 30 COSMIC events in March, April, and May of 2014 and 2015 over latitude $17^{\circ}N - 23^{\circ}N$ and longitude $160^{\circ}W - 155^{\circ}W$. The mean and standard deviation of the differences are 0.10km and 0.58km, respectively.

5.4.1 PBLH results from MRO, IGRA, and COSMIC

The refractivity gradient method is applied to the IGRA and COSMIC data, and their RMG values are calculated. The signal amplitude method is applied to the MRO data for all available GNSS frequencies tracked by the PolaRxS, and their ARM values are calculated. Different frequencies' PBLHs from the same satellite are averaged. No significant discrepancies among the different frequencies are found, mainly due to that the troposphere being non-dispersive for L-band signals.

Fig. 5.9 shows a map containing the PBLH results obtained from the MRO and COSMIC measurements. The values of the PBLH are color-coded according to the color bar on the right. Some GNSS satellites have orbit periods of around 12 hours. Therefore, the receiver intercepts the same GNSS satellite signal at almost the same time and location on consecutive days. The closely spaced events are organized into groups as outlined by the boxes. Numbers are assigned to successful PBLH detection events and are annotated in the figure. Within each group of events, the numbers are ordered from high to low latitude. These numbers are in accord with those in Fig. 5.7. The PBLH events' number, date, time, location, PBLH value, RMG for COSMIC events, ARM for MRO events, and GNSS name (GLO for GLONASS, GAL for Galileo, BDS for Beidou and QZS for QZSS) are summarized in Table 5.1.

The quality check described in Section 5.3.2 is applied to filter out outliers. There are a total of 107 MRO events, including 55 GPS, 32 GLONASS, 6 Galileo, 9 Beidou, and 5 QZSS. Among them, 77 events (72%) satisfied the quality check criteria, and these include 32 GPS, 27 GLONASS, 6 Galileo, 8 Beidou, and 4 QZSS. Most of the un-qualified events are due to not covering elevation range from -2.2 to 0 degree in the signal amplitude measurements.

Fig. 5.9 indicates that the COSMIC events are much sparser compared to the

Table 5.1: PBLHs for MRO events #1–32, #35–79 using the signal amplitude method on all collected GNSS signals, and COSMIC events #33–34 using the refractivity gradient method. For each event, the UTC date, time, latitude (degree), longitude (degree), detected PBLH (km), corresponding RMG or ARM, and GNSS name are shown. the three events in bold font are used in Section 5.4.2. See remaining rows in Table 5.2.

Event #	Date (UTC)	Time (UTC)	Lat (deg)	Lon (deg)	PBLH (km)	RMG/ARM	GNSS name
1	24-Apr	12:56	18.19	-155.6	2.27	-0.38	GPS
2	26-Apr	01:21	18.59	-157.53	2.24	-0.46	GPS
3	26-Apr	00:38	19.56	-158.42	2.17	-0.60	GPS
4	24-Apr	19:09	19.27	-157.11	2.03	-0.54	GPS
5	24-Apr	16:34	18.41	-157.40	2.40	-0.63	GPS
6	24-Apr	15:22	18.30	-157.16	2.26	-0.58	GPS
7	24-Apr	11:22	18.99	-158.15	2.56	-0.54	GPS
8	25-Apr	16:29	18.55	-157.32	2.27	-0.54	GPS
9	25-Apr	15:17	18.44	-157.11	2.00	-0.66	GPS
10	25-Apr	13:45	18.75	-157.66	2.14	-0.69	GPS
11	24-Apr	01:29	18.62	-157.51	1.90	-0.65	GPS
12	24-Apr	00:46	19.57	-158.39	2.09	-0.44	GPS
13	22-Apr	16:42	18.44	-157.38	2.44	-0.73	GPS
14	22-Apr	15:31	18.34	-157.15	2.59	-0.60	GPS
15	23-Apr	19:11	19.27	-157.11	2.28	-0.56	GPS
16	23-Apr	16:38	18.45	-157.37	2.38	-0.63	GPS
17	23-Apr	15:25	18.34	-157.15	2.07	-0.65	GPS
18	23-Apr	13:54	18.67	-157.72	2.48	-0.56	GPS
19	23-Apr	11:25	19.02	-158.11	2.16	-0.61	GPS
20	20-Apr	11:37	18.99	-158.14	2.13	-0.65	GPS
21	20-Apr	14:06	18.63	-157.75	2.22	-0.66	GPS
22	20-Apr	15:38	18.30	-157.16	2.21	-0.62	GPS
23	20-Apr	16:49	18.41	-157.39	1.98	-0.61	GPS
24	21-Apr	11:34	19.07	-158.06	2.58	-0.66	GPS
25	21-Apr	14:01	18.73	-157.68	1.86	-0.72	GPS
26	21-Apr	15:34	18.41	-157.12	2.14	-0.73	GPS
27	21-Apr	16:44	18.51	-157.34	1.84	-0.69	GPS
28	21-Apr	20:15	19.19	-156.49	2.32	-0.53	GPS
29	25-Apr	00:41	19.57	-158.4	1.74	-0.53	GPS
30	25-Apr	01:24	18.61	-157.52	1.76	-0.54	GPS
31	25-Apr	19:08	19.13	-157.17	1.78	-0.45	GPS
32	25-Apr	20:02	18.98	-156.55	2.53	-0.47	GPS
33	24-Apr	14:44	19.44	-157.42	2.14	1.84	GPS
34	24-Apr	09:14	18.98	-158.92	2.06	1.82	GPS
35	26-Apr	09:57	18.40	-157.10	2.28	-0.68	GLO
36	26-Apr	09:12	18.22	-156.26	1.96	-0.61	GLO
37	26-Apr	04:26	19.64	-157.58	1.88	-0.46	BDS

