Responses to RC1

We thank the reviewer for his/her 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.

1. Please highlight what is really new and what is the outcome and applicability of this approach in a more prominent way.

Response: This comment asks about (1) innovative aspects, (2) outcome and applicability of this approach. Below, we are addressing the innovative aspects of this study in terms of methodology, new findings, and merits of using GPS-IR for studying permafrost. We will respond to the 2nd part of reviewer's comment in a separate thread.

(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.

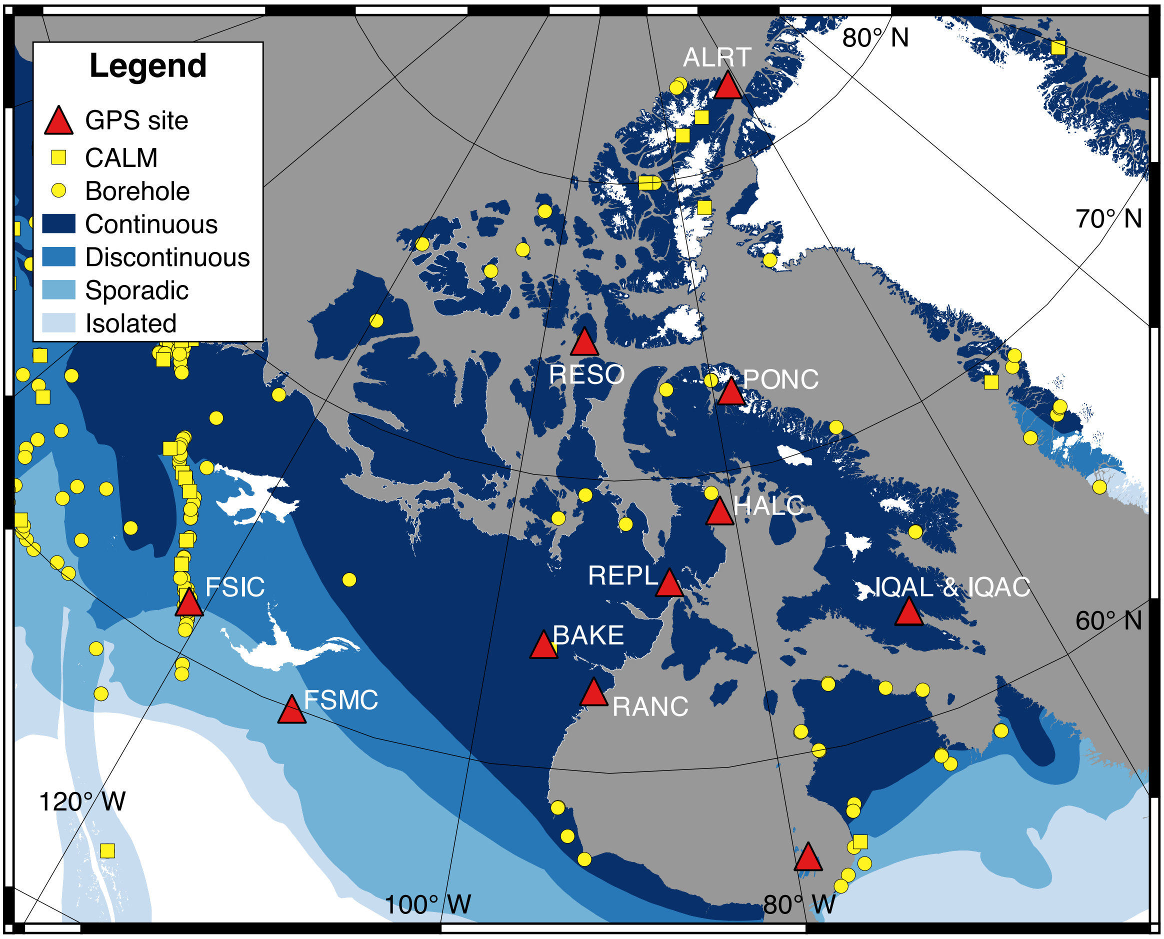

Figure R1: Locations of the identified GPS stations in Northern Canada and the CALM sites and GTN-P boreholes. The IDs of GPS stations are presented. The types of permafrost distribution are indicated by various colours.

