Sensing Snow Depth Over Arctic Sea Ice Using GPS Reflectometry

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Abstract

In the Arctic Ocean, sea ice processes are partly regulated by the thickness of the snow layer above it. Therefore, it is important to obtain reliable estimates of snow depth over sea ice to understand ongoing changes in the Arctic Ocean. Here, we explore the feasibility of snow depth estimation using Global Navigation Satellite System-Interferometric Reflectometry (GNSS-IR). This remote sensing technique uses the interferometric pattern in the GNSS Signal-to-Noise Ratio (SNR) observable, which results from the direct and reflected GNSS signal interference, to estimate the reflector height. In the case of Arctic sea ice, the reflector is snow, and vertical distance changes are due to snow accumulation or melt. The cm-level precision of the GNSS-IR technique has previously been demonstrated using stationary GNSS antennas. Here, data from the Sea Ice Dynamic Experiment (SIDEx) is used to investigate the precision of dynamic GNSS antennas anchored to an ice floe, drifting with the Arctic Ocean ice pack. We have processed approximately one month of GNSS data from 12 identical GNSS systems deployed during the March 2021 SIDEx campaign, forming a small-scale network of ~5 km. There are noticeable differences between systems' reflector heights, possibly attributed to the quality of the reflecting environment.

GNSS-IR and Reflector Heights

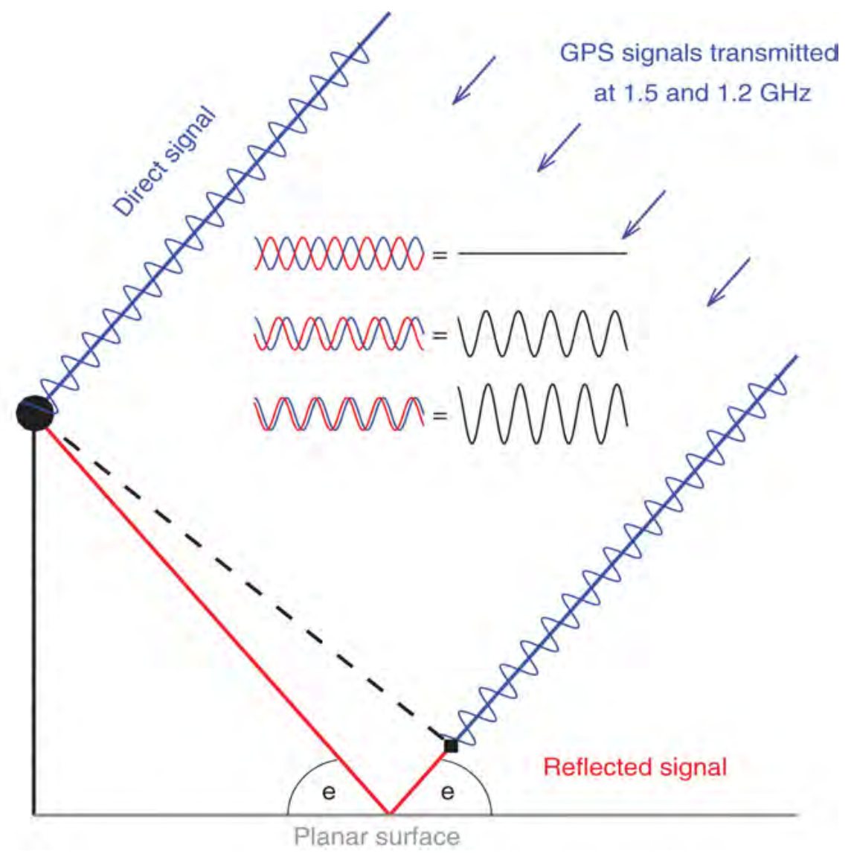

Fig. 1 (above): visualization of the GNSS-IR process[1].