Table 5.2: The remaining rows in Table 5.1.

Event #	Date (UTC)	Time (UTC)	Lat (deg)	Lon (deg)	PBLH (km)	RMG/ ARM	GNSS name
38	24-Apr	17:20	18.12	-156.23	2.08	-0.61	GLO
39	25-Apr	17:56	18.44	-157.01	2.11	-0.61	GLO
40	25-Apr	11:59	18.80	-157.91	1.91	-0.66	GAL
41	25-Apr	10:31	18.17	-156.91	2.06	-0.63	GLO
42	24-Apr	10:33	18.14	-156.91	2.18	-0.59	GLO
43	24-Apr	10:04	18.29	-157.14	2.00	-0.65	GLO
44	24-Apr	04:28	18.09	-158.43	2.14	-0.54	GAL
45	24-Apr	02:40	18.09	-156.88	2.16	-0.61	GLO
46	22-Apr	23:44	18.42	-157.01	1.69	-0.60	GAL
47	22-Apr	18:11	18.03	-157.21	1.84	-0.73	GLO
48	22-Apr	17:25	18.17	-156.20	2.20	-0.68	GLO
49	22-Apr	14:56	19.80	-158.55	2.55	-0.57	GAL
50	22-Apr	09:43	18.53	-157.55	2.04	-0.66	BDS
51	23-Apr	17:11	17.86	-155.46	2.14	-0.59	BDS
52	23-Apr	15:04	18.17	-156.14	2.10	-0.54	GLO
53	23-Apr	12:25	19.18	-158.23	2.04	-0.65	BDS
54	22-Apr	10:17	18.36	-157.16	2.18	-0.65	GLO
55	22-Apr	09:23	18.59	-156.26	2.76	-0.65	GLO
56	22-Apr	04:51	19.64	-157.58	2.33	-0.57	BDS
57	22-Apr	03:56	18.68	-157.55	2.50	-0.67	GLO
58	22-Apr	02:46	18.28	-156.85	2.39	-0.62	GLO
59	20-Apr	17:40	18.13	-156.24	2.08	-0.68	GLO
60	20-Apr	10:54	18.16	-156.96	2.11	-0.58	GLO
61	20-Apr	09:39	18.13	-156.27	2.30	-0.66	GLO
62	21-Apr	07:23	18.29	-157.11	2.10	-0.61	BDS
63	21-Apr	08:21	18.29	-157.13	2.41	-0.72	GAL
64	21-Apr	10:17	18.35	-157.14	1.96	-0.74	GLO
65	21-Apr	10:44	18.19	-156.89	2.44	-0.73	GLO
66	21-Apr	16:07	18.31	-155.79	2.04	-0.67	GLO
67	23-Apr	04:48	19.65	-157.57	2.52	-0.58	BDS
68	23-Apr	08:37	18.24	-156.71	2.42	-0.71	GLO
69	23-Apr	09:28	18.17	-156.26	2.41	-0.69	GLO
70	23-Apr	10:09	18.36	-157.12	1.84	-0.73	GLO
71	24-Apr	06:11	17.51	-157.49	2.33	-0.51	GAL
72	25-Apr	02:06	18.25	-157.13	1.84	-0.59	GLO
73	25-Apr	04:28	19.58	-157.65	1.77	-0.48	BDS
74	25-Apr	09:13	18.15	-156.26	2.40	-0.59	GLO
75	25-Apr	09:59	18.34	-157.14	1.98	-0.63	GLO
76	26-Apr	07:14	18.89	-157.99	2.15	-0.59	QZS
77	24-Apr	07:26	18.81	-158.08	2.46	-0.60	QZS
78	23-Apr	07:32	18.86	-158.03	2.58	-0.58	QZS
79	25-Apr	07:21	18.83	-158.04	2.26	-0.56	QZS

