MEASURING ICE THICKNESS WITH CYGNSS ALTIMETRY

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ABSTRACT

Cyclone Global Navigation Satellite System (CYGNSS) is collecting GPS signals reflected from two high altitude lakes with ice cover during Winter 2017-2018. Coherent reflections occur at the ice/water interface and carrier phase altimetry is used to estimate the draft of the ice cover. Simulated data are created using a forward model. Signal processing methodology is presented to show how relative phase information can be extracted from the simulated data most accurately, and how the phase can be related to draft.

Index Terms— CYGNSS, GNSS-R, carrier phase altimetry, ice, remote sensing

1. INTRODUCTION

CYGNSS is a constellation of eight satellites that were successfully launched on 15 December 2016 into a common orbit plane at 520 km altitude and 35° inclination. It is designed to measure surface winds in tropical cyclones by receiving GPS signals reflected from the ocean surface in the storm. The signal is largely unattenuated by heavy precipitation because of the long wavelength of the GPS L1 frequency (19 cm). As required by the fast-changing nature of tropical cyclones, CYGNSS has an excellent revisit time due to there being 8 satellites in the constellation—the median and mean revisit times in the tropics are 3 and 7 hours, respectively. CYGNSS has an orbital inclination of 35° and observes up to +/- 40° latitude. Therefore, the only ice typically seen by CYGNSS is at high elevations. For more on CYGNSS, see [7].

GNSS-R can make measurements using either scattered power or phase. The scattering cross section is calculated from the scattered power measurement, which allows for calculation of additional quantities such as soil moisture and surface wind speed. The phase of the signal is derived from the time dependent carrier signal and is used for ranging and altimetric purposes. The latter will be used here for estimating ice thickness from measurement of the draft.

Ice extent is an important indicator of how much ice is melting from year to year, but most of the ice is below the surface. The ice thickness is needed to know the volume of ice present. While ice coverage affects albedo, ice volume is important for the ocean heat budget and knowing how much of sea level rise is due to melting of ice versus other factors such as run-off and thermal expansion of the ocean [8]. Both ice thickness and extent are very important indicators of climate change. Ice thickness is also an important input into sea ice simulations in atmosphere-ocean climate models [9].

Current methods for measuring sea ice include GRACE, which measures the ice mass using gravitational perturbations, and ESA's ERS-1, ERS-2, and ENVISAT, which are radar altimeters not designed specifically for ice measurements. Dedicated ice altimeters are CRYOSAT-2, which measures ice height using Ku band radar altimetry, and ICESat, a laser altimeter which also measures the elevation of the surface/air interface relative to a reference ellipsoid, then derives the ice thickness from a buoyancy equation, a function of freeboard, snow depth, and snow/ice/water densities [5]. GNSS-R ice altimetry could improve upon previous satellite methods because it is cheaper due to the use of an existing signal. Since it is cheaper, there can be more satellites which allows for better temporal and spatial coverage. GNSS-R also measures the ice draft directly since the signal penetrates ice and snow. Radar altimeters such as ICESat, which do not penetrate snow or ice, measure freeboard and must solve for the draft using other considerations as

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mentioned previously. The draft uncertainty propagates into ice thickness measurements with a smaller factor than the freeboard uncertainties [1].

This work was directly motivated by Li et. al. [1] who measure sea ice draft in Hudson Bay, Canada, using a Master-Slave sampling technique in which the phase of the direct signal is compared to the phase of the reflected signal. We hope to make similar measurements of ice draft using the carrier phase of the GPS signal, but there some significant differences.

This work only tracks the carrier phase of the reflected signal whereas Li et al. use the phase difference between the direct and reflected signal. The interferometry advantage is the ability to measure an ice draft depth relative to a reference ellipsoid whereas the method in this paper can only determine changes in ice thickness. However, using only one signal removes errors that are consistent throughout the short measurement, such as tidal effects and additional delay due to the ionosphere and troposphere. This greatly simplifies the problem.

CYGNSS carrier phase analysis uses its Raw IF mode of data-taking. Raw IF mode means that the raw sampled data are sent to the ground and not processed into delay doppler maps on board, thereby retaining phase information [10]. This mode was activated for overpasses of two high altitude lakes with ice cover in winter—Namtso Lake, China (elevation 4718 m, 30.6° N), and Qinghai Lake, China (elevation 3260 m, 37° N). CYGNSS collected raw IF data reflected from these lakes biweekly throughout the winter, and this will continue into the summer. This allows for observation of ice draft increasing through winter, then decreasing in spring. Coherent reflection of the GPS signal from the ice/water interface will be used for altimetric purposes. This coherence is critical because it allows for tracking of the phase of the GPS carrier signal, which in turn allows for the calculation of altimetric height with significantly better accuracy than traditional group phase altimetry.

This paper will use a simulator to create raw intermediate frequency data received by CYGNSS. Then a signal processing method for isolating the ice draft is presented, and errors that might affect the measurement are discussed.

