Response to Editor

We thank the editor and the reviewers for their insightful and constructive comments. We have addressed all of them and made the suggested changes in the new version of our manuscript. In addition, we took this chance to add the recent data and extend the data time span to 2018 in Alert and to 2019 in Repulse Bay and Iqaluit, and updated the results and interpretation correspondingly.

Please refer to the attached pdf for our point-by-point responses (in black) to the critical comments (in blue). Please note that the page/line numbers in our responses refer to the new line numbers in the revised manuscript.

The two anonymous referees and Dr. Felipe Nievinski mostly focused on the innovative aspect of the work from the perspective of methodology and raised many questions which substantially improve the manuscript. In addition to assessing the usability of existing GPS stations in Canada for studying permafrost, we also made significant efforts to interpret the GPS-IR results of surface elevation changes at the identified sites in the Canadian Arctic. We found surface subsidence in Alert (2010–2018), Resolute Bay (2003–2014), and Repulse Bay (2014–2019) with warming summers, which indicate permafrost degradation at these sites and air temperature is the dominant driver. We also found that, in Resolute Bay, ground uplift in the middle of summer in most of the years during 2003–2014 and end-of-thaw elevations were low with cool summers in 2013 and 2014. Such abnormal and complex changes cannot be explained by the simple Stefan equation. Our results and interpretation provide new insights into studying permafrost dynamics.

Our study is the first one of this kind assessing the usability of existing GPS stations in Canada for studying permafrost by GPS-IR. It is also the first one using multiple GPS sites to study frozen ground dynamics. This study is significant in the following three aspects: (1) it provides multiple usable GPS sites, complementary to the existing permafrost monitoring programs; (2) it provides daily measurements of surface elevation changes at five sites in the Canadian Arctic spanning from several years to more than a decade, with comprehensive consideration of possible errors; (3) it also puts new insights into permafrost studies. We believe that this study is worthwhile to be published in *The Cryosphere*. It will bring new and significant measurements and scientific findings to the readers of TC from permafrost and the related fields such as hydrology and remote sensing.

Responses to RC1

We thank the reviewer for his/her insightful and constructive comments. We have addressed all of them and made the suggested changes in the new version of our manuscript. In addition, we took this chance to add the recent data and extend the data time span to 2018 in Alert and to 2019 in Repulse Bay and Iqaluit, and updated the results and interpretation correspondingly. Below are our point-by-point responses (in black) to the critical comments (in blue). Please note that the page/line numbers in our responses refer to the new line numbers in the revised manuscript.

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 2^{nd} 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 (*Page 4, Lines 121–144*). To our knowledge, this framework is the first of this kind for studying 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 200+ GPS stations that are operating continuously in the circumpolar permafrost areas 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 in section 5.4 (*Page 11, Lines 322–341*). 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.

(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 in section 5.3 (*Page 10, Lines 280–320*). We evaluated the magnitudes of the biases caused by these variables and corresponding impacts on our results and interpretation.

(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 5.5 and summarized in Table 4, clearly show that these two methods and their measurements are complementary to each other (*Page 11, Lines 342–356*). 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.

<u>(b) new findings:</u>

(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 2012–2018, Resolute Bay during 2003–2014, and Repulse Bay during 2014–2019 (*Page 7, Lines 203–207*. We found the negative correlation between the linear trends of surface deformation and those of thawing indices (*Page 9, Lines 264–273*). 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 (*Page 8, Lines 238–242*). However, in 2013 and 2014, the end-of-thaw elevations were low with cool summers (*Page 9, Lines 251–252*). This phenomenon is possibly due to the Markovian behaviour of the active layer, which is worthwhile to be documented and investigated further.

(iv) In Resolute Bay, we observed summer heave of surface in most of the thaw seasons during 2003–2014 (*Page 7, Lines 212–213*). 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.

<u>(c) Merits of using GPS-IR for studying permafrost:</u>

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 the significant increase in the 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 (*Page 2, 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.

We have refined the abstract (*Page 1, Lines 19–22*) and the conclusion (*Page 12, Lines 358–381*) to explicitly show our innovations.

