Ground-Based GNSS-Reflectometry Sea Level and Lake Ice Thickness Measurements

Dissertation

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Abstract

Rising sea levels, originated from global climate change, lead to increasing number of inhabitants exposed to catastrophe damages. Hence, monitoring and observing sea level and its variation are of great significance, especially for the population living in the coastal regions. Recently, the ground-based Global Navigation Satellite System Reflectometry (GNSS-R) technique has been developed and applied to measure coastal sea level and lake level, to complement contemporary methods such as tide gauges and satellite radar altimetry. Compared with conventional techniques of tide gauge, this GNSS-R altimetry is capable of measuring absolute or geocentric sea level, or lake level height without land vertical motion contaminations. Additionally, it behaves much better in the coastal regions than traditional pulse-limited radar altimetry. As a result, the GNSS-R altimetry technique can potentially mitigate the temporal and spatial deficiency of historical and current sea level records.

A list of concisely stated study objectives is as follows:

The GNSS-R altimetry operates in a bistatic radar configuration, and its forward-scattering signal that is an electromagnetic (EM) wave is impacted by surface scattering properties, in addition to other error sources such as media delay. As one of the primary error sources, the EM bias resulted from the lesser reflectivity of sea wave crests rather than troughs, results in the underestimation of sea level height. To model the EM bias, a numerical simulation was initially conducted using linear and nonlinear wave models. The modeling results confirmed that GNSS-R altimetry measurement EM bias increases with decreasing incidence angle and increasing wind speed, with a constant
GNSS antenna height above the reflected sea surface. We used two realistic GNSS-R sea level measurements from two GPS sites located in the Gulf of Mexico for empirical EM bias modeling, which is a function of wind speed and the elevation angles along which GNSS reflected signals were collected by the GNSS antennae. We used the wind speed data to generate empirical GNSS-R EM bias models, which resulted in the improvement of the GNSS-R sea level accuracy. Also, the empirical EM bias models were shown to be more effective in improving GNSS-R sea level accuracy than the theoretical EM bias model. When the simulated and empirical models were applied to the original GNSS-R sea levels, it demonstrated that the RMS error decreased from ~7.3 cm to ~4.8 cm and ~3.4 cm, respectively.

To comprehensively assess the accuracy of the in situ GNSS-R sea levels, two adjacent geodetic-quality GPS sites 30 m apart at Robinson Point, and the closest tide gauge 13-km away at Tacoma, Washington, were selected for our validation study. The GNSS-R sea level time series has an 8-year sea level data span. The consistency between two adjacent GNSS-R sea level time series was significantly closer than the cases between either of the GNSS-R sea level and tide gauge time series. The root-mean-squares (RMS) errors between the adjacent 8-year GNSS-R altimetry time series were 4.6 cm and 1.1 cm, for hourly and weekly sampling, respectively, indicated excellent agreement and a robust error estimate. When the GPS-derived sea level was compared with tide gauge sea level 13-km away, the results illustrated that the GPS-derived hourly sea level time series has a consistency of 8.0 cm RMS, while the weekly smoothed sea level time series increased the consistency accuracy to 1.5 cm RMS. To further the detection, the tidal harmonic analysis was performed for the two adjacent GPS sites and the tide gauge. The results showed the largest differences occurred by
the underestimation of amplitudes of large tidal constituents in GPS-derived sea levels and the phase difference in smaller tidal constituents.

As one of the most populated coastal regions of the world, the annual freezing and thawing of the Great Lakes and its influence on regional severe weather patterns significantly impact the local economy and ecosystems. Thus, accurate knowledge for the extent and thickness variations of lake ice in the Great Lakes, and their roles in the severity of winter storm and lake effect patterns are of importance to mitigate winter weathers for the people and the economies in the region. In this study, a novel method for lake ice thickness retrieval was proposed and developed, which was mainly based on a combination of a single geodetic quality GNSS receiver and a collocated water level lake gauge. For the first time, we estimated a 12-year lake ice thickness time series near the vicinity Harbor Beach on Lake Huron, and its reliability was validated by ice coverage product. The result initiates the opportunity for the potential use of this new measurement type of near shore lake ice thickness variations, in the assimilative modeling of Great Lakes Forecasting System, to improve the predictability of lake effects and severe winter storms.

Keywords: GNSS-R, Sea Level, Lake Ice Thickness, Electromagnetic Bias, Tide, Signal-to-Noise Ratio (SNR)
Dedication

Dedicated to the students at The Ohio State University
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Chapter 1: Introduction

Sea level rise has large impacts on human society, in particular for the population living in coastal regions and small islands. With rising sea levels, millions of residences living in such as Bangladesh, Lower Egypt and Mekong Deltas suffer permanent migrations and displacements. Also, the influence of rising sea level on human world is primarily through the terrible climate hazards such as tropical cyclones, tsunamis, rather than the straight consequence of mean sea level rise. Together with more intense tropical storm activities, rising sea levels increase the number of people suffering from coastal flooding by between 180 million and 230 million (Watkins, 2007). There are mainly several contributions to sea level changes, and understanding these contributions is cross-disciplinary efforts. Generally speaking, the global mean sea level changes are primarily related to the thermal expansion and water exchanges between the ocean and other resources such as ice sheet, glaciers, and land water. The local sea level variations are caused by some oceanographic factors such as ocean circulation, atmospheric pressure, and geophysical factors such as glacial isostatic adjustment (GIA), tectonics (Bindoff et al., 2007). To understand the process of rising sea level and to reduce the exposures to the catastrophes, monitoring and observing sea levels are necessary for human well-being and prosperity.
There are two types of techniques to measure the present-day sea level change. Tide gauge is conventionally used to observe local sea level variation by measuring the vertical distance between the sea surface and the land surface. This type of observation not only consists of water volume change and other oceanographic signals but also includes land motion signals. Even the land motion caused by GIA can be modeled, the other land motions are not easily estimated. The cooperation with adjacent geodetic measurement is a preferred way to access the whole land motion, but it is usually unavailable. Thus, the observation from conventional tide gauge can result in considerable uncertainties for global sea level estimates. The satellite altimetry, which measures the sea level refer to the Earth’s center of gravity, is not impacted by land motions. Since its uniform and global covered observation, it has been the popular technique for the last three decades. However, the performance of satellite altimetry is poor-behaved in coastal regions. With the large footprint size of few kilometers in diameter, the returned waveform is severely contaminated by the presence of land when approaching the coasts, leads to a drastic reduction of observation accuracy. Therefore, the observation from satellite altimetry in also unreliable over coastal regions. From the observation of stable situated tide gauges, the global mean sea level rise was $1.8 \pm 0.5$ mm yr$^{-1}$ for the period of 1961-2003. On the contrary, the results of satellite altimetry showed the global mean sea level rise was $3.1 \pm 0.7$ mm yr$^{-1}$ for the period of 1993-2003 (Bindoff et al., 2007). This discrepancy between tide gauge and satellite altimetry possibly originates from inefficient coastal tide gauge records in the southern hemisphere.

The Global Navigation Satellite Systems (GNSS) observes both of the direct signals to obtain antenna height with respect to the International Terrestrial Reference
Frame (ITRF) and the reflected signals from the sea surface to acquire the distance between the antenna and specular point, has the capability to measure the absolute sea level height. Additionally, it has good performance on coastal sea level observation, because the smaller footprint size can resist to the contamination of land signals. Therefore, this technique offers an opportunity to make up the shortfall of historical sea and current level records.

1.1 The GNSS-R Altimetry

The GNSS comprises of the Global Positing System (GPS), the Global Navigation Satellite System (GLONASS), the Galileo, and Beidou. It was designed for global positioning and navigation purposes by using direct signals operating in L-band. Creatively, researchers find that the GNSS signals reflected from the sea and ground surface are loaded with productive information including sea level height, wind speed, soil moisture, canopy height, ice thickness and snow depth. This remote sensing technique that takes advantage of GNSS reflected signals, known as GNSS Reflectometry (GNSS-R), has the brilliant potential of development especially on ocean wind speed measurement, weather observation, and forecasting. The concept of measuring sea level using GNSS reflected signal was firstly introduced by Martín-Neira (1993), with the experimental illustration from the space-borne system. Compared with traditional monostatic radar altimetry, GNSS reflectometer operates in a bistatic radar configuration that the transmitter and the receiver are insulated by a very long distance. Accessing the delay between the direct signal and the reflected signals from the Earth’s surface turns GNSS bistatic radar into an altimetry (Zavorotny et al., 2014). Since the receiver located either on a low orbit satellite, an aircraft or on the ground, there are
two main types of space-borne and ground-based GNSS-R altimetry.

Figure 1.1 The schematics of space-borne GNSS-R altimetry. Credit: Google Earth background. The TDS-1 and CYGNSS satellite images are from UK Space Agency and National Aeronautics and Space Administration (NASA), respectively.

As the first space-borne GPS reflectometer, TecDemoSat-1 (TDS-1) was launched in July 2014 aims at imaging the global sea level height. Clarizia et al. (2016) demonstrated the first estimation of sea level height from TDS-1 observation by the Leading Edge Derivative (LED) method. Compared with global DTU10 mean sea surface height model, the results showed that the RMS residual is 8.1 m for the South Atlantic region and 7.4 m for the North Pacific region. The discrepancies are possibly
caused by the limitation of poor resolution of GPS-R instrument and orbit determinations. Hu et al. (2017) improved the algorithm to retrieve the sea level height using TDS-1 data with RMS error of 4.4 m, which is much smaller that Clarizia’s. The Cyclone Global Navigation Satellite System denoted as CYGNSS was launched in December 2016, is a multi-satellite constellation, can provide rapidly updated information of sea surface up to several minutes (Lang et al., 2017). There are also multiple space-borne missions such PARIS, GEROS, and 3CAT-s that are currently in the planning phases, which will extend the availability of GNSS-R measurements.

Figure 1.2 The schematics of ground-based GNSS-R altimetry reflectometry. Credit: Google Earth provides the background, the satellite images are from NASA, and the GNSS receiver figures are from UNAVCO.
For the ground-based GNSS-R altimetry, Larson et al. (2013) first presented a method based on multipath theory that estimate local sea level variations from a single geodetic GPS receiver. Three months of signal-to-noise ratio (SNR) data from two test sites were employed, one of which is from the GPS station at Onsala Space Observatory (OSO) in Sweden; another is from the Friday Harbor GPS site in the USA. The validations of the methodology were conducted by a nearby tide gauge and a collocated tide gauge, respectively. However, the parameter of elevation range was selected improperly, and the result of ~5 cm RMS residual for OSO station was unconvincing. Afterward, Larson et al. (2013b) analyzed one-year period data from an existing geodetic quality GPS receiver near Kachemak Bay at Alaska. The daily-sampling sea level height was compared with the closest conventional tide gauge operating in Seldovia, and the result of 2.3 cm RMS residual can ensure that GPS instrument can measure long-term sea-level changes reliably. Löfgren et al. (2014) further developed this technique by analyzing GPS data from five sites all around the world, which are OSO (Sweden), Friday Harbor (USA), O’Higgins (Antarctica), Burnie (Australia), and Brest (France). Since the multipath environments and tidal features are various, the RMS residuals are from 6.2 cm to 43 cm. Löfgren et al. (2014) used the GLONASS to verify the SNR technique. In this study, the sea level results from SNR technique were compared with the sea level results from phase delay technique. The comparison showed that the phase delay method was better than SNR technique in conditions of low sea surface roughness, and the SNR technique performed better in the state of high sea surface roughness inversely. Strandberg et al. (2016) proposed a new method based on B-spline representation for sea level height retrieval by a single geodetic-quality GPS receiver. As the results show, this method can increase the precision of sea level
results notably, but the only four-day time span of time series was not persuasive.