1. Please highlight what is really new and what is the outcome and applicability of this approach in a more prominent way.

Response: Corresponding to the innovations presented above, the major outcomes of this approach in this study are (1) a framework guiding to filter out suitable GPS stations in permafrost areas, where GPS-IR is feasible, (2) 12 identified suitable GPS stations distributed across Northern Canada, (3) Multi-year, continuous, and daily measurements of surface deformation at five geodetic-quality GPS sites, (4) new findings in the dynamics of the active layer and permafrost.

Applicability of GPS-IR depends on the surface conditions, which should be relatively horizontal and smooth. This is the reason why we proposed a framework to identify suitable ones from existing stations. We also summarize the limitations of GPS-IR measurements in permafrost studies. The applicability and limitations of GPS-IR indicate that better location choices and instrument maintenance should be made in the future to fully realize the potentials of the GPS stations installed in frozen areas.

2. It is already proved by Larson et al. (2008) that the reflector height (H) and the phase of SNR observations are highly correlated. Therefore, some of the H variations should come from the phase variations.

Response: We do not think Larson et al. (2008) proved the high correlation between reflector height and the phase of SNR series. Instead, their study found a high correlation between the phase of SNR series and surface soil moisture. To explain this finding, they introduced the term of apparent reflector height, which is converted from the phase (equation (1) can be rewritten as $SNR = A(e)\sin(\frac{4\pi}{\lambda}\left(H + \frac{\lambda\phi}{4\pi\sin e}\right)\sin e)$). They thought that soil moisture affects apparent reflector height (i.e., "When the soil is wet, the apparent reflector is close to the surface; as it dries, the reflection depth is several cm deeper" in Larson et al. (2008)), then affects phase. Apparent reflector height (converted from the phase) cannot be mixed up with the reflector height (converted from the frequency).

3. SNR observations also are a function of GPS receiving antenna and GPS signals. The authors have not discussed what types of antennas and signals are investigated, and how their impacts have been moved from the estimated heights.

Response: In this study, we used SNR data of GPS L1 C/A signals, as L1 C/A is the legacy civilian signal broadcasted by all satellites and long-term measurements can be obtained. As for the antenna, its gain pattern impacts GPS-IR measurements. The GPS stations used in this study were originally installed and maintained for geodetic or ionospheric studies. Their antennas were designed to favour direct signals with high elevation angles and suppressing signals with low and negative elevation angles, by using asymmetric antenna gain patterns. During the data time spans, antennas were not replaced. The impact of antenna gain pattern can be regarded as a system bias, and barely impact the GPS-IR results.

In the revised manuscript, we have explicitly presented the antenna types and included more details of data processing. And we also have added a subsection discussing possible error sources of GPS-IR measurements.

4. In addition, the penetration depth of microwave signals should be physically estimated to correct the estimated heights.

Response: The penetration depth of microwave signals, i.e., the depth where the power of signal reduces to 1/e of its value at soil surface, is not appropriate for defining the depth of reflector (Chew et al., 2014). The signal might penetrate into soil to some depth, but it does not mean that a significant part of the signal would reflect back from that depth to antenna. The interaction between signal and ground surface is rather complex. Comparing to penetration depth, it is more important to consider how changes of ground permittivity would affect SNR data. Zavorotny et al. (2010) built a forward model to simulate SNR, with consideration of antenna gain pattern and surface reflectivity however no penetration depth. The simulated SNR and their GPS-IR retrievals have a good agreement with the experimental ones. This simulation indicates that reflected signal from the penetration depth has a minor contribution to SNR. Furthermore, we focus on the temporal variations of reflector heights. We do not expect significant temporal changes in penetration depth during the data time spans. Therefore, we do not see a need to estimate penetration depth and correct for it.

