Responses to RC2

This is a review three-in-one: GPS-IR measurements of ground surface elevation changes, soil moisture, and snow depth at a permafrost site in the northeastern Qinghai-Tibet Plateau by Jiahua Zhang et al. The authors used one GNSS station to estimate soil moisture, snow depth, and ground surface elevation changes. They used the estimated ground surface elevation to improve the soil moisture estimates. Although GNSS-IR looks very promising these days, the manuscript in the current format is rejected and it is not recommended for the publication.

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. Larson et al. (2019) used several stations from the PBO network and reported soil moisture, snow depth, vegetation water content, and water loading.

The key difference between our study and Larson (2019) is that our study is dedicated for permafrost studies. We obtain surface elevation changes, surface soil moisture, and snow depth at the same GPS site. These three variables are all closely linked with frozen ground dynamics and directly pertinent to the readership of TC (*Page 2, Lines 40–57*).

The main contributions of this study have been explicitly stated in the discussion paper as: (1) the improvement of the default GPS-IR algorithm for estimating soil moisture in permafrost areas to correct the impact of seasonal surface elevation changes; (2) the GPS-IR measurements at a site in the Qinghai-Tibet Plateau (QTP); and (3) the three-in-one framework to fully utilize the potential of GPS-IR in permafrost studies (*Page 1, Lines 24–28*).

The significance of this study: The commonly used GPS-IR algorithm for soil moisture estimation does not consider the typical seasonal surface vertical movement in permafrost areas. Our improved method can remove the errors caused by seasonal surface deformation and estimate soil moisture reliably in permafrost areas. Permafrost coverage is extensive in the QTP but with scarcely and unevenly distributed monitoring sites. Our study site, one of the first of this kind in the QTP, can fill a critical spatial gap and may raise the community's interest to set up more sites likewise. Moreover, our GPS-IR measurements can be supplementary to the permafrost temperature and provide new insights into frozen ground dynamics. The GPS-IR measurements can also calibrate/validate remote sensing observations (Zhang et al., 2020). The three-in-one framework integrates the measurements of these three variables at the same site, which can fully utilize the potentials of GPS-IR in permafrost studies (*Page 4, Line 81–92*).

2. It should be noted that the reported soil moisture estimates from 11 GNSS sites by Small et al. (2016) look way better than what is reported in this manuscript for the soil moisture.

Small et al. (2016) estimates soil moisture content at 11 sites with various vegetation conditions. They use different strategies at different sites based on vegetation water content. For individual sites, by using the optimal algorithms, their RMSEs range from 1.5% to 5.1% (Table R1). In our study, the RMSE by using our improved method is 1.5%. It indicates that the accuracy of our results is better than those at most of the sites in Small et al. (2016).

In our study, we do not consider the vegetation impact because the vegetation at our site (and many GNSS sites in continuous permafrost areas) is very short and relatively sparse, which is nearly transparent for the L-band GPS signals.

Table R1: The root-mean-square error (RMSE) of GPS-IR-estimated soil moisture content at various sites with different vegetation water content (Source: Small et al., 2016).

Site	**RMSE**	**Vegetation Water Content (kg·m^{-2})**
P036	1.5%	0.65
P037	2.7%	No data
P038	Not available	No data
P039	Not available	0.33

P040	Not available	0.47
P070	3%	0.41
P123	Not available	0.24
MFLE	3.5%	0.32
OKL2	3.8%	1.02
OKL3	3.6%	1.01
OKL4	5.1%	1.40

3. In addition, ground surface elevation changes over the permafrost area using GNSS-IR were already reported by Liu and Larson (2018).

This study is the first one using GPS-IR to measure ground surface elevation changes at a site in the QTP. Permafrost is extensive in the QTP but the monitoring sites, such as boreholes, are scarce and unevenly distributed. Most of the monitoring sites are along the Qinghai-Tibet highway and railway. The GPS site in our study can fill a spatial gap in the QTP. The GPS-IR measurements can be supplementary to the existing ground temperature observations to provide insights into frozen ground dynamics in a new perspective.

The GPS-IR-estimated surface elevation changes are also the basis of our solution to improve the default algorithm for estimating soil moisture in permafrost areas. Furthermore, they are also the indispensable component of the three-in-one framework to fully utilize GPS-IR in permafrost studies.

Liu and Larson (2018) did not estimate snow depth or soil moisture.

4. The reported bias for the snow depth estimates is also much larger than what is already reported, i.e. Larson et al. (2016); Siegfried et al. (2017). Therefore, the authors should explicitly answer which challenge/challenges of GNSS-IR is tackled where recent publications have demonstrated even way better results.

The dominant reason for the relatively large bias is the inconsistency of sampling areas of GPS-IR and manual probing locations. The GPS-IR measurements are derived by using the SNR data within the azimuth range of 0–360°. Whereas, the manual probing locations are generally in the area with azimuth angle of 90°–135°.

We 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 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. 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)). Our new GPS-IR results have comparable quality with those of Larson and Small (2016) and Siegfried et al. (2017).

