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Key Points:

- Greenland ice sheet melt detection is demonstrated using spaceborne GNSS reflectometry for the first time
- Results show good agreement with the Special Sensor Microwave Imager/Sounder Greenland ice sheet melt product
- GNSS reflectometry shows potential to provide complementary information on melt occurrence in ice sheet subsurface

Supporting Information:

- Supporting Information S1

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Measuring Greenland Ice Sheet Melt Using Spaceborne GNSS Reflectometry From TechDemoSat-1

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Abstract The capability of spaceborne Global Navigation Satellite System-reflectometry (GNSS-R) for Greenland ice sheet melt detection is investigated using the TechDemoSat-1 satellite (TDS-1) data. The melt detection is based on the sensitivity of GNSS-R signal to the presence of liquid water in snow pack. Statistical analysis during the 2018 melt season shows melt detection using GNSS-R is possible with an agreement of 90% comparing to the microwave radiometer (MWR) data. In 37% of the cases GNSS-R detects melting when MWR does not. The inconsistency observed between GNSS-R and MWR is mainly due to the different features of the two observation concepts and the limitations of currently available GNSS-R data. Furthermore, the large penetration depth of the GNSS signal can potentially provide complementary information on melt occurrence in ice sheet subsurface. These results show the potential of future GNSS-R missions for ice sheet melt detection.

Plain Language Summary Melt of Greenland ice sheet (GrIS) plays important roles in sea level change, global climate, and other areas of global environmental issues. Satellite microwave remote sensing has been increasingly used to produce maps of snow melt over Greenland during the past decades. The use of signals transmitted by navigation satellites after reflected from the Earth surface, known as Global Navigation Satellite System Reflectometry (GNSS-R), provides a cheap solution of measuring the Earth surface with exceptional spatiotemporal coverage. Using the data collected from U.K. TechDemoSat-1 mission, we investigate the feasibility and performance of spaceborne GNSS-R for GrIS melt detection. The results obtained with GNSS-R measurements give good agreement with GrIS melt data from other microwave sensors and also show potential of providing complementary melt information in deep layers of the GrIS due to the penetration of GNSS signal into the snow pack. These results, obtained from a technique demonstration platform, show the potential of future GNSS-R missions for provide high spatial and temporal resolution melt data over the Greenland and Antarctica ice sheet.

1. Introduction

Greenland ice sheet (GrIS) melt is a sensitive indicator of global warming and a contributing factor of climate change (Gregory et al., 2004; Hanna et al., 2008; Wood et al., 2018). It is also the main component of the Greenland mass balance (Mouginot et al., 2019), which is one of the largest sources of uncertainties in estimates of sea level rise (Rignot et al., 2011; van den Broeke et al., 2016). Satellite remote sensing has been an effective way of measuring GrIS melt on large spatial scales. The presence of liquid water in snow pack can dramatically impact the electrical properties of the snow at microwave frequencies. Passive microwave radiometer (MWR) can detect GrIS melt by measuring the changes in microwave emission (Abdalati & Steffen, 1997; Mote & Anderson, 1995; Mote et al., 1993; Tedesco, 2007). Snow wetness can also change the near surface permittivity and thus the microwave backscatter signatures. Microwave scatterometer measurements have been also used for GrIS melt detection (Ashcraft & Long, 2000; Nghiem et al., 2001; Wismann, 2000). Further combinations of these satellite microwave data can represent more complete melt conditions of the extreme melt events over the GrIS (Ashcraft & Long, 2006; Nghiem et al., 2012).