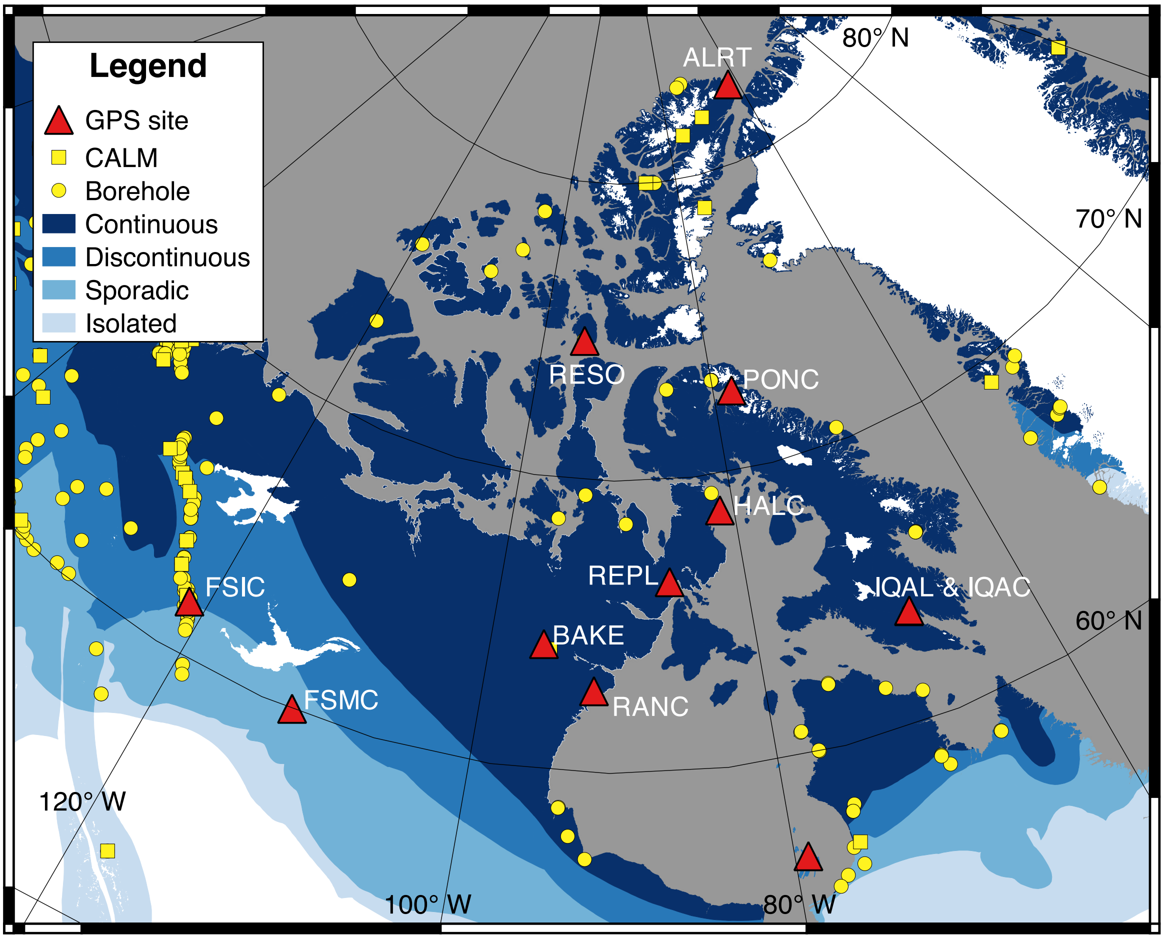

Figure R1: Locations of the identified GPS stations in Northern Canada and the CALM sites and GTN-P boreholes. The IDs of GPS stations are presented. The types of permafrost distribution are indicated by various colors.

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 identify 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), i.e., $SNR = A(e)\sin\left(\frac{4\pi H}{\lambda}\sin e + \phi\right)$, 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 favor 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 in the supplementary by Table S1 and included more details of data processing (*Page 4, Lines 106–112; Page 5, Lines 146–148*). And we also have added a subsection (*section 5.3, Page 10, Lines 280–320*) discussing possible error sources of GPS-IR measurements, including antenna gain patterns.

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 affect SNR data. Zavorotny et al. (2010) built a forward model to simulate SNR, with consideration of antenna gain pattern and surface reflectivity but not 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 a significant seasonal variability. 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.

We have added a subsection (*section 5.3, Page 10, Lines 280–320*) discussing possible error sources of GPS-IR measurements, including tropospheric delays.

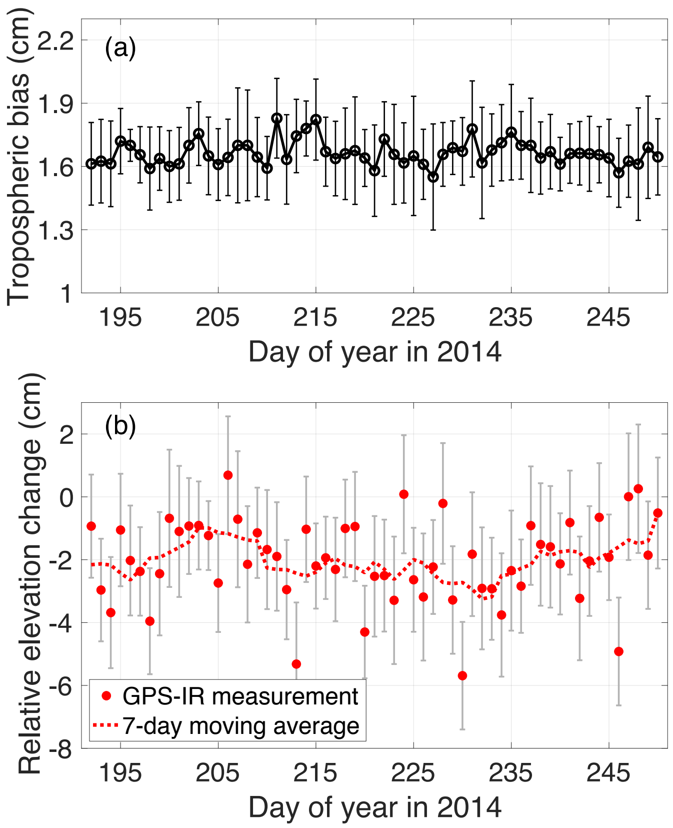

Figure R2: (a) Time series of tropospheric biases in estimated reflector heights in Resolute Bay in the thaw season (i.e., DOY 192–250) of 2014. They are the mean values of the tropospheric biases of all satellite tracks; their standard deviations are indicated by error bars. (b) Time series of GPS-IR-estimated surface elevation changes shown in Fig. 6 in the revised manuscript 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 $11{\sim}13 \times 10^{-6}$ 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. We have added a subsection (*section 5.3, Page 10, Lines 280–320*) discussing possible error sources of GPS-IR measurements, including monument material.

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 2012–2018. 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 5.4 (*Page 11, Lines 322–341*).

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 the median reflector height 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

Responses to RC2

We thank the reviewer for his/her insightful and constructive comments. We have addressed all of them and made the suggested changes in the new version of our manuscript. In addition, we took this chance to add the recent data and extend the data time span to 2018 in Alert and to 2019 in Repulse Bay and Iqaluit, and updated the results and interpretation correspondingly. Below are our point-by-point responses (in black) to the critical comments (in blue). Please note that the page/line numbers in our responses refer to the new line numbers.

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 (*Page 4, Lines 121–144*). To our knowledge, this framework is the first of this kind for studying 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 200+ GPS stations that are operating continuously in the circumpolar permafrost areas 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 in section 5.4 (*Page 11, Lines 322–341*). 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.

(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 in section 5.3 (*Page 10, Lines 280–320*). We evaluated the magnitudes of the biases caused by these variables and corresponding impacts on our results and interpretation.

(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 5.5 and summarized in Table 4, clearly show that these two methods and their measurements are complementary to each other (*Page 11, Lines 343–356*). 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.

<u>(b) new findings:</u>

(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 2012–2018, Resolute Bay during 2003–2014, and Repulse Bay during 2014–2019 (*Page 7, Lines 203–207*). We found the negative correlation between the linear trends of surface deformation and those of thawing indices (*Page 9, Lines 264–268*). 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 (*Page 8, Lines 238–242*). However, in 2013 and 2014, the end-of-thaw elevations were low with cool summers (*Page 9, Lines 251–252*). This phenomenon is possibly due to the Markovian behaviour of the active layer, which is worthwhile to be documented and investigated further.

(iv) In Resolute Bay, we observed summer heave of surface in most of the thaw seasons during 2003–2014 (*Page 7, Lines 212–213*). 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.

<u>(c) Merits of using GPS-IR for studying permafrost:</u>

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 the significant increase in the 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 (*Page 2, 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.

