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Published in:
Remote Sensing

Link to article, DOI:
10.3390/rs14112563

Publication date:
2022

Document Version
Publisher's PDF, also known as Version of record

remote sensing

Technical Note

Snow Depth Measurements by GNSS-IR at an Automatic Weather Station, NUK-K

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Abstract: Studies have shown that geodetic Global Navigation Satellite System (GNSS) stations can be used to measure snow depths using GNSS interferometric reflectometry (GNSS-IR). Here, we study the results from a customized GNSS setup installed in March through August 2020 at the Programme for Monitoring of the Greenland Ice Sheet (PROMICE) automatic weather station NUK-K located on a small glacier outside Nuuk, Greenland. The setup is not optimized for reflectometry purposes. The site is obstructed between 85 and 215 degrees, and as the power supply is limited due to the remote location, the logging time is limited to 3 h per day. We estimate reflector heights using GNSS-IR and compare the results to a sonic ranger also placed on the weather station. We find that the snow melt measured by GNSS-IR is comparable to the melt measured by the sonic ranger. We expect that a period of up to 45 cm difference between the two is likely related to the much larger footprint GNSS-IR and the topography of the area. The uncertainty on the GNSS-IR reflector heights increase from approximately 2 cm for a snow surface to approximately 5 cm for an ice surface. If reflector height during snow free periods are part of the objective of a similar setup, we suggest increasing the logging time to reduce the uncertainty on the daily estimates.

Keywords: automatic weather stations; GNSS-IR; reflectometry; snow depth; Greenland

Citation: Dahl-Jensen, T.S.; Citterio, M.; Jakobsen, J.; Ahlstrøm, A.P.; Larson, K.M.; Khan, S.A. Snow Depth Measurements by GNSS-IR at an Automatic Weather Station, NUK-K. *Remote Sens.* **2022**, *14*, 2563. https://doi.org/10.3390/rs14112563

Academic Editors: Dariusz Ignatiuk and Shridhar Jawak

Received: 7 April 2022
Accepted: 23 May 2022
Published: 27 May 2022

1. Introduction

The Greenland ice sheet has recently become the largest individual ice mass contributor to global eustatic sea level rise [1]. In recent years, the Surface Mass Balance (SMB) has come to dominate the mass loss from the Greenland ice sheet and, consequently, its contribution to global sea level rise [2,3]. In situ observations of snow depth are important for constraining or verifying models of surface mass balance and improving SMB estimates [4–6].

In the last decade, Global Navigation Satellite System Interferometric Reflectometry (GNSS-IR) has been introduced as a method to estimate snow depth using existing geodetic GNSS stations (e.g., [7–9]). The method is highly suitable for remote regions, as the stations are simple to run and often deployed for other purposes. The footprint of the daily snow depth estimates depend on the height of the antenna above the surface and is typically on the order 1000–10,000 m^2 (e.g., [10,11]). In comparison, sonic rangers, traditionally installed for in situ measurements of snow depth, have a footprint of just around 1 m^2. The result is a measurement which is very sensitive to local snow conditions [12]. Furthermore, it has a delicate membrane that degrades over time due to the thaw-freeze cycles and needs to be replaced regularly, preferably each year [13]. In remote locations such as the Greenland ice sheet, yearly visits are expensive and time consuming, and compared to sonic rangers, a GNSS station requires little maintenance. Another advantage of using GNSS-IR to measure snow depth is that the position of the antenna can be determined with a high precision using GNSS positioning, and thus, the snow surface elevation can be determined in a geocentric reference frame. This snow surface estimate can be useful as reference points for altimetry products.

The Programme for Monitoring of the Greenland Ice Sheet (PROMICE) runs 27 automatic weather stations in Greenland. Most of these are located in the ablation zone of the Greenland ice sheet. The weather stations measure multiple meteorological parameters as well as snow depth (using sonic rangers) and ablation [14]. In order to locate the weather stations on flowing glaciers, they are currently equipped with a simple GPS, logging and transmitting only the position and time.

In an effort to measure precise ice flow velocities, a dual-frequency carrier phase GNSS station was installed at NUK-K to test if a suitable setup could be made at the weather stations. Even though this experiment was sub-optimally designed for GNSS reflections, we will use this dataset to compute snow accumulation and compare the results with data collected with a sonic ranger.