MRO results during this period and in this area. The small number of COSMIC data points made it impossible to conduct a statistical comparison with the MRO results. However, it is evident from Fig. 5.9 and Table 5.1 that both the COSMIC and MRO generated PBLH results are of the same order of magnitude, ranging from 1.7km to 2.8km.

Fig. 5.10 plots the PBLH results obtained from the COSMIC, MRO, and the IGRA, and the RMG and ARM values of these measurements. Note that the COSMIC and MRO measurements are not at the same location, and that the RMG and ARM values are based on different parameters. Except for the two balloon releases on April 26 at the LIHUE station, all IGRA results have RMG values larger than 2, indicating sharp inversion layers [32]. The IGRA detected PBLHs are more affected by the nearby terrain and are generally higher compared to the PBLHs from COSMIC and MRO. The IGRA PBLH results associated with RMG values larger than 2 are in the range of 1.7km to 3.4km. Due to the differences in location and time of the measurements, the MRO-derived PBLHs should not be compared directly with the COSMIC and IGRA results. However, the figure indicates that both results are of the same order of magnitude. Since there is no literature on setting the ARM threshold for a sharp inversion layer, we took a heuristic approach in this study to determine that -0.74 may serve as a reliable reference. This value is obtained by analyzing the MRO events' ARM values and corresponding amplitude variations. For all the MRO events observed, ARM values larger than -0.74 showed obvious sharp drops and rises in their amplitude profiles.

Compared to the IGRA radiosonde measurements where the refractivity profiles and the obtained PBLHs are with relatively fine horizontal resolution, the RO measurements' horizontal resolution is rather coarse (e.g., [28]). During an occultation

Figure 5.10: (a) PBLH results for “HILO HI” (solid circles), “LIHUE” (empty circles), COSMIC (diamonds), and MRO (crosses) from April 20–26, 2015; (b) corresponding RMG values for the refractivity gradient method; (c) corresponding ARM values for the signal amplitude method. The legend is the same for three plots and is only shown in (b).

event, the tangent point drifts. This drift distance is the distance between two observation epochs, and is determined by the relative position and motion between the transmitter and receiver. RO’s coarse horizontal resolution is due to the tangent point drifts during a RO event and the measurements are mean representations of the atmospheric parameters along the tangent point drift path [21] [137]. For airborne RO, this drift distance can range from 200km to 470km [138]. According to [89], a MRO experiment on Mt. Fuji had a tangent point drift in the range of 200km to 400km. For space-based RO such as COSMIC, this distance is reported to be 50km to 200km (e.g., [28] [138]). Fig. 5.11 shows the tangent point drift distance as a function of occulting satellite elevation for the MRO events considered in this study. The zero distance is at the beginning of the occultation. The closer events are grouped together with their event numbers shown in the legend. For event #4, #15, #28, #31, #32, the drift distances are in the range of 210km to 245km, whereas the rest are from 330km to 489km. Events #4, #15, and #31 and their drift distances are marked in Fig. 5.11. Beidou events #73 and #37 show

more prominent curvatures which are caused by the Inclined Geosynchronous Orbit (IGSO) of the satellites.

Figure 5.11: The tangent point drift distance as a function of satellite elevation for the MRO events presented in this study. The positive and negative gradients indicate the rising and setting events, respectively. The event numbers are marked in the legend.

