Responses to RC2

We thank the reviewer for his/her insightful and constructive comments. We have addressed all of them in the revised version of our manuscript. Our point-by-point replies are given below. As the reviewer may not be able to read our revised manuscript at this stage of The Cryosphere's review process, 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.

GPS-IR has been used in many terrestrial parameter inverses. The determination of permafrost surface elevation changes via GPS-IR is an interest research. The theory and method of measuring the elevation is the universal method in snow depth and water elevation inverses proposed by Larson. The main work of the manuscript is to filter out a large number of stations that meet the conditions and select the GPS data that can be used in elevation measure. So, this manuscript is unacceptable in its present form and need to add more innovative work.

Response: The main work is not limited to the 12 identified useful GPS stations. Below, we present the innovative aspects of this study in terms of methodology, new findings, and merits of using GPS-IR for studying permafrost.

(a) Methodology innovations:

(i) We implemented a framework to identify usable GPS stations from the existing networks to study permafrost by GPS-IR (*Lines 108–133*). To our knowledge, this framework is the first of this kind for permafrost. Previous works by Liu and Larson (2018) and Hu et al. (2018) only used one GPS station (SG27 in Barrow, Alaska). Before our work, it is unknown how many among the more than 200 GPS stations that are operating continuously in the circumpolar permafrost area can be used for GPS-IR. The framework described in this work also serves as a reference for other researchers who would like to screen other GPS stations in other permafrost areas. To our knowledge, the only similar 'data mining' effort for the cryosphere is the PBO H2O project, which lists sites suitable for GPS-IR-based estimates of snow depth (and soil moisture). However, the PBO H2O project ended in 2017 and only archived products are available (https://cires1.colorado.edu/portal/).

(ii) Towards a robust use of GPS-IR, we summarized the limitations of using GPS-IR-estimated surface elevation changes in permafrost studies (*Lines 260–279*). These limitations are related to surrounding environments around stations, instrumentation maintenance, and auxiliary observations such as ground temperature, soil moisture, and ground ice. These limitations indicate that better location choice and maintenance of GPS sites are needed. As GNSS networks are expanding in the cold regions, the lessons we learned from this study and our recommendations will be helpful for the planning of major geodetic infrastructures while considering the potential applications in permafrost monitoring.

(iii) We considered comprehensively the error sources of GPS-IR-measured surface elevation changes, including tropospheric delay of GPS signals, antenna gain pattern, monument thermal extension/contraction, soil moisture, and vegetation (to be detailed in a new subsection in the revised manuscript).

(iv) We compared the advantages and limitations of GPS-IR measurements and InSAR observations, the latter of which has emerged as a tool for measuring elevation changes over permafrost areas. Our comparisons, detailed in section 5.4 and summarized in Table 4, clearly show that these two methods and their measurements are complementary to each other (*Lines 281–294*). GPS-IR measurements can be used to calibrate and validate InSAR observations and provide baseline information for historical, current, and future remote sensing measurements from air and space.

(b) new findings:

(i) This study is the first one to use multiple GPS sites to study permafrost changes across a broad region by GPS-IR. It is also the first in Canada to use GPS-IR to study permafrost.

(ii) We observed that the surface subsided in Alert during 2012–2017 and Resolute Bay during 2003–2014, in contrary to the uplift in Iqaluit during 2010–2017 (*Lines 185–190*). We found the negative correlation between the linear trends of surface deformation and those of thawing indices (*Lines 251–252*). It indicates that near-surface permafrost is sensitive to air temperature changes and that air temperature is the dominant driver for permafrost stability at these study sites.

(iii) In Resolute Bay, we found that end-of-thaw elevations during 2003–2012 had high negative correlation with the square root of thawing indices. However, in 2013 and 2014, the end-of-thaw elevations were low with cool summers (*Lines 220–224*). This phenomenon is possibly due to the Markovian behaviour of the active layer (*Lines 233–241*), which is worthwhile to be documented and investigated further.

(iv) In Resolute Bay, we observed summer heave of surface in most of thaw seasons during 2003–2014 (*Lines 194–195*). A similar phenomenon is also observed at a different site near Yellowknife in Canada by Gruber (2019) using an inclinometer. These findings reveal that frozen dynamics is rather complex and cannot be all explained by simple Stefan equations.

