Responses to RC3

This paper introduces GPS interferometric reflectometry technique as a tool for remote sensing of surface elevation changes, soil moisture contents, and snow depth at a single permafrost site. In addition, authors proposed an improved method for soil moisture estimation by modeling surface vertical movements and removing its bias on reflected GPS SNR phase shifts.

Overall, the objectives and approaches are clear and the proposed solution for soil moisture estimation at permafrost areas with vertical displacements is a genius idea. However, there are some concerns which convince me to call for a major revision for this paper.

We thank the reviewer for his/her constructive comments. We have addressed all of them with our point-by-point replies given below. The line numbers refer to the previously submitted discussion paper, aiming to point out where the discussion paper has partly addressed the reviewer's comments.

1. The inconsistency between GPS-IR-driven and in-situ-measured snow depth values is out of acceptable range. GPS-IR capability of snow depth measurement has been examined several times in many studies, and strong agreements have been achieved. Although the correlation in this paper looks promising and reflects the general patterns of snow accumulation, the bias is not acceptable as previous studies have reached to better agreements. In addition, the way that the authors explained this "systematic" inconsistency does not make sense. The reflectivity difference between snow and the underlying frozen ground is not so much for GPS L-band signals. Moreover, this reflectivity difference, even if we consider it as a potential source of error, would not affect neither the amplitude nor the polarization because signals are assumed to be reflected off the "top" of the snowpack. Furthermore, "possible penetration into the soil when manually probing the rod", if happened, would reduce the bias as it would cause an overestimation in in-situ snow depth measurements. I would seek for either a better explanation or a reconsideration in the snow depth retrieval method. Looking into "higher-

order frequencies" can be a solution for this issue as proposed by Cardellach, Fabra, et al. (2012) and Ghiasi (2020).

We divide this comment into four points and address them accordingly.

1.1 The inconsistency between GPS-IR-driven and in-situ-measured snow depth values is out of acceptable range. GPS-IR capability of snow depth measurement has been examined several times in many studies, and strong agreements have been achieved. Although the correlation in this paper looks promising and reflects the general patterns of snow accumulation, the bias is not acceptable as previous studies have reached to better agreements.

The dominant reason for the relatively large bias of our reported GPS-IR snow depth is the inconsistency of the sampling areas. The spatial coverage of the GPS-IR observations is around the GPS station. Whereas, the probing positions are generally in the southeast direction of the station and close to the automatic snow sensor, which is generally within the azimuth range of 90°–135°.

We now use the SNR data within the azimuth range of 90°–135° to calculate snow depth, which are presented in Fig. R1. We can observe that the new GPS-IR measurements have a better agreement with the in situ ones. The correlation coefficient, RMSE, and bias are 0.73, 4.11 cm, and 2.49 cm, respectively, for the new GPS-IR observations (Fig. R1(c) and (d)), whereas 0.72, 7.57 cm, and 6.52 cm, respectively, for the reported ones in the discussion paper (Fig. R1(a) and (b)). In the review paper of Larson (2019), the agreement level of the GPS-IR measurements to the in situ ones in their validation experiments ranges from 4 cm to 6 cm. Our new GPS-IR measurements show comparable accuracy.