5.4.2 MRO and CALIOP derived PBLH comparison

To ensure a fair comparison with the MRO results, we used CALIOP data at locations within 200km and collected within 2 hours of the MRO events (e.g., [74]). Three MRO events (#20, #21, and #60) on April 25, 2015 have corresponding CALIOP data and are used for comparison. These events are denoted in bold font in Table 5.1. The CALIOP level 2 cloud 1-km layer products (V4.01) are used and the cloud top altitude provided in the data set is assumed to be the PBLH [30].

Two data points are discarded as they contain multiple cloud layers. The CALIOP PBLH results are plotted in Fig. 5.12 and Fig. 5.13.

Figure 5.12: Comparison between the CALIOP and the MRO derived PBLH results for MRO event #20, #21, and #60. The nearly continuous ground track is the CALIOP data and the crosses are the MRO events. The results are for April 20, 2015.

Fig. 5.12 shows a regional map of the CALIOP ground track and MRO events with colors representing the PBLH values. The MRO event number, UTC, and the detected PBLH results are marked on the plot. Fig. 5.13 shows the same results. The x-axis is the time of the measurement, and the left and right y-axes are the PBLH values and the ground track's latitude at the time of the measurement, respectively. The 3 MRO events' PBLH values are also marked as references but not plotted against either time or latitude. The CALIOP measurements fluctuate between 0.5km and 3km while the 3 MRO events' PBLH values are between 2.11km

Figure 5.13: The CALIOP PBLH results (left y-axis) and the event latitudes (right y-axis) as functions of UTC on April 20, 2015. The three MRO events' PBLH results are also shown. Note that their values do not correspond to the time (x-axis) or latitude (right y-axis).

and 2.22km. To reduce the PBLH difference brought by different locations, we compare the three MRO events with the CALIOP data between $18.3^{\circ}N$ and $19^{\circ}N$ where the PBLH standard deviation is 40m and the measurements are closer from the MRO events. Compared to the CALIOP data point at 12:26:26 ($\sim 19^{\circ}N$) with a PBLH of 2.4km for comparison, the 3 nearby MRO events have slightly smaller PBLH values of between 2.11km and 2.22km. The difference in the time and location could be one of the reasons causing the difference in the PBLH values. Note that the MRO's vertical resolution is 150m–250m [89], and the PBLH difference is approximately the scale of the vertical resolution.

5.5 Summary

PBLH is an important parameter for climate and weather modeling. This study presents a technique that utilizes MRO signal amplitude measurements to derive

PBLH. The method is based on detection of the occurrence of minimum signal amplitude to determine the time and magnitude of PBLH. MRO can achieve high resolution measurements in space and time over ocean surfaces using relatively low cost equipment. The signal amplitude-based PBLH detection method is simple, easy to implement, and avoids some of the assumptions and steps associated with the conventional refractivity gradient-based method.

This study uses data collected during a MRO experiment conducted on the summit of the Haleakala on the Hawaiian island of Maui from April 20–26, 2015. The objectives are to demonstrate the feasibility, advantage, and validity of the signal amplitude-based method and its applicability to MRO measurements. The MRO data include measurements generated by a commercial receiver with conventional CL tracking and raw IF samples recorded by an array of SDRs. All open signals on GPS, GLONASS, Galileo, Beidou, and QZSS were recorded. Comparison of GPS measurements using the OL processed SDR data and the commercial receiver results indicate that their corresponding PBLH values are very similar. This is the result of using the high-gain antenna which elevates the deep amplitude fading when the signal traverses the PBL. Therefore, the commercial CL tracking results are used for an analysis of the MRO-derived PBLH estimates.

Application of the signal amplitude method to a triple-frequency GPS MRO event shows that the PBLH estimated using the three GPS signals (L1, L2 CL, L5Q) are consistent with each other with a standard deviation of 0.07km.

A total of 77 GNSS MRO events were used for this study. The PBLH values of these events are computed to be between 1.7km and 2.8km, well within the expected range of the PBLH in the area. The signal amplitude method is also compared with the refractivity gradient method, as they are both applied to measurements obtained for 67 MRO events, and their mean PBLH difference is 0.09km. We introduced ARM as a measure of the sharpness of the amplitude drop. A high ARM value corresponds

to a sharp amplitude drop and indicates a more reliable PBLH estimation. Our heuristic analysis of the measurements suggests that ARM values above 0.74 will result in reliable estimations. The ARM values are computed for these 77 events and they are between -0.74 and -0.38.