We have refined the abstract (*Page 1, Lines 19–22*) and the conclusion (*Page 12, Lines 358–381*) to explicitly show our innovations.

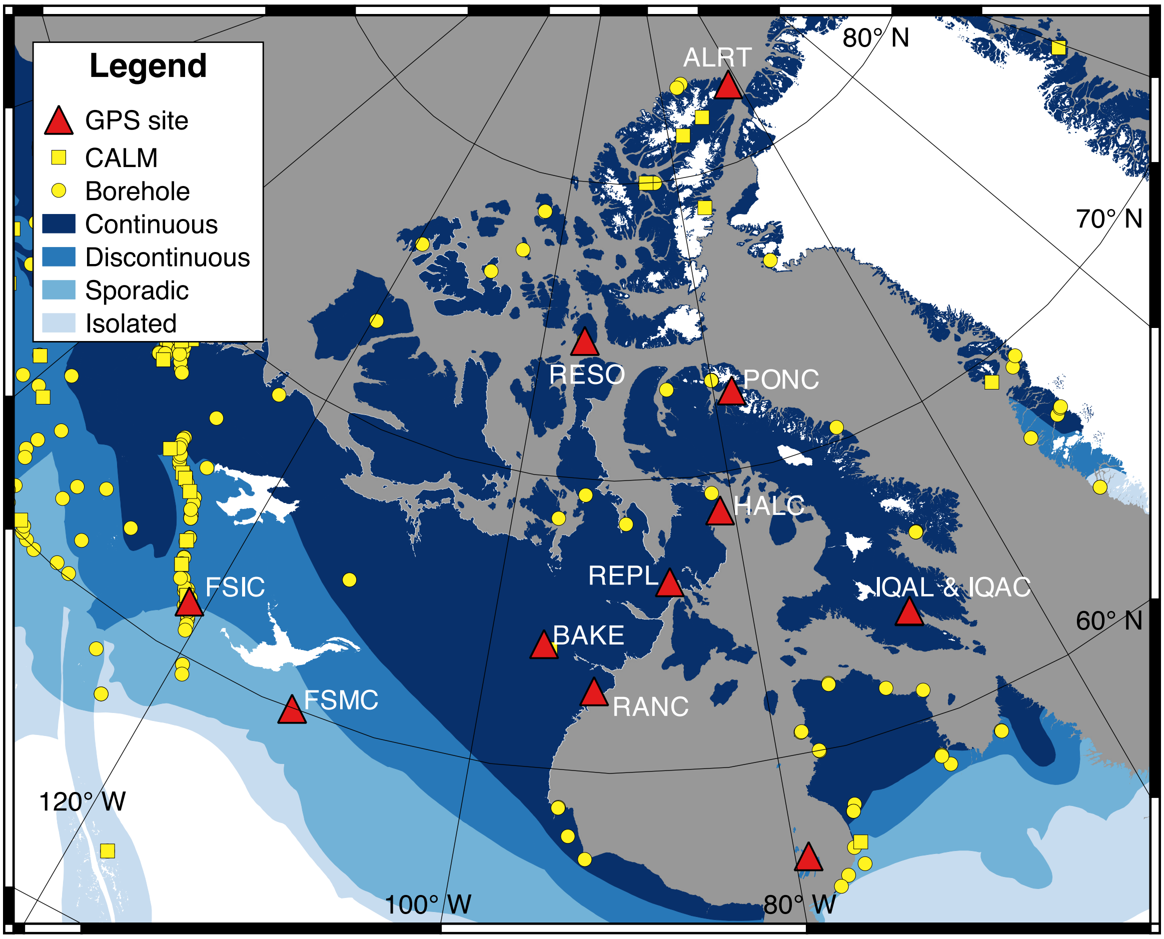

Figure R1: Locations of the identified GPS stations in Northern Canada and the CALM sites and GTN-P boreholes. The IDs of GPS stations are presented. The types of permafrost distribution are indicated by various colors.

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 (*Page 2, 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 the 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, directly reflect the changes of the active layer and permafrost (*Page 2, Lines 55–58*).

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 (*Page 5, Lines 143–144*).

We have included Fig. R2 as supplementary.

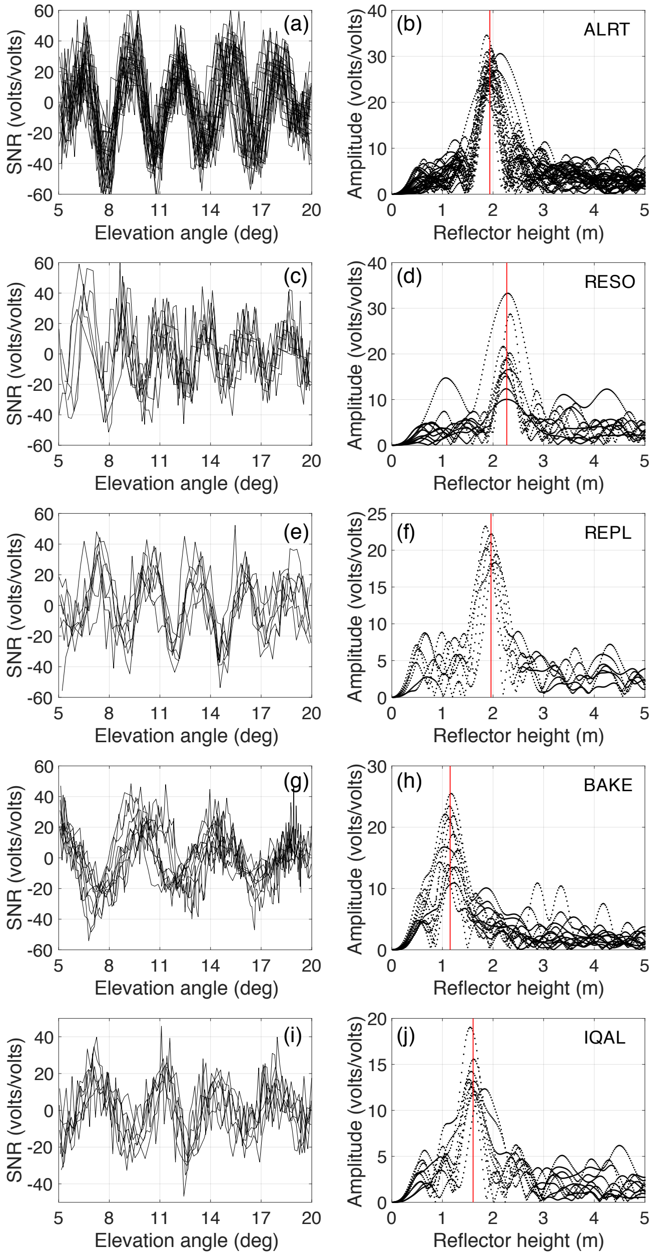

Figure R2: Examples of SNR series (left) and their frequency spectrums (right, expressed as reflector height in the x-axis) at the identified CACS site. The 2-order polynomial fits of SNR series have been removed. And the frequencies have been converted to reflector heights by equation (3) in Sect. 2. 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 Line 322 (*Page* 11). 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. We have added a subsection (*section 5.3, Page 10, Lines 280–320*) discussing possible error sources of GPS-IR measurements, including vegetation.