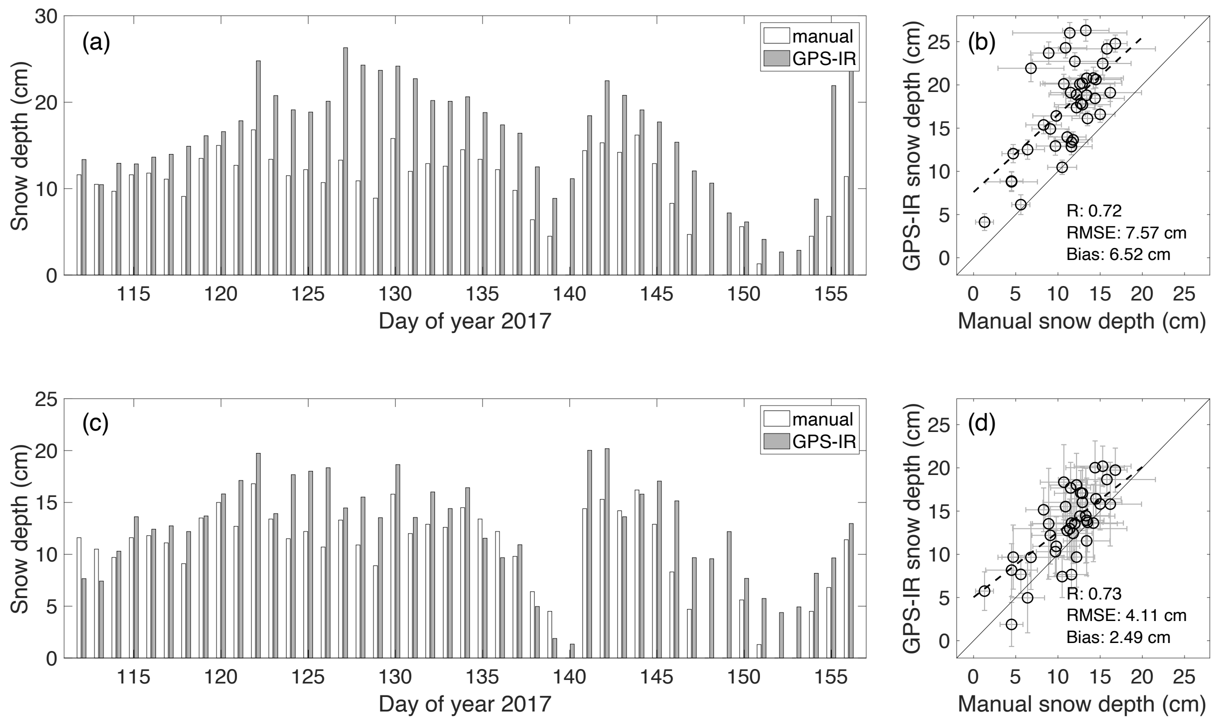

Figure R1: (a) Bar plots of snow depth measured manually and by GPS-IR using SNR within the 0–360° azimuth range. (b) Scatter plot of the manual snow depth and GPS-IR-estimated ones. The correlation coefficient (R), root-mean-square error (RMSE), and bias are presented. (c) and (d) are similar to (a) and (b), respectively, but for the GPS-IR measurements over the azimuth range of 90°–135°.

1.2 In addition, the way that the authors explained this "systematic" inconsistency does not make sense. The reflectivity difference between snow and the underlying frozen ground is not so much for GPS L-band signals. Moreover, this reflectivity difference, even if we consider it as a potential source of error, would not affect neither the amplitude nor the polarization because signals are assumed to be reflected off the "top" of the snowpack.

We compare the reflectivity between snow and the ground at the beginning of thawing season rather than the underlying frozen ground. In the framework of GPS-IR, the snow depth is derived as the difference between the reflector height of snow surface and the one of ground surface serving as reference (Fig. R2). In permafrost areas, the ground surface is subject to progressive subsidence in summer. If we use the mean value of the reflector heights during the entire thaw season as reference (which is normally used in previous studies), a bias would be introduced into snow depth. Thus, in this study, we use the average reflector height at the beginning of the thawing season (i.e., DOY 167–173 in 2017) to be the reference (*Page 12, Lines 249–250*).