Here we discuss an additional way in which the reflected signals from GNSS (Global Navigation Satellite System) are used for GrIS melt detection. This technique, known as GNSS reflectometry (GNSS-R), was proposed for multistatic ocean scatterometry by Hall and Cordey (1988) and later by Martín-Neira (1993) for ocean altimetry. It can provide exceptional spatial-temporal sampling capability over the Earth surface by observing several simultaneous tracks of reflection points in parallel. In fact, Larson et al. (2015) used

the multipath contribution to GPS signal-to-noise ratio (SNR) data to measure the snow surface heights, with which dramatic changes were observed over GrIS during the 2012 melt season. However, Larson's method can be only applied to in situ and ground-based setups. Alternatively, the presence of liquid water can significantly change the forward scattering signature of the GNSS signal at L-band ($\sim 1.2\text{--}1.6$ GHz). Previous airborne and spaceborne GNSS-R data have clearly shown the sensitivity of reflected GNSS signal to the presence/content of near surface water (Nghiem et al., 2017), which have been applied over land surface for inland water/wetland detection, and soil moisture measurement (Chew & Small, 2018; Chew et al., 2018; Gerlein-Safdi & Ruf, 2019; Nghiem et al., 2017). The same idea can be also applied over ice sheet for melt detection. In principle, the GNSS signal can penetrate much deeper into the dry snow, on the order of tens of meters to hundred meters (Cardellach et al., 2012; Fabra et al., 2010; Rius et al., 2017). The liquid water and wet snow formed during the melt events can change the dominant scattering mechanism from volume to surface scattering and thus increase the power of the reflected GNSS signal. The aim of this paper is to demonstrate the possibility of using spaceborne GNSS-R to reveal surface melt occurrence over the GrIS. The main data set used in this study is collected by the Space GNSS Receiver Remote Sensing Instrument (SGR-ReSI) on board the U.K. TechDemoSat-1 (TDS-1) satellite (Unwin et al., 2016).

2. Data Sets and Method

2.1. GrIS Melt Data From MWR

The Greenland daily surface melt maps derived from spaceborne MWR data (available at <https://greenland-measures.labs.nsidc.org/>) are collected as the reference for validation. During the time frame of TDS-1 GNSS-R data collection, the MWR data are mainly acquired by the Special Sensor Microwave Imager/Sounder (SSMIS) on board the Defense Meteorological Satellite Program satellites (Kunkee et al., 2008). By using a dynamic threshold algorithm based on a simple microwave emission model (Mote, 2007; Mote & Anderson, 1995), the presence of melting is detected from 37-GHz horizontally polarized daily brightness temperatures. It is noted that the MWR GrIS melt data is produced in the Equal Area Earth Scalable Grid 2.0 version at 25-km resolution (Brodzik et al., 2012).

2.2. U.K. TDS-1 GNSS-R Data

A milestone of the spaceborne GNSS-R technique was the launch of the TDS-1 satellite on July 2014 with the SGR-ReSI receiver onboard (Unwin et al., 2016). Its primary objective is to demonstrate GNSS-R ocean wind measurements (Foti et al., 2015). Its high orbit inclination allows it to cover polar regions, leading to new GNSS-R cryospheric applications, for example, sea ice detection and classification (Alonso-Arroyo et al., 2017; Cartwright et al., 2019; Rodriguez-Alvarez et al., 2019; Yan & Huang, 2016), ice sheet altimetry (Cartwright et al., 2018; Rius et al., 2017), and sea ice altimetry and ice thickness retrieval (Hu et al., 2017; Li et al., 2017). The main GNSS-R data product of this mission (Level 1b (L1b) data) are the delay-Doppler map (DDM) of GPS scattered power from the Earth's surface around the specular point. Each DDM has 20×128 pixels in Doppler and delay domains, with a Doppler resolution (Δf) of 500 Hz per pixel and a delay resolution ($\Delta \tau$) of ~ 246.40 ns per pixel, respectively (SSTL, 2019). For this study, we use the TDS-1 L1b data collected between April 2015 and September 2018.

