Responses to RC1

General comments: This paper presents a modified GPS-IR algorithm for soil moisture retrieval in permafrost regions. The authors find that the modified algorithm performs slightly better than the default method, which can be seasonally-biased due to surface deformation changes resulting from the thawing active layer. The authors find a significant bias between their GPS-IR snow depth retrievals and in situ observations near the antenna.

Overall, I found the paper to be well written with clear objectives. Since the results presented in this paper are only from one GPS antenna with a limited time series, they are preliminary, and it is difficult to know if the methodology will be successful at other GPS monuments. However, it makes for a good initial study in this topic.

We thank the reviewer for his/her constructive comments. We have addressed all of them with 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.

Specific comments:

1. Figure 2: I think the antenna anchoring position should be drawn not in the permafrost, but in the active layer, since that is where your antenna monument is anchored.

We have revised Figure 2 to draw the anchoring position near the active layer base (Fig. R1).

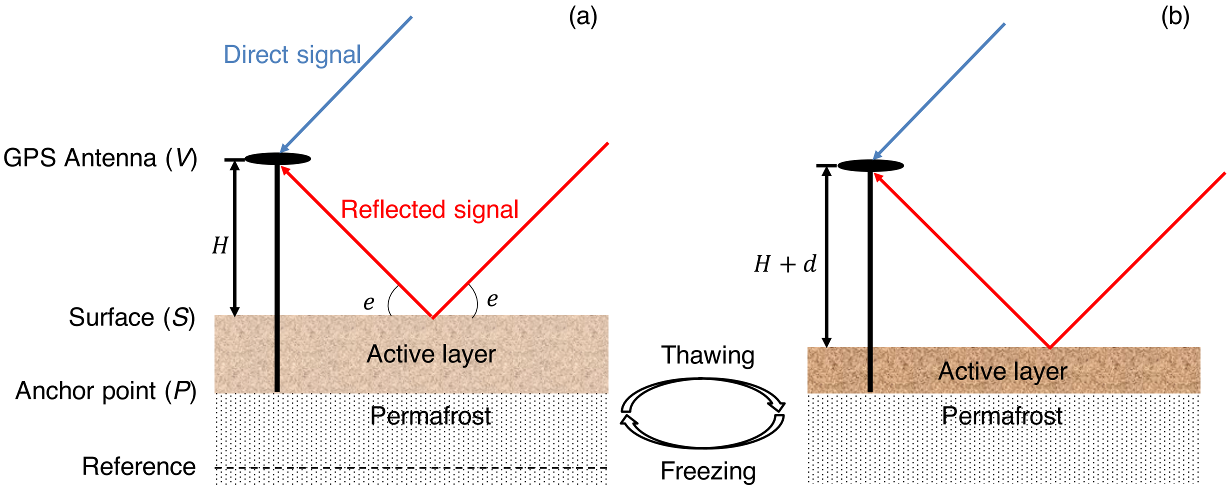

Figure R1: Diagrams showing the geometries of GPS-IR in the thawing/freezing active layer conditions. The symbols *V*, *S*, and *P* denote the vertical positions of the GPS antenna, reflecting surface, and the monument anchor point with respect to an arbitrary reference in the deep permafrost, respectively. *H* denotes the reflector height. *d* represents the surface deformation due to active layer freezing/thawing.

2. Line 160: Why do you only use 5-15 degrees in this study, when other GPS-IR studies more commonly use 5-30 degrees?

In the framework of GPS-IR, one of the bases is that SNR observations should have a clear sinusoidal pattern. Then the SNR metrics of frequency, phase, and amplitude can be utilized to estimate environmental variables. In Fig. R2, we present a piece of SNR observations at the elevation angles of 5–30 degrees recorded by our GPS station as an example. The SNR observations at 5–15 degrees show a clear sinusoidal pattern. However, they are irregular from 15 to 30 degrees, thus we choose not to use them in our analysis. Since the sampling rate of SNR data is 15 s, we still have enough data points at 5–15 degrees to determine the dominant frequency and phase.

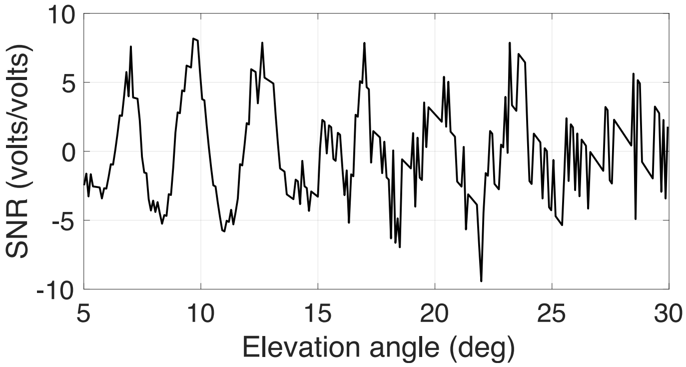

Figure R2: SNR observations with elevation angles of 5–30 degrees of the GPS-02 satellite on DOY 220 in 2018. The second-order polynomial has been removed.