GNSS signals at low elevation angles reflect off the horizontal plane surrounding a receiver and interfere with the direct signal (Fig. 1). The receiver can detect this interference as noise, which is represented with the SNR. The SNR is related to the antenna phase center height above the reflecting surface, known as the reflector height, h_R. Therefore, the receiver's observed SNR can be used to derive h_R and observe its changes through GNSS-IR.

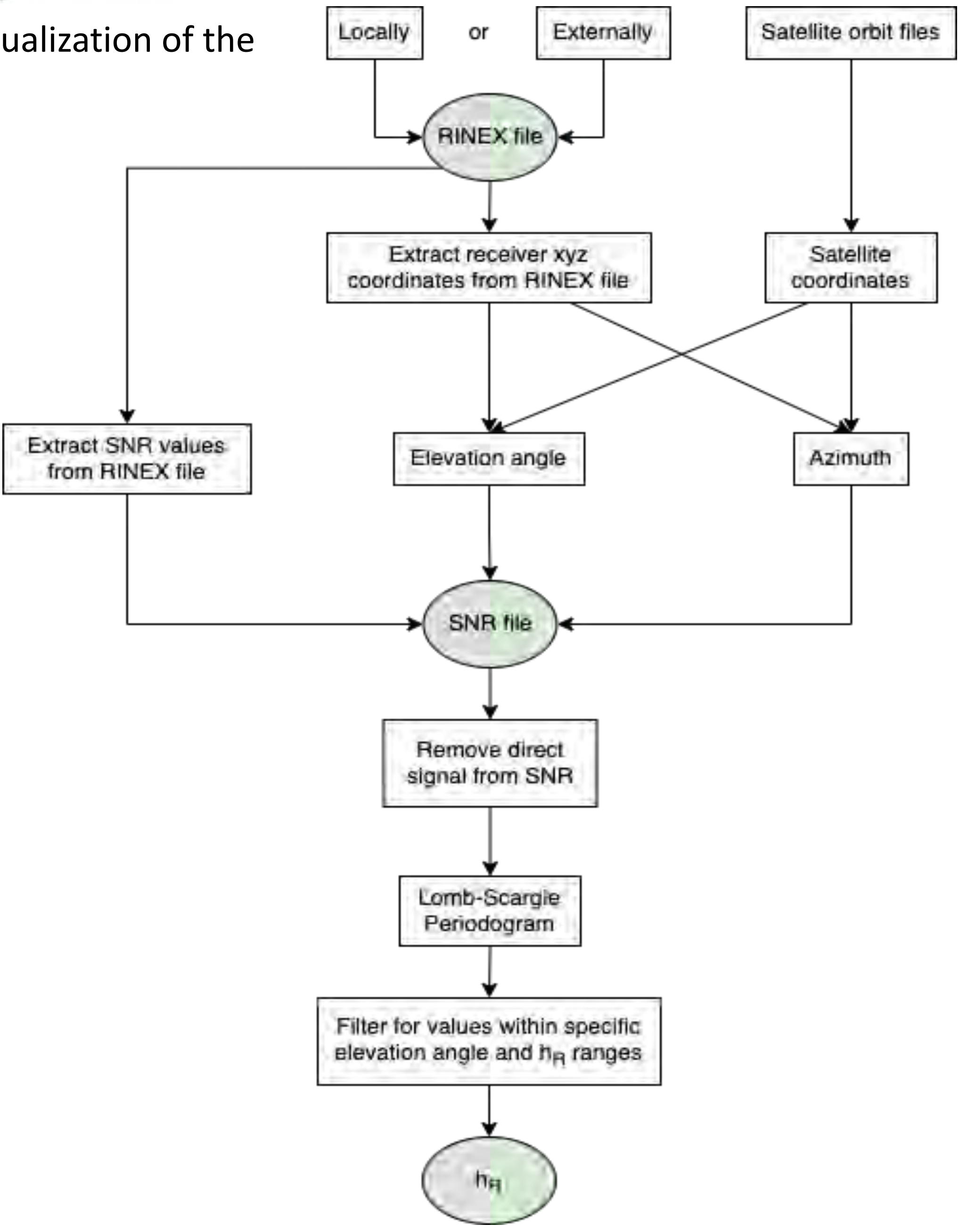

Fig. 2: Flowchart of h_R calculation using the gnssrefl Python package[1]. The package streamlines the process of retrieving and converting raw RINEX files from the GNSS receivers to h_R.