1.2 Study Objectives

For the purpose of improving the accuracy of ground-based GNSS-R altimetry, the electromagnetic (EM) bias that results in underestimation of sea levels will be modeled by both of numerical simulation and realistic GNSS observation. In the simulation, the Pierson-Moskowitz and Choppy wave methods will be used for linear and nonlinear realizations, and the EM bias can be defined as the difference between the linear pulse return and the nonlinear pulse return. In the realistic calculation, two GPS sites with collocated tide gauge and anemometer observation, located in the Gulf of Mexico, will be selected to conduct the empirical EM bias model. In the end, both of simulated and empirical EM bias models will be applied to GNSS-R sea levels for comparison.

For the objective of comprehensively assessing the accuracy of the in situ GNSS-R sea levels, two adjacent geodetic-quality GPS sites at Robinson Point, and the closest tide gauge at Tacoma, Washington, will be used for validation study. The consistency between two 8-year GNSS-R sea level time series and the consistency between either of the GNSS-R sea level and tide gauge time series will be investigated. Then, he tidal harmonic analysis will be performed for further estimation.

A novel method for lake ice thickness retrieval will be proposed, which is mainly based on a combination of a single geodetic quality GNSS receiver and a collocated tide water level lake gauge. For the validation, a 12-year lake ice thickness time series at Harbor Beach on Lake Huron will be calculated, and its reliability will be validated by coverage product.
1.3 Dissertation Structure

This research focused on the refinement of the data processing of ground-based GNSS-R altimetry to retrieve sea level, lake level, and innovative method to retrieval lake ice thickness change.

Chapter 1 described the scientific rationale of studying ground-based GNSS-R retrieval of sea level to complement contemporary sea level measurement techniques, coastal and island tide gauges, and satellite radar altimetry. A concise review of GNSS-R or altimetry sea level was conducted, including previous studies of GNSS-R altimetry using spaceborne platform and ground-based GNSS sites. A list of scientific objectives of the research is presented, followed by the structure of this dissertation.

Chapter 2 provided a description of the GNSS reflectometry theory, particularly the signals reflected off the sea surface and ice surface. For the objective of analyzing and understanding reflected GNSS signals, it is essential to investigate what is the divergence between direct and reflected signals. First, the properties of electromagnetic wave propagation were illustrated by the polarization and Fresnel reflection coefficients. Then the footprint size of reflected signal by the approximation of first Fresnel zone was described as a function of different satellite elevation angles. Finally, the concept on how to derive reflected heights from multipath signals was described, and the numerical simulation was conducted for validation.

The GNSS signal is an electromagnetic (EM) wave, and its reflected signals are influenced by the non-symmetric property of ocean wave that result in the underestimation of sea surface height. For the purpose of assessing the EM bias, a theoretical EM bias model was described in Chapter 3, and the results showed that EM bias increases with decreasing incidence angle and increasing wind speed. Through the
validation by two GPS stations located in the Gulf of Mexico, and the derivation of an empirical EM bias model, we proved that the accuracy of ground-based GNSS reflectometry retrieved sea level could be effectively improved by accounting for EM bias.

In Chapter 4, two neighboring GPS stations located at Robinson Point, Washington State, and an adjacent tide gauge 13 km away, were utilized to conduct a comprehensive analysis on the accuracy of SNR technique to retrieve 8-year sea level time series. We then conducted ocean tide modeling using both the tide gauge and the two GNSS-R sea level time series.

A new application of ground-based GNSS-R altimetry was presented in Chapter 5. Data from a single geodetic-quality GPS receiver, and a collocated water level gauge were used to determine lake ice thickness offshore at Harbor Beach, Lake Huron, the Great Lakes. The GNSS-R retrieved lake ice thickness was qualitatively compared with lake ice coverage or extent data product from remote sensing.

Finally, Chapter 6 summarized the conclusions of this dissertation and proposed some ideas for future work.
Chapter 2: The Reflected GNSS Signals

The GNSS antenna is designed to receive the direct signals from satellites, and to suppress unwanted reflected signals from the surrounding of the GNSS stations. Nevertheless, a portion of the reflected signals, known as multipath, is always capable of reaching the antenna, and interfering with the received direct signals. As one of the primary error sources, multipath results in the degradation of GNSS observations, there are many studies on how to alleviate the multipath effects (e.g., Getrgiadou et al., 1988; Park et al., 2004; Bilich et al., 2008). However, the reflected signals are signals of opportunity, contain useful information of reflecting surfaces and worthy to be exploited. Martin-Neira (1993) first introduced the concept of measuring sea level using GNSS reflected signal. Garrison et al. (1998) and Katzberg et al. (1999) used the GNSS reflected signals to measure ocean surface roughness and wind speed detections. Larson et al. (2008, 2009, 2013) derived the soil moisture, snow depth and sea level height using a signal geodetic-quality GPS receiver. Clarizia et al. (2016) demonstrated sea level height estimations from the first spaceborne GPS reflectometry using data from TDS-1. To better utilize and to understand the GNSS reflections, it is essential to study the properties of reflected signals.
This Chapter gave a general introduction of the GNSS reflections, particularly the signals reflected off the sea surface, lake surface, and ice surface. The polarization and the Fresnel reflection coefficients were first presented, to investigate the difference between direct and reflected signals. Then the footprint size of reflected signal was calculated as a function of different incidence angles. The principle on reflectometry height using the signal-to-noise ratio (SNR) approach is then derived, followed by a validation using numerical simulation.

### 2.1 Signal Polarization

GPS signal is an electromagnetic wave consists of electrical and magnetic fields, and its polarization can be used to describe the electric and magnetic field propagation in space (Rees, 2013). The polarization of the radar signal is defined by the direction of the electric field vector. If the electric field vector is perpendicular to the direction of transmission, it is called vertical polarization, and if the vector is parallel to the direction of transmission, it is called horizontal polarization. The Fresnel reflection coefficients for horizontal ($\Gamma_H$) and vertical ($\Gamma_V$) polarization can be expressed as follows,

\[
\Gamma_H = \frac{(\sin \theta - \sqrt{\eta - \cos^2 \theta})/(\sin \theta + \sqrt{\eta - \cos^2 \theta})}{(2.1)}
\]

\[
\Gamma_V = \frac{(\eta \sin \theta - \sqrt{\eta - \cos^2 \theta})/(\eta \sin \theta + \sqrt{\eta - \cos^2 \theta})}{(2.2)}
\]

Where, $\theta$ is the satellite elevation angle (incidence angle) and $\eta$ is the complex dielectric constant. The complex dielectric constant is a function of relative permittivity $\eta_r$, reflecting medium conductivity $\sigma$, and wavelength $\lambda$. It can be expressed as,

\[
\eta = \eta_r - j60\lambda \sigma \quad (2.3)
\]

For convenience, the above linear reflection coefficients are transformed to circular reflection coefficients due to the circularly polarized GNSS satellite signals. The co-
polarized component $\Gamma_O$ and cross-polarized component $\Gamma_X$ are as follow,

$$\Gamma_O = (\Gamma_H + \Gamma_V)/2 \quad (2.4)$$

$$\Gamma_X = (\Gamma_H - \Gamma_V)/2 \quad (2.5)$$

A numerical simulation of relative magnitude and phase of circular reflection coefficients was conducted for the reflection surface of sea water and ice.

![Graph](image)

**Figure 2.1** The magnitude of the circular Fresnel reflection coefficients for sea water and ice surface.

When the GPS $L_1$ frequency is considered, the values of the relative permittivity are 70 and 5 and the conductivity are $3 \ S \ m^{-1}$ and $10^{-3} \ S \ m^{-1}$ (ITU, 1992). As shown in Figure 2.1, the cross-polarized component increases with the increasing incidence angle, whereas the co-polarized component decreases with increasing
incidence angle. Since the transmitted signals from GNSS satellites are Right-Hand Circular Polarized (RHCP), the co-polarized and cross-polarized components can be viewed as RHCP and Left-Hand Circular Polarized (LHCP) (e.g. Löfgren, 2014; Rees, 2003). For the elevation angles below the Brewster angle, which has equal magnitudes of co-polarized and cross-polarized components, the dominating signal component is the RHCP. Conversely, the LHCP dominate the signals with the elevation angle larger than the Brewster angles. For most of the GNSS instrument installed with RHCP antenna, the GNSS reflected signals were recorded at low elevation angles.

### 2.2 Reflection Zone

All the reflections from the illuminating area toward GNSS receiver contribute to the total reflected signals. To access the reflection zone, known as footprint size in Altimetry, the specular reflection is considered. Under this assumption, the first Fresnel zone can approximate the reflection zone (Löfgren et al., 2014). The semi-major axis $a$ and the semi-minor axis $b$ of the first Fresnel zone can be calculated as,

$$a = \sqrt{\lambda h \sin \theta / \sin^2 \theta} \quad (2.6)$$

$$b = \sqrt{\lambda h \sin \theta / \sin \theta} \quad (2.7)$$

Where $h$ is the height of antenna over reflection zone.
From the equation, the reflection zone increases with antenna height increasing or signal wavelength increasing. For GPS $L_1$ band, Figure 2.2 illustrates the size of the first Fresnel zone for different satellite elevations with antenna heights of 5, 10 and 15 m, respectively. It shows that the lower elevation angle corresponds to the larger reflection zone, and the higher elevation angle corresponds to smaller reflection zone.

### 2.3 The SNR Method

For the GNSS-R altimetry, the observation is a combination of direct signals and reflected signals. Figure 2.3 shows the schematic drawing of a GPS antenna affected
by multipath from the sea surface. The sea surface is assumed to be a homogeneous plane, which means only specular reflection occurs. Compared with antenna height over reflective surface, the GNSS satellites have infinite altitude. Thus, the incidence angles $\theta$ of direct and reflected signals are assumed to be identical.