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

Responses to SC1

We thank Dr. Felipe G. Nievinski for his insightful and constructive comments. We have addressed all of them and made the suggested changes in the new version of our manuscript. In addition, we took this chance to add the recent data and extend the data time span to 2018 in Alert and to 2019 in Repulse Bay and Iqaluit, and updated the results and interpretation correspondingly. Below are our point-by-point responses (in black) to the critical comments (in blue). Please note that the page/line numbers in our responses refer to the new line numbers.

Major:

1. The GPS antenna foundation should be discussed in more detail. Currently only the distinction between buildings and steel pipes is given. But not all steel pipes are the same. At least the foundation depth should be given. For example, ALRT is 6-m deep while REPL seems to have concrete slab under the metal pedestal.

Response: The monuments of the identified CACS stations are anchored into bedrocks. The monument materials are aluminium for REPL and IQAL, and steel for ALRT, RESO, and BAKE. The foundation depths of ALRT, RESO, REPL, and IQAL are 6 m, 3 m, 1.5 m, and 1 m, respectively. The foundation depth for BAKE is not available.

We have updated Table 1 in the revised manuscript to explicit the foundation types and depths and monument materials.

Moderate:

2. The pioneering work of Hu et al. (2018) should be compared and contrasted with the present submission.

Response: Hu et al. (2018) proposed a composite model to fit surface elevation changes in both thawing and freezing seasons, by using the GPS-IR measurements in Barrow, Alaska from Liu and Larson (2018). Based on the measurements during 2004–2015, Liu and Larson observed a subsidence trend of 0.26 ± 0.02 cm yr-1, which indicated permafrost degradation. During the same time span, the thaw season had a warming trend with 4.79 °C·day yr-1. This is consistent with our finding that the trend of surface elevation changes is negatively correlated with that of thawing indices (*Page 9, Lines 268–269*). Air temperature is the dominant driver of permafrost dynamics at the study sites. The GPS site SG27 in Barrow and our newly identified sites in Northern Canada provides complementary study sites for permafrost studies. They can be used to study the permafrost changes across a broad region. We have added a paragraph (*Page 9, Lines 275–279*) in section 5.2 to compare the work of Liu and Larson (2018) and ours.

3. More details of the GPS-IR data processing is necessary. For example, what GPS signal was employed – L1-C/A?

Response: We use SNR data of GPS L1 C/A signals. In practice, we divide SNR series into individual segments corresponding to rising/setting satellite tracks. Then we remove the 2-order polynomial fits from them and use the residual ones. We conduct Lomb-Scargle Periodogram (LSP) analysis on any given SNR series to obtain its frequency spectrum, then use its peak value to represent the oscillating frequency, which is converted to reflector height. The oversampling parameter of LSP is determined to produce a resolution of 1 mm of reflector height. We use the software tools of GNSS Interferometric Reflectometry (Roesler and Larson, 2018).

We have revised the methodology section to show the details of data processing (*Page 4, Lines 106–112; Page 5, Lines 146–148*).

4. Authors should document the GPS receiver and antenna models used in each station, including the time of replacement, at least as supplementary material.

Response: We summarize the instrumentation information in Table R1, where the receiver types and antenna models during the data time span of each site are presented. We have included the table R1 into the revised manuscript as supplementary.

Table R1. Receiver and antenna types of the identified GPS stations.

ID	Receiver type	Antenna model	Radome	Data time span	Source
ALRT	ASHTECH UZ-12	ASH701945D_M	NONE	2012–2018	https://webapp.geod.nrcan.gc.ca/geod/data-donnees/cacsscca.php?locale=en
RESO	ASHTECH UZ-12	ASH700936A_M	NONE	2003–2014	
REPL	TRIMBLE NETR9	TRM59800.00	NONE	2014–2019	

BAKE	TPS NETG3 (before 2013/07/11) TPS NET-G3A	TPSCR.G3	NONE	2010–2017	
IQAL	TPS NETG3 (before 2011/09/12) TPS NET-G3A	TPSCR.G3	NONE	2010–2019	
PONC	NOVATEL GSV4004	NOV702GG	NONE	2008–2018	RINEX observation files
HALC	NOVATEL GSV4004	NOV702GG	NONE	2008– 2018	
IQAC	NOVATEL GSV4004	NOV702GG	NONE	2008–2018	
RANC	SEPT POLARXS	POLANT+_GG	NONE	2014–2018	
FSIC	SEPT POLARXS	POLANT+_GG	NONE	2014–2018	
FSMC	SEPT POLARXS	POLANT+_GG	NONE	2014–2018	
SANC	NOVATEL GSV4004	NOV702GG	NONE	2008–2018	

5. Authors should also acknowledge some of the possible error sources in the simplistic mathematical formulation of eq.(1), where the phase term (phi) is not necessarily constant and can actually vary with soil moisture, vegetation cover, etc.

Response: We agree that equation (1), i.e., $SNR = A(e)\sin\left(\frac{4\pi H}{\lambda}\sin e + \phi\right)$ is the simplified expression of SNR series. Phase ϕ is not constant for each point of the series and also a function of satellite elevation angle. Equation (1) can be rewritten as $SNR = A(e)\sin\left(\frac{4\pi}{\lambda}\left(H + \frac{\lambda\phi}{4\pi\sin e}\right)\sin e\right)$. ϕ

can be expressed as a part of reflector height as $\frac{\lambda\phi}{4\pi \sin e}$. Phases at different elevation angles have different impacts on reflector height. Taking phase as a constant in practice might introduce bias to reflector height. However, such bias is limited. Based on the simulations of Zavorotny et al. (2010), the variation range of the impact of phase on reflector height during the elevation angles 5°–30° is ~1 cm. Furthermore, we focus on the temporal variations of reflector height. So, the bias caused by taking phase as a constant does not have a significant impact on our results.