Station Coordinate Error

The variety of Arctic conditions, including wind, temperature changes, and currents, yield dynamic GNSS stations that may move up to 35 km daily. As a result, the elevation angle at which a signal from a given GNSS satellite reflects and causes multipath changes throughout the experiment.

In a test of whether error in station coordinates affected the calculated h_R, the P041 station, located in Colorado, is studied. P041 was chosen because its receiver antenna is stationary, and the site is planar and relatively free of obstructions. Therefore, it provides a reliable control for whether error in the station coordinates affects the h_R.

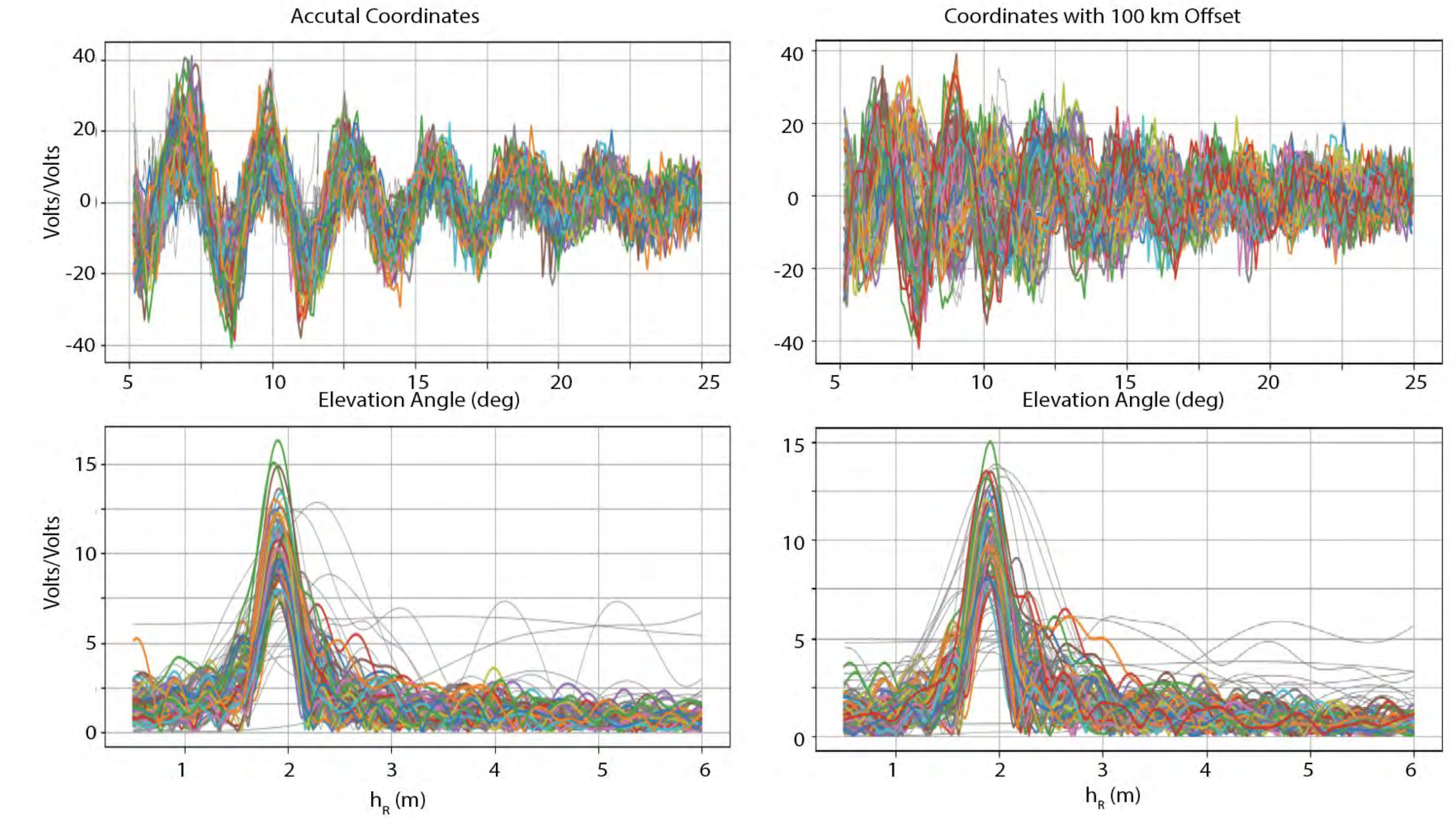

Fig. 3: P041 SNR data (top) and Lomb-Scargle Periodogram (bottom). The phase shifts in the SNR data result from a 100 km station coordinate change, though the overall h_R was preserved in the Lomb-Scargle Periodogram.