3. Line 167: Reflector height does have a dependence on soil moisture, though it is not as linear as the dependence of phase on soil moisture. How do you know that your summertime reflector height variations are due to ground surface elevation changes and not due to soil moisture?

Yes, we agree that reflector height can be affected by soil moisture. For a given SNR series, phases of the data points are not the same, but slightly vary with respect to elevation angle (i.e., $\phi(e)$ is not a constant but varies with elevation angle). In data processing, treating the phase as a constant introduces an error into the reflector height, which is usually called as compositional reflector height (Nievinski, 2013).

The compositional reflector height can be simulated by a multipath model from Nievinski and Larson (2014). As the gain pattern of the GPS antenna at our site is not available, we alternatively use the one of TRM29659.00 with a radome of SCIT to run simulations. We also use the daily in situ soil moisture observations at our site as the input. The simulated results are presented in Fig. R3. The parameters for the simulations are shown in Table R1.

In Fig. R3, the simulated compositional heights are within the range of 2–2.7 cm. The peak-to-peak magnitude of their variations is 0.7 cm. This is less than the magnitude of the uncertainty of reflector height retrieval, which is on the order of several centimeters. As we focus on the temporal variations of the retrieved reflector heights (not the absolute heights), the soil moisture’s impact is limited.

Furthermore, we observe a decreasing trend from the compositional heights with a rate of 0.0039 cm/day, which leads to a surface uplift (as surface elevation changes are the reverses of reflector height variations) and makes the GPS-IR measurements underestimate surface subsidence. However, the introduced uplift has a negligible magnitude. The overall uplift is only 0.24 cm during DOY 182–243 in 2018, which barely affects the clear subsidence trend presented by the GPS-IR measurements (*Page 13, Lines 265–281*).

Given the limited magnitude of compositional height variations and its negligible decreasing trend (causing surface uplift), the reflector height variations are mainly caused by surface elevation changes due to thawing active layer rather than soil moisture changes.

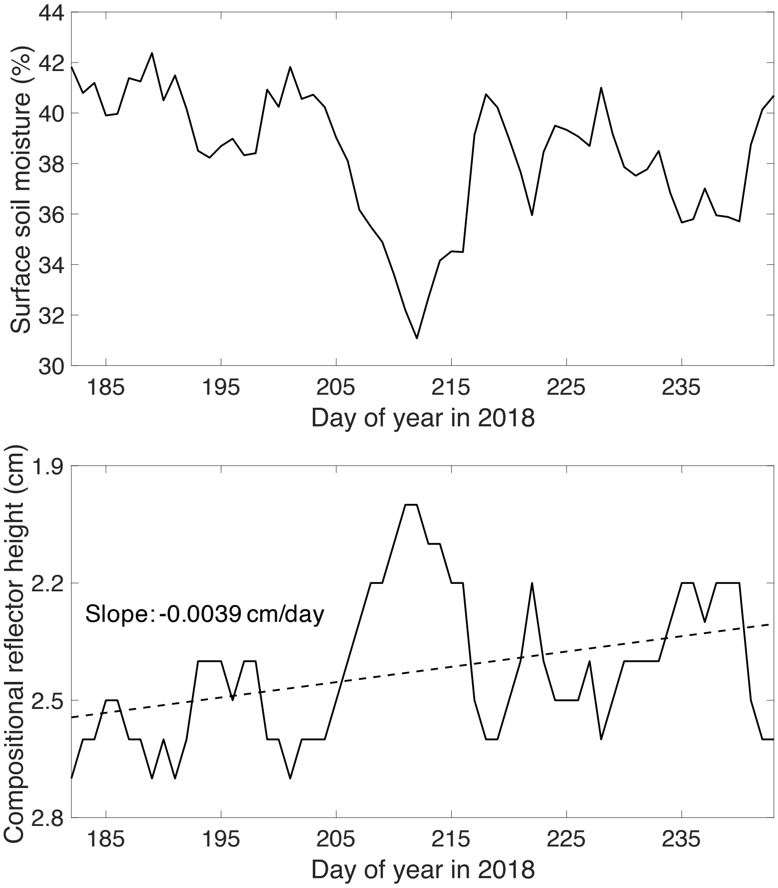

Figure R3: (a) In situ surface soil moisture during DOY 182–243 in 2018 at our study site. (b) Simulated compositional reflector height by using the in situ soil moisture. The y axis has been reversed to make the variations of compositional height consistent with surface vertical movement. The dashed line is the best linear fit of the simulations, whose slope is presented as well.

Table R1: Key parameters used in the simulations

Parameter	**Value**
Antenna (Radome)	TRM29659.00 (SCIT)
Signal	L1 C/A
Antenna height	2 m
Azimuth angle range	0–360°
Elevation angle range	5–15°

Reflector material	Sandy loam
Soil moisture content	Daily in situ measurements during DOY 182–243 in 2018

4. Line 323: You say that one reason for the difference between in situ snow depth observations and snow depths derived from GPS-IR is the difference in sampling areas. Couldn't you check this by excluding the SNR observations that lie outside the manual probing positions?