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

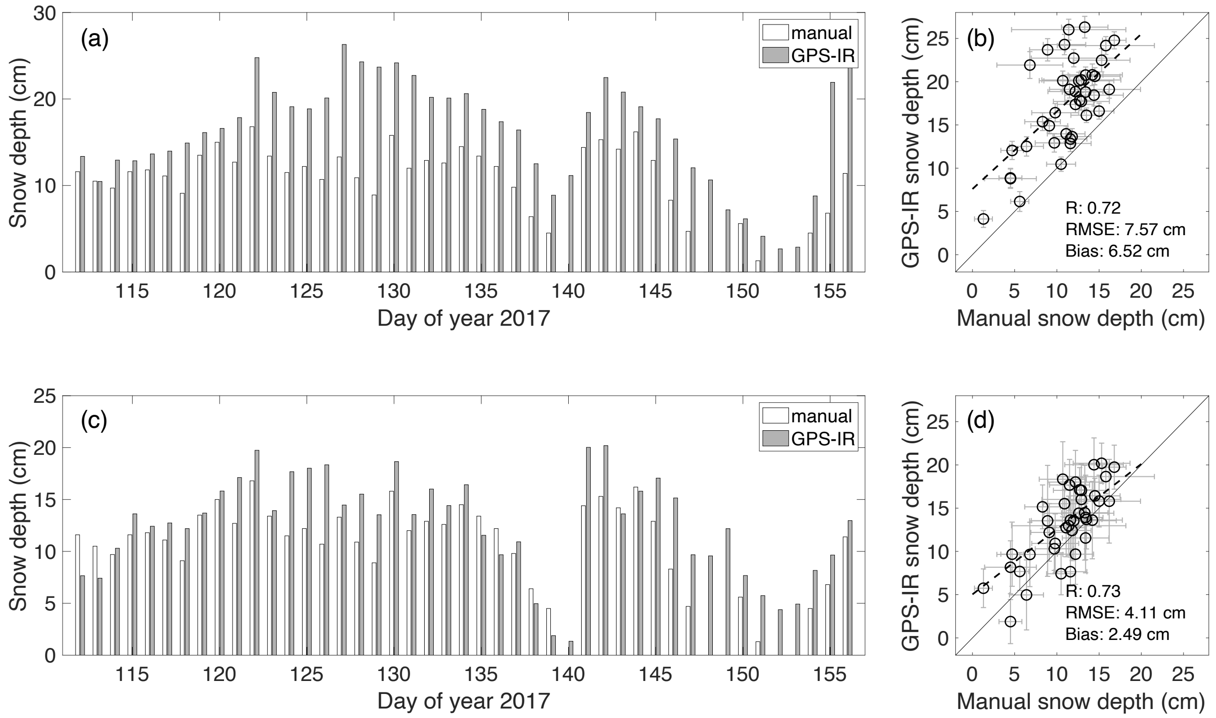

Figure R1: (a) Bar plots of snow depth measured manually and by GPS-IR using SNR within the 0–360° azimuth range. (b) Scatter plot of the manual measured and GPS-IR-estimated snow depth. The correlation coefficient (R), root-mean-square error (RMSE), and bias are presented. (c) and (d) are similar to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

We have reiterated and demonstrated our contributions in reply to comment #1. The highlight of this paper is the improvement of the default algorithm for estimating soil moisture in permafrost areas. Our method can correct the impact of seasonal surface elevation changes and improve the accuracy of results. Another contribution is the three-in-one framework, integrating the GPS-IR measurements of snow depth, surface elevation changes, and soil moisture at one site. Our snow depth result is the necessary component of the framework implementation. The three-in-one framework can fully utilize the potential of GPS-IR in studying permafrost. Moreover, this study is also the first one reporting GPS-IR measurements in the QTP.

4. In addition, it is very hard to assess the results qualitatively using just one single GNSS station.

To validate the improved method, we need a suitable GPS site and in situ soil moisture content within 0–5 cm layer in permafrost areas. However, it is challenging to find such a site because most of the existing GPS sites are designed and maintained for monitoring solid earth movement and ionospheric variations. Soil moisture observations are usually absent at these sites. At our site, it is fortunate to have a co-located integrated weather station recording soil moisture content for assessing and validating our method. Though only using one site, the proof of concept of improving the default algorithm for estimating soil moisture content in permafrost areas has been clearly presented. Though only using one site, we have not only presented the concept the improved method but proved its effectiveness by comparing the GPS-IR estimates and in situ observations.

5. The authors also discard the impact of the GNSS antenna by using the gain pattern of TRM29659.00.

The gain pattern of TRM29659.00 is used to simulate SNR observations by using the model of Nievinski and Larson (2014). At our study site, the antenna gain pattern of QLBG is not available. We alternatively use the one of TRM29659.00.

The impacts of gain pattern on the simulated phase bias and the GPS-IR results are negligible. The gain pattern is usually designed to be nonuniform along elevation angle, to favor the reception of the direct signals and suppress the reflected. For any given SNR series, the antenna gain's impact varies at each data point. But for any pair of SNR series with the same elevation angles, they suffer the same impact from the gain pattern. Therefore, the influence of antenna gain pattern on the SNR metrics (i.e., frequency, amplitude, phase) can be regarded as a systematic bias. To sum up, as we focus on the temporal variations, the impact of antenna gain pattern is negligible.

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