Errors in the station coordinates, even over vast distances, do not affect the h_R derivation accuracy. Because the SNR data is observed, changes to the calculated elevation angle do not affect the periodicity, and therefore, h_R derived from the data. Also, SNR is recorded only during the GNSS satellite rising and setting arcs, which span about one hour. As a result, the sea ice movement in this duration is not significant enough to observe notable changes in the station coordinates. Additionally, any daily change in station coordinates is negligible in comparison to the distance between the stations and the GNSS satellite.

Time Series Analysis

Time series of the SIDEx h_R calculations demonstrate the overall precision of GNSS-IR, in addition to sea ice characteristics in relation to the stations. The station deployed on an ice ridge (Fig. 3) can be identified as SX20. Its h_R values vary between 4 - 6 m, which can be attributed to reflections from different locations on the ice ridge.

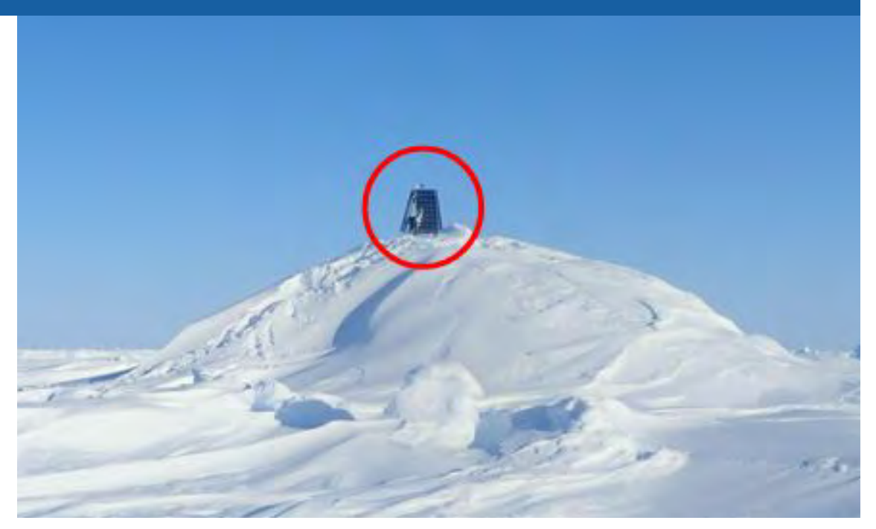

Fig. 4: SIDEx station on an ice ridge (Source: SIDEx Project).