2. Materials and Methods

2.1. Automatic Weather Station

On 6 March 2020, a GNSS station was installed at the PROMICE weather station NUK-K, situated on a small local glacier outside Nuuk, Greenland (Figure 1). The setup consists of a Novatel pinwheel 704 antenna and a Septentrio AsteRx-m receiver. The GNSS station was equipped with its own power supply consisting of a 2 watt solar panel and a small internal battery. The glacier is approximately 1100 m (north–south) by 600 m (east–west). The purpose was to test the setup for high precision positioning with the goal of installing a similar setup on other PROMICE weather stations to measure ice velocities. As it was a test setup, it was removed when the data were collected on August 31st of the same year. The GNSS station tracks GPS, Galileo and Glonass signals at 5 s intervals. Due to the remote location of the weather station, the power supply is very limited, and therefore, the GNSS data logging is limited to three hours each day. The GNSS antenna is placed at the top of the central mast of the weather station with the antenna phase center approximately 2.95 m above the ice surface (Figure 2).

Figure 1. Map of the area including Nuuk and the weather station. The red triangle marks the position of the weather station (NUK-K). Map data ©2015 Google.

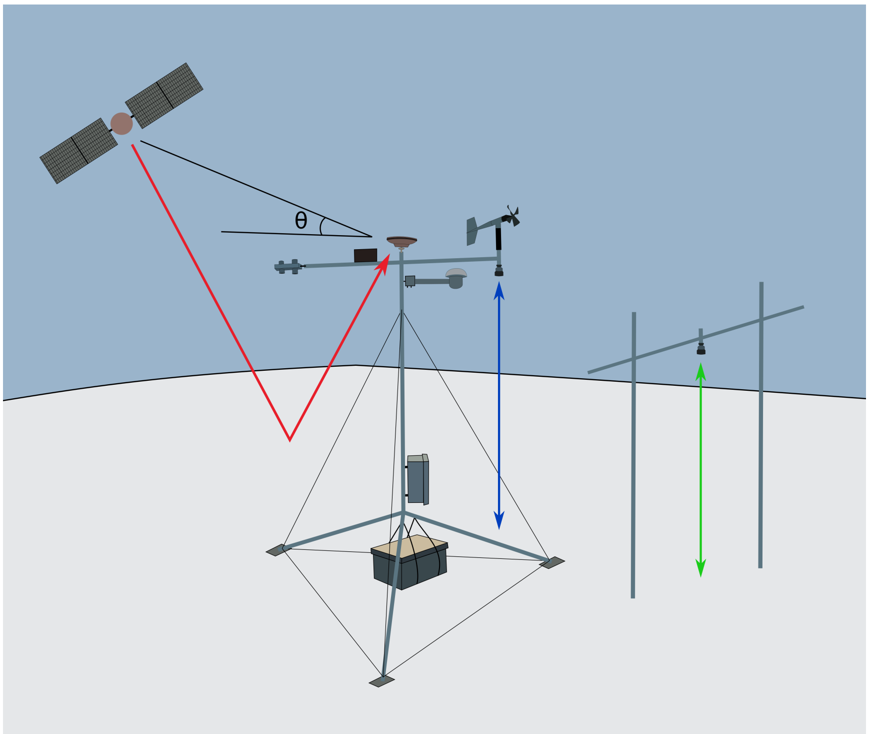

Figure 2. Illustration of PROMICE weather station NUK-K. The red arrow illustrates reflected signal used for Global Navigation Satellite System Interferometric Reflectometry (GNSS-IR) reflector heights. The blue arrow illustrates reflector height measured by the sonic ranger on the boom. The green arrow illustrates the distance to the snow surface as measured by the sonic ranger on stakes.

The weather station, NUK-K, has been running since July 2014 and continuously measures a number of climate variables such as radiation (in and out), temperature, pressure, wind speed and direction, humidity and snow height [14,15]. Currently, snow height is measured using sonic rangers. A sonic ranger measures the distance to the surface by transmitting a ultrasonic pulse and measuring the time it takes for the pulse to return. The pulse is sent out in a cone of 22 degrees resulting in a footprint of less than one m^2 for a distance up to 2.6 m [12]. The station is equipped with two sonic rangers. One is placed on the sensor boom (blue arrow on Figure 2) and located approximately 2.6 m above the ice surface. As the station is standing on the ice, it will follow any ice melt, and therefore, the sonic ranger on the boom is unable to measure ice melt. The other sonic ranger is installed on stakes drilled into the ice and, thus, also measures the ice melt (green arrow in Figure 2).