Before the data processing, an initial quality control has been applied. To guarantee the reflected signal is received with sufficient SNR, we only use the DDMs with the antenna gain along the direction of the specular point greater than 3 dBi. In addition, data that are flagged as containing the direct signal in the DDM are also excluded due to its contamination to the reflected signal. As the SGR-ReSI is mainly designed for ocean applications, the DDM window is computed using the ellipsoid as the reference to allocate the DDM peak around the center of the tracking window (Jales, 2012). As a consequence, in SGR-ReSI acquisitions over the high elevation regions, such as those of the Antarctic and GrIS, the DDMs can be allocated out of the delay-Doppler window, losing crucial information. These cases have been filtered out by checking if the estimated specular reflection delay lays within the correlation window, which is computed based on the GrIS topography height derived from BedMachine Greenland (Morlighem et al., 2017), and taking into account the geometry of the reflected signal.

The tracks of GNSS-R measurements (i.e., specular point tracks) are presented separately in Figures 1a and 1b for different seasons, that is, nonmelt season between November and March next year and melt season between April and October, in which each point represents the SNR from one DDM. Note that tracks across

Figure 1. Specular points tracks of the TDS-1 data overpass the Greenland ice sheet during April 2015 and September 2018. Each point represents the signal-to-noise ratio computed from one delay Doppler map. These tracks are divided into two groups by season: (a) nonmelt season (between November and March next year) and (b) melt season (between April and October).

the areas of highest elevation have been filtered out because of the tracking window issue. The difference between Figures 1a and 1b highlights the sensitivity of the GNSS-R data to changes in the permittivity of the reflecting surface (e.g., liquid water content). There is a seasonal SNR change over the GrIS, with SNR tending to increase during the melting seasons, especially along the west and northeast coast of GrIS, where the surface melt events happen more frequently (van den Broeke et al., 2009). In addition, there is a large substructure variability in observed SNR over the GrIS, which is likely due to a combination of different ice sheet properties (e.g., surface topography, roughness, and subsurface characteristics).

2.3. Methodology

Figure 1 indicates that the SNR of the reflected signal can represent the features of different surface conditions. The high SNR regions across coastal and ocean areas are mainly covered by sea ice, where the smooth surface can generate strong coherent reflections. In contrast, diffuse scattering from the open ocean can significantly reduce the SNR. The use of GNSS-R power to detect and characterize sea ice has been widely studied (e.g., Alonso-Arroyo et al., 2017; Cartwright et al., 2019; Nghiem et al., 2019; Yan & Huang, 2016), and it is not further investigated here. The DDMs collected over the GrIS show moderate SNR, and it is hypothesized that the reflected signal from the GrIS is a combination of coherent, volumetric, and incoherent scattering components. The SNR or power of the reflected signal is not only sensitive to the surface condition but also affected by the transmitted power, antenna gain, and distances (Voronovich & Zavorotny, 2018; Zavorotny & Voronovich, 2000), which should be corrected before further analyses. Due to the lack of a simple model for ice sheet reflected GNSS signal to determine both the coherent and incoherent scattered

power, these effects are corrected by simply assuming a coherent reflection to calculate the reflectivity Γ_{rl} similar to (Chew & Small, 2018)

$$\Gamma_{rl} \propto SNR - N_0 - G_r - G_t - P_t + 20 \log(R_{ts} + R_{rs}) - 20 \log(\lambda) + 20 \log(4\pi), \quad (1)$$

where SNR is the SNR ratio of the DDM provided in the TDS-1 L1b data, N_0 is the thermal noise floor, G_r is the receiving antenna gain, G_t and P_t are the transmitting antenna gain and transmitting signal power provided in Wang et al. (2019), which are estimated with a ground-based GPS signal power monitor system, R_{ts} is the distance between the transmitter and the specular point, R_{rs} is the distance between the receiver and the specular point, and λ is the GPS L1 signal carrier wavelength.

GNSS-R measurements are made along individual tracks of the specular points. The positions of these specular points are determined jointly by the positions of the transmitter and receiver, which generates a series of pseudorandom tracks over the surface (also see Figure 1). To facilitate the comparison between the TDS-1 GNSS-R data and the GrIS daily surface melting data, the corrected reflectivities are also gridded to the Equal Area Earth Scalable 2.0 25-km grid. The correspondence between the GNSS-R data and the grid cell is determined through a k-dimensional tree-based minimum distance algorithm between the specular point position and the grid cell center.