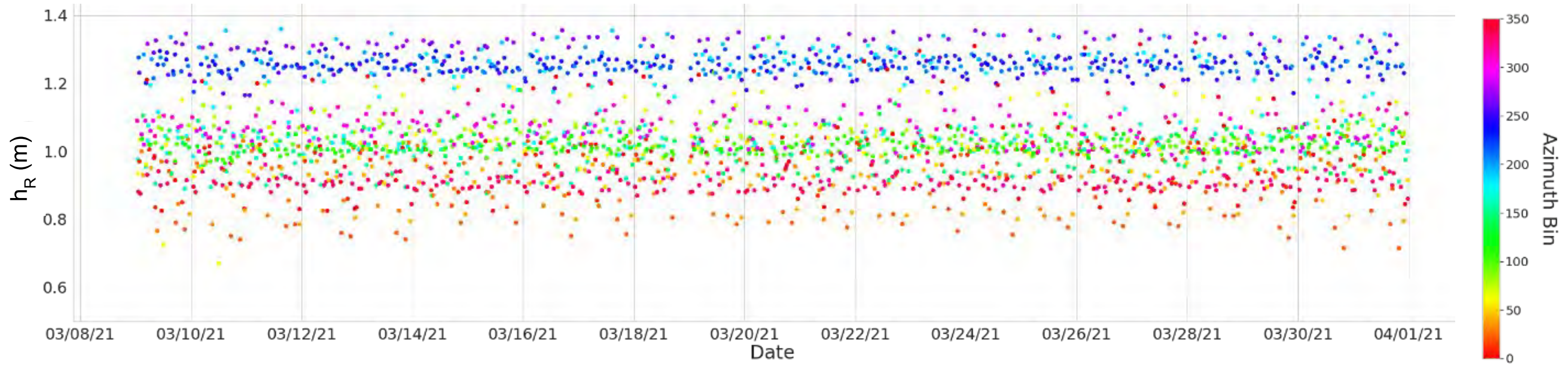

Fig. 5: SX19 time series, colored by 10° azimuth bins.

The bimodal distribution of SX19 h_R values (Fig. 5) may be attributed to differences in the reflecting surface surrounding the station, such as the station being in proximity to a lead. The time series allow us to identify different characteristics of the stations, including differences between the physical surroundings at different stations and azimuths.

Azimuthal Variation

While typical GNSS-IR stations involve a relatively planar horizontal reflecting surface, such as that of P041, the surrounding environments of the SIDEx stations were not uniform. As a result, the reflector height measured from different azimuths varied (e.g. Fig. 6), introducing variation to the overall dataset.