The manual probing positions are located in the southeast direction of the GPS station and close to the automatic snow sensor, which are generally within the azimuth range of 90–135 degrees. We now use the SNR data within this azimuth range to calculate snow depth, which are presented in Fig. R4. We can observe that the new GPS-IR measurements have a better agreement with the in situ observations. The correlation coefficient, RMSE, and bias are 0.73, 4.11 cm, and 2.49 cm, respectively, for the new GPS-IR estimates (Fig. R4(c) and (d)), whereas 0.72, 7.57 cm, and 6.52 cm for the reported ones in the discussion paper (Fig. R4(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 a comparable accuracy.

We have updated the results of snow depth by using the azimuth range of 90°–135° in our revised manuscript.

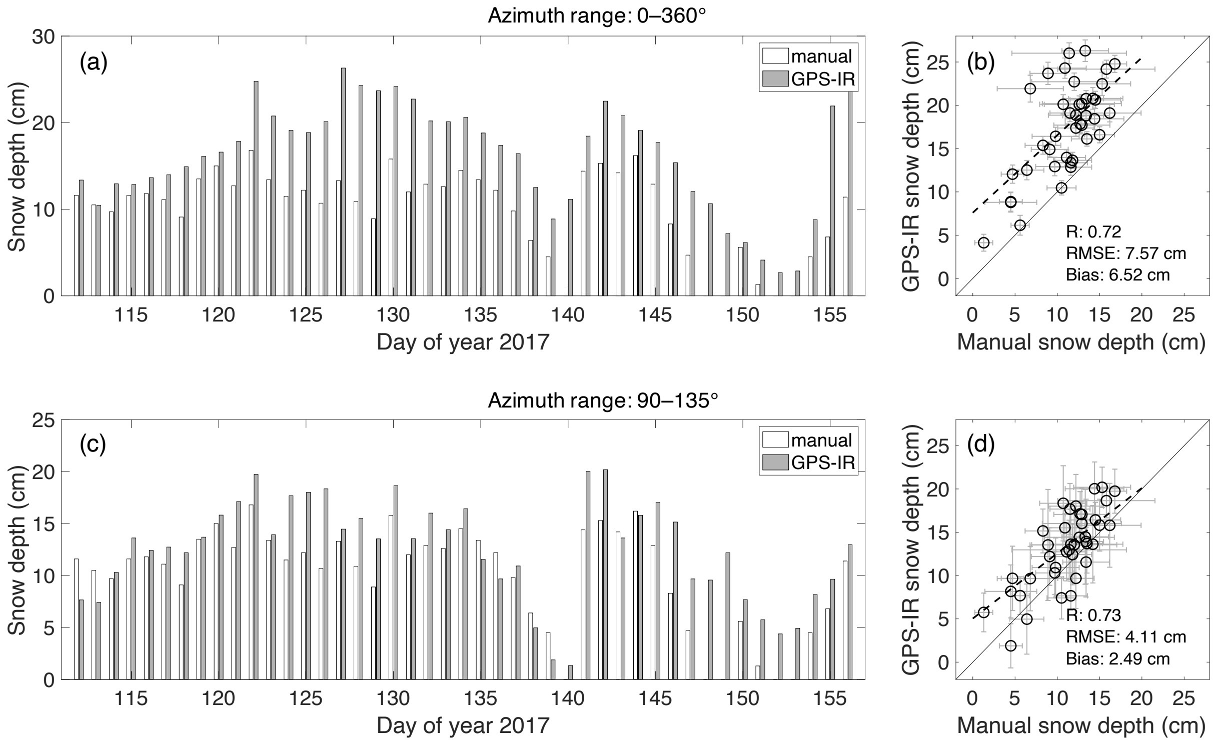

Figure R4: (a) Bar plots of snow depth measured manually or by GPS-IR during DOY 112–156 in 2017. The GPS-IR results are derived by using the SNR observations within the azimuth range of 0–360°. (b) Scatter plot between the manually measured and GPS-IR-retrieved snow depth. The correlation coefficient (R), root-mean-square error (RMSE), and bias are shown as well. (c) and (d) are similar plots to (a) and (b) correspondingly but for the GPS-IR results by using the SNR observations within 90°–135° azimuth range.

References:

Larson, K. M.: Unanticipated Uses of the Global Positioning System, Annu. Rev. Earth Planet. Sci., 47(1), 19–40, doi:10.1146/annurev-earth-053018-060203, 2019.

Nievinski, F. G.: Forward and Inverse Modeling of GPS Multipath for Snow Monitoring., 2013.

Nievinski, F. G. and Larson, K. M.: An open source GPS multipath simulator in Matlab/Octave, GPS Solut., 18(3), 473–481, doi:10.1007/s10291-014-0370-z, 2014.