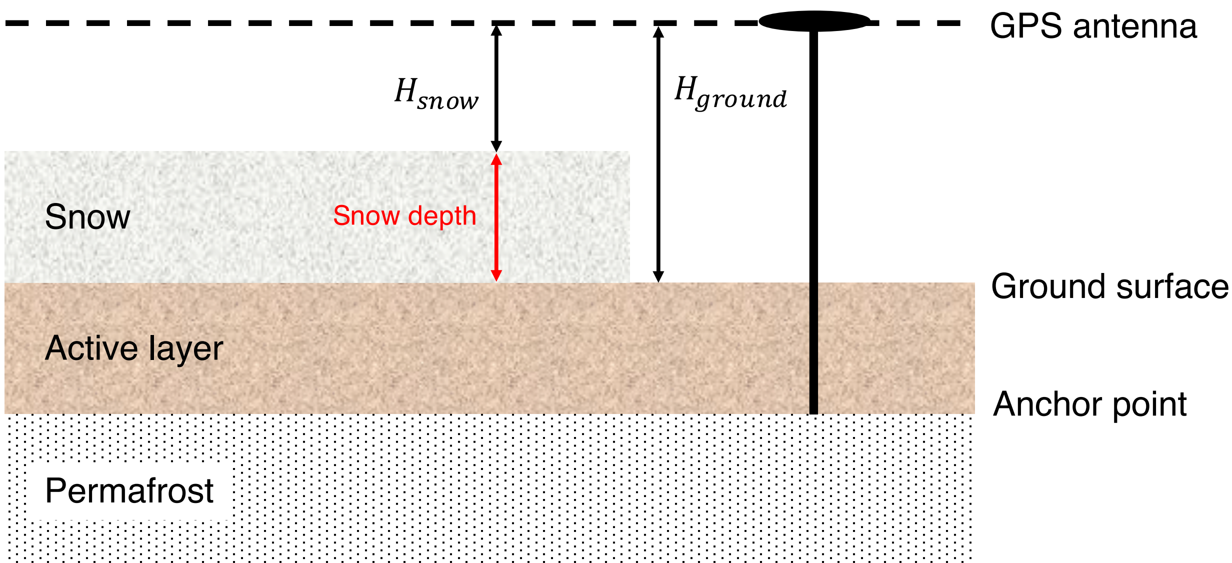

Figure R2: Schematic diagram showing the reflector heights in snow and snow-free conditions, denoted by H_{snow} and H_{ground}. Snow depth is the difference between H_{snow} and H_{ground} serving as a reference. In this study, H_{ground} refers to the average reflector height at the beginning of the thawing season.

At the beginning of thawing, the ground is not covered by snow and the soil starts to thaw downward from the surface. Based on the in situ measurements, the mean surface soil moisture at the depth of 1 cm during DOY 167–173 in 2017 was around 38% volumetrically. Given the significant difference of moisture content between snow and thawed soil, their difference in reflectivity for GPS signals cannot be ignored.

By only considering surface reflection, Zavorotny et al. (2010) developed a forward physical model to simulate reflected signals and SNR in a bare-soil condition. By varying soil moisture content, the top-soil reflectivity changes, then the amplitude and phase of the simulated SNR vary correspondingly. Thus, even only considering surface reflection, the reflectivity of substrate has impact on SNR observations.

We use the open-source physical model of Nievinski and Larson (2014) to simulate SNR in the conditions of snow and wet soil, to investigate the impact of their reflectivity difference on reflector height retrieval. The key parameters for the simulations are presented in Table R1. The simulated SNR observations are presented in Figure R3(a). We can observe a clear difference between the amplitude of the SNR series. We conduct Lomb-Scargle Periodogram analysis on the SNR simulations to obtain their frequency spectrums, which are shown in Figure R3(b). The SNR in the snow case has a larger amplitude. The dominant reflector height corresponding to the peak power is 1.99 m, whereas 2.03 m for the wet soil. The difference in the reflectivity of snow and wet soil does affect SNR observations and introduce bias to reflector height retrievals consequently to snow depth measurements. In the simulations, the introduced bias is 4 cm, which makes the GPS-IR measurements overestimate the snow depth.

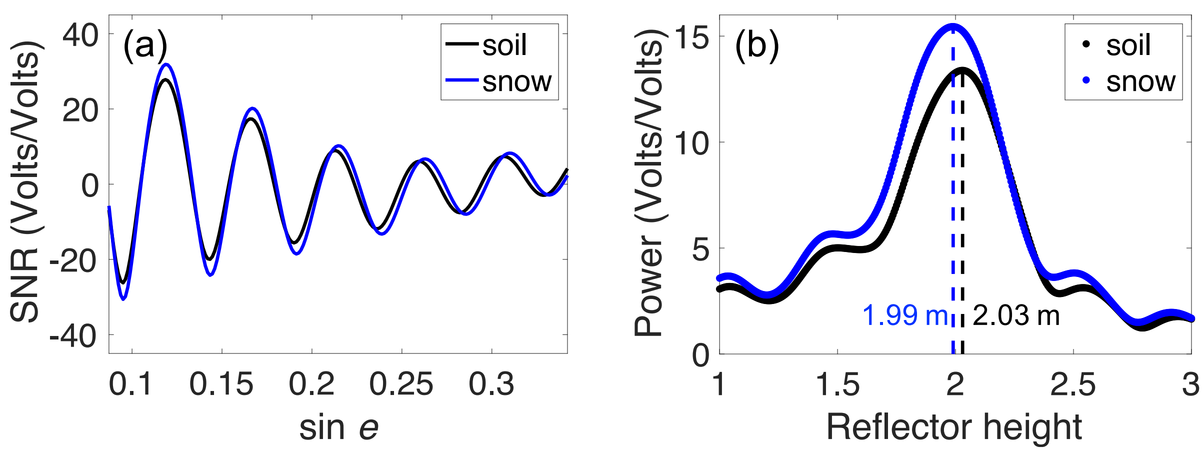

Figure R3: (a) Simulated SNR observations with the reflector of wet soil (black curve) and snow (blue curve). (b) Frequency spectrum of the simulated SNR observations. The frequency has been converted into reflector height. The dominant reflector height is 2.03 m for wet soil, whereas 1.99 m for snow.