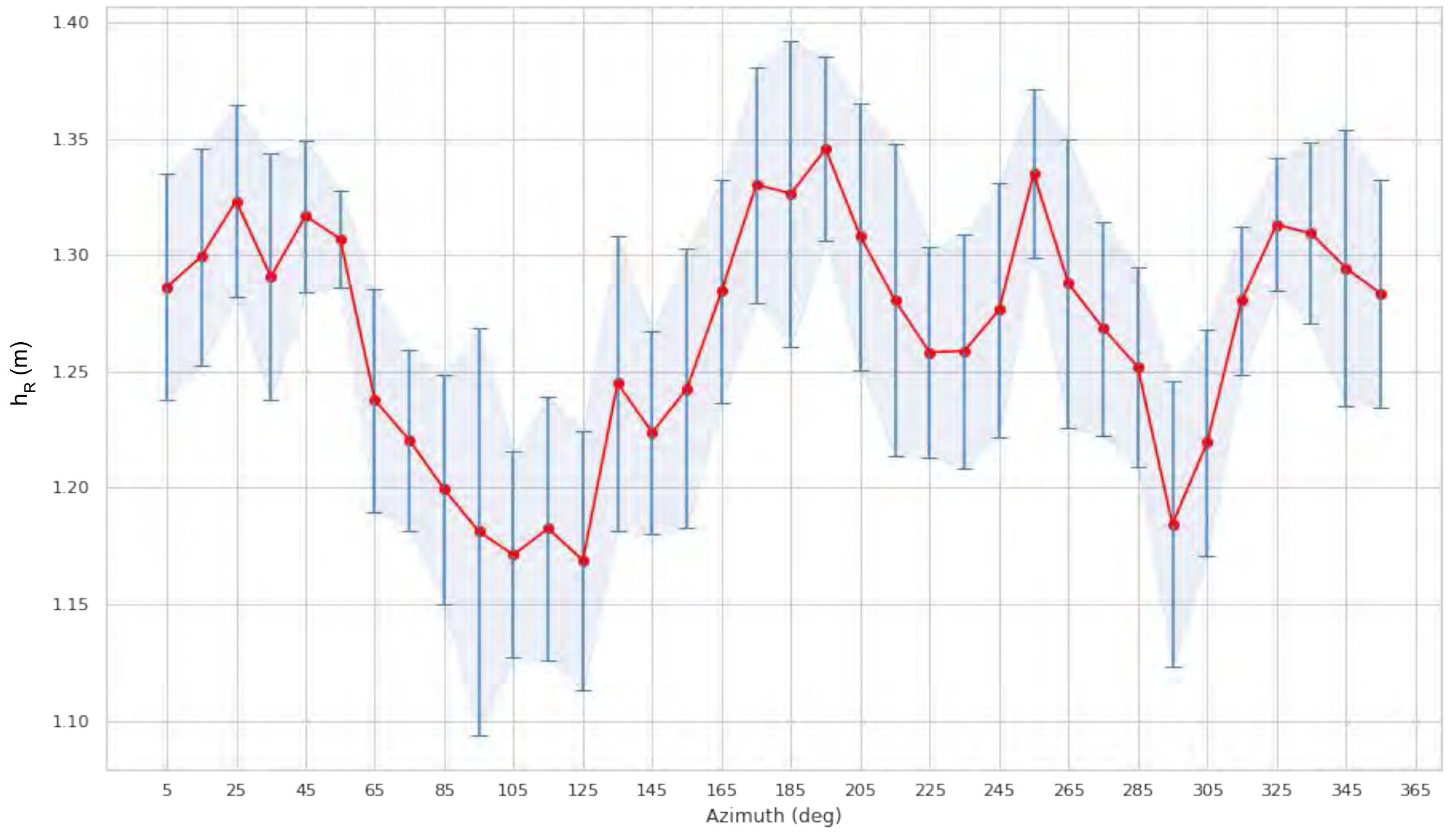

Fig. 6: SX13 binned h_R mean vs. azimuth, including standard deviation.

We detrended the SIDEx time series data using an azimuthal model, specific to each station, which decreased each station's variation in the h_R calculations (e.g. Fig. 7). As further support for the efficacy of the model removing variation due to azimuthal differences, the detrended SX19 time series no longer exhibited a bimodal distribution. Overall, the precision of the GNSS-IR h_R estimates can be greatly improved by removing the effect of azimuthal surrounding differences, which can be accomplished via detrending with the azimuthal model.