Figure 2.3 The schematics of SNR technique with the assumption of the homogeneous flat reflecting sea surface. The antenna directly receives the GNSS signals from the satellite. Additionally, a portion of satellites signals are reflected off the sea surface, and then reaches the antenna. The direct signals interfering with the reflected signals result in distorted GNSS observations.
By the geometry of multipath concept, the length of additional path can be written as a function of reflector height and incidence angle,

\[ \Delta \rho = \Delta t c = 2h \sin \theta \]  

(2.8)

Where, \( \Delta t \) is the time delay, \( c \) is the speed of light. Multiplying both sides of equation by \( 2\pi/\lambda \), we have,

\[ \Delta \varphi = 2\pi \Delta tc / \lambda = 4\pi h \sin \theta / \lambda \]  

(2.9)

Where, \( \Delta \varphi \) is the phase delay. The phase delay between the direct and the reflected signals changes with the incidence angle changing,

\[ d\Delta \varphi / dt = 4\pi h \cos \theta d\theta / (\lambda dt) \]  

(2.10)

Where, \( d\theta / dt \) is the changing rate of incidence angle. When the substitute of \( x = \sin \theta \) is applied to the above equation, we have the following expression,

\[ d\Delta \varphi / dx = d\Delta \varphi dt / dxdt = d\Delta \varphi dt / \cos \theta d\theta dt = 4\pi h / \lambda \]  

(2.11)

This interference pattern is visible as oscillation in the SNR data that offers an opportunity to derive the reflector height between antenna and the reflective surface (Larson et al., 2013). As another characteristic of SNR data, the overall trend is primarily controlled by the antenna pattern. Usually, a low-order polynomial is used as background model to remove the overall trend. The remaining SNR signal that comprises the multipath oscillations can be expressed by,

\[ dSNR = A \cos(2\pi f \sin \theta + \omega) = A \cos(4\pi h \sin \theta / \lambda + \omega) \]  

(2.12)

Where, \( A \) is the amplitude that decreases with incidence angle increasing, \( f \) is the frequency of the oscillations, and \( \omega \) is the phase offset. When the SNR data is observed, the frequency can be estimated by spectral analysis. Then the reflector height between antenna and reflective surface is,

\[ h = \lambda f / 2 \]  

(2.13)
2.4 The Numerical Simulation

The signal power varies depending on the type of reflecting surface and the incidence angle. Higher reflective surface can reflect higher number of signals, while a more transparent surface permits a portion of signals to pass through, and leaves less signals to be reflected. The bistatic radar equation (BRE) (Skolnik, 1970) is,

\[ P_r = P_t G_t G_r \lambda^2 \sigma / (64\pi^3 R_t^2 R_r^2) \]  
(2.14)

Where,

- \( P_r \) and \( P_t \) are the received and transmitted power;
- \( G_t \) and \( G_r \) are the transmitting and receiving antenna gains;
- \( R_t \) is the distance between transmitter and specular point;
- \( R_r \) is the distance between specular point and receiver;
- \( \sigma \) is the radar cross section (RCS) which can be expressed as follows,

\[ \rho_s = e^{-(4\pi\sin\theta/\lambda)^2/4} \Gamma_0 \]  
(2.15)

From the above equation, the received signal power can be easily determined. In the realistic observations, the transmitted power, wavelength, and two antennas gain patterns that have been configured. Thus, the received power varies on the RCS, and the distance between the transmitter, specular point, and receivers.

The thermal noise that has a constant power spectral density is a function of the temperature and the noise bandwidth, and can be expresses as,

\[ P_n = kT = 4.0\times10^{-21}(W/Hz) = -204dBW/Hz \]  
(2.16)

Where, \( k \) is Boltzmann’s constant \((1.38\times10^{-23}J/K)\) and \( T \) (290 K in general) is the absolute temperature.

Therefore, the signal-to-noise ratio (SNR) is,

\[ P_{snr} = P_r - P_n / P_n \]  
(2.17)
For convenience, an open source code of GPS multipath simulator was used to generate the SNR time series (Nieviski et al., 2014), and some parameters were tabulated in Table 2.1. For the objective of straight illustration, only the GPS $L_1$ band was considered for the sea water and ice reflecting surface.

Table 2.1 Parameters in the numerical simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>GPS $L_1$</td>
</tr>
<tr>
<td>Antenna Model</td>
<td>TRM29659.00</td>
</tr>
<tr>
<td>Modulation Code</td>
<td>C/A</td>
</tr>
<tr>
<td>Top Material</td>
<td>air</td>
</tr>
<tr>
<td>Bottom Material</td>
<td>sea water/ice</td>
</tr>
<tr>
<td>Reflector Height</td>
<td>5 m</td>
</tr>
<tr>
<td>Surface Roughness</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 2.3 shows the simulated SNR time series mainly has two characteristics: the oscillations and the overall trend. The former is caused by the interference pattern of direct and reflected signals; the latter is primarily controlled by the antenna gain pattern, which reduces the amplitude of direct signal at lower elevation angles. After applying a two-order polynomial, the overall trend was removed to obtain the de-trended SNR time series in Figure 2.4. As Figure 2.3 and Figure 2.4 show, the magnitude of SNR for ice surface is larger than the magnitude of SNR for sea water surface at low elevation.
angle due to the co-polarized component of the Fresnel reflection.

Figure 2.3 The simulated SNR for sea water and ice surface.
To estimate the dominant multipath frequency in the detrend SNR time series, the Lomb Scargle Periodogram (LSP) was used for spectral analysis. The advantage of the LSP to Fast Fourier Transform is that the detrend SNR time series can be unevenly sampled as a function of the sine of the elevation angle. The spectral analysis used an oversampling factor of 40, which corresponded to a precision of 4 mm. From Equation (2.13), the estimated antenna reflector height over sea water and ice surfaces are 5.007 m and 5.006 m. Compared with reflector height in Table 2.1, we can conclude that the SNR technique is theoretically able to determine the antenna reflector height within the accuracy of 1 cm.
2.5 Conclusions

For the purpose of investigating the properties of the reflected GNSS signals, the co-polarized component and cross-polarized component Fresnel reflection coefficients were computed. When the GPS $L_1$ frequency is considered, the cross-polarized component (LHCP) increases with increasing incidence angle, whereas the co-polarized component (RHCP) decreases with increasing incidence angle. Hence, the reflected signals recorded by receivers are stronger at low incidence angles. To access the reflection zone, the first Fresnel zone was calculated. It showed that the lower elevation angle corresponds to larger reflection zone. After introducing the concept of how to derive the antenna reflector height by SNR data, a numerical simulation was conducted to verify that the SNR method can theoretically determine the antenna
reflector height within the accuracy of 1 cm. In the realistic data processing, the GNSS receiver can record several SNR time series from different satellites at the same time. Thus, the accuracy of derived sea level height can be effectively improved by averaging or using a smoothing window.
Chapter 3: The Electromagnetic Bias Estimation

The reflected GNSS signals not only consist of useful information about the Earth’s surface, such as the sea surface roughness (Garrison et al., 1998), wind speed (Katzberg et al., 1999), soil moisture (Larson et al., 2008), and snow depth (Larson et al., 2009; 2013), but also comprise of thermal noise, media delays and other errors. To understand the GNSS reflected signals, it is essential to quantify these error sources. For the ground-based GNSS-R altimetry, there are several studies on the error analysis and on how to improve the measurements. When the reflecting sea surface is nonstationary, the dominating frequency of SNR time series will be biased. Larson et al. (2013; 2017) concluded that this bias is a function of reflector height and elevation angles, and can be corrected by considering the height variation rate during the sea level analysis. Since the SNR frequency decreases with rising sea surface and decreases with declining sea surface, Santamaría-Gómez et al. (2015) proposed an approach based on inverse Doppler-like effects to improve the accuracy of sea level measurements. From eight case studies, the resultes showed that the new approach worked well. In the experiments, an elevation dependent error below 12° was found and was possibly derived from sea surface roughness or tropospheric refraction. Strandberg et al. (2016) presented a B-spline model that accounts for temporal sea level changes. The verifications were conducted over two GNSS sites, and the results showed that the accuracy was 1.4 cm at Onsala, Sweden and 3.1 cm at Spring Bay, Tasmania, respectively.
The electromagnetic (EM) bias originates from the non-symmetric property of sea wave that is significant in sea level measurement by the remote sensing technique. Because the sea wave crests are sharper than sea wave troughs, more electromagnetic signals are reflected from wave troughs than crests that result in the underestimation of sea level height (Park et al., 2016). For the monostatic satellite altimetry that measures sea surface backscatters in a nadir-looking configuration, the EM bias has been studied extensively (Elfouhaily et al., 2000; Arnold et al., 2012; Elfouhaily et al., 2001; Naenna et al., 2010). In brief, there are two methods of the weakly nonlinear (WNL) theory and the modulation transfer function (MTF) model. Jackson et al. (1979) applied the WNL theory to one-dimension sea surface at near-vertical incidence angles. Later, Srokosz et al. (1986) and Glazman et al. (1996) applied the WNL theory for a two-dimension sea surface to estimate the EM bias, but it was only appropriate for long waves. To overcome these limitations, Elfouhaily et al. (1999; 2000) proposed a modified WNL theory to access the EM bias, which was capable of accounting for short and long waves. Then, an analytical MTF model was introduced based on the on the two-dimension hydrodynamic modulations to investigate the EM bias (Elfouhaily et al., 2001). Recently, Millet et al. (2005, 2006) used a combination of the WNL and MTF models to estimate the EM bias for small off-nadir incidence angles.

However, the conclusions from these previous studies cannot be applied to the bistatic GNSS-R altimetry. Compared to monostatic satellite altimetry, the GNSS-R altimetry operates in different wave frequencies and has a larger range of incidence angles. For the space-borne GNSS-R altimetry, Picardi et al. (1998) provided an analysis of the EM Bias in a bistatic geometry but include only the surface height skewness effect without considering the correlation of surface height and slope.
Ghavidel et al. (2015; 2016) conducted the numerical computations of EM bias for GNSS-R altimetry by the combining WNL and TFM models, and the results showed the EM bias was a function of frequency, wind speed, and incident angles. Park et al. (2016) presented a simulation of the EM bias using two linear and nonlinear models, and it was concluded that the EM bias was roughly a cosine function of the incident angles.

This chapter focuses on the estimation of EM bias for ground-based GNSS-R altimetry, which was the first study to conduct empirical EM bias modeling using real data. The structure of this Chapter is as follows: the EM bias was first computed using numerical or theoretical simulations. In the simulation, a time-dependent linear sea surface was created using the Pierson-Moskowitz spectra, and the corresponding nonlinear sea surface was generated by the Choppy wave model. After the computation of pulse returns, the EM bias can be defined as the difference between the linear pulse return and the nonlinear pulse return (Park et al., 2016). For the objective of performing an empirical EM bias calculation, two GPS stations with collocated tide gauge and anemometer data and located in the Gulf of Mexico were selected to conduct the study.

3.1 The EM Bias Simulation

Figure 3.1 demonstrated the primary simulation procedures, in which the cool (green to blue) tones represent the linear processes, and the warm (pink to red) tones are nonlinear processes. In the first step, a set of linear sea surface was generated and went through a hydrodynamic transformation to obtain the corresponding nonlinear sea surface realizations. Then, the pulse returned from both linear and nonlinear sea
surfaces were achieved by the bistatic geometry of GNSS-R altimetry. Finally, the EM bias was estimated by comparing the averaged linear and nonlinear surface pulse returns.