Table R1: Key parameters used in the simulations

Parameter	Value
Antenna (Radome)	TRM29659.00 (SCIT)
Signal	L1 C/A
Antenna height	2 m
Azimuth range	0–360°
Elevation angle	5–20°
Reflector material #1	Sandy loam with soil moisture content of 38% volumetrically
Reflector material #2	Dry snow with default properties

1.3 Furthermore, "possible penetration into the soil when manually probing the rod", if happened, would reduce the bias as it would cause an overestimation in in-situ snow depth measurements.

Thank you for the clarification. The penetration into soil when manually probing to measure snow depth is another possible error source. It would overestimate the snow depth and compensate to some extent the overestimation of the GPS-IR measurements. The bias of the GPS-IR measurements is the integrated impact from all of the error sources. Its sign depends on the magnitude of each impact factor. The reflectivity difference leads to positive, whereas the probing penetration results in negative. In the discussion of GPS-IR snow depth (*Page 17, Lines 322–330*), our objective is to clarify the error sources.

1.4 I would seek for either a better explanation or a reconsideration in the snow depth retrieval method. Looking into "higher-order frequencies" can be a solution for this issue as proposed by Cardellach, Fabra, et al. (2012) and Ghiasi (2020).

The "higher-order frequencies" means the other frequencies than the dominant first-order one with peak power in the frequency spectrum, if we understand this term correctly. Cardellach et al. (2012) used a dual-polarized (right and left-hand circular polarized, RHCP and LHCP in short) side-looking antenna to receive reflections and developed a forward model to detect and identify the signals from internal layers a few hundred meters deep within the snow cover in Antarctica. In our study, the antenna is RHCP and in up-right direction. At low elevation angles, on one hand, the RHCP reflections are already weak due to de-polarization; on the other hand, the dominant reflection occurs at the air-snow interface, the basis of using GPS-IR to estimate snow depth. Thus, the reflections from the deeper layers are expected to be negligible and barely disturb the dominant reflections. Therefore, the dominant first-order frequency should be used for estimating snow depth in our study.

As for Ghiasi et al. (2020, Application of GNSS interferometric reflectometry for the estimate of lake ice thickness), they put an antenna directly on the lake ice to receive the reflected signals off the interface between ice and underneath water. They also utilized the dominant frequency of SNR observations to obtain the distance between antenna and ice-water interface then lake ice thickness.

Given the better agreement of our new GPS-IR-estimated snow depth (Fig. R1), we believe it is unnecessary to use other methods to estimate snow depth at our site.

2. The authors have used Stefan's equation for modeling the surface elevation changes as they believe GPS-IR elevation retrievals are not accurate enough because their uncertainties are in the order of few centimetres. I would say that "a few centimetres" is an acceptable accuracy for this purpose since Stefan's equation has not shown a better accuracy in literature. I would suggest conduct the same validation using surface elevations directly obtained by GPS-IR. Besides, the term "uncertainty" used by the authors does not look very exact because it is driven based on the standard deviation of the mean values which are not necessarily to be normally distributed.

We separate this comment into two points and address them correspondingly.

2.1 The authors have used Stefan's equation for modeling the surface elevation changes as they believe GPS-IR elevation retrievals are not accurate enough because their uncertainties are in the order of few centimetres. I would say that "a few centimetres" is an acceptable accuracy for this purpose since Stefan’s equation has not shown a better accuracy in literature. I would suggest conduct the same validation using surface elevations directly obtained by GPS-IR.

The reason we do not use the GPS-IR-estimated surface elevation changes directly is that they have relatively large daily oscillations. In reality, the ground surface typically subsides progressively. The GPS-IR measurements cannot represent the real evolution of surface subsidence on a daily scale. Alternatively, we turn to use the Stefan model to fit the GPS-IR measurements to obtain the smoothed seasonal time series. We have revised the manuscript to remove the misleading contents.

In Fig. R4, we show the comparison between the in situ measurements and the GPS-IR ones by using the default method, our improved method, and the GPS-IR surface elevation changes directly (denoted by raw data for simplicity). We can observe that the GPS-IR results by our improved method are more reliable compared with the ones by default method and the raw data directly. The raw-data method has the worst performance, giving a moderate-to-low correlation coefficient of 0.43 and an RMSE of 2.34%.