Regarding the vegetation, at the study sites, the biomes are Arctic desert or tundra. The ground is barely or sparsely vegetated. The vegetation is short enough, i.e., less than the wavelength of GPS signals. The vegetation is approximately transparent for GPS signals. The impact of vegetation on GPS-IR measurements is negligible.

Soil moisture is highly correlated to phases of SNR observations, manifested as an approximately linear relationship at low elevation angles (Larson et al., 2008; Zavorotny et al., 2010; and Chew et al., 2014). Changes of soil moisture introduce biases to reflector height retrievals. Soil moisture variation leads to surface permittivity changes, which affect reflected GPS signals and then phases of SNR observations. Such impact on phase at different elevation angles is different. The inconsistency of phase changes introduces bias to reflector height. Such impact is called compositional reflector height, as it manifests itself by a part of reflector height (Nievinski, 2013). Liu and Larson (2018) simulated the compositional height due to soil moisture changes between 15% and 40% and found that they are less than 2 cm and their variation range is less than 1 cm. In this study, the compositional heights and their variation range are expected to be limited, as the precipitation is light and limited due to the cold and dry polar climate. Moreover, as we focus on the temporal variations of reflector heights at interannual and sub-decadal time scales, we expect a negligible impact of compositional heights on our results and interpretation.

We have added a subsection (*section 5.3, Page 10, Lines 280–320*) discussing possible error sources of GPS-IR measurements, including tropospheric delays, soil moisture, vegetation, antenna gain patterns, and monument materials.

Minor:

6. "The uncertainty of H-bar is represented by its standard deviation." -> It should be the standard error of the mean, i.e., the standard deviation divided by the square-root of the sample size.

Response: We have revised the manuscript to explicit that the uncertainty of the daily reflector height measurement is represented by the standard deviation of the mean value, i.e., the standard deviation divided by the square root of the sample size. (*Page 5, Lines 142–143*)

7. replace bullet for dot in: ˚CâĂ˘c´day yr-1 -> ˚CÂu˚dayÂu˚yr-1

Response: We have revised the units of thawing index to °C·day. (e.g., *Page 9, Line 255*)

8. for a 2-m-height antenna -> for a 2-m-high antenna [or: for 2-m antenna height.]

Response: We have revised the manuscript accordingly. (*Page 2, Line 54*)

9. As the monument is deep anchored (e.g. Fig. 2), the GPS antenna is stable with respect to the permafrost -> If the monument is deep anchored (e.g. Fig. 2), the GPS antenna is stable with respect to the permafrost

Response: We have revised the manuscript accordingly. (*Page 4, Lines 114–115*)

Reference:

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

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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

Nievinski, F. G.: Forward and inverse modeling of GPS multipath for snow monitoring, PhD thesis, University of Colorado, Boulder, CO, USA, 2013.

Roesler, C., & Larson, K. M. (2018). Software tools for GNSS interferometric reflectometry (GNSS-IR). GPS Solutions, 22(3), 80. https://doi.org/10.1007/s10291-018-0744-8

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

GPS Interferometric Reflectometry measurements of ground surface elevation changes in permafrost areas in northern Canada

Jiahua Zhang[1], Lin Liu[1], Yufeng Hu[2]

[1]Earth System Science Programme, Faculty of Science, The Chinese University of Hong Kong, Hong Kong, 999077, China
[2]College of Geology Engineering and Geomatics, Chang'an University, Xian, 710000, China

Correspondence to: Jiahua Zhang (zhangjiahua@link.cuhk.edu.hk)

Abstract. Global Positioning System Interferometric Reflectometry (GPS-IR) is a relatively new technique which uses reflected GPS signals to measure surface elevation changes to study frozen ground dynamics. At present, more than 200 GPS stations are operating continuously in the Northern Hemisphere permafrost areas, which were originally designed and maintained for tectonic and ionospheric studies. However, only one site in Barrow, Alaska was assessed to be usable for studying permafrost by GPS-IR. Moreover, GPS-IR has high requirements on ground surface condition, which needs to be open, flat, and homogeneous. In this study, we screen 3 major GPS networks in Canada and identify 12 out of 38 stations located in permafrost areas as useful ones where reliable GPS-IR measurements can be obtained. We focus on the 5 Canadian Active Control System stations and obtain their daily GPS-IR surface elevation changes. We find that the ground surface subsided in Alert, Resolute Bay, and Repulse Bay respectively by 0.61 ± 0.04 cm yr^{-1} (2012–2018), 0.70 ± 0.02 cm yr^{-1} (2003–2014), and 0.26 ± 0.05 cm yr^{-1} (2014–2019). At the other two sites of Baker Lake and Iqaluit, the trends are not statistically significant. The linear trends of deformation were negatively correlated with those of thaw indices in Alert, Resolute Bay, and Repulse Bay. Furthermore, in Resolute Bay, we also find that the end-of-thaw elevations during 2003–2012 were highly negatively correlated with the square root of thaw indices. This study is the first one using multiple GPS stations to study permafrost by GPS-IR. It highlights the multiple useful GPS stations in northern Canada, providing multi-year, continuous, and daily GPS-IR surface deformation, which provide new insights into frozen ground dynamics at various temporal scales and across a broad region.

1 Introduction

Since the International Polar Year (2007–2009), permafrost has undergone a warming trend globally, with an average increase of ground temperature at or near the depth of zero annual amplitude by 0.29 ± 0.12 °C during 2007–2016 (Biskaborn et al., 2019; Romanovsky et al., 2010; Smith et al., 2010). Warming permafrost causes ground ice melting, active layer thickening, and the release of previously sequestered carbon (Brown et al., 2000; Trucco et al., 2012). It affects hydrological, geomorphological, and biogeochemical processes (Mackey, 1966; Shur and Jorgenson, 2007; Lantuit and Pollard, 2008; Kokelj and Jorgenson, 2013). Measuring and quantifying permafrost changes are crucial for understanding the dynamics of the active layer and near-surface permafrost (collectively called as frozen ground in this paper), studying the response of permafrost environments to climate change, and assessing the risk of permafrost changes to infrastructures.