(c) Merits of using GPS-IR for studying permafrost:

The identified usable GPS sites in this study complement the existing permafrost monitoring programs such as CALM (circumpolar active layer monitoring) and GTN-P (global terrestrial network for permafrost), and provide multi-year, continuous, and daily measurements with intermediate spatial coverages. The changes of permafrost areas have large spatial heterogeneity, due to location, topography, precipitation, and vegetation. Despite of the significant increase of number of in situ sites in the past decades, the CALM and GTN-P sites are still sparse and unevenly distributed. The 12 suitable GPS stations in our study distributed across Northern Canada. Their locations fill in the spatial gaps of the CALM and GTN-P sites (Fig. R1). Moreover, the spatial coverage of GPS-IR at one site is on the order of 1000 m^2, nicely bridging point observations and regional-scale remote sensing measurements (*Lines 54–56*). Moreover, numerous GPS stations, e.g., RESO in resolute Bay, have been in operation for more than a decade. They can provide long-term, continuous, and daily measurements, which aid in studying permafrost in a detailed manner and provide new insights to permafrost dynamics.

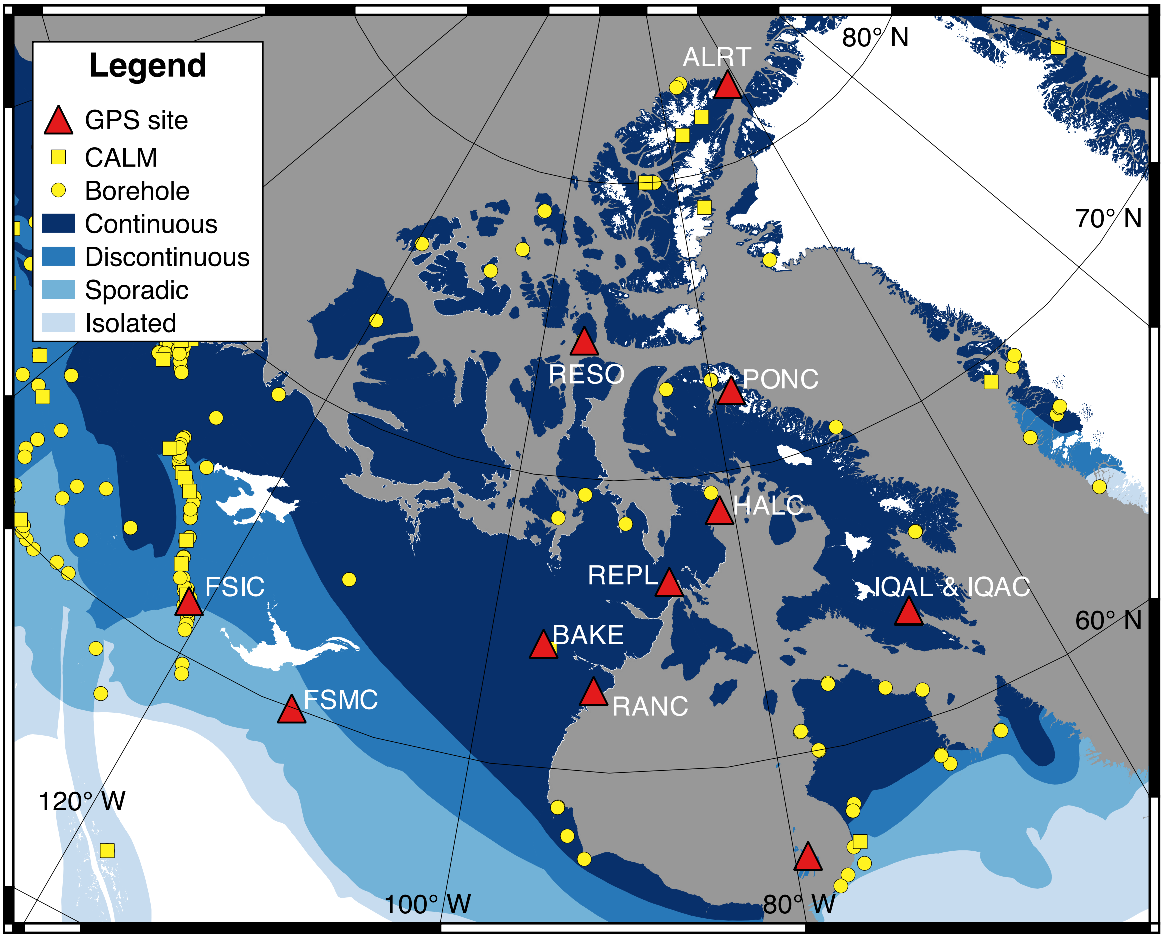

Figure R1: Locations of the identified GPS stations in Northern Canada and the CALM sites and GTN-P boreholes. The IDs of GPS stations are presented. The types of permafrost distribution are indicated by various colours.

The following questions should be answered:

1. According to the description in the manuscript, the ground of the GPS is buried deep in the permafrost layer and will not change with the settlement of the active layer. The settlement results obtained are also sub-centimeter level, but the movement of the Earth's plate is vertical to the GPS receiver. The effect of displacement cannot be ignored. It is necessary to consider whether the spatial coordinates of the GPS antenna are constant, so that the ground subsidence can be measured with the GPS antenna as a reference.