5. The authors just used low elevation angle observations as SNR oscillations are clearer. However, the tropospheric impact is not negligible for low elevation angle observations even for 2-3 m antenna heights, so its impact should be studied in the paper. The tropospheric refractions seem to have a seasonal impact on GPS-IR (Williams and Nievinski, 2017). The authors have not corrected their GPS-IR solutions. Therefore, the reported slopes are tropospheric-contaminated.

Response: Tropospheric refraction may introduce biases in the estimated reflector height, which, however, barely affect the retrieved temporal elevation changes as presented in this study. The tropospheric bias mainly depends on antenna height and atmospheric conditions at a given satellite elevation angle (Williams and Nievinski, 2017). The GPS stations used in this study are located in the Canadian Arctic, where the climate is dry and cold. The antenna heights of these stations are ~2 m. Conceptually, the tropospheric bias of GPS-IR measurements of reflector height is limited.

We calculate the tropospheric bias by using the astronomical refraction model of Bennett (1982) and SNR data in Resolute Bay in the thaw season of 2014. The results show that the mean bias is 1.6 cm, and that they are relatively steady with a variation range of merely 3 mm

(Fig. R2(a)). The biases do not show significant seasonal pattern. And their magnitudes are comparable to the uncertainties of our GPS-IR measurements (Fig. R2(b)). As we focus on the temporal variations of reflector heights, instead of their absolute values, it is unnecessary to correct for the tropospheric biases.

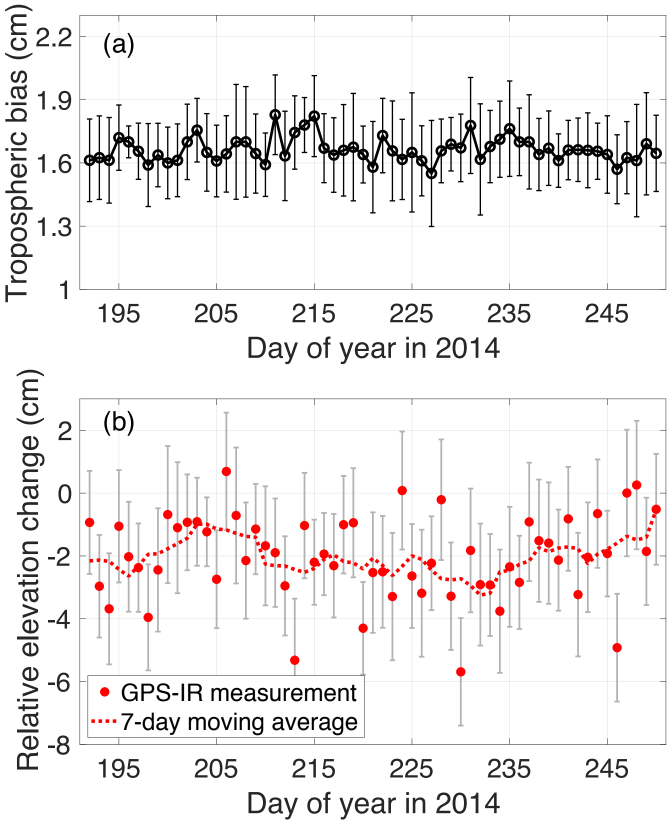

Figure R2: (a) Time series of tropospheric biases in estimated reflector heights in Resolute Bay in the thaw season (i.e., DOY 192–250) of 2014. They are the mean values of the tropospheric biases of all satellite tracks; their standard deviations are indicated by error bars. (b) Time series of GPS-IR-estimated surface elevation changes shown in Fig. 6 in the submitted discussion paper and their 7-day moving averages.

6. In addition, the authors used different antenna monuments (Figure 4), but they did not study the thermal expansion of monuments.