2. PROBLEM SETUP

The specular surface, or the primary surface of specular reflection, is determined by the relative permittivity of the materials involved. This is because the reflection coefficient is proportional to the permittivity contrast in the materials. At the GPS L1 frequency, 1575.42 MHz, the imaginary part ϵ'' is quite small, so for making these estimations, only the real part ϵ' needs to be considered. Obviously, $\epsilon'_{air} = 1$. $\epsilon'_{water} = 83$ at 10^o C with no salinity [2]. $\epsilon'_{ice} = 3.17$ with no salinity and does not change significantly with temperature [3]. Because the relative permittivity contrast between air and ice is much less than that between ice and water, scattering at the air/ice interface is relatively weak and most of the GPS signal strength propagates through the ice until reflection at the ice/water interface. Also note that ϵ'' is small for snow and ice so the signal will not be diminished traveling through these materials. Also, the permittivity of dry snow is about 1.6 at the L1 frequency, and it can get as high as 15 when old and wet [6], so even if there is a layer of snow on top of the ice, the dominant specular surface remains the ice/water interface. Now that the specular surface has been identified, the simulated data can be constructed.

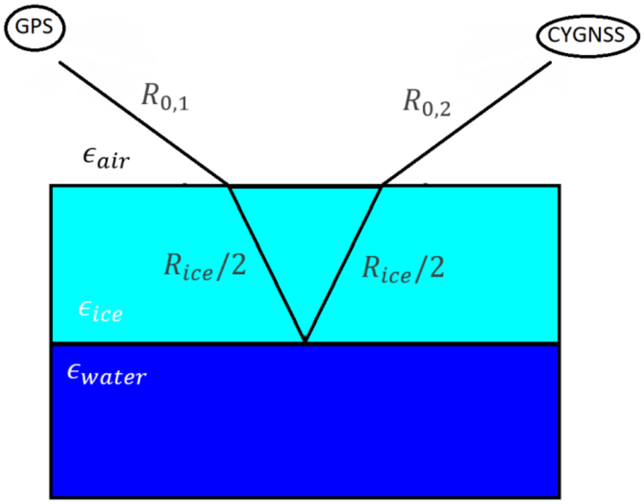

Figure 1: The surface of specular reflection is the ice/water interface. The signal path is traced, and the respective ranges are labeled. The free space range $R_0(t) = R_{0,1} + R_{0,2}$ and clearly $R_{ice}(t)$ is the sum of the two ranges labeled above.

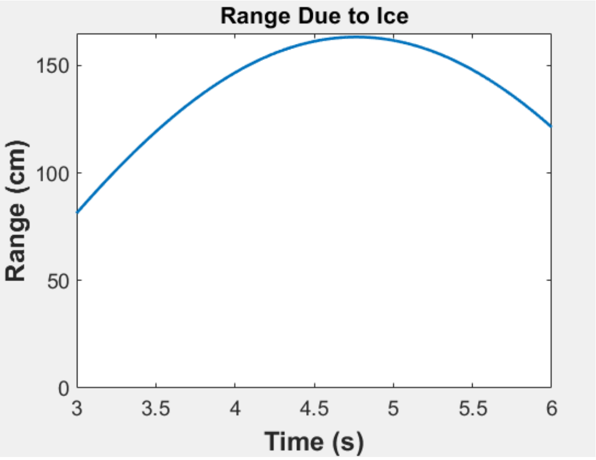

Figure 2: The range due to ice as a function of time, $R_{ice}(t)$. Note that only the second half of the 6 seconds of data is used.

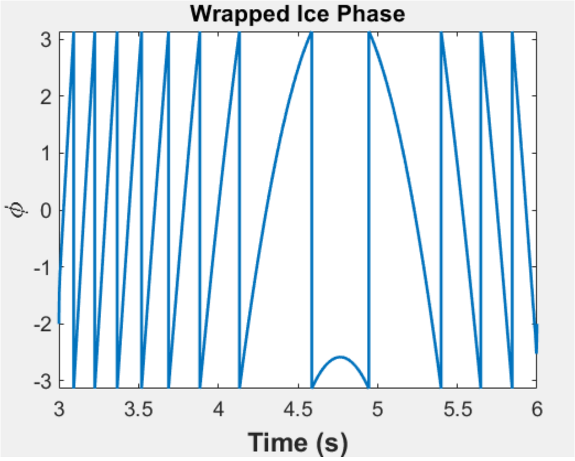

Figure 3: The wrapped ice phase, $\phi_{ice,wrapped}(t)$. Note that the maximum ice depth corresponds to a critical point in the phase around t = 4.75 s.

After the Raw IF signal measured by CYGNSS has had its ranging code and navigation data stripped off, and assuming there is no noise present, the signal can be expressed as

$$s(t) = Cos[2\pi f_{IF}t - \phi(t)] = Cos\left[2\pi f_{IF}t - 2\pi \frac{R(t)}{\lambda}\right] \quad [1]$$

where f_{IF} is the intermediate frequency on-board CYGNSS which is the difference between the GPS L1 frequency, 1575.42 MHz, and the frequency of the local oscillator on-board CYGNSS, 1571.5476 MHz. R(t) is the range of the signal between transmission from the GPS satellite to reception by CYGNSS, λ is the GPS L1 wavelength, and $\phi(t)$ is the carrier phase of the signal.