The approach we suggest to detect surface melting is based on the reflectivity increment in each grid cell corresponding to an empirical background reflectivity map. We suggest this approach to deal with the lack of a complete forward model of the ice sheet response to GNSS-R, making it difficult to properly correct the GNSS-R observables to obtain absolute values of reflectivity. As the surface reflectivity at a given grid cell is relatively constant during the nonmelt period, we can estimate the averaged reflectivity at each of these cells as the reference over the winter period when no melt is expected to occur, thus generating the empirical background reflectivity map (as shown in Figure S1). This map was derived from 3 years of surface reflectivity during the nonmelt seasons and averaged at each 25-km grid cell. With the background reflectivity, the change in reflectivity $\Delta\Gamma_{rl}$ is then computed by

$$\Delta\Gamma_{rl}(\phi, \theta) = \Gamma_{rl}(\phi, \theta) - \overline{\Gamma_{rl}^{bgr}}(\phi, \theta) \quad (2)$$

in which ϕ and θ are the latitude and longitude of the specular point, Γ_{rl} is the corrected reflectivity in Equation (2), and $\overline{\Gamma_{rl}^{bgr}}$ is the background reflectivity interpolated at (ϕ, θ) .

3. Results and Discussion

3.1. Observations During GrIS Melt Events

To examine the sensitivity of $\Delta\Gamma_{rl}$ to the GrIS melt, we explore the GNSS-R observations during two intense GrIS melt events between late July and early August 2018. The tracks of the specular points for the melt event on 31 July are shown in Figure 2a, with the color scale representing the change in reflectivity $\Delta\Gamma_{rl}$. The tracks are traced over the MWR melt map (orange/white), showing in orange the melted extension (above 724,000 km², roughly 44% of the GrIS). Similarly, Figure 2f shows the GNSS-R reflectivity collected during the melt event on 9 August, with the highest melt extent of 499,000 km² (or roughly a third of the GrIS), in which the transition in $\Delta\Gamma_{rl}$ can be also seen over the melt regions.

The measured surface reflectivity Γ_{rl} and the background reflectivity $\overline{\Gamma_{rl}^{bgr}}$ are compared in detail in Figures 2b–2e and 2g–2j for different tracks during these two melt events. It can be seen that the measured reflectivity, as expected, shows good consistency in amplitude and trend with the background reflectivity over the nonmelt regions. Conversely, the surface melt can significantly increase the reflectivity by up to 10 dB. However, it is noted the reflectivity increments over the melt occurrences vary between different regions. For example, the reflectivity increases by ~ 5 –8 dB on the northwest of the GrIS along the Track 3 but only by ~ 3 dB on the northeast along the same track. It could be due to the spatial variations in surface topography/roughness, ice sheet substructure, and the presence of the melt ponds over the GrIS surface. It is also noted that there are inconsistencies between the $\Delta\Gamma_{rl}$ transitions at the edge of the melt regions, for example, along the Tracks 6 and 7. These inconsistencies, as will be discussed below in section 3.2, can be attributed to uncertainties in both GNSS-R and MWR measurements, the different sensitivity of the GNSS

Figure 2. The tracks of the specular points over two Greenland ice sheet (GrIS) melt event on 31 July and 9 August 2018. (a) The tracks of the specular points over the GrIS melt event on 31 July 2018. The melt extent indicated in orange is derived from the Special Sensor Microwave Imager/Sounder brightness temperature, and the color scale of each point along the specular point tracks represents the change in reflectivity $\Delta\Gamma_{rl}$. (b–e) The upper panel of each plot presents the melt status along the specular point tracks according to the SSMI MWR (melt: 1, nonmelt: 0). The measured surface reflectivity and the background reflectivity are compared in the lower panel of each plot. (f) The same as (a) but for the melt event on 9 August. (g–j) The same as (b)–(e) but for the tracks during the melt event on 9 August 2018.