Response: The monuments of the 5 identified CACS stations are made of aluminium or Galvanized/Stainless steel, whose linear thermal expansion/contraction coefficients are 11~13 × 10^{-6} and 23.1 × 10^{-6} m/(m K), respectively. Given a temperature variation range of 20 °C in thaw season, for a 2-m-high aluminum/steel monument, the magnitude of thermal expansion is less than 1 mm, at least one order of magnitude smaller than the elevation changes. The thermal expansion/contraction impact is ignorable for GPS-IR measurements.

7. The authors used the mean value of each year after the outliers are rejected to estimate and report the slopes, while the results presented in Figure 5 are somehow confusing. For example, at Alert what is the mean for 2016? It seems it is very different from the other 5 years and 2016 cannot represent the reported slope. There are other examples like 2014 at Iqaluit, 2004 and 2011 at Resolute Bay.

Response: Sorry about the confusion caused. We would like to clarify that we use all daily GPS-IR measurements in thaw seasons during the entire data time span to obtain the linear trend at each site. For example, in Alert, the linear trend corresponds to the daily measurements in thaw seasons during 2012–2017. We do not use the mean value of each year or reject any outliers.

The deviation of the measurements of Alert in 2016 (or those of Iqaluit in 2014 and those of Resolute Bay in 2004 and 2011) from the best linear fit is due to the interannual variability of changes in the active layer and near-surface permafrost. Such interannual variability is related to environmental variables including precipitation, soil temperature, soil moisture content, and ground ice condition. However, it is challenging to study the interannual variability as most of these ancillary records are not available. This is one of the limitations of using GPS-IR measurements to study permafrost as we discussed in section 5.3 (*Lines 272–276*).

8. In addition, it is more complex at Bakes Lake as it seems just a linear fit doesn't represent the GPS station and higher-order polynomials should be used. It would be easier if the median reflector heights for each year were also plotted together with the time series in Figure 5. That would help us to understand if the linear fit is good enough to report surface elevation changes.

Response: The linear trend is superimposed by seasonal variation, interannual variability, and possibly sub-decadal pattern. Given the data time span, it is not justified to simply use a high-order polynomial to fit the time series, as it is not long enough. The GPS site in Baker Lake is still operating. It would be clearer whether a sub-decadal pattern exists when we have at least decade-long measurements.

We tend not to use median reflector heights of each year. The time series of measurements is a combination of linear trend, interannual variability, seasonal variation, and possible sub-decadal pattern. It cannot be represented by the time series of median reflector heights.

Reference:

Bennett, G. G. (1982). The Calculation of Astronomical Refraction in Marine Navigation. Journal of Navigation, 35(2), 255–259. https://doi.org/DOI:10.1017/S0373463300022037

Chew, C. C., Small, E. E., Larson, K. M., & Zavorotny, V. U. (2014). Effects of near-surface soil moisture on GPS SNR data: Development of a retrieval algorithm for soil moisture. IEEE Transactions on Geoscience and Remote Sensing, 52(1), 537–543. https://doi.org/10.1109/TGRS.2013.2242332

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

Larson, K. M., Small, E. E., Gutmann, E. D., Bilich, A. L., Braun, J. J., & Zavorotny, V. U. (2008). Use of GPS receivers as a soil moisture network for water cycle studies. Geophysical Research Letters, 35(24), 1–5. https://doi.org/10.1029/2008GL036013

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

Williams, S. D. P., & Nievinski, F. G. (2017). Tropospheric delays in ground- based GNSS multipath reflectometry—Experimental evidence from coastal sites. Journal of Geophysical Research: Solid Earth, 122(3), 2310–2327. https://doi.org/10.1002/2016JB013612

Zavorotny, V. U., Larson, K. M., Braun, J. J., Small, E. E., Gutmann, E. D., & Bilich, A. L. (2010). A Physical Model for GPS Multipath Caused by Land Reflections: Toward Bare Soil Moisture Retrievals. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 3(1), 100–110. https://doi.org/10.1109/JSTARS.2009.2033608