Response: GPS-IR measurements obtained at the identified CACS sites are free of soil earth movement and glacier isostatic movement. Permafrost is the ground whose temperature is at or below 0 °C for at least two consecutive years. On top of permafrost is the active layer, which thaws/freezes seasonally and accordingly is subject to subside/uplift (*Lines 33–35*). The monuments of the used CACS stations are anchored deep into permafrost, which means the monuments are stable with respect to the permafrost. Tectonic movements would have same impact on the monument foundation, the antenna aligned to the monument, and the active layer. The changes of reflector height, the distance between the antenna and surface, reflect directly the changes of the active layer and permafrost (*Lines 56–59*).

2. The photos of the stations showed the surrounding environment are still relatively complicated. The reflected SNR oscillation obtained by this environment should be disordered. The measured reflection SNR sequence diagrams and spectrum analysis results of several stations should be given.

Response: The photos are the only ones we can find. The azimuth coverages of the ground in the photos might not coincide with the ones we determine by following the method in section 2.2.

We show examples of SNR series in the determined azimuth coverages and their frequency spectrums of the 5 identified CACS sites in Fig. R2. We can clearly observe the consistent sinusoidal oscillations of SNR series. Such oscillations indicate that the surface condition within the determined azimuth coverage meets the requirements of GPS-IR. These SNR series are useful to retrieve reflector heights by frequency-spectrum analysis. In the right panels in Fig. R2, dominant frequencies, corresponding to reflector heights, of SNR series can be identified and they are clearly aligned.

Superimposed on the sinusoidal oscillations are high-frequency noises, which possibly caused by surface roughness and other unexpected disturbances. Those noises might introduce uncertainties to reflector height retrieved by spectrum analysis. To lower the uncertainty, more than 10 usable SNR series are required (*Lines 132–133*).