Albedo estimates are used to confirm the transition from a snow surface to an ice surface. They are distributed with the data from the weather station and based on measured incoming and outgoing shortwave radiation, as described in Fausto et al. [14].

2.2. GNSS-IR

It has long been known that reflected signals cause error in GNSS positioning because the modeled direct signal path is different than the observed reflected signal path. The impact of reflected signals on Signal to Noise Ratio (SNR) data is less appreciated because SNR data are rarely used in positioning applications. The direct GNSS signal observed in SNR data smoothly increases as a satellite rises and then smoothly decreases as the satellite sets. Without the multipath effect, this effect can be modeled as a low-order polynomial. When a GNSS site is impacted by reflected signals, the observed SNR data include the direct signal and the interference between the direct signal and the reflected signal. In the GNSS-IR method, the direct signal is removed by fitting a low-order polynomial to SNR data for either the rising or setting satellite arc. What remains in the satellite arc is only the interferometric data. For convenience, in the figures, we call this SNR data, but it should be understood that this is the interferometric effect retrieved from the SNR data. If the contribution from the direct signal is removed, the SNR can be modeled as a function of the satellite elevation angle, θ (e.g., [16–18]):

$$\mathrm{SNR}(\theta) = A(\theta) sin\left(\frac{4\pi H_R}{\lambda} sin(\theta) + \phi\right) \tag{1}$$

where A is the amplitude, which depends on the transmitted GNSS signal power, the elevation angle, the antenna gain pattern and the dielectric constant and roughness of the reflecting surface, H_R is the reflector height, λ is the wavelength of the transmitted signal and ϕ is a phase constant. Changing the variable from elevation angle to the sine of the elevation angle, the SNR has a constant frequency of:

$$f = \frac{2H_R}{\lambda} \tag{2}$$

thus, the reflector height can be determined from the dominant frequency in the SNR data. In order to be able to estimate the reflector height, it has to be at least two times the wavelength, which, depending on the GNSS signal, corresponds to between 0.4 and 0.5 m.

The footprint of GNSS-IR estimates of snow depth is determined by the first Fresnel zones and depends on the elevation angle of the satellite and the height of the reflector [19]. For elevation angles down to 5 degrees, as used here, the daily reflector heights are sensitive to snow height in an area between approximately 4000 m^2 (for a reflector height of 0.5 m) and 20,000 m^2 (for a reflector height of 3 m). However, at NUK-K a hill on the south-eastern side of the weather station is blocking the view at low elevation angles, and thus, we have no reflector height extractions between 85 and 215 degrees and the area of sensitivity is reduced to between approximately 2500 m^2 and 13,000 m^2 (see Figure 3).

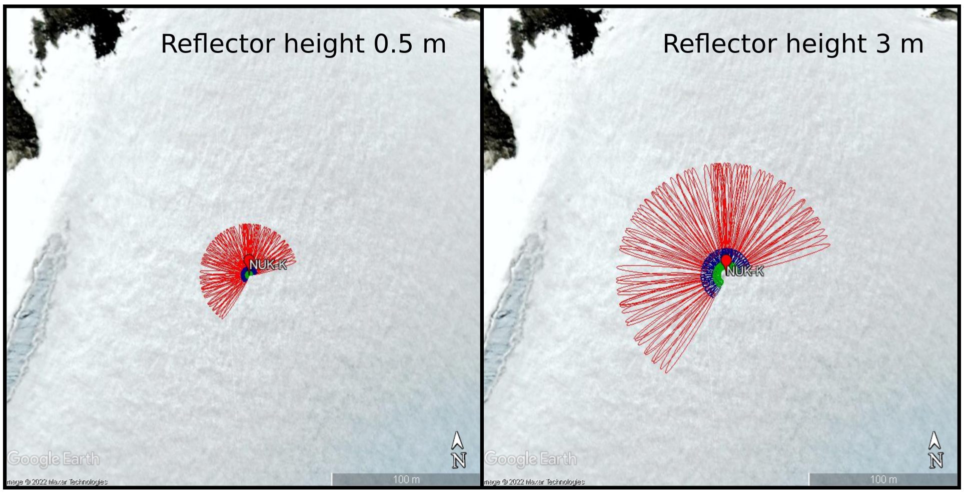

Figure 3. Reflection zones at NUK-K for a reflector height of 0.5 and 3 m at three satellite elevation angles. Red: 5 degree elevation, blue: 15 degree elevation and green: 25 degree elevation.