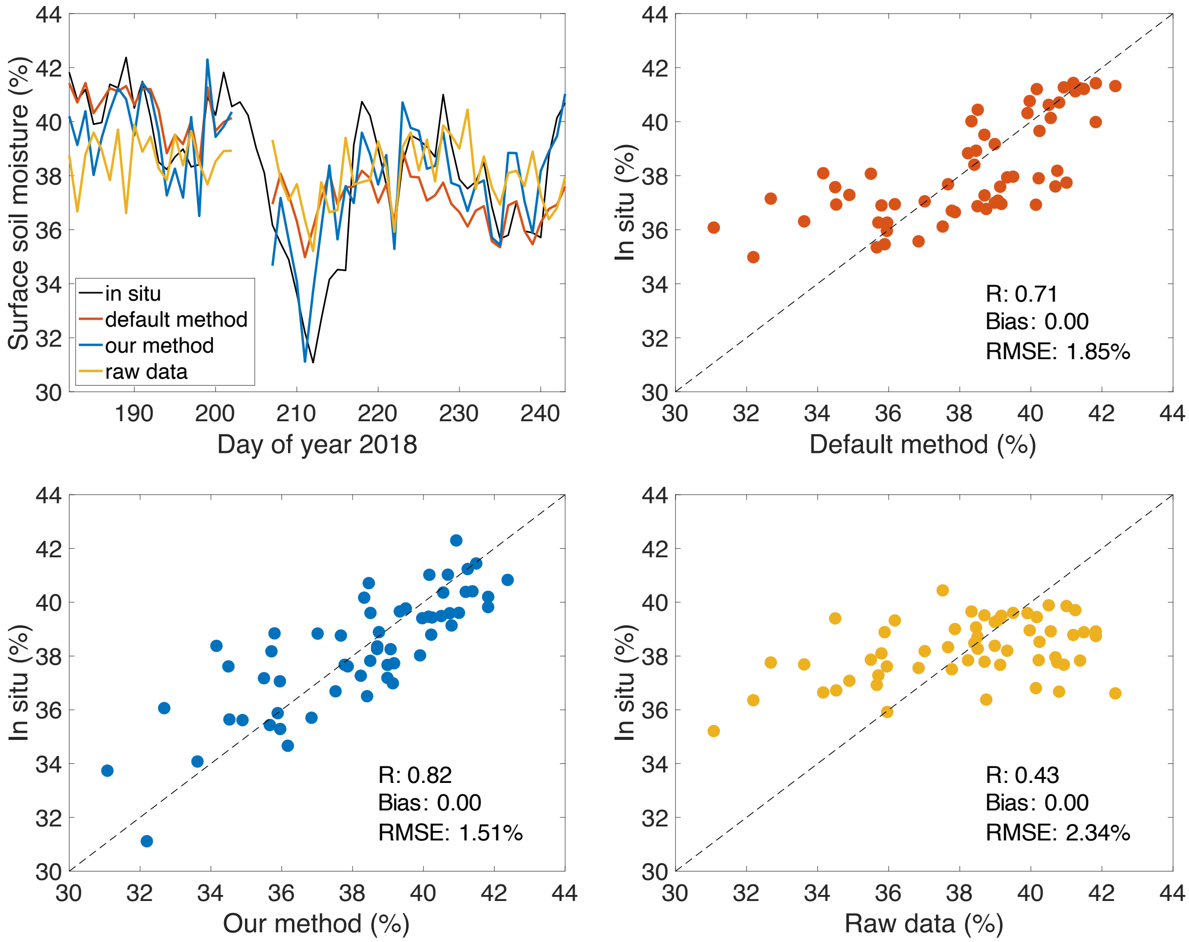

Figure R4: Comparison between in situ soil moisture and GPS-IR measurements estimated by using default method, our improved method, and GPS-IR-estimated surface elevation changes (denoted by raw data for simplicity) directly. The correlation coefficient (R), bias, and root-mean-square error (RMSE) are presented as well. We do not present the uncertainties of the GPS-IR estimates for clarity.

2.2 Besides, the term "uncertainty" used by the authors does not look very exact because it is driven based on the standard deviation of the mean values which are not necessarily to be normally distributed.

On any given day, multiple SNR interferograms are available. We retrieve the reflector heights from these SNR data initially, then use their mean to be the daily measurement. The uncertainty is the standard deviation of the mean value. The following figure shows the distribution of reflector heights on four given days, i.e., DOY 190, 200, 210, and 220 in 2018, and their normal distribution fit. We can find that the distribution of the reflector height on each given day generally follows the normal distribution.