The simulator allows the GPS and CYGNSS satellites to orbit around a circular Earth in the same plane. As a simplification, the model is two dimensional, but this does not have any negative impact on the following. By knowing the exact positions of the satellites with respect to the Earth, the range R(t) can be calculated.

Finally, the range is modified to include an ice draft layer below the surface. It is arbitrarily chosen to vary sinusoidally with a maximum depth of 1 meter. Since the signal needs to travel through both air and ice, the range-dependent phase term in eqn. (1) is expanded as

$$\frac{R(t)}{\lambda} = \frac{R_0(t)}{\lambda_0} + \frac{R_{ice}(t)}{\lambda_{ice}} \quad [2]$$

where $R_{ice}(t)$ and λ_{ice} are the range and wavelength of the signal in ice, respectively, and $R_0(t)$ and λ_0 are the range and wavelength of the signal elsewhere (assumed free space). $R_{ice}(t)$ due to the sinusoidally varying ice draft is shown in Figure 2. The goal is to derive $R_{ice}(t)$ from measurements of carrier phase. The ice draft can then be calculated from $R_{ice}(t)$ using buoyancy and geometry considerations.

3. ICE THICKNESS MEASUREMENT

Using the best orbit information available, a locally generated copy of the signal, $s'(t)$, is given by

$$s'(t) = Cos\left[2\pi f_{IF}t - 2\pi \frac{R_0'(t)}{\lambda_0}\right] \quad [3]$$

where $\frac{R_0'(t)}{\lambda_0}$ is an estimated phase term. A complex (quadrature) correlation between the true and locally generated signals is given by

$$I = Cos[\phi_0(t) - \phi_0'(t) - \phi_{ice}(t)] \quad [4]$$
$$Q = Sin[\phi_0(t) - \phi_0'(t) - \phi_{ice}(t)]$$

Now, assume the free space range, $R_0(t)$, is exactly known. This involves precise orbit and topographic information, as well as complete knowledge of all layers of the atmosphere. This would mean the local free space phase term, $\phi_0'(t)$, is exactly equal to the true free space phase term, $\phi_0(t)$, for all times. This allows I and Q to simplify and $\phi_{ice}(t)$ can be extracted by an inverse tangent.

$$\phi_{ice,wrapped}(t) = \arctan\left(\frac{Q}{I}\right) \quad [5]$$

This is the wrapped phase. After unwrapping and rearranging, the ice range is found as,

$$R_{ice}(t) = \frac{1}{2\pi}\lambda_{ice}\phi_{ice,unwrapped}(t) \quad [6]$$

This results in the exact range due to ice. Note that even if $\phi_0(t)$ were known exactly, the answer would not be exact with real data due to noise. Ice thickness can be derived from geometry and buoyancy considerations. Details of this process are found in [11].

4. ERROR SOURCES

One important consideration is the sources of error that will affect the measurement. It isn't necessary to know $\phi_0(t)$ exactly to get an exact answer. Since this is a relative measurement, $\phi_0(t)$ only needs to change across the lake surface in the correct way. There could be a constant error ϵ' such as

$$2\pi \frac{R_0'(t)+\epsilon'}{\lambda_0} = 2\pi \frac{R_0(t)}{\lambda_0} \qquad [7]$$

If epsilon prime is constant over the course of the measurement, the answer can still be exact. Recall that a typical measurement is less than 10 seconds in duration. Now consider the possible error sources and if they are changing over this time scale.

An important error to characterize is the GPS/CYGNSS orbit error. At this point it is unknown to what accuracy we know the positions of the satellites, how these errors will change in 10 seconds, or if they the errors might change in an unpredictable way over this time interval.

Another possible source of error is delay or bending due to the ionosphere and troposphere. Over 10 seconds, the GPS signals are going through nearly the same part of the atmosphere and the atmosphere, and neither the ionosphere's electron density nor the troposphere's humidity level change significantly in this amount of time. Therefore, for this relative measurement these layers of the atmosphere should not contribute much error.

Noise will be present in the real data. Since that is not accounted for here, results from real data are not expected to be as accurate.

Another phenomenon to be aware of is melting that may occur on the ice surface. This would occur most often in data that were taken during the daytime. Solar heating of the lake can cause a thin water layer above the ice and, depending on the water thickness, could change the specular surface and degrade the measurement.

5. CONCLUSION

Highly coherent signals reflected from a flat water surface allow for continuous phase tracking, and the relative phase can be used to calculate the ice thickness. [1] was able to perform ice thickness measurements using TDS-1 data, and we are hopeful that the same thing can be done with CYGNSS data. The results using simulated data show promise, but there is uncertainty about how noise and orbit errors will behave over the duration of a real measurement.

Future work includes applying these methods to real data to find the relative ice thickness along the specular point track. We also want to use raw IF data scattered from the lakes over the summer (with no ice) to characterize the consistency of these measurements.

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