L-band and SSMIS Ka-band signals to melt occurrence, and different local time of day sampling for the GNSS-R and MWR data.

3.2. Validation With Statistical Analyses

The TDS-1 GNSS-R reflectometry data were only available for 2 out of 8 days before February 2017. Thus, only the data collected in 2018, when the GNSS-R payload was in full operation mode (7/7 days), were used in our statistical validation. In Figures 3a and 3b, the numbers of melt days during the 2018 melt season (May–October) are compared to the averaged changes in reflectivity for each cell. In general, the

Figure 3. (a) The number of melt days over the Greenland ice sheet for each 25-km grid cell, which is accumulated from the Greenland daily MWR surface melt map during the 2018 melt season (May–October). (b) The averaged changes in GNSS-R reflectivity for each grid cell computed with the TDS-1 data collected during the 2018 melt season (May–October). (c) The probability density functions of $\Delta\Gamma_{rl}$ for different melt status (melt and nonmelt).

spatial pattern of observed changes in reflectivity agrees with the spatial pattern of the number of melt days, particularly along the west and east coast of GrIS. However, because of the random surface sampling and the relatively limited number of the GNSS-R data, we are not able to find strong correlation between the reflectivity change and the number of melt days (with the correlation coefficient of 0.64). In other words, the number of melt days are computed from a full set of data daily available for each grid, while the GNSS-R data can only revisit a grid cell in a couple of days, which can not fully sample the melt occurrence in either temporal and spatial scales.

Table 1

Greenland Ice Sheet Melt Detection Performance using TechDemoSat-1 GNSS Reflectometry Data

$n_{\text{melt}}^{\text{M}}$	$n_{\text{melt}}^{\text{F}}$	$n_{\text{nonmelt}}^{\text{F}}$	$n_{\text{nonmelt}}^{\text{M}}$	P_{d}	P_{f}	P_{e}
5158	580	39098	3093	0.90	0.07	0.37

Note. $n_{\text{melt}}^{\text{M}}$ is the number of correct melt detection samples. $n_{\text{melt}}^{\text{F}}$ is the number of missed melt detection samples. $n_{\text{nonmelt}}^{\text{F}}$ is the number of correct nonmelt detection samples. $n_{\text{nonmelt}}^{\text{M}}$ is the number of missed nonmelt detection samples. P_{d} is the probability of melt detection. P_{f} is the probability of false alarm. P_{e} is the probability of false detection.

Taking into account the limitation of the TDS-1 GNSS-R data, the sensitivity of GNSS-R reflectivity to surface melt has been evaluated through a Bayesian approach. Given the collocated MWR surface melt status for each GNSS-R sample, the changes in reflectivity $\Delta\Gamma_{\text{r}}$ are classified into two groups. The probability density functions (PDFs) of $\Delta\Gamma_{\text{r}}$ are presented in Figure 3c for the melt and nonmelt cases, respectively, from which a clear separation between the PDFs can be seen. The mean change in reflectivity is ~ 0 dB for the nonmelt case and is ~ 5.4 dB over the melt occurrence. From these PDFs, the following statistics are defined:

$$P_{\text{d}} = \frac{n_{\text{melt}}^{\text{M}}}{n_{\text{melt}}^{\text{M}} + n_{\text{melt}}^{\text{F}}} \quad (3)$$

$$P_{\text{f}} = \frac{n_{\text{nonmelt}}^{\text{M}}}{n_{\text{nonmelt}}^{\text{M}} + n_{\text{nonmelt}}^{\text{F}}} \quad (4)$$

$$P_{\text{e}} = \frac{n_{\text{nonmelt}}^{\text{M}}}{n_{\text{melt}}^{\text{M}} + n_{\text{nonmelt}}^{\text{M}}} \quad (5)$$