The software used to estimate reflector heights from the GNSS data is available on GitHub [20] and the method described in Roesler and Larson [21]. First, SNR data are extracted from the Rinex files. The direct signal is removed by fitting and subtracting a fourth-order polynomial. The reflector height is then estimated from each satellite track and frequency using a Lomb-Scargle periodogram [22]. For each estimate, a set of requirements are set in order to accept the estimated reflector height and include it in the daily estimates: the track has to cover the elevation angles from 10 to 20 degrees, the peak to noise ratio over estimated heights between 0.5 and 5 m has to be 3 or higher and the peak amplitude has to be at least 5. There is one exception from these general Quality Control (QC) parameters, namely the minimum peak amplitude for GPS L2C, which is set to 2 since the signal is considerably weaker than for the other frequencies. These QC parameters were determined from inspection of periodograms for a number of days evenly spread over the measuring period and at all tracked frequencies. We find useful reflections from GPS L1 and L2C, Glonass L1 and L2 and Galileo E1, E5a and E5b. Unfortunately, GPS L5 was not tracked at this station.

After estimating the reflector heights from the satellite tracks, daily solutions are obtained from the average of the accepted tracks.

3. Results

Figure 4a shows the distance to the snow surface measured by GNSS-IR and the sonic ranger on the sensor boom. There is a period of missing data from day 154 to 183 due to issues with the power supply limiting the logging to a degree where it was not possible to extract reflector heights. The uncertainty for the daily GNSS-IR reflector heights are estimated as the standard deviation of mean and has an average of 3 cm. There is also a sonic ranger on stakes next to the weather station. However, it did not function during most of the measurement time for the GNSS station, and as it also measures the ice melt, and is, therefore, not directly comparable to the GNSS-IR reflector height, it was not included in the plot.