Figure 3.1 The flowchart of EM Bias Simulation. The cool tones represent the linear processes and the warm tones are nonlinear processes.

3.11 Sea Surface

For the linear sea surfaces, the Pierson-Moskowitz spectrum was used as an initial model that was expected to have no differences in surface properties in the wave and trough portions of the surface, and therefore produce no EM bias (Pierson et al., 1964; Mobley et al., 2014). The essential process of sea surface realization is as follows,

a. Choose the domain size to generate a time series at given point $x$, and the
number of points for the Fast Fourier Transforms (FFT);

b. Choose the variance spectrum. The omnidirectional Pierson-Moskowitz one-sided spectrum is,

\[ S_{1S}(k) = S_{PM}(k) = \frac{\alpha}{2k^3} \exp \left[ -\beta \left( \frac{\hat{a}}{k} \right)^2 \frac{1}{1.026\hat{u}_{10}} \right] \quad [m^2/(\text{rad}/\text{m})] \quad (3.1) \]

Where,
\[ \alpha = 0.0081; \]
\[ \beta = 0.74; \]
\[ g = 9.82 \text{ m s}^{-2} \text{ is the acceleration of gravity;} \]
\[ U_{10} \text{ is the wind speed in m s}^{-1} \text{ at 10 m above the sea surface;} \]
\[ k \text{ is the angular spatial frequency in rad m}^{-1}. \]

c. Create random Hermitian Fourier amplitudes for both positive and negative frequencies;

\[ \hat{z}(k) = \frac{1}{\sqrt{2}} \left[ \hat{z}_0(k) + \hat{z}_0^*(-k) \right] \quad (3.2) \]

Where,
\[ \hat{z}_0(k) = \frac{1}{\sqrt{2}} \left[ \rho_k + i\sigma_k \right] \sqrt{S_{2S}(k)}; \]
\[ \rho_k \text{ and } \sigma_k \text{ are independent random numbers drawn from a normal distribution with zero mean and unit variance, denoted } \rho, \sigma \sim \mathcal{N}(0,1); \]
\[ S_{2S}(k) \text{ is the corresponding two-sided spectrum of } S_{1S}(k); \]
\[ \hat{z}_0^* \text{ denotes the complex conjugate of } \hat{z}_0; \]

d. Extract the sea surface elevation by the inverse FFT of \( \hat{z}(k) \).

\[ z(\chi) = \text{Re}(\text{FFT}^{-1}\{\hat{z}(k)\}) \quad (3.3) \]

For the nonlinear sea surfaces, the “Choppy wave” model is used for approximating nonlinear hydrodynamic effects. The choppy wave method is based on a non-uniform
horizontal displacement of the original linear surface. For one realization, the choppy wave transformation from the linear surface creates a nonlinear surface (Nouguier et al., 2009) which can be expressed as follows,

\[(x, z(x)) \rightarrow (x + D(x), z(x))\] (3.4)

Where, \(D(x, t)\) is the Hilbert transformation of the surface elevation.

Figure 3.2 illustrates the linear and nonlinear realizations of an example profile. In this example, a 20 m s\(^{-1}\) wind speed was used with a 200-m surface profile. For two thousand data numbers, the two-point wavelength or Nyquist wavelength was 2 cm. Because the choppy wave transformation can modify the spectrum of the original linear surface, a spectrum “undressing” procedure was required to ensure that the linear and nonlinear sea surfaces retain the same spectral properties (Nouguier et al., 2009).
Figure 3.2 Example of linear and nonlinear sea surface generation. The wind speed of 20 m s\(^{-1}\) was used for the Pierson-Moskowitz spectrum. The upper-right panel shows the original variance spectrum, and the upper-left panel shows the recovery of the variance spectrum from the generated sea surface.

3.12 Pulse Return

Figure 3.3 illustrates the geometry of the bistatic configuration in which a GNSS-R transmitter illuminates a sea surface facet.
Figure 3.3 the geometry of the bistatic GNSS-R configuration.

With the generated sea surface, the pulse returns of the GNSS receiver in the time domain can be expressed as (Park et al, 2016),

\[
v_2 = C \int_{-\infty}^{\infty} \int_S W(\omega) \frac{e^{ikl(R_t+R_r)/\sqrt{R_tR_r}}}{\sqrt{R_tR_r}} \cdot \frac{z-H_r-(\partial z/\partial x)(x-x_r)}{R_r} e^{-i\omega ds d\omega} \tag{3.5}
\]

Where,

- \( C \) is a constant, and the unit value is used for computation convenience;
- \( G_t(\theta_t) \) and \( G_r(\theta_r) \) are Gaussian approximations of the antenna gain patterns for the transmitter and receiver, respectively;
- \( R_t \) and \( R_r \) are the distance between GPS transmitters and specular points, respectively;
- \( k_l \) is the angular wavenumber;
- \( H_r \) is the antenna height of GPS receiver relative to sea surface;
- \( X_r \) is the horizontal distance between specular point and GPS receiver;
\( \omega \) is the frequency;

\( W(\omega) \) is a Gaussian window function that determines the waveform shape, center frequency, and bandwidth.

The average of the returned power can be computed for a large number of surface realizations,

\[
P = \langle v_2^* v_2 \rangle / (8 R_{rad})
\]

(3.6)

Where, \( R_{rad} \) is the antenna radiation resistance, and the unit value is used for computation convenience; \( v_2^* \) is the complex conjugate of \( v_2 \).

### 3.13 Results

The EM bias results from the offset between the means of the true surface height and the specular surface height. The EM bias can be defined as the difference between the normalized first moments of the linear pulse return \( P_L(t) \) and the nonlinear pulse returns \( P_{NL}(t) \) (Naenna et al., 2010),

\[
\beta_{EM} = \frac{c}{2} \left( \frac{\int t P_{NL}(t) dt}{\int P_{NL}(t) dt} - \frac{\int t P_L(t) dt}{\int P_L(t) dt} \right)
\]

(3.7)

With the ensemble, averaged pulse returns for the two cases were obtained as described in the previous section. Because the difference between these waveforms can be small, a large number of surface realizations are necessary. The computation utilized L1 band of 1.575 GHz with a bandwidth of 24 MHz. Figure 3.4 plotted the simulated EM bias as a function of the incident angle and wind speed. Simulations with 100,000 linear and nonlinear surface realizations were performed for each geometry. The property of EM bias can be concluded that the absolute EM bias increases with the decreasing incidence angle and increasing wind speed.
Figure 3.4 the simulated EM bias for GPS L1 band with a constant antenna height of 10 m. The absolute EM bias increase with the decreasing incidence angle and increasing wind speed.

3.2 The Empirical EM Bias Estimation

On purpose of performing an empirical modeling of the L-band GNSS-R forward scattering electromagnetic bias, two GPS sites located in the Gulf of Mexico were selected as the case study as shown in Figure 3.5. These two GPS stations are collocated with a tide gauge and an anemometer, respectively, that measure sea level and wind speed. These two stations were also installed on the offshore platforms that have open views of the ocean without obstacles. Therefore, these two GPS sites provided the perfect configurations to conduct the EM Bias modeling experiment.
3.21 Station Installation

The Continuously Operating Reference Station (CORS) network, operated by NOAA’s National Geodetic Survey (NGS), offers an open source to access the GNSS data. The Calcasieu Pass GPS site is known as “CALC” is located at Cameron of Los Angeles, which was originally installed in April of 2013. At that time, it operated a Trimble NetRS receiver, a geodetic-quality dual-frequency carrier phase GPS receiver. In October of 2014, Trimble NetRS was replaced with a newer Trimble model, the NetR9 receiver that can receive both of the GPS and GLONASS signals. The Shell Beach GPS sites are known as “SBCH” is located at New Orleans. It was installed in
March of 2012 with NetRS receiver, and was replaced with Trimble NetR9 receiver in October of 2014. Both of their antennas have 15-s sampling rate that could generate the observation every 15 s for geodetic users. As shown in the photograph (Fig. 3.5b and 3.5c), the two stations were installed on the offshore platforms that have an open view of the water. Thus, the received multipath signals are reflected from the sea surface. The platforms were drilled into bed rock so that the position estimated from the GPS data would be “anchored.” The GPS antenna is ~12 m and ~15 m above the mean sea surface. Both of their antennas are attached to the NOAA Tide Gauge Sentinel, so the sea surface gradient and the vertical motion could be regardless in the sea surface comparison.

The Center for Operational Oceanographic Products and Services (CO-OPS), also maintained by the U.S. National Oceanic and Atmospheric Administration (NOAA) provides access to the tide gauge and wind speed data for the Calcasieu Pass and the Shell Beach stations. Digital tide gauge data at 6-minute sampling are available, each 6-minute observation represents an average of 181 one-second measurements, with additional filtering imposed by the gauge’s protective well. The anemometers are 12.25 m, and 15.58 m above mean sea surface at two GPS sites respectively, which can also provide 6-minute observations. These two collocated pattern GPS sites with high-quality observations are more than adequate for our experiments.

3.22 Data Processing

This Chapter aims at evaluating the EM bias; a concise data processing that is present based on the principle of SNR method. A detailed data processing will be introduced in the next chapter with some comments. For processing the SNR data, the
broadcast ephemerides were used to calculate the satellite angles at each station. The azimuth and elevation masks were created to make sure that the reflected signals are totally from the sea surface. After detrending, the dSNR arcs for each station were then analyzed using the Lomb Scargle Periodograms (LSP) with an oversampling factor of 40 (resulting in a precision of 4 mm). The highest spectral power in searching window corresponds to the reflector height. In the end, the reflector heights were converted into sea level heights, and time labels for each sea level heights were calculated from the mean time of the corresponding satellite arc.

The study mainly focuses on the contribution of SNR technique to the historic dataset. Here, the L1 signal of GPS was selected with considering its quality and availability. L1 and L2 are the two most widely used frequency bands, the period of observation for one group-based station is possibly more than 20 years long. Compared with the results from L1 signals, the sea level results from L2 SNR data are much noisier (Löfgren et al. 2015). The SNR data from L5 is better than L1 and L2, but it is only available from 2009 (Force et al., 2011). Nevertheless, assimilating other different GNSS observations such as GLONASS, Galileo, Beidou and different frequencies such as L1, L2C, L5 can increase the temporal resolution and the spatial resolution of the sea level time series, it is not capable of improving the accuracy of sea level results (Löfgren et al. 2015; Strandberg et al. 2016). The hourly sea level result from L1 SNR data was adequate for our study, thus only the GPS L1 signal was chosen here.

### 3.23 Results

The approach described in the last section has been implemented using L1 GPS observations at the Calcasieu Pass site. An elevation mask of 2.5°–40° was used because
there was no significant SNR oscillation at higher elevation angles. The range of azimuth angles was from 40° to 320° that ensured the GPS receiver could capture the reflected signal from sea surface without obstacles. For the objective of investigating the EM bias, the one-year time series of sea level height for 2015 was calculated. For the demonstration, a one-week subset was selected that showed the GPS-derived sea levels were highly correlated with tide gauge sea levels (Figure 3.6). Since the GPS receiver can receive the signals from more than four satellites at the same time, there were about 1-3 sea level observations per hour based on the data process in the last section.