Three additional data sources, COSMIC, IGRA, and CALIOP are used to determine the PBLHs during the same time period around the location of the MRO experiment. These analyses are intended to further validate the signal amplitude method and the quality of the MRO measurements. Six months of COSMIC data are used for this purpose. Both signal amplitude and refractivity gradient methods are applied to the COSMIC data and the mean difference between the two methods' PBLH estimates is 0.10km. In addition, 2 COSMIC events during the MRO experiment and near the MRO site are processed using the refractivity gradient method. The PBLH results are 2.16km and 2.06km. They are within the range of 1.7km to 2.8km and agree with the values obtained from the MRO events in the area during that time.

A total of 28 sets of IGRA measurements obtained from daily balloon releases at two nearby stations are used in this study. The IGRA refractivity profiles have finer horizontal resolution and sharper gradients compared to RO measurements. The PBLHs from the IGRA data are obtained using the refractivity gradient method, and they range between 1.7km and 3.4km. As the IGRA data are more affected by the nearby terrain, the corresponding PBLH values are generally larger than those over the open ocean obtained by the MRO and COSMIC measurements.

One set of cloud top altitude measurement obtained by the CALIOP lidar onboard the CALIPSO satellite was identified to be within 200km of the MRO locations and taken within 2 hours of three MRO events. The PBLHs estimated from the CALIOP data are compared to those of the three MRO events and they show close agreement.

While the above-stated validation efforts clearly indicate the feasibility of the

MRO measurements and the signal amplitude method for PBLH estimations, there are limitations in using MRO for PBLH detection. Similar to the space-based RO and IGRA radiosonde measurements, the MRO data are only applicable for well-defined PBL top where the refractivity gradient is evident. Compared to the IGRA radiosonde and CALIOP space-borne lidar, the RO methods (e.g., COSMIC, MRO) have coarser horizontal resolution. Finally, a MRO receiver has to be located on mountaintops at high altitude (comparable to the PBLH) and with minimal obstructions in the signal path.

Chapter 6

Conclusion and Recommendations

6.1 Conclusion

In this thesis the GNSS RO technique and the error propagation properties are first investigated. The effects of the transmitter's and receiver's errors on the OL Doppler frequency model and retrieved refractivity are investigated through simulations. The position and velocity errors affect the OL Doppler frequency model accuracy and thus will affect the OL tracking performance. The study suggests a quantitative relationship between the orbit errors and the refractivity retrieval errors under an OL tracking scenario. The RO processing chain consisting of GO, FSI, and Abel transform is derived and tested. The error from excess phase to bending angle and refractivity is also propagated, which quantifies the error propagation characteristics of the RO processing chain.

With the orbital errors' effect on the RO in mind, we study how different RO inversion algorithms differ in terms of accuracy. A comparison study of the ROPP processed results and the CDAAC processed results is carried out. The ROPP shows excellent consistency with the CDAAC results in term of bending angle and refractivity. At about 4km, both the bending angle and refractivity standard deviations

between the CDAAC and ROPP processed results are the largest, being about 2.3 micro radian and about 3 N-units, respectively. The normalized error variance results show that the ROPP performs slightly poorer than the CDAAC at altitudes above 30km, and slightly better at other altitude levels. The different background bending angle models used are the major reasons for the performance difference.

We modify the space-based RO algorithm to a ground-based RO algorithm, and implement it for the collected MRO GNSS data. During the MRO experiment, different error sources are carefully controlled and 107 MRO events are collected. The ground-based RO algorithm inverts the MRO GNSS data and outputs refractivity profiles, which are used to determine the PBLHs. Using the MRO GNSS data, the derived PBLH results are of higher local temporal and spatial resolutions compared to those derived from LEO-based GPS RO such as COSMIC.