in which $n_{\text{melt}}^{\text{M}}$ is the number of samples identified as melt in both GNSS-R and MWR (correct melt detection), $n_{\text{melt}}^{\text{F}}$ the number of samples identified as melt in MWR but not in GNSS-R (missed melt detection), $n_{\text{nonmelt}}^{\text{F}}$ is the number of samples identified as nonmelt in both GNSS-R and MWR (correct nonmelt detection samples), $n_{\text{nonmelt}}^{\text{M}}$ is the number of samples identified as nonmelt in MWR but as melt in GNSS-R (missed nonmelt detection), P_{d} is the ratio between the number of correct melt detection samples and the total number of samples identified as melt in MWR (probability of melt detection), P_{f} is the ratio between the number of missed nonmelt detection samples and the total number of samples identified as no-melt in MWR (the probability of false alarm), and P_{e} is the ratio between the number of missed nonmelt detection samples and the total number of samples identified as melt in GNSS-R (the probability of false detection).

The statistics are computed by using a threshold of 2.4 dB, which is the intersection of the two PDFs. As shown in Table 1, the probability of correct melt detection is 0.90, with the probability of false alarm and probability of false detection being 0.07 and 0.37, respectively. The errors in melt detection are mainly due to the large width of the PDFs, which represents the variations of the observed reflectivity over each grid cell and under the same melt condition. There are several factors for these variations, including the errors in GNSS-R data calibration and correction, differences in spatial and temporal sampling strategies between the GNSS-R data and the SSMIS MWR data, the frequency difference between the two instruments, and the ice sheet heterogeneity within the grid cells, which are discussed below.

1. The background reflectivity is derived from 3 years of GNSS-R data, which could be affected by the amount of winter snow accumulation every year. Moreover, the ice sheet in each grid cell can be heterogeneous due to factors like snow density, surface topography, and subsurface characteristics, which can generate significant variations in background reflectivity within each grid cell. A background reflectivity map with higher spatial resolutions and computed during the previous winter for individual years may help to remove these confounding effects, which would be possible with the availability of large amount of GNSS-R data from future spaceborne missions, for example, CYGNSS follow-on mission (Ruf et al., 2018) and SPIRE's commercial GNSS-R CubeSat constellation.
2. The PDF of $\Delta\Gamma_{\text{r}}$ shows a significant skewness when the surface is classified as melting with the MWR data. This can be attributed to the difference in penetration depth due to the frequency difference between

the two instruments. The MWR data are limited to detect the melt onset occurring within the first few centimeters of snowpack, while the larger penetration depth of the L-band signal makes the GNSS-R measurements sensitive to the subsurface melt remaining after surface refreeze. This phenomenon of extended melt detection is justified by the larger probability of positive $\Delta\Gamma_{\text{rl}}$ under nonmelt condition, which could be one of the main reasons for the large P_f and P_e . On the other side, this result suggests that GNSS-R data could be exploited to determine the melt events up to tens to hundreds of meters, which can provide new information compared to the existing melt product derived from higher frequencies observation, for example, the presence of subsurface melt remaining after surface refreeze (see Figure S2 in the supporting information).