![Figure 3.6](image)

Figure 3.6 One-week sea level time series of 2015 for demonstration purpose. There are about 1-3 sea level observations per hour.
For the direct comparison and classification, the sampling rates of sea levels with wind speed observation were resampled to one hour. This procedure guaranteed that all of the observations were in the same time tags. Figure 3.7 showed the wind speed observations in January of 2015, its maximum was less than 16 m s\(^{-1}\). Since the number of observations larger than 10 m s\(^{-1}\) was inadequate, the range of wind speed from 0 m s\(^{-1}\) to 10 m s\(^{-1}\) was chosen for the EM bias computation. As the wave propagates towards the coastline, as the wind speed, the wind direction can straight affect the wave shape. However, it was out of the scope of this study, and the wind direction will be considered in future investigations.

Figure 3.7 the wind speed observations in January of 2015 from NOAA. The sampling rate was resampled from 6-minute to 3-hour for illustration purpose.
When the tide gauge records were taken as “ground truth,” the GPS-derived sea level height residual can be calculated. Figure 3.8 showed the sea level residuals with specular point distributions, which were classified by different wind speeds. There were about eight thousand GPS-derived sea level observations for the whole year of 2015, the number of specular points varied from 400 to 1200 for each particular weed speed. For clearer illustration, the median value of sea level residuals in a 3-hour window was used in plotting. The bin of 1 m s\(^{-1}\) was used to divide the wind speeds into different categories, the sea level residuals with the same time tags of specific wind speed were assigned in the same category. The sea levels residuals with wind speeds from 1 m s\(^{-1}\) to 8 m s\(^{-1}\) were plotted in Figure 3.8. Overall, the absolute sea level residuals increased with increasing wind speeds. For the central specular points, there were no variations with changing wind speeds. On the contrary, the largest rate of sea level residual change occurred on the peripheral specular points. The coordinate of the specular point was a function of azimuth and elevation angle with a constant antenna height. When the elevation angle was larger, the specular points were closer to the antenna marked by the largest white point in Figure 3.8. As each subplot showed that the absolute sea level residuals were not impacted by azimuth but increased with decreasing elevation angles. The same approach also has been implemented at the Shell Beach site. A dual-azimuth masks of 30°–120° and 210°–330° were used to avoid the jetted piles in Figure 3.5c. From Figure 3.9, the characteristic of sea level residuals agreed with the simulated EM bias properties. That is, EM bias increases with the decreasing incidence angle and increasing wind speed.
Figure 3.8 The specular point distribution with sea level height residuals at the Calcasieu Pass site. The largest white point represents the GPS station, and the unit of color-bar is cm. The range of the wind speeds was from 1 m s$^{-1}$ to 8 m s$^{-1}$.
Figure 3.9 The specular point distribution at the Shell Beach station. The sea level residuals were classified by the wind speeds from $1 \text{ m s}^{-1}$ to $8 \text{ m s}^{-1}$. The masks of elevation and azimuth angles were set to be $30^\circ$–$120^\circ$ and $210^\circ$–$330^\circ$ to avoid the jetted piles.
In this study, all the sea level residuals were assumed to be caused by EM bias. Thus, the least squares estimation can be employed to model the EM bias empirically using the sea level observations. When we have adequate GPS-derived sea level and tide gauge observations, the overdetermined equation can be written as follows,

\[ h_{i}^{\text{gnss}} - \sum_{j=1}^{n} X_{ij} \beta_i = h_{i}^{\text{tg}} \quad (i = 1, 2, 3 ... m) \]  

(3.8)

Where,

- \( m > n \),
- \( i \) represents the elevation angle,
- \( m \) represents the equation number,
- \( X_{ij} \) is coefficient matrix,
- \( \beta_i \) is elevation dependent EM bias,
- \( h_{i}^{\text{gnss}} \) is the GNSS-derived sea level height,
- \( h_{i}^{\text{tg}} \) is the tide gauge observation.

When the \( X^TX \) is nonsingular, \( \beta \) has the unique solution,

\[ \hat{\beta} = (X^TX)^{-1}X^T (h^{\text{gnss}} - h^{\text{tg}}) \]  

(3.9)

The results are the empirical EM bias model, shown in Figure 3.10 and Figure 3.11. It seems much nosier than the simulated EM bias model due to limited observations. When the simulated and empirical EM bias models were applied to the original GPS-derived sea levels from the Calcasieu Pass, the RMS error was reduced from 7.27 cm to 4.77 cm, and to 3.42 cm, respectively. For the Shell Beach station, the RMS of difference was reduced from 7.33 cm to 4.84 cm, and to 3.36 cm by simulated and empirical model corrections, respectively. We concluded that both the simulated (theoretical) and the empirical EM bias models significantly improved the accuracy of original GPS-derived sea levels.
Figure 3.10 The empirical EM bias model at the Calcasieu Pass site.

Figure 3.11 The empirical EM bias model at the Shell Beach station.
Figure 3.12 The Electromagnetic Bias Correction. a) one-day example of EM Bias correction for sea level height; b) original sea level height from GPS L1 data; c) corrected sea level height using the simulated (theoretical) EM bias model; d) corrected sea level height using the empirical EM bias model.
3.3 Discussion

In the numerical simulation, the one-dimensional sea surfaces were generated for simplicity from the Pierson-Moskowitz and the Choppy wave models. Considering a steady wind, the Pierson-Moskowitz spectrum can realize the gravity waves in a fully developed sea. Since the data number cannot be infinite, the recovered variance spectrum from the generated sea surface is inconsistent with the original variance spectrum. Therefore, a large number of sea surface realization is necessary for the simulation, particularly at the high wind speed. For the selection of sea surface models. Ghavidel et al. (2016) compared the Pierson–Moskowitz model with Elfouhaily model, it showed that the largest difference of derived EM bias could be 1 cm at the wind speed of 13 m s$^{-1}$ for L-band. Park et al. (2016) assessed the performances of different sea surface models. The results showed that the EM bias from Creamer model was about two times larger than from choppy wave model for L-band. Hence, different sea surface models can lead to different EM bias estimation, the optimized selection of sea surface model will reduce the uncertainties. The first Fresnel zone is used to approximate the illuminating area by reflected GNSS signals, which is an ellipse. Thus, the two-dimensional sea surface models are appropriate than the one-dimensional sea surface models. However, it is computationally challenging to create a large number of two-dimensional sea surface realizations. For example, Kay et al. (2011) spent 6 hours in generating one two-dimensional sea surface with 65,536×65,536 points on a 3 GHz computer.

With the constant antenna height of 10 m, the simulated EM bias increase with the decreasing incidence angle and increasing wind speed. The higher wind speed can drive higher significant wave height. Because of the non-symmetric property of sea waves,
the reflected signals from sea wave crests decrease more rapidly than reflected signals from sea wave troughs with decreasing incidence angles and increasing wind speed. Therefore, the EM bias is directly proportional to the wind speed and inversely proportional to the signal reflectance incidence angles.

In the realistic data processing, the bias caused by antenna vertical phase center offset was estimated by minimizing the residual between selected GPS-derived sea level heights and tide gauge measurements. When the wind speeds were below $2 \text{ m s}^{-1}$ and the incidence angles were larger than $35^\circ$, the EM bias can be considered to be negligible. These thresholds were used to select sea level heights for the bias assessment.

The values of EM bias estimated from realistic data were larger than the simulated EM bias. One reason perhaps was that the Pierson-Moskowitz and the Choppy wave models underestimated the EM bias, and it could be verified by other hydrodynamic models. Another reason may be the empirical model consisted of other elevation dependent errors. Santamaría-Gómez et al. (2015) reported an elevation dependent error below $12^\circ$ that probably originated from the tropospheric refraction. Hobiger et al. (2017) also proposed estimating and modeling the troposphere errors for the GPS station at Onsala, Sweden. Even though the EM bias is the main error source for ground-based GNSS-R, understanding and investigating other error sources could further improve its accuracy.

### 3.4 Conclusions

In the bistatic forward-scattering GNSS-R altimetry, the electromagnetic bias originates from the smaller reflectivity of wave crests than troughs that lead to underestimation of sea level heights. This Chapter first performed a numerical
computation through the linear and nonlinear models to derive a theoretical EM bias model. The simulated or theoretical model showed that the EM bias increases with decreasing incidence angle and increasing wind speed. Two GPS stations with collocated tide gauge and anemometer located in the Gulf of Mexico, were selected to conduct real data analysis. The sea level residuals were calculated between GPS-derived sea level heights and tide gauge measurement, and divided into different values of wind speeds. Under the hypothesis that all the sea residuals were caused by EM bias, the least squares estimation was employed to generate the empirical EM bias models at the Calcasieu Pass and the Shell Beach sites. When the simulated and empirical models were applied to the GPS-derived sea levels, the RMS difference decreased from 7.3 cm to 4.8 cm and to 3.4 cm, respectively. We concluded that both EM bias models improved the accuracy of the GNSS-R derived sea level, with the empirical EM bias model has the best performance. The remaining errors are possibly resulting from tropospheric refraction, other media corrections, or distorted SNR time series, and future study is warranted to further improve the GNSS-R sea level accuracy.
Chapter 4: An 8-Year Comparison of Sea Level Heights

Typically, there are two methods of ground-based GNSS-R altimetry. The one is known as SNR method using one RHCP zenith-looking antenna. The reflected signals off sea surface interfere with direct signals from satellites, and this interference pattern is recorded by the antenna as the oscillation of SNR data. Hence, the SNR data can be employed to derive the reflector height of antenna above the sea surface at low elevation angles. Usually, the sampling rate is 10~60 minutes depends on the GNSS installations. Another one is known as the phase delay method using two collocated antennas. The RHCP zenith-looking antenna that records the direct signals from satellites, and LHCP nadir-looking antenna that captures the reflected signals off the sea surface. As described in Chapter 2, the reflected signal is still RHCP at low elevation angle below the Brewster angle, but the amplitude of LHCP Fresnel reflection coefficients increases with increasing elevation angles. Therefore, the nadir-looking antenna can monitor better quality reflected signals at higher elevation angles. According to the GNSS phase observation equation, the travel paths of direct and reflected signals can be calculated (Blewitt, 1997; Hofmann et al., 2014). Considering the vertical offset between the phase centers of two antennas, the additional travel path can be used to estimate the reflected height to the antenna above the sea surface (Figure 2.3). Compared with the SNR technique, the phase delay method can be up to 1-second sampling rate and better accuracy (Löfgren et al., 2014), but the required nadir-looking antenna is usually unavailable. Instead, the SNR method can be widely applied to historical GNSS stations.
in the coastal region.