Surface elevation changes can serve as an indicator of frozen ground changes. The freeze/thaw of frozen ground is associated with the phase transition of soil moisture, leading to ~9% change of ice volume, due to the density difference between water and ice. Such volume change in freeze/thaw cycle causes the ground surface to uplift or subside seasonally. Surface deformation can be measured by either traditional benchmark-based methods or modern geodetic and remote sensing ones. The traditional methods use vertical tubes or pipes, anchored deep into the permafrost, as datum references of ground surface for repeat leveling surveys (Mackey, 1983). Modern methods include Interferometric Synthetic Aperture Radar (InSAR), Light Detection and Ranging (LiDAR), and Global Navigation Satellite System (GNSS) positioning. InSAR has been used to measure and quantify surface subsidence in various permafrost landforms (Liu et al., 2010, 2014, and 2015; Chen et al., 2018). However, InSAR suffers from coarse temporal resolutions and interferometric coherence loss. Furthermore, InSAR measurements need reference points where the surface deformation is known or assumed to be zero. LiDAR has been used to construct differential elevation models to investigate surface deformation (Jones et al., 2015). However, LiDAR surveys are usually conducted at annual or multi-annual intervals. GNSS positioning has also been used to measure and quantify surface subsidence and uplift (Little et al., 2003; Shiklomanov et al., 2013; Streletskiy et al., 2017). However, those GNSS surveys are usually conducted at the beginning or end of thaw seasons.

Global Positioning System Interferometric Reflectometry (GPS-IR) is a technique which uses reflected GPS signals to measure ground surface changes, such as elevation, soil moisture content, and vegetation growth condition (Larson, 2016, 2019). GPS-IR has been successfully used to study frozen ground dynamics by measuring surface deformation at one station in Barrow, Alaska (Liu and Larson, 2018; Hu et al., 2018). Compared with the aforementioned modern methods, GPS-IR measurements of surface elevation changes have higher temporal resolutions, usually at daily intervals. Their accuracies are on the order of a few centimeters (typically ~2 cm). Their spatial coverage is antenna-height dependent, e.g., 1000 m^2 for a 2-m-high antenna. Such spatial coverage fills a gap between regional-scale satellite observations and in situ point measurements. Furthermore, GPS-IR measurements are free of solid earth movement, such as glacier isostatic adjustment and plate movement (Liu and Larson, 2018). GPS-IR measurements are converted from the vertical distances between the antenna and the reflecting surface. As both the antenna and the surface are equally affected by solid earth movement, GPS-IR measurements can directly reflect frozen ground dynamics.

However, some limitations exist when using GPS-IR. This technique can only be usable in certain surface conditions. It needs the reflecting surface to be open, nearly flat, and relatively homogeneous (Larson, 2016). More than 200 GPS stations are continuously operating in permafrost areas in Northern Hemisphere (Fig. 1). However, only one station, located in Barrow, Alaska has been examined and proved for the use of GPS-IR (Liu and Larson, 2018). The underutilization of the

GPS-IR technique to a large number of existing stations motivates us to assess the usability of all of these sites. We choose Canada as our study area due to the public accessibility of GPS data, abundant weather records, and detailed geological surveys. We first design a three-step framework to identify useful stations under the same protocols and to ensure the reliability of measurements. We then screen all of the major public GPS networks in Canada to identify the usable stations. We then estimate surface deformation by GPS-IR and use them in turn to study frozen ground dynamics.

The significance of this study relies on that it first can provide usable GPS sites in permafrost areas for GPS-IR studies, which are complementary to the existing permafrost monitoring programs such as Circumpolar Active Layer Monitoring (CALM) and Global Terrestrial Network for Permafrost (GTN-P). Permafrost changes have large spatial heterogeneity, due to location, topography, precipitation, and vegetation. Despite the significant increase in the number of in situ sites in the past decades, the CALM and GTN-P sites are still sparse and unevenly distributed. The identified suitable GPS stations can fill in the spatial gaps of the CALM and GTN-P sites. Moreover, GPS-IR measurements are typically continuous and span multiple years. They can be used to study permafrost in a detailed manner and provide new insights into frozen ground dynamics.

In Sect. 2, we describe the mechanism of GPS-IR to measure surface elevation changes, our proposed framework to identify useful GPS stations, and the datasets we used in this study. In Sect. 3, we present basic information of the identified useful GPS stations (e.g., monument material, foundation depth, and antenna height above ground) and environment conditions of the study sites such as biome and surficial material. We then show the results of surface elevation changes in thaw seasons at the study sites in Sect. 4. In Sect. 5, we interpret the GPS-IR results in revealing frozen ground dynamics in various temporal scales, discuss the possible error sources of the results and their limitations in permafrost studies, and present their potential for validating and calibrating space-borne InSAR measurements. We conclude by summarizing the results and findings.

2 Methodology

2.1 GPS Interferometric Reflectometry (GPS-IR)

Larson (2016 and 2019) presented the principle of GPS-IR and its applications in measuring snow depth, surface soil moisture, vegetation growth condition, and water level. However, the use of GPS-IR for studying permafrost was not explicitly presented. So, here, we describe how GPS-IR retrieves surface elevation changes and their link to ground deformation in permafrost areas.

The input of GPS-IR is signal-to-noise ratio (SNR) data of GPS signals, one of the observables recorded by GPS receivers. It represents the strength of the received signal. SNR series at low satellite elevation angles (e.g., 5°–20° used in this study) oscillate with respect to the elevation angle, due to the interference between direct and reflected signals. The oscillating frequency mainly depends on the vertical distance between the antenna and the reflecting surface (called reflector height and denoted as H). If a GPS station is located above a smooth horizontal surface (e.g., Fig. 2), SNR can be expressed by a sinusoidal function of elevation angle e (Larson, 2016):

$$SNR = A(e)\sin\left(\frac{4\pi H}{\lambda}\sin e + \phi\right), \quad (1)$$

where $A(e)$ is the oscillation amplitude, also varying with e; λ is the wavelength of the carrier wave of GPS signal; and ϕ is the phase. When taking $\sin e$ as an independent variable, the oscillating frequency is:

$$f = \frac{2H}{\lambda}, \quad (2)$$

If f is determined, H can be obtained numerically as

$$H = \frac{f\lambda}{2}, \quad (3)$$

In practice, we divide the SNR series into individual segments corresponding to rising/setting satellite tracks. Then we remove their 2-order polynomial fits and use the residual ones, which are mainly contributed from the reflected signals. For simplicity, we use SNR series hereafter to denote the residual SNR series. We conduct the Lomb-Scargle Periodogram (LSP) analysis on any given SNR series to obtain its frequency spectrum. Then we use the peak value of the spectrum to represent the frequency f and obtain H by using equation (3). The oversampling parameter of LSP can be determined based on the expected resolution (e.g., 1 mm in this study) of the estimated reflector height. The programs for data processing are available in the software tools of GNSS Interferometric Reflectometry (Roesler and Larson, 2018).