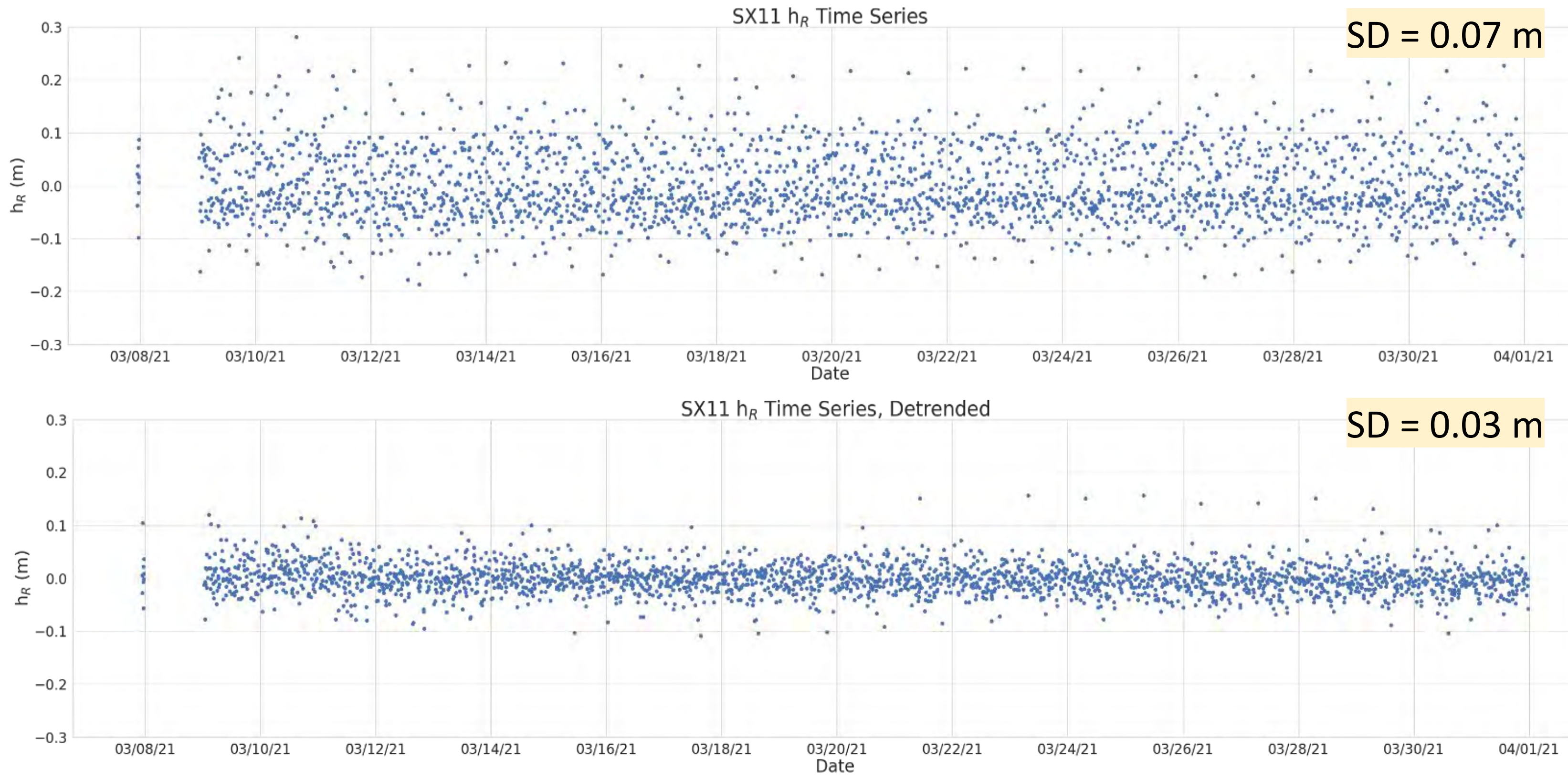

Fig. 7: SX11 time series, before and after detrending with the azimuthal model.

Future Research

- Sensitivity analysis for the effect of station coordinate error on the calculated h_R.
- Examine additional SIDEx observations beyond March 2021.
- Extract sea ice thickness and/or snow depths from SIDEx observations.
- Use SIDEx snow depths to validate ICESat-2 and CryoSat-2 snow depths[2].

References

1. gnssrefl/gnssrefl at master · kristinemlarson/gnssrefl. *GitHub* https://github.com/kristinemlarson/gnssrefl.1.
2. Kacimi, S. & Kwok, R. Arctic Snow Depth, Ice Thickness, and Volume From ICESat-2 and CryoSat-2: 2018–2021. *Geophysical Research Letters* **49**, (2022).

MIT Haystack Observatory REU 2022