The first study on GPS-derived local sea level height using Signal-to-Noise Ratio (SNR) data was first published by Larson et al. (2013a). Three months of data from two test sites, one is from the GPS station at Onsala Space Observatory (OSO) in Sweden; another one is from the Friday Harbor GPS location in the USA. The validations were made by nearby and collocated tide gauge, respectively. However, the difference of 5 cm RMS residual for the OSO station case, may be too good to be true or questionable due to possible data processing deficiency including not addressing height rate effect and elevation dependence, and that the study dealt with only a short data span. Afterwards, Larson et al. (2013b) analyzed one-year of data from an existing geodetic quality GPS receiver near Kachemak Bay, Alaska. The daily-sampling sea level height was compared with the sea level data from the closest tide gauge site operating in Seldovia, and the difference of 2.3 cm RMS residual provide more convincing results that GNSS-R technique could measure long-term coastal sea level. Löfgren et al. (2014) further developed this technique by analyzing GPS data from five sites distributed in different regions of the world, which are OSO (Sweden), Friday Harbor (USA), O’Higgins (Antarctica), Burnie (Australia), and Brest (France). Since the multipath environments and tidal dynamics are different from these regions, the RMS difference between GNSS-R and tide gauges ranges from 6.2 cm to 43.0 cm.

As previous researches have illustrated, the accuracy of GNSS-R SNR technique was estimated by the external conventional tide gauge, but there has not been a study conducted on the internal precision of GNSS-R sea level measurements. In this Chapter, two neighboring, 30 m apart, and a coastal tide gauge 13 km from the GPS sites, were utilized to conduct a comprehensive analysis on the precision and accuracy of GNSS-
R SNR sea level retrieval technique.

4.1 GNSS Stations and Locations

The Robinson Point GPS site is named as “RPT1”, managed by NOAA’s National Geodetic Survey (NGS), is located in the south of Seattle, Washington. It was originally installed in September of 1995 with an ASHTECH Z-XII3 receiver, a dual-frequency geodetic-quality carrier phase GPS receiver. After the upgrades conducted in April of 2008, the 4-character site name was changed to “RPT5”, and it operated until October of 2016. Figures 4.1c & 4.1d show that the GPS antennae were mounted on the top of the watchtowers that have an unobstructed view of the water. Thus, maximum number of multipath signals reflected from the water surface were collected. The bottom of the watchtower was drilled into bedrock so that the station would be “anchored.” Like its neighbor, “RPT2” was also installed in September of 1995 and renamed to be “RPT6”. The “RPT6” is ~38 m away from “RPT5” with the same instrument configuration, which received the same multipath signals reflected from the water surface. The above described characteristics of RPT5 and RPT6 provide us with a unique opportunity to validate the internal precision or repeatability of GNSS-R SNR technique derived sea level measurements.

The closest tide gauge station at Tacoma is ~13 km away from the Robinson Point, which is one of the continuously operating Center for Operational Oceanographic Products and Services (CO-OPS) gauges maintained by the National Oceanic and Atmospheric Administration (NOAA). The data at 6-minute sampling were used in this study, which is more than adequate for the validation purpose.
Figure 4.1 The Robinson Point GPS stations.  a) The Robinson Point GPS sites are located south of Seattle, Washington, with the closest tide gauge located at Tacoma, 13 km south of the GPS sites; b) the two neighboring GPS stations are separated by 38 m from each other and have near-identical views of the ocean surface (background is from Google Earth); c) the antennae are mounted on the top of watchtower, which is 11 m above the ocean surface; d) photographs of GPS sites RPT5 and RPT6, taken by John Fisher in 2009. (Credit: NOAA/NGS GPS images).
4.2 Methodology

In this Section, a detailed data processing flowchart of the SNR method is illustrated in Figure 4.2 that is based on the theory in Chapter 2 and Larson et al. (2013). As described in the previous Chapter, a single geodetic quality GNSS receiver with open view of water can act as a “tide gauge”, except that GNSS-R measurement potentially senses higher frequency sea level signals. Since different reflecting surface such as sea water, snow, and ice can create different interference patterns, one way is to select the data based on the chrematistic of interference patterns. Another simple way is to mask the data by the coordinate of specular points, which is a function of the antenna height above the reflecting surface, the elevation angle of the satellite on the horizon, and the satellite azimuth. The elevation angle and azimuth can be calculated by combining the antenna coordinate and the broadcast ephemerides of GPS satellites. The mask that is created by azimuth and elevation angle is an effective way to ensure that all the reflected signals are completely from the sea surface. The masked SNR data has two main characteristics of oscillations and overall trend. The former one is caused by the interference pattern of direct and reflected signals; the latter one is primarily controlled by the antenna gain pattern, which reduces the amplitude of the direct signal at lower elevation angles. Usually, a low-order polynomial is used as background model to remove the overall trend. The detrended SNR data is dominated by the frequency, that corresponds to the reflector height between antenna and sea surface. Since the observation is not evenly sampled as a function of the sine of the elevation angle, the Lomb Scargle Periodograms (LSP) is used to estimate this dominating frequency. The down-sampling factor of 4 is set to speed up the analysis, and the over-sampling factor is set to be 40 to guarantee the reflector height retrieval precision to ~4 mm. Then the
antenna reflector height can be calculated by the equation (2.13). In the end, the reflector heights were converted into sea level height with the EM bias correction, and time tags for each height were calculated from the mean time of the corresponding satellite arc.

Figure 4.2 The flowchart of data processing for the SNR method
4.3 Comparison

In this section, the internal precision of GNSS-R SNR technique derived sea level measurements is estimated by comparing the sea level retrieved by the two neighboring GPS stations at Robinson Point. Furthermore, the accuracy of SNR technique is investigated by the ground truth of independent tide gauge measurement at Tacoma that is ~13 km far from Robinson Point.

4.3.1 Hourly Sea Level

At the Robinson Point site, the two GNSS-R derived sea level time series are compared to the independent tide gauge measurement at Tacoma that is ~13 km away from Robinson Point. For the ease of viewing, a subset of the sea level for the first week of February of 2014 was displayed instead of the 8-year time series. Figure 4.2 indicates that the GPS-derived sea level time series has a high correlation with the tide gauge observation, and follows the diurnal and semi-diurnal variations.
Figure 4.3 shows the availability of observations from 2008 to 2016. Even though the two neighboring GPS station have similar configurations, RPT5 generally has a better data integrity than RPT6, especially for 2008 and 2010. In order to compare directly, a running window of size 1-hour generated the hourly time series of sea level from “RPT5”, “RPT6,” and tide gauge. With the identical time-tags, the difference between two neighboring GPS station and tide gauge sea level were investigated by Van de Casteele diagrams in Figure 4.5. Based on the shape of the Van de Casteele diagrams, it is possible to analyze the errors source. For the comparison between RPT5 and RPT6 sea levels, the diagram is centered around zeros differences, which means there is no systematic error. The symmetric shape of diagram indicates the noise follows normal gaussian distribution. For the other two comparisons, which are RPT5 vs. tide
gauge and RPT6 vs. tide gauge, the diagrams are tilted and the further study is conducted by the tidal harmonic analysis in the following section. Over the whole 8 years, the RMS of RPT5 vs. TG and RPT6 vs. TG were found to be 8.02 cm and 8.04 cm, respectively. The RMS of RPT5 vs. RPT6 was found to be 4.63 cm.

Figure 4.4 The data availability for the RPT5, RPT6 and tide gauge for the period of 2008-2016.
4.32 Tidal Harmonic Analysis

The tidal harmonic analysis was performed for the two neighboring GPS stations and conventional tide gauge, using the “T_TIDE” package that is widely utilized by oceanographers (Pawlowicz et al., 2002). In this classical harmonic analysis, a set of sinusoids at specific periods based on astronomical parameters was employed to model the tide signals. The observations from May to October of 2008 were cut off due to the large deficiency of RPT6 data. Finally, the 8-year time series from November of 2008 to October of 2016 was used for three stations.

In our analysis of 8-year observation, 68 tidal constituents with 95% confidence interval were calculated. The principle semi-diurnal and diurnal with selected tidal constituents were tabulated in Table 4.1. From the Table, it was clear that the two adjacent GNSS-R and tide gauge sea level time series all embed strong semi-diurnal and diurnal tides. As the largest constituent, the “principal lunar semi-diurnal” of $M_2$
has the amplitude larger than 30 cm. And the “lunar diurnal constituent” of $K_1$ is the second largest tidal constituent with the amplitude larger than 27 cm. In general, there is a good agreement between the amplitudes and phases for the GPS-derived sea level and the tide gauge records.
Table 4.1 the results of tidal harmonic analysis calculated for the period of 2008-2016 at the Robinson Point and Tacoma. The confidence interval was 95%.

<table>
<thead>
<tr>
<th>Tide</th>
<th>RPT5 A(cm)</th>
<th>error θ(°)</th>
<th>RPT6 A(cm)</th>
<th>error θ(°)</th>
<th>Tide Gauge</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA</td>
<td>5.33</td>
<td>1.53</td>
<td>356.89</td>
<td>16.42</td>
<td>5.64</td>
</tr>
<tr>
<td>SSA</td>
<td>4.4</td>
<td>1.53</td>
<td>220.15</td>
<td>19.9</td>
<td>3.88</td>
</tr>
<tr>
<td>MSF</td>
<td>17.52</td>
<td>1.53</td>
<td>31.47</td>
<td>4.73</td>
<td>17.75</td>
</tr>
<tr>
<td>MF</td>
<td>14.99</td>
<td>1.53</td>
<td>175.41</td>
<td>5.84</td>
<td>14.64</td>
</tr>
<tr>
<td>Q1</td>
<td>1.96</td>
<td>0.98</td>
<td>56.97</td>
<td>3.20</td>
<td>1.94</td>
</tr>
<tr>
<td>O1</td>
<td>6.2</td>
<td>0.98</td>
<td>204.23</td>
<td>9.84</td>
<td>6.56</td>
</tr>
<tr>
<td>P1</td>
<td>7.22</td>
<td>0.98</td>
<td>306.95</td>
<td>7.75</td>
<td>7.22</td>
</tr>
<tr>
<td>S1</td>
<td>3.1</td>
<td>0.98</td>
<td>279.68</td>
<td>25.65</td>
<td>3.15</td>
</tr>
<tr>
<td>K1</td>
<td>27.27</td>
<td>0.98</td>
<td>322.93</td>
<td>2.18</td>
<td>27.18</td>
</tr>
<tr>
<td>J1</td>
<td>0.97</td>
<td>0.98</td>
<td>66.11</td>
<td>20.26</td>
<td>1.17</td>
</tr>
<tr>
<td>OO1</td>
<td>0.59</td>
<td>0.98</td>
<td>280.84</td>
<td>149.96</td>
<td>0.89</td>
</tr>
<tr>
<td>N2</td>
<td>5.24</td>
<td>1.94</td>
<td>80.4</td>
<td>20.86</td>
<td>5.15</td>
</tr>
<tr>
<td>M2</td>
<td>32.82</td>
<td>1.94</td>
<td>116.02</td>
<td>3.33</td>
<td>32.54</td>
</tr>
<tr>
<td>S2</td>
<td>7.36</td>
<td>1.94</td>
<td>134.31</td>
<td>15.13</td>
<td>7.16</td>
</tr>
<tr>
<td>K2</td>
<td>4.08</td>
<td>1.94</td>
<td>55.87</td>
<td>31.33</td>
<td>3.76</td>
</tr>
<tr>
<td>MK3</td>
<td>9.11</td>
<td>0.63</td>
<td>283.14</td>
<td>4.1</td>
<td>9</td>
</tr>
<tr>
<td>M4</td>
<td>8.26</td>
<td>0.35</td>
<td>38.17</td>
<td>2.34</td>
<td>8.41</td>
</tr>
<tr>
<td>MS4</td>
<td>3.88</td>
<td>0.35</td>
<td>57.64</td>
<td>5.09</td>
<td>3.63</td>
</tr>
<tr>
<td>MK4</td>
<td>2.59</td>
<td>0.35</td>
<td>243.41</td>
<td>8.75</td>
<td>2.05</td>
</tr>
</tbody>
</table>
For the direct comparison, the absolute difference of tidal constituent was calculated by the equation,

\[
\text{dif} = \sqrt{\left(A_g \sin(\theta_g) - A_t \sin(\theta_t)\right)^2 + \left(A_g \sin(\theta_g) - A_t \sin(\theta_t)\right)^2} \tag{4.1}
\]

Where, \(A\) is the amplitude of tidal constituent, and \(\theta\) represents the Greenwich phase lags.