A PBLH determination method based on the signal's amplitude is proposed in the thesis. This method does not have some of the drawbacks of the refractivity gradient method. It simplifies the procedure by avoiding the RO inversion steps. In addition, it is more robust by using the amplitude only for the detection. This PBLH detection method is applied to the collected MRO data. The derived PBLH results are compared with nearby PBLH measurements from other independent sources. The PBLH comparison shows good consistency. This method is also compared with the more common refractivity gradient method using both the MRO and COSMIC data sets. This comparison shows very small mean PBLH difference between them, indicating the reliability of the proposed method. In the proposed method, we define and calculate the ARM values which represents the sharpness of the PBL. A ARM threshold of 0.74 is suggested in the study. ARM values larger than this threshold indicate reliable PBLH estimations.

6.2 Recommendations for future research

Several aspects of the atmospheric profiling using GNSS RO technique are investigated in this thesis. The following directions are proposed for future work.

1. Most of the space-based RO experiments using COTS GNSS receivers cannot track the GNSS signals into the lower troposphere. As a result, the PBLH detection using these experiments is difficult. The OL tracking algorithm's capability of deeper altitude penetration has been verified when it is applied to the MRO data in this thesis. The implementation of the GNSS OL tracking algorithm on a space-based platform can be a future research direction, enabling global coverage of PBLH measurements.
2. The signal amplitude-based PBLH detection method is verified in the thesis using both the collected MRO and the COSMIC data in the same region and period. A more comprehensive comparison study can be carried out using the global COSMIC data. The COSMIC data can be categorized into slots based on different locations and months. The PBLH detection accuracy comparison between the signal amplitude method and the refractivity gradient method can be investigated for each slot. The PBLH differences between the two methods can be statistically analyzed and possible trends in the PBLH differences for different regions and seasons detected.
3. The MRO experiment collected both the raw IF data using the SDR, and the CL tracked data using the PolARxS receiver. The OL tracking algorithm can be applied to the raw IF data and the tracked excess Doppler can be used to derive vertical refractivity profiles. The derived refractivity profiles can then be compared with those obtained using the CL tracked data. This comparison can indicate how the differences in OL and CL affect the retrieved refractivity profiles under a MRO scenario.

Author's Publications

1. B. Han, E. Gunawan, K.-S. Low, Y. Morton, and Y.-F. Tsai, "Simulation study of the effect of orbital errors on open-loop tracking in GPS radio occultation," in *2014 IEEE/ION Position, Location and Navigation Symposium*, Monterey, CA, May 5–8, 2014, pp. 82–86.
2. B. Han, E. Gunawan, K.-S. Low, Y. Morton, and T.-Y. Koh, "Performance evaluation of radio occultation data processing software in Southeast Asia," presented at the Joint CEDAR-GEM Workshop, Santa Fe, NM, Jun. 19–24, 2016.
3. Y. Morton, H. Bourne, B. Han, S. Taylor, D. Xu, R. Yang, F. van Graas, and N. Pujara, "Mountain-top radio occultation experiment and recent results," presented at the Consortium of Ohio Universities on Navigation and Timekeeping, Columbus, OH, Apr. 4–5, 2017.
4. R. Yang, D. Xu, B. Han, Y. Morton, K. V. Ling, and E. K. Poh, "GNSS receiver signal processing under challenging conditions," presented at the Consortium of Ohio Universities on Navigation and Timekeeping, Columbus, OH, Apr. 4–5, 2017.
5. B. Han and E. Gunawan, "Planetary boundary layer height detection using COSMIC satellites," presented at the 14th Annual Meeting Asia Oceania Geosciences Society, Singapore, Aug. 6–11, 2017.

6. B.-X. Li, B. Han, W.-S. Lim, Y.-F. Tsai, and K.-S. Low, “Performance assessment of the radio occultation experiment for commercial off-the-shelf receivers on VELOX-CI microsatellite,” in *ION GNSS+ 2017*, Portland, OR, Sep. 25–29, 2017, pp. 1669–1677.
7. R. Yang, Y. Morton, and B. Han, “An adaptive carrier tracking method to improve mountain-based GPS radio occultation signal processing,” in *ION GNSS+ 2017*, Portland, OR, Sep. 25–29, 2017, pp. 3767–3774.
8. B. Han, Y. Morton, E. Gunawan, and D. Xu, “Planetary boundary layer height detection using mountain-based GPS radio occultation signal amplitude,” submitted to *IEEE Transactions on Geoscience and Remote Sensing* on Jan. 31, 2017, revised on Jun. 14, 2017 and Jan. 25, 2018.

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