3. The PDF of $\Delta\Gamma_{\text{rl}}$ for the melt case is wider than the nonmelt case, indicating larger dispersion of reflectivity increment over the melt zones. This is likely due to the sensitivity of GNSS-R reflectivity to some other factors, for example, the degree of melt (e.g., liquid water content) and the area of the surface melt ponds. In addition, the sensitivity of $\Delta\Gamma_{\text{rl}}$ to melt onset could also depend on the geolocation of the measurement over the GrIS due to the variability of the ice sheet features. The detection algorithm could increase robustness in the future, when more polar GNSS-R data sets are available and the threshold for melting detection at a given cell would be based on the internal dispersion of the winter period at the same cell. The limited amount of observations at some cells hinders this approach in the present data set.
4. Another factor affecting GNSS-R melt detection is the local time of the GNSS-R samples. Due to the pseudorandom sampling nature of the GNSS-R technique, the measurements are not collected following fixed time schedule over the GrIS. In addition, the TDS-1 GNSS-R data can only cover a grid cell in a couple of days due to the limitation of its platform and instrument as a demonstrator. It means that, even being collected on the same day, the TDS-1 GNSS-R measurement and the MWR observations can be many hours apart from each other, which could also affect the melt detection comparison. Moreover, it would be also helpful to develop a set of background reflectivity maps for different local time of day, which relies on the availability and accumulation of spaceborne data over the GrIS from future polar GNSS-R missions.
5. The uncertainties of GNSS-R data calibration and correction are considered to be the main error sources in GNSS-R reflectivity calculation. First, the power of the reflected signal is not well calibrated, in which the variations of the receiver and antenna noise temperatures, the uncertainty in antenna gain due to the satellite altitude errors, and the variation of transmitted signal power are not taken into account due to the nature of the instrument and platform as a demonstrator mission. These factors, however, can be eliminated in future missions dedicated to GNSS-R scatterometry applications. Moreover, the computation of the reflectivity in (1) is based on the assumption of completely coherent reflection, in which the effects of incoherent component due to the volumetric and diffuse scattering are not taken into account. The development of a model to quantify all these effects for spaceborne GNSS-R data would be helpful for improving the correction in reflectivity.

4. Conclusions and Prospects

The capability of spaceborne GNSS-R on GrIS melt detection has been demonstrated for the first time using the TechDemoSat-1 data. The melt detection is based on the fact that the presence of liquid water in snow pack can produce an increase in reflectivity and thus the power of the reflected GNSS signal. By using the reflectivity increment from the empirical background reflectivity, the melt occurrence can be detected. The statistical analyses have shown that melt detection using GNSS-R is possible with an agreement of 90% comparing with the MWR data but with a relative large probability of false detection of 37%. However, these inconsistencies do not necessarily indicate shortcomings of GNSS-R technique but rather the different features of the two observation concepts and the limitations of the currently available spaceborne GNSS-R data.

An important reason for the difference observed between the GNSS-R data and the MWR data is the difference in penetration depth due to the electromagnetic wave frequencies. The MWR data can only detect the liquid water within the surface layer (few centimeters) over the GrIS, while the GNSS signal can penetrate into the snow pack by up to hundreds of meters, which makes the GNSS-R measurements sensitive to the presence of the liquid water in the subsurface. A combination of these measurements from both frequencies may provide more information about the melt event, for example, the intensive of melt, and the process of the melt water percolation to the subsurface.

Better understanding on the interaction of L-band electromagnetic wave with the ice sheet and corresponding forward scattering model are important for improving the performance of GNSS-R GrIS melt detection. Moreover, other GNSS-R observables, like the altimetric feature, the characteristics of the DDM (e.g., its shape and width), may also include the melt information of the ice sheet. The combination of these observables can be explored to better understand the response of the reflected GNSS signal to the melt occurring at different depth. Such analysis relies on further collection of airborne/spaceborne GNSS-R data, as well as corresponding in situ data.

The results shown in this work are obtained with limited amount of spaceborne GNSS-R data collected by a technique demonstration platform. A sensor optimized for GNSS-R scatterometry or polar applications (Camps et al., 2018; Cardellach et al., 2018) would reduce the measurement uncertainty, avoid the loss of data by the correlation window issue, and allow better melt detection performance. Moreover, the main advantage of the GNSS-R concept is its spatiotemporal sampling capability. The low-power, low-cost, and lightweight features of such payload make it possible to build a constellation of small satellites. For example, the CYGNSS mission can cover the tropical oceans ($\pm 40^\circ$) with spatial resolution of 25 km and mean revisit time of 7 hr by only using the signal from the GPS satellites (Ruf et al., 2018). A similar constellation with polar orbit, and carrying sensors capable of receiving signals from the other GNSS constellations (e.g., Galileo, BeiDou, and GLONASS), would provide higher spatial and temporal resolutions (e.g., 2- to 3-hr revisit time with 25 km or better spatial resolution) data over the GrIS and the other polar regions.

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