Following the reviewer's suggestion, we have replaced the uncertainty with the standard deviation of the mean.

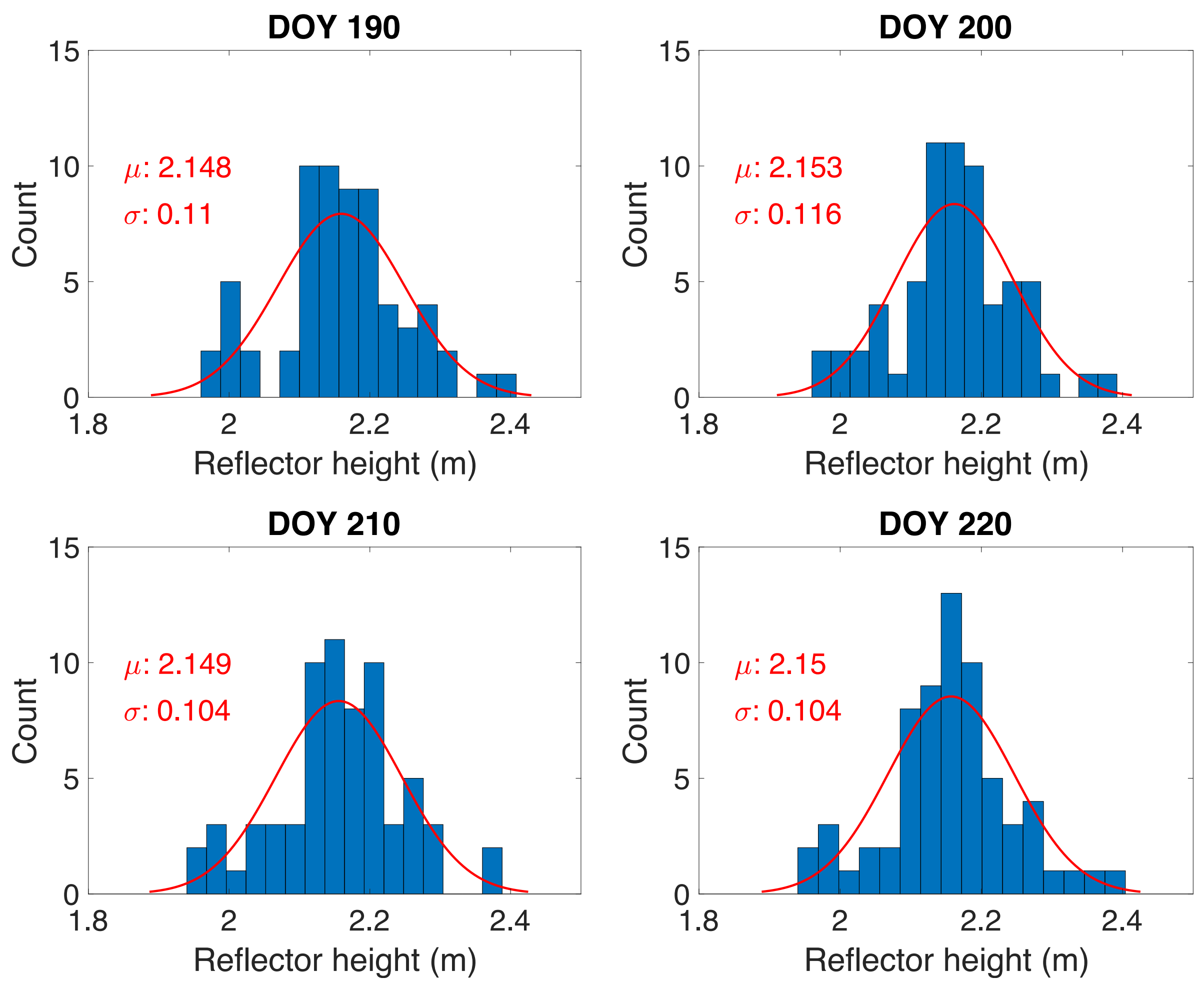

Figure R5: Histograms of reflector heights on the given days of DOY 190, 200, 210, and 220 in 2018, and their normal distribution fit. The mean (μ) and standard deviation (σ) are also presented (units: m).

3. Although the paper appears in a very clear and accurate English writing, some sentences are too short, e.g., line 221, and some sentences start with "And" which looks somehow inappropriate in academic English writing, e.g., lines 236 and 266.

We have revised the manuscript accordingly.

References:

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