If the monument is deep anchored (e.g., Fig. 2), the GPS antenna is stable with respect to the permafrost. The variation of the distance H only depends on the change in surface elevation. The change of H is opposite to that of surface elevation, i.e., surface uplift (subsidence) leads to decreasing (increasing) H (Liu and Larson, 2018). For the daily measurements of reflector height, we first assign minus signs to them and then remove the average to represent surface elevation changes.

2.2 A framework for identifying useful GPS stations for studying permafrost by GPS-IR

GPS-IR requires the ground surface to be open and relatively flat and smooth. To identify suitable ones from the existing GPS stations under the same protocols and to ensure the reliability of GPS-IR measurements, we have designed a three-step framework, which is described in detail as follows.

Step 1: Selecting GPS stations in permafrost areas

We first check whether permafrost is present where the GPS station is located. This step aims to identify the GPS stations in permafrost areas. We use the International Permafrost Association map compiled by Brown et al. (1997), which shows the spatial distribution of permafrost in the Northern Hemisphere.

Step 2: Estimating an azimuth range with an open, flat, and homogeneous ground surface

In this step, we aim to estimate an azimuth range, where the surface is open, nearly flat, and relatively homogeneous at each selected station in step 1. Normally, ground photos of a GPS station are taken as a part of metadata. In practice, we use ground photos and Google Earth images of a GPS site to check its surrounding environment, then estimate an azimuth range free of obstructions. We also use these images to recognize whether the selected surface is nearly planar and smooth. In Fig. S1, we present ground photos of two GPS stations as typical positive and negative examples, respectively.

Step 3: Ensuring high reliability of GPS-IR measurements

At present, 32 operational GPS satellites orbit around the Earth twice daily. Therefore, multiple SNR series are available within a day. In practice, for any given day, we first process all SNR series within the determined azimuth range and elevation angle range to obtain their H using the standard method summarized in Sect. 2.1. Then, we calculate their median and discard the ones deviating from the median by 0.25 m or more. Then we compute the mean value and the standard deviation (σ) of the remaining H, and remove those H deviating from the mean value by larger than 3σ as outliers. The final retained H and their corresponding SNR series are regarded as reliable. We average the final retained H (denote the average as $\overline{H}$) to represent the vertical distance between the antenna and the reflecting surface on that day. The uncertainty of $\overline{H}$ is represented by its standard deviation, i.e., the standard deviation of H divided by the square root of the sample size. To further ensure the reliability of $\overline{H}$, a minimal number of 10 pieces of reliable SNR series are required.

2.3 Dataset and information

We use SNR data of L1 C/A signals of the identified GPS sites. L1 C/A is the legacy civilian code broadcasted by all the GPS satellites. By using them, we can obtain GPS-IR measurements spanning over from several years to more than a decade, which enable us to study permafrost in various temporal scales and reveal its response to the changing climate.

To understand and interpret GPS-IR results, we use air temperature and snow depth at the study sites. These measurements are recorded by the nearest weather stations of GPS sites, and can be downloaded from Environment Canada (http://climate.weather.gc.ca/historical_data/search_historic_data_e.html). We also use borehole ground temperatures at the study sites, which are provided by GTN-P (http://gtnpdatabase.org/boreholes).

We also summarize the climate and environment information of the study sites, such as mean annual air/ground temperature (Ednie and Smith, 2015; Environment Canada, http://climate.weather.gc.ca/climate_normals/index_e.html), surficial material (Cruishank, 1971; Dredge, 1994; Taylor, 1982; Throop et al., 2010), and ground ice content of near-surface permafrost (O'Neill et al., 2019), to provide background information for reference.

3 Identified GPS stations and study sites

We have screened all of the three major GPS networks in Canada, namely Canadian Active Control System (CACS), Canadian High Arctic Ionospheric Network (CHAIN), and Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity (POLARIS) (Fig. 3). CACS is a nationwide network and is maintained by the Geodetic Survey Division in conjunction with the Geological Survey of Canada (Lahaye et al., 2001). It serves to build and maintain the Canadian Spatial Reference System, which is fundamental for mapping, navigation, studying crustal deformation. CHAIN was designed to investigate the impact of solar output on planetary environment (Jayachandran et al., 2009). The network is operated by the University of New Brunswick. It consists of 25 GPS stations, of which three (KUGC, REPC, and QIKC) are shared with CACS. It is important to note that most of the receiver antennas of CHAIN stations are anchored onto the roofs of buildings. Consequently, the monuments may move due to the foundation instability and thermal expansion/contraction of buildings. When using these stations for GPS-IR studies, corrections for such instability should be conducted. POLARIS, operated by the University of Western Ontario, was initiated for mapping solid Earth's structure and assessing earthquake hazards (Eaton et al., 2005). It includes seven geodetic-quality GPS stations.

Following the framework in Sect. 2.2, we identified 12 GPS stations out of 38 ones located in permafrost areas as suitable ones for GPS-IR studies. Table 1 gives their basic information, including locations, monument types, foundation conditions, data time spans, and spatial coverages of GPS-IR measurements. The receiver and antenna types are listed in Table S1. Five of them are from CACS, and the rest are from CHAIN. None of the POLARIS stations was identified as suitable.

Given that the GPS-IR measurements of the CHAIN stations might be affected by the unstable buildings, in this study we present and interpret the measured elevation changes at the 5 identified CACS stations. Their monuments are all anchored into bedrocks (Table 1). Figure 4 shows their ground photos and Fig. S2 shows examples of their SNR series and corresponding LSP spectrum analysis.

These 5 sites are all located in the Canadian Arctic. The climate in this region is dominantly Polar climate due to high latitude. The biomes are mainly tundra and Arctic desert. Permafrost is continuous in this area, and normally its thickness increases with latitude. In the far north latitude of 75°, permafrost can be thicker than 500 m (Sladen, 2011). Ground temperatures at or near the depth of zero annual amplitude ranged from colder than -15 °C to warmer than -2 °C, and they decreased northward in concert with climate (Smith et al., 2013). During 2008–2014, ground temperatures at the depth of 15 m increased at an average rate of ~0.17 °C yr^{-1} at ten extensively distributed sites in the Canadian Arctic (Ednie and Smith, 2015). Thawing ice-rich permafrost has initiated wide-spread development of thermokarst landforms in this region, such as retrogressive thaw slump (Lantuit and Pollard, 2008; Kokelj et al., 2015) and active layer detachment (Lewkowicz and Harris, 2005; Lewkowicz and Way, 2019).