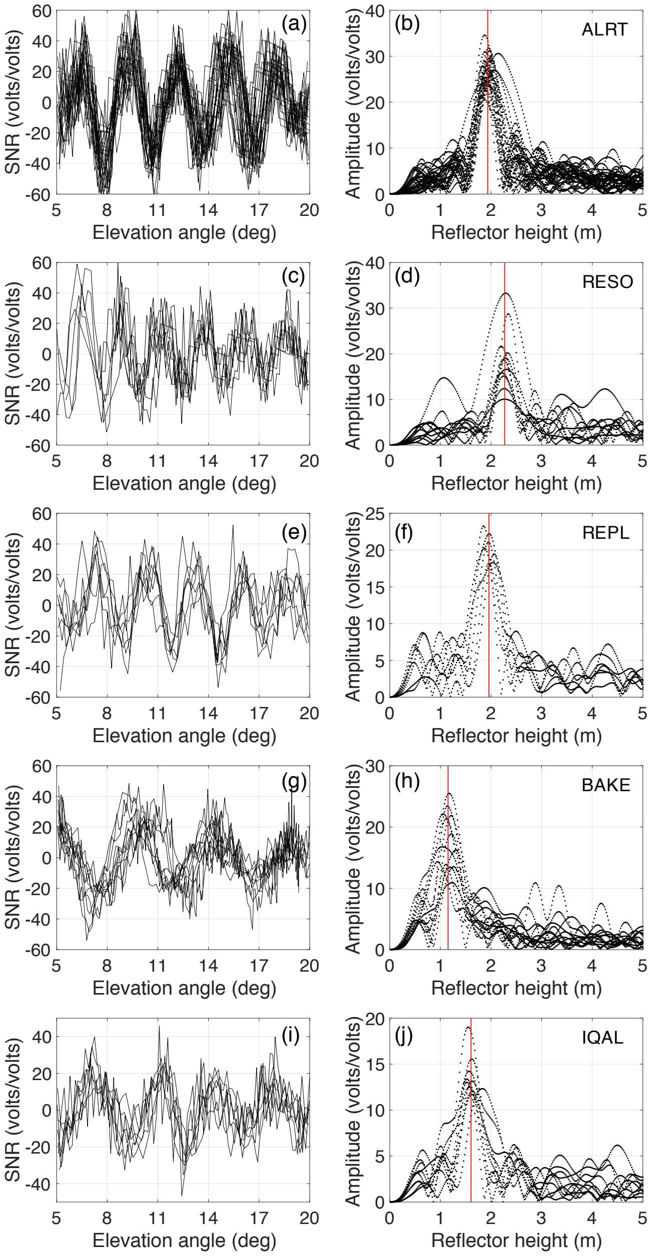

Figure R2: Examples of SNR series (left) and their frequency spectrums (right, expressed as reflector height in the x-axis) at the identified CACS site. The 2-order polynomial fits of SNR series have been removed. And the frequencies have been converted to reflector heights by equation (3) in Sect. 2. Each vertical red line in the right panels marks the dominant reflector height.

3. The noise of SNR measurement is relatively large, which results in the accuracy of snow thickness measurement with approximate specular reflection being only 0-5cm. The surface of the bare soil is rougher, and the error of height measurement will be larger, but the result is sub-centimeter, how to explain it.

Response: The uncertainties of our GPS-IR measurements are on the order of a few centimeters, which we demonstrate explicitly in lines 260–261. We also have published our results in PANGAEA (https://doi.pangaea.de/10.1594/PANGAEA.904347). The uncertainty is presented by the standard deviation of the mean value, i.e., the standard deviation divided by the square root of the sample size. Therefore, the magnitude of uncertainty partly depends on the sample size, which is more than 10 in our study.

4. The researches of Chew and Small (2014, 2016) showed that vegetation will affect the reflection signal. How to process the influence of vegetation on the reflection signal and height measurement needs to be explained in the manuscript.

Response: The study sites are located in the Canadian Arctic, where the biomes are dominantly Polar desert and tundra. The vegetation is either sparse or short. They are nearly transparent for L-band GPS signals. Therefore, the impact of vegetation on reflected signals and SNR is limited and can be ignored.

Reference:

Gruber, S. (2019). Ground subsidence and heave over permafrost: hourly time series reveal inter-annual, seasonal and shorter-term movement caused by freezing, thawing and water movement. The Cryosphere Discussions, 2019, 1–18. https://doi.org/10.5194/tc-2019-227

Hu, Y., Liu, L., Larson, K. M., Schaefer, K. M., Zhang, J., & Yao, Y. (2018). GPS Interferometric Reflectometry Reveals Cyclic Elevation Changes in Thaw and Freezing Seasons in a Permafrost Area (Barrow, Alaska). Geophysical Research Letters, 45(11), 5581–5589. https://doi.org/10.1029/2018GL077960

Liu, L., & Larson, M. (2018). Decadal changes of surface elevation over permafrost area estimated using reflected GPS signals. The Cryosphere, 12(2), 477–489. https://doi.org/10.5194/tc-12-477-2018