Figure 4.6 the absolute differences of RPT5 vs. TG and RPT6 vs. TG. The tidal constituents were ordered by the frequency.

As figure 4.5 showed, the agreement between two GPS sites was better than the agreement between GPS-derived sea levels and tide gauge measurement that was consistent with the results from time domain comparison. All the tidal constituent residuals between two GPS sites were under 0.75 cm, the large residuals were
accompanied by large amplitude and phase errors in Table 4.1. For the comparison between GNSS-R sea levels and tide gauge measurements, the tidal constituents with absolute difference larger than 1 cm were analyzed. Figure 4.7 and Figure 4.8 illustrated the amplitude and phase of tidal constituents that were ordered by tidal amplitude. The first two largest tidal constituents of $M_2$ and $K_1$, it's showed that their phase lags were very close and the amplitude of tidal constituents were underestimated in the GPS-derived sea levels. The same characteristic was found from tidal constituents of $MSF$, $MK_3$, $S_2$ and $P_1$. For the smaller tidal constituents of $O_1$ and $MK_4$, Figure 4.8 showed that the phase lag difference was the main reason for the absolute difference. The smallest tidal constituent of $OO_1$ also showed the large phase lag difference, but the it was not convincing due to the very large estimation errors. If the tidal constituents of $OO_1$ and $Mf$ were not taken into account, there were two reasons which lead to sea level discrepancies. One reason was that the amplitudes of large tidal constituents were underestimated in GPS-derived sea levels. Another reason was that the phase difference from smaller tidal constituents. For the tidal constituents of $OO_1$ and $Mf$, a more robust estimation for tidal solutions are necessary for future studies.
Figure 4.7 the amplitudes and phases of the tide constituents that were ordered by amplitude.
Figure 4.8 the amplitudes and phases of the amplitudes that were ordered by frequency.
4.33 Weekly Sea Level

After the determination of tidal coefficients, the diurnal and shorter tides could be removed from the GNSS-R sea level time series. For the analysis of the 8-year time series, the RMS difference between GNSS-R and tide gauge sea level time series is 1.53 cm.

Figure 4.9 the weekly sea level height residuals of RPT5 vs. tide gauge, RPT 5 vs. tide gauge and RPT5 vs. RPT6.
4.4 Discussion

For the Robinson Point, the GPS was initially installed in 1995 with the 4-char site names of “RPT1” and “RPT2.” After the upgrade in 2008, the 4-character site name was changed to “RPT5”, and it operated until 2016. Thus, there were more than 20-year GPS observations available, and possibly could be used for the sea level studies. Since different GNSS receiver types were used before and after the upgrade, which have different observation quality. In order to simplify the problem, the data period from 2008 to 2017 was selected for the accuracy estimation.

Compared with the tide gauge, the RMS error of GNSS-R derived sea level height was ~8.0 cm at the Robinson Point, which was ~3 cm larger than the RMS error at Calcasieu Pass (or Shell Beach) site. One reason was that the ranges of tidal amplitude are different. Since the SNR method was based on the assumption of the homogeneous flat reflecting sea surface, it performed better for the ocean surface with smaller variation or ocean dynamics. Compared with tidal amplitude range of 1.6 m at Calcasieu Pass, the range of tide amplitude at the Robinson Point was 4 m. It resulted in the worse performance of SNR technique at the Robinson Point. Another reason was that the GNSS receiver and the tide gauge were collocated exactly at Calcasieu Pass site, but the tide gauge was ~13 km far away from the Robinson Point site. The difference of ocean dynamics or sea state would also contribute to the sea level differences.

4.5 Conclusions

From results of the 8 years comparison between GPS and tide gauge sea level, we find that the hourly sea level from a single geodetic-quality GPS receiver has an RMS
residual of ~8.0 cm compared with tide gauge. After the tidal harmonic analysis, the results show the largest differences occurred by the underestimation of amplitudes of large tidal constituents in GPS-derived sea levels and the phase difference in smaller tidal constituents. The generation of the daily sea level time series could reduce the RMS difference to ~1.53 cm, which is nearly comparable to the conventional tide gauge measurements. The agreement between two neighboring GPS stations is better than the agreement between GPS station and tide gauge, which indicates the SNR technique has a good inner precision. Therefore, a single geodetic-quality GPS receiver with unobstructed view of sea surface, can act as a tide gauge.

Since the primary function of GPS receiver is to calculate the position of antenna, the solution of vertical land motion is critical to conventional tide gauge. The GPS antenna installed on the top of towers and end of a pier, which can be regarded as additional free datasets to the sea level study. However, the sampling rate of GPS derived sea level is approximately one hour, which is incomparable with 6-minute sampling rate of conventional tide gauge. The simplest way is to upgrade the GNSS receiver that is to capture more satellite constellations (Galileo, GLONASS, BeiDou) and more frequency signals (L2C, L5).
Chapter 5: GNSS-R Lake Ice Thickness Retrieval

The Laurentian Great Lakes, located in the mid-latitude of North America, is one of the most populated coastal areas in the world. The annual freezing in each winter directly impacts the local economy, such as via accurate forecasting of severe weather patterns or lake effects, lake water transportation, drinking water supply, commercial fishing, beach recreation and recreational sports for citizens. In addition, the freezing period will affect the water evaporation volume that results in water level changes, lake circulation and genesis of severe weather patterns (Wang et al., 2012). At present, lake ice extents (not thickness) are observed using imageries or radars, and arguably with no timely or near-real time observations. Higher temporal (daily or better) and spatial resolution observations of coastal lake ice coverage and thickness change, would plausibly be critical to improve the winter storm and weather nowcasts and forecasts of the Great Lakes regions in the US and Canada.
Rodionov et al. (2000) used the Classification and Regression tree method, to investigate the relationship between Great Lakes winter severity and atmospheric circulation. The results show that the warm winter has a strong correlation with the Pacific pattern and El Niño events in the equatorial Pacific. Assel et al. (2003) analyzed a 39-year historical observation of annual maximum fraction of lake ice coverage. It shows that the seasonal change of ice coverage repeats each year, but the large inter-annual variation also exists, which possibly corresponds to the inter-annual climate variability and global climate warming. Assel et al. (2004) developed an empirical statistical model to predict the 30-day lake ice coverage. Wang et al. (2012) investigated the temporal and spatial variability of Great Lake ice coverage from historical satellite measurement. The results show that the variation of lake ice coverage mainly responds to the pattern of Arctic Oscillation and El Niño–Southern Oscillation.

The previous studies have a comprehensive investigation on the Great Lake mainly based on the ice coverage or extent observations. When the ice coverage is no longer increasing, the ice thickness can still grow in the winter. This implies that using only the measurement of lake ice coverage, from imagery and radar, is not sufficient to improve Great Lakes forecasting system, the exact knowledge of ice thickness and its changes are necessary. In this Chapter, we present a new method to estimate lake ice thickness and its changes in Lake Huron, using collocated GNSS-R and tide gauge data sets. First, the concept of lake ice thickness retrieval using a single geodetic GPS receiver is introduced. Then, GNSS-R data analysis using data collected at the Harbor Beach GNSS site, on Lake Huron is utilized to generate a 11-year lake ice thickness product, 2004–2016.
5.1 Station Installation

The Harbor Beach GPS site is named as “HBCH”, managed by NOAA’s National Geodetic Survey (NGS), is located at the coastal areas of Lake Huron, Michigan (Figure 5.1a). It was originally installed in April of 2003 with a Trimble 5700 receiver, a dual-frequency geodetic-quality carrier phase GPS receiver. The GPS antenna was mounted on the top of a steel mast with unobstructed view of water (Figure 5.1b). Thus, it is an ideal scenario to retrieve the multipath signals reflected from the water surface as lake level measurements.

The collocated tide gauge measurement at Harbor Beach is from the continuously operating Center for Operational Oceanographic Products and Services (CO-OPS), maintained by the U.S. National Oceanic and Atmospheric Administration (NOAA). Digital 6-minute sampling data are available, which is more than adequate for our study. As Figure 5.1 shows, the tide gauge measures the water level from the stilling tide well in which the well water would not freeze and allows the measurements in the winter. This configuration can keep providing year-around water level observations of Lake Huron.
Figure 5.1 The station installation. a) the geolocation of station site on the Lake Huron, Michigan; b) the GPS antenna that is mounted on the top of steel mast with free view of water; c) the tide gauge instrument; and d) the stilling tide well (Credit: Photographs from National Geodetic Survey).

5.2 Methodology

The satellite (laser and radar) altimetry, which provides global and consecutive observations, is a prevailing technique used to derive sea ice thickness especially on the Polar Regions at basin scales (Laxon et al, 2003; Giles et al., 2008; Farrell et al., 2009;
Kurtz et al., 2012; Kwok et al, 2009; Laxon et al., 2013). However, the application of satellite altimetry to derive lake ice thickness is very challenging. In winter, the lake begins to freeze starting from coastal area, then toward to center of the lake. With the large footprint size at several km’s, the accuracy of altimetry measurement decreases drastically at the littoral zone due to the contamination by the multiplicity of coastal surface. Here, we describe a new approach that uses a single geodetic-quality GPS receiver with a collocated conventional tide gauge, to accurately determine the coastal lake ice thickness.

Figure 5.2 The schematics of lake ice thickness retrieval by a single geodetic-quality GPS receiver with a collocated conventional tide gauge

From Figure 5.1 and Figure 5.2, the conventional tide gauge measures the lake (or
sea) level using stilling wells for lake or sea ice covered water surfaces, to mitigate the influence from short period waves. The instrument is designed to allow the water flow into the stilling well by the bottom inlet pipe. In this way, the levels of water inside and outside the stilling well are always equal. Since the temperature of stilling well is still above zero degrees Celsius, this configuration is able to provide water level measurements in the winter.