We summarize the basic regional information of the five sites respectively in Table 2, including biome, land cover, ground ice content of near-surface permafrost, mean annual air temperature (MAAT), and mean annual ground temperature (MAGT). In Alert and Resolute Bay, the biomes are both Arctic Desert due to the high latitude, and the land surfaces are dominantly bare soil. The biomes at the other three sites are all tundra. But, due to their specific locations, the ground surface is mainly bare soil in Repulse Bay, but is covered by a peat layer in Baker Lake, and is sparsely vegetated in Iqaluit.

4 Results: surface elevation changes measured by GPS-IR

We obtain multi-year and seasonal time series of surface elevation changes at the 5 CACS sites. In this study, we only present the measurements in thaw seasons, when air temperature is above 0 °C and ground is not covered by snow. The measurements can be found in Zhang et al. (2019, https://doi.pangaea.de/10.1594/PANGAEA.904347).

We build best linear fit to the thaw-season measurements and obtain the trends at the five sites (Fig. 5). We find that in Alert, Resolute Bay, and Repulse Bay, the ground surface subsided at a rate of 0.61 ± 0.04 cm yr^{-1} (2012–2018) and 0.70 ± 0.02 cm yr^{-1} (2003–2014), and 0.26 ± 0.05 cm yr^{-1} (2014–2019), respectively. However, at the other two sites, the displacements of ground surface were 0.04 ± 0.02 cm yr^{-1} in Baker Lake during 2010–2017 and -0.05 ± 0.02 cm yr^{-1} in Iqaluit during 2010–2019. These last two trends were not statistically significant (t-test, $\alpha = 0.05$).

In Fig. 6, we present the seasonal surface elevation changes in Resolute Bay. The seasonal results of the other sites can be found in Zhang et al. (2019). During a thaw season, the ground surface typically subsides progressively and reaches its lowest position at the end of season. However, at the Resolute Bay site, the surface elevation changes in the thaw seasons were irregular. The surface uplifted abnormally and significantly within the thaw seasons, for instance in 2003 and 2007. A similar phenomenon was also observed at a site near Yellowknife in Canada by Gruber (2019) using an inclinometer. This phenomenon could be due to the refreezing of soil moisture which migrated from the thawed active layer, or the swelling of soil when it became wet. However, we lack measurements of soil moisture and ice content to investigate the cause of the observed uplift. In addition to such abnormal changes, the elevation changes among the thaw seasons were inconsistent. Given the complexity of these seasonal elevation changes, we turn to investigate the interannual variability and linear trends of surface deformation in Resolute Bay.

5 Discussion

In this section, we first interpret GPS-IR measured surface elevation changes in Resolute Bay, as they are the longest among the five sites. We then qualitatively study the linear trends of surface deformation at the five sites. We also discuss the possible error sources of these GPS-IR measurements, the limitations of using GPS-IR measurements in permafrost studies, and their capability in validating and calibrating space-borne InSAR observations.

5.1 Interannual variability of end-of-thaw elevations in Resolute Bay

Net seasonal subsidence is an effective indicator of the response of frozen ground to the atmosphere, as it mainly depends on the soil moisture content within the active layer and the heat from the atmosphere. But, as shown in Sect. 4 and Fig. 6, it is challenging to reliably obtain seasonal subsidence in Resolute Bay due to the irregularity and inconsistency of surface elevation changes in thaw seasons. As an alternative, we use the end-of-thaw-season surface elevations to investigate the frozen ground dynamics.

The end-of-thaw elevation is determined as the mean value of the elevations at the last seven days of a thaw season, since the thawing front moves slowly at the end of thaw and the further surface deformation is limited. According to the Stefan equation, active layer thickness is approximately proportional to the square root of thaw index (Brown et al., 2000; Smith et al., 2009; French, 2017). Thaw index is represented by the degree days of thawing (DDT) derived by the accumulation of daily air temperatures above 0 °C till the end of thaw season. As surface subsidence is mainly caused by ice-melting within the active layer, we compare the end-of-thaw elevations to the square root of the annual thaw indices (Fig. 7).

In Fig 7a, the end-of-thaw-season elevations and $\sqrt{DDT}$ were highly negatively correlated between 2003 and 2012, whereas the end-of-thaw elevations were low with cool summers in 2013 and 2014. To further investigate their correlation, we draw a scatter plot of end-of-thaw-season elevations versus $\sqrt{DDT}$ (Fig. 7b), but find that the linear line fitted poorly. After removing the measurements in 2013 and 2014, the R^2 and Root Mean Square Error (RMSE) of the best linear fit improves significantly, from 0.24 to 0.83 and 2.57 cm to 1.19 cm, respectively (Fig. 7c).

We postulate that the highly negative correlation between the end-of-thaw elevations and $\sqrt{DDT}$ during 2003–2012 was due to thickening active layer. A larger DDT indicates that more heat is available to penetrate into the deeper part of the frozen ground, leading to active layer thickening, more ice melting within the frozen ground, and thus larger subsidence and lower surface elevation. This assumption of thickening active layer during 2003–2012 is consistent with the borehole ground temperatures during 2008–2012 (Fig. 8). The ground temperatures showed that the thawing front (i.e., the 0 °C isotherm) deepened and exceeded 1 m depth in 2011.

However, in 2013 and 2014, the end-of-thaw elevations were low, even in the relatively cool summers (corresponding to low DDT). This is possibly due to the Markovian behavior of the active layer. Markovian behavior describes the reset of the active layer's response to air temperature after an extremely warm or cold summer, and this new response regime will last till the next extreme thaw season (Nelson et al., 1998). In Resolute Bay, the year 2011 had the warmest summer with the DDT of 542.9 °C·day, more than 4 times larger than that in 2004 (132.3 °C·day). After 2011, the response of the active layer to the atmospheric forcing may have changed due to the changes in thermal properties of the active layer and ice content at the permafrost table. So, even with low DDT, the maximal thaw depths were still larger than expected, resulting in low end-of-thaw-season surface elevations. Yet, ancillary data such as thermal properties, ice content, soil moisture, and thaw depth are needed to test these postulated changes in the active layer.

5.2 Linear trends of surface deformation at the CACS sites

The ground surface deformed differently among the five sites. In this subsection, we study the possible links between linear trends of surface deformation and air temperature, landcover, as well as ground ice near the permafrost table.

We make basic statistics of the annual thaw indices during the study periods at the sites of Alert, Resolute Bay, and Repulse Bay (Table 3). All of these sites had warming thaw seasons, with trends of 