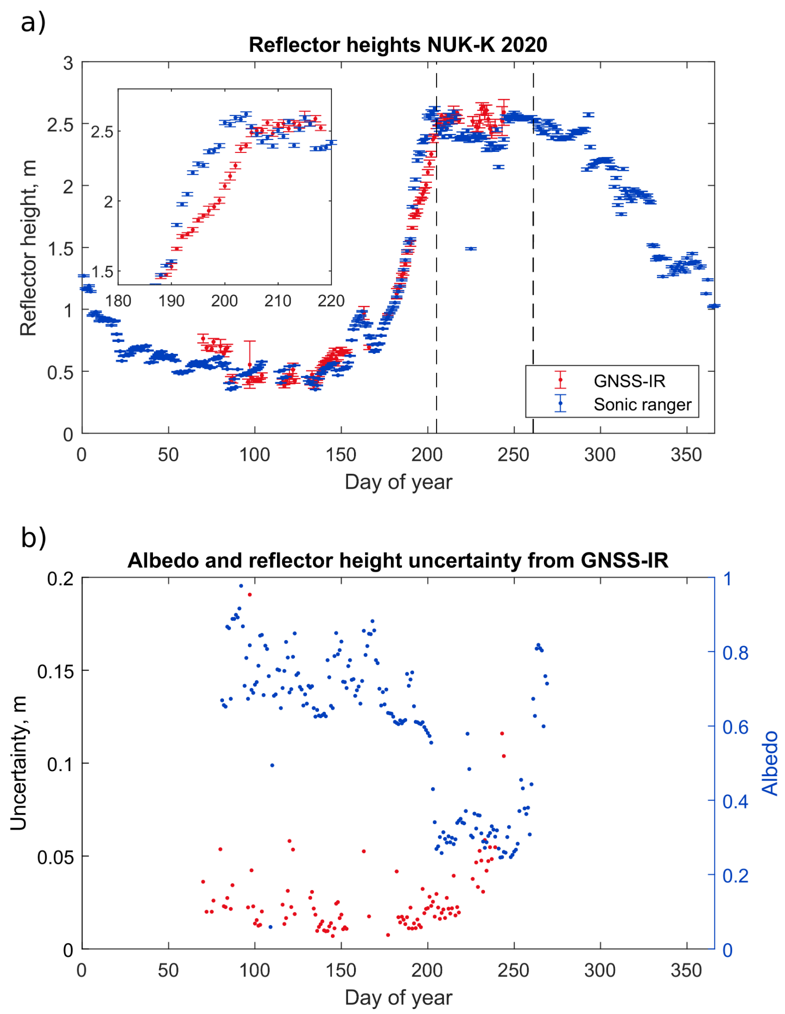

Figure 4. (**a**) Daily average reflector heights measured by GNSS-IR and the sonic ranger on the boom. The GNSS-IR reflector height has been corrected for a bias as compared to the sonic ranger. The bars are the uncertainty estimated as the daily standard deviation of mean. The dashed lines indicate when the snow cover is effectively lost in the summer and when the first snow returns in the autumn as indicated by the albedo. (**b**) Albedo estimated from in- and outgoing shortwave radiation together with the uncertainty on the estimated daily reflector heights from GNSS-IR.

Before comparison, we correct the GNSS-IR data for a bias of 26.5 cm to align the two data series as the GNSS antenna and the sonic ranger is not located at the same height above surface and the GNSS setup measures snow height over a much larger area. The GNSS-IR reflector height clearly captures the snow melt as measured by the sonic ranger. However, in some periods there are significant differences between the two, most clearly from day 190 to 210, where the sonic ranger shows faster melt than the GNSS station, reaching a difference between the two reflector heights of 45 cm on day 200. The linear correlation between the results from the sonic ranger and the GNSS station is 0.98 and the RMSD is 17 cm.

The estimated uncertainty on the daily GNSS-IR reflector heights vary over the measurement period. It is generally small (average of 2 cm) during most of the melt period and increasing towards the end of the data series (average of 5 cm). Figure 5 shows the periodograms for all tracked signals from day 140, where the uncertainty is low, and day 229, where it is high. The two days are chosen as they are representative of the two states of the measurement. On both days there are multiple successful extractions (red curves). However, while the peaks of all accepted tracks are close together on day 140, there is considerable noise on day 229.

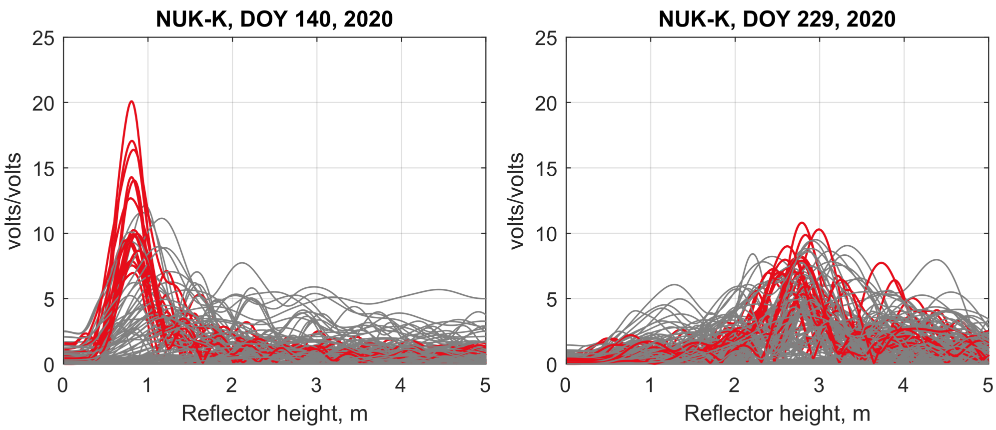

Figure 5. Periodograms from the GNSS-IR extractions of all tracked frequencies on day 140 (**left**) and 229 (**right**). The grey lines are satellite tracks that are discarded in the QC process and the red lines are tracks that are accepted.

We expect that the reason for the increased noise in the periodograms and resulting uncertainty is a change in the reflecting surface. When the snow melts, the smooth snow surface is exchanged for a potentially much rougher ice surface, which is not as good a reflector. Figure 4b shows the estimated albedo together with the uncertainty on the daily reflector heights from GNSS-IR. Around the time where the albedo drop to ice levels, the uncertainty starts to increase and continues to do so. Thus, changes in surface properties and in particularly smoothness after the snow has melted is a likely reason for the increased uncertainty.

4. Discussion

The reflector height from the GNSS-IR shows a snow melt similar to what is measured by the sonic ranger on the weather station. However, the RMSE is considerably larger than the estimated uncertainty on the measurements. The difference between the two measurements is not evenly distributed over the year; while it is small in the first part of the melt season, it is large towards the second half of the melt season (approximately day 190–210), reaching up to 0.5 m. As the glacier is not completely horizontal, a possible reason for this change could be that the azimuths of the accepted reflections changed, resulting in a different area of sensitivity and a different reflector height. However, comparing the number of accepted tracks in three azimuth quadrants over the measurement period, no clear change is seen around this time (Figure 6). The quadrant from 90 to 180 degrees is not included in the figure, as it is completely obstructed by the hill, and thus, there are no extractions. We also observe larger differences between the GNSS-IR and sonic ranger results from before the melt season. In this case, there is a difference in the azimuths compared to later with a significantly larger part of the measurements coming from the 180–270 degree bin. This can be explained by that part of the glacier being uphill from the station resulting in lower reflector heights.

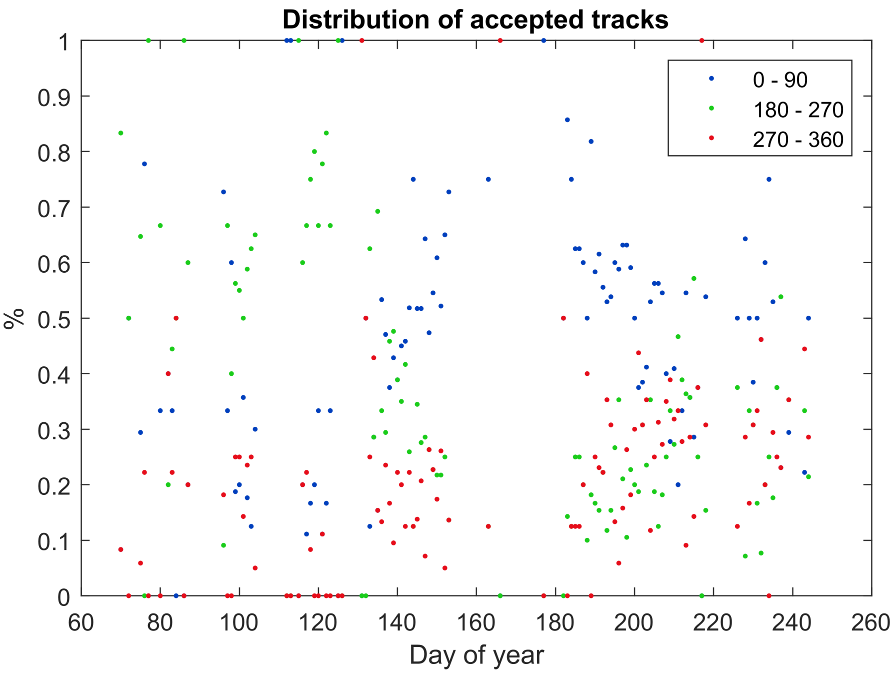

Figure 6. Azimuthal distribution of accepted satellite tracks for GNSS-IR.

Larson and Nievinski [11] ran simulations of the error resulting from slopes up to 8 degrees for a reflector height between 1 and 2 m and found that the error as a result of the slope was within 10 cm. Thus, though slope in some parts of the sensing area may be just slightly larger than 8 degrees, the slope in itself cannot explain the large differences from day 190 to 210.

The snow density also affects the reflections. However, Gutmann et al. [23] modeled the effect of snow density, and though it has significant influence on the amplitude of the SNR oscillations, it did not affect the frequency (and thereby reflector height) significantly.

Larson et al. [10] calculated reflector height at the old radar station DYE-2 and compared the result with in situ measurements of snow accumulation. They found a standard deviation of difference between 9.4 and 9.5 cm, which is about half of what we find here. However, there are several reasons we should not expect results at NUK-K to be equally good. DYE-2 is located at the interior of the ice sheet with no obstructions and logging every 15 s all day. In comparison, the GNSS station at NUK-K is logging 3 h a day at best (often less due to lack of power) and is obstructed over an angle of 130 degrees, corresponding to a data loss of 36%. Furthermore, the topography of the area likely results in an uneven snow distribution, and since the GNSS-IR and sonic ranger have different areas of sensitivity, a considerable part of the difference may also be an actual difference in the surface height changes at the point right below the sonic ranger and over the area covered by the GNSS-IR measurement.

The increased uncertainty after the snow has melted is not an issue as long as the goal is measuring changes in snow depths. Since the GNSS-IR is mounted on the weather station, GNSS-IR reflector heights will not directly capture any melt of the ice after the snow is gone. However, the ice melt could be estimated from the change in the vertical position of the GNSS antenna and the surface could be estimated in a geocentric reference frame by combining position and reflector height (e.g., [9,10]). In this case, one should take into account that the uncertainty of the measurement might increase significantly for an ice surface. This ability to measure ice melt and absolute surface heights is an advantage compared to the sonic rangers. A second sonic ranger on stakes is needed in order to measure ice melt, and this setup is relatively unstable, as it needs regular re-drilling in order to keep it from melting out or collapsing [13].

If more GNSS stations are installed at PROMICE stations in the future, the power consumption could be decreased by setting the logging rate to once each 30 s. This would decrease both the power consumption of the GNSS station and the needed disk space while being safely within the pseudo-Nyquist limit for the antenna height of this setup [21]. If it is possible to increase the logging time by decreasing the sampling rate, this would be highly beneficial, as it would increase the number of daily extractions and, thereby, decrease uncertainty. This is particularly important if there is interest in the absolute height of the ice surface, as we have seen that the uncertainty of the measurement increases significantly after the transition from a snow to an ice surface. Currently, this setup is not stable enough to replace the sonic rangers on the PROMICE weather stations as the power issues result in some gaps in the data set (e.g., day 154 to 183). Furthermore, as these weather stations are already visited regularly for other forms of maintenance, the membranes can be exchanged without additional travel cost. However, it is valuable as it estimates the melt over a larger area of the glacier and adds the possibility of measuring ice melt and the position of the ice surface in a geocentric reference frame.

In studies where high precision positioning is not needed, an option could be to install a simple GPS for GPS-IR. Williams et al. [18] installed a consumer-type GPS unit for measurements of sea level from reflectometry. They found that reflectometry results were at least as good as for a geodetic station, though positioning accuracy is a couple of orders of magnitude worse than a geodetic station.

It should be noted that the method may not be suitable at all PROMICE locations, as the surface may be too rough and fractured or there may be too much topography or obstruction by mountains.

5. Conclusions

A dual-frequency carrier phase GNSS unit was installed to measure velocity changes at the NUK-K site from early March to end of August 2020. The deployment was poorly designed for GNSS reflections because of local obstructions and the need to restrict tracking to three hours to save power. These restrictions resulted in only 1/20 of a typical polar deployment dataset being available. This degraded the results compared to previous studies (e.g., [5,10]). Even so, we were able to successfully extract snow accumulation from the three constellations being tracked which compared reasonably well with a sensor that is nearby but not in a coincident footprint.

We find that the uncertainty on the measurement is low when the surface is snow covered, while it increases when the snow has melted, leaving a rougher ice surface. We compare the results to data from a sonic ranger on the instrument boom. We find that the two measurements generally capture similar snow melt, but that in the second half of the melt season, the total snow melt as measured by the sonic ranger is higher than measured by GNSS-IR. We expect that this is because the footprint of GNSS-IR ($\sim$10,000 m^2) is much larger than for the sonic ranger ($\sim$1 m^2), thus capturing snow melt over a larger area.

If a similar setup is made with the purpose of doing both positioning and reflectometry, several changes to this setup could be made to improve it for GNSS-IR:

- A measurement frequency of 5 s is much higher than needed. A 30 s sampling would be sufficient.
- The reflectometry is severely obstructed by the landscape. If possible, this should be considered when placing the station.
- GPS L5 was not tracked here. It is more suited for reflectometry than L1 and should be tracked if possible.

Author Contributions: Methodology, T.S.D.-J.; Formal analysis, T.S.D.-J.; Hardware and Fieldwork: M.C.; Software, K.M.L.; Resources, J.J., A.P.A. and M.C.; Writing—original draft preparation, T.S.D.-J.; Writing—review and editing, All; Visualization, T.S.D.-J.; Supervision, S.A.K. and K.M.L. All authors have read and agreed to the published version of the manuscript.

Funding: Design and construction of the GNSS receiver was supported by the EU Horizon 2020 Integrated Arctic Observation System (INSTAROS) Project GA No. 727890. Field deployment and the AWS were supported by the Danish Energy Agency through the Programme for the Monitoring of the Greenland Ice Sheet (PROMICE) and the Greenland Ecosystem Monitoring (GEM) GlacioBasis Programme. The field visits were carried out in coordination with Asiaq Greenland Survey.

Data Availability Statement: Weather station data from NUK-K can be downloaded from the PROMICE database [15]. The GNSS data from NUK-K are available upon request.

Conflicts of Interest: The authors declare no conflict of interest.

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