Figure 5.2 shows the schematic of a GPS antenna affected by multipath signal reflected from the ice surface. The direct signals are interfered by the reflected signals due the phase difference. Although the ice has different properties of conductivity and relative permittivity with sea water, this interference pattern is visible as oscillations in the SNR data. From the simulated results in Chapter 2, the reflector height between GPS antenna and ice surface, can be accurately calculated by the dominant oscillation frequency. In other words, the ice surface height can also be obtained by the SNR technique. Therefore, the lake ice thickness $T$ is as follow,

$$T = h_{ice} - h_{water}$$

(5.1)

Where, $h_{ice}$ is the GNSS-R derived ice surface height, and $h_{water}$ is lake level measured by conventional tide gauge.

The error in the lake ice thickness retrieval can be written as,

$$\sigma = \sqrt{\sigma_{gps} + \sigma_{tg}}$$

(5.2)

Where, $\sigma_{gps}$ is the uncertainty of the GNSS-R derived ice surface height, and $\sigma_{tg}$ is the uncertainty of conventional tide gauge lake level measurement.
Figure 5.3 The daily surface heights from GPS observation and conventional tide gauge. The ice thickness is equal the difference between two types of measurements.

5.3 Results

In order to validate the ice thickness product, the gridded ice coverage data was used for the identical period, which was provided by Great Lakes Environmental Research Laboratory (GLERL) of NOAA. The ice coverage data was obtained by a model, integrating all available data, including meteorological observations, oceanographic information, shipborne, and airborne measurements (Assel et al. 2003). This data provides a nominal spatial resolution of 2.55 km for 2003–2006, and evolved in a nominal spatial resolution of 1.275 km for 2007–2011 (the true scale is at 45° N). The ice coverage is also named as ice concentration for each grid area, and it is a sensitive indicator of climate variation (Assel et al. 1995; Assel and Robertson 1995;
Magnuson et al. 1997, 2000). Figure 5.4 shows model data for the Lake Huron ice evolution from initial ice freeze-up to the complete ice cover, and then the break-up during the winter of 2015, with 4 snapshots (Assel et al. 2003). This seasonal ice coverage repeats each year with most probably interannual variations, and could be the criteria used to verify the ice thickness product. In addition, the inter-annual cycle and long-term trend were investigated in following study.

Figure 5.4 The daily ice coverage on the Lake Huron that shows the cycle from initial ice freeze-up to the complete ice cover, and then break-up, with 4 snap shots (Assel et al. 2003).
5.31 Seasonal Variability

The GNSS-R lake ice coverage observation is extracted from an area with 2.55 km radius at the Harbor Beach point (82°38′35″W, 43°50′47″W), and a running window of size one-week was employed to generate equal interval sampling time series. For the same period of 2004–2015, the ice thickness time series is also smoothed by a one-week window for comparison. From Figure 5.5, both of these two data sets (GNSS-R and model) have annual freezing and water-clear variations. For the water-clear period, the ice thickness observation with cm-level amplitude is limited by the accuracy of this technique.

![Graph](image)

Figure 5.5 The weekly average ice coverage (upper-panel) and ice thickness (lower-panel) at Harbor Beach for eleven years. Data gaps are denoted by broken green lines.
The observations of 2014 are taken as an example to investigate the ice forming procedure. Figure 5.5 shows that the ice coverage reaches its maximum at Harbor Beach on Feb. 18th, 2014, and lasted roughly 40 days with above 95% coverage. However, the maximum ice thickness occurs on Mar. 6th, 2014, which is approximately two weeks after ice coverage was at its maximum. This observation implies ice coverage was no long increasing, but the ice thickness could still grow in freezing period. Therefore, the ice thickness derived from the combination of GPS and conventional tide gauge can provide additional information on lake ice variation.

Figure 5.6 shows that the red lines indicate the freeze-onset and water-clear dates, both of ice coverage and thickness have almost the same freeze-onset and water-clear dates. In other words, these two types of observations have nearly the identical ice-cover duration. In order to further detect the reliability of ice thickness observation, the freeze-onset and water-clear dates for the whole 12-year time series were collected in figure 5.7. As the results indicate, the freeze-onset occurs in December except 2004 and 2007, and water-clear happens from March to April at Harbor Beach. The GPS observations are missing from Dec. 14th of 2011 to Mar. 9th of 2012, so freeze-onset date was not collected for ice thickness to lessen the uncertainties. By comparison, the RMS of residual for freeze-onset date is 0.81 day with mean value of 0.53 day. For the water-clear date, the RMS difference is 0.86 day with mean value of 0.69 day. Therefore, the ice thickness observed by the combination of GPS and tide gauge is a reliable and sensitive indicator for the lake ice variation.
Figure 5.6 The weekly average NOAA/GLERL model ice thickness data (upper-panel), and the GNSS-R ice coverage (lower-panel) at Harbor Beach in 2014. The red lines indicate the freeze-onset and water-clear dates.
Figure 5.7 The comparison of freeze-onset date (upper panel) and water-clear date (lower panel) between Lake Huron ice coverage and ice thickness observations.
5.32 Inter-annual Variability and Long-term Trend

We now investigate the inter-annual variability and long-term trend of ice coverage and ice thickness, based on the 11-year GNSS-R Lake Huron ice thickness evolution, 2004–2016. The observations outside of the ice season were removed, then an averaging window was applied to generate annual-mean time series of ice coverage and thickness. There was one large GPS data gap that occurred in ice season from Dec. 14th of 2011 to Mar. 9th of 2012. Since the ice thickness might reach the maximum before Mar. 9th, the annual-mean value was slightly underestimated for 2012. The spectral characteristics of the 12-year time series were further investigated. Figure 5.9 shows that the two close periods of three years and four years were found for ice coverage and thickness, respectively. Both of these two periods may be related to El Niño-Southern Oscillation (ENSO), which generally has strong inter-annual time scales of 3-5 years (Bai et al. 2010, 2012).

The linear trend was fitted using least squares regression by the linear equation in the form of $y = ax + b$. In the equation, the $y$ is the ice coverage or ice thickness, $x$ represents the time, $a$ is the slope with time varying, and $b$ is a constant. Both the Lake Huron ice coverage and thickness show a positive trend, implying that the ice volume has been increasing since 2004.
Figure 5.8 The annual mean lake ice coverage (upper panel) and ice thickness (lower panel). The linear lines are the trend in annual lake ice coverage and thickness estimated by least squares fit.
Figure 5.9 The spectral analysis of lake ice coverage and thickness. Top: NOAA/GLERL model, Bottom: GNSS-R and tide gauge.
5.4 Conclusions

In this study, a new method is introduced, to derive coastal lake ice thickness using a single geodetic-quality GPS receiver with a collocated tide gauge. The derived ice thickness at Harbor Beach is validated with model ice coverage data provided by NOAA/GLERL. The results show that, as ice coverage product, the ice thickness is also a reliable indicator of lake ice variation, and a critical input. When the ice coverage stops increasing, the ice thickness can still grow in freezing period. Therefore, the GNSS-R based ice thickness data set could plausibly be used as additional information to improve Great Lakes forecasting system.
Chapter 6: Conclusions and Future Works

With the influence of global climate changes, the sea level rise caused mainly by ice sheet and glaciers melting and sea water expansion constituted great threat for the population living in coastal regions (Bindoff et al., 2007). Compared to conventional tide gauge and satellite altimetry, the ground-based GNSS-R altimetry provided a novel perspective to measure the sea level variations and the properties of other surface types (Figure 6.1).

![The advantage of ground-based GNSS-R altimetry](image)

Figure 6.1 The advantages of ground-based GNSS-R altimetry
As an electromagnetic (EM) wave, the reflected GNSS signals are largely impacted by the reflecting sea surface. The EM bias is one of the main error sources in ground-based GNSS-R altimetry, which results in the underestimation of sea level height. In order to access the EM bias, the Pierson-Moskowitz spectra was employed to generate the linear one-dimension sea surface. With the Choppy wave model, the corresponding nonlinear sea surface was also created for the computation of pulse returns. At the end of numerical simulation, the EM bias was modeled by the difference between linear and non-linear pulse returns. Then, two realistic GPS station located in Gulf of Mexico were utilized in further investigation, verifying that the accuracy of ground-based GNSS reflectometry technique can be efficiently improved by accounting for EM bias model. However, the different sea surface models can lead to different EM bias estimation. Thus, the optimization of selection on different sea surface models will be addressed in the next investigation. As indicated in Chapter 2, the footprint of ground-based GNSS-R altimetry is shaped by an ellipse, with the major axis ranging from several meters to hundreds of meters. Hence, the one-dimension sea surface model is inadequate and the two-dimension sea surface model is needed in future studies.

Two neighboring geodetic GPS stations at the Robinson Point of Washington and their adjacent conventional tide gauge were used to comprehensively estimate the accuracy and precision of 8-year sea level measurement from GPS reflected signals. When the GPS-derived sea level was compared with “ground truth” of tide gauge, the results illustrated that this technique was capable of determining hourly sea level with an accuracy of ~8.0 cm. Generating the weekly sea level time series could increase accuracy to ~1.5 cm, which was almost comparable to the conventional tide gauge measurements. The agreement between the two neighboring GPS stations was better
than the agreement between GPS station and tide gauge, which demonstrated that the inner precision of GPS-derived sea level was 4.63 cm. After the tidal harmonic analysis, 19 tidal constituents were selected for the analysis. For the large tidal constituents, their phase lags were very close and the amplitude of tidal constituents were underestimated in the GPS-derived sea levels. For the smaller tidal constituents, the phase lag difference was the main reason for discrepancies. However, the closed tide gauge at Tacoma is \(\sim 13\) km far from Robinson Point. Considering the complicated surrounding environment, it was unclear that the discrepancies were limited by the precision and accuracy of observation, or caused by the real tidal variations over 13 km. Therefore, the additional experiments by collocated GNSS receiver and tide gauge sites are need to be conducted over different tidal environments. Also, a more robust estimation for the tidal constituents of \(\Omega_1\) and \(Mf\) were necessary in further investigation.

A novel method on lake ice thickness retrieval was proposed by combining a single geodetic-quality GPS receiver with a collocated tide gauge. In order to validate this method, a 12-year product of ice thickness at Harbor Beach was derived, and compared with ice coverage data provided by NOAA/GLERL. The results show that, as ice coverage product, the ice thickness is also a reliable indicator of lake ice variation. When the ice coverage stops increasing, the ice thickness can still grow in freezing period. Therefore, the ice thickness product used as additional information is capable of improving the interpretability and predictability of climate models. However, a comprehensive analysis on the accuracy of ice thickness product is needed with external observations such as radar echo. In addition, the computation of ice thickness over the whole Great Lakes is necessary for climate forecast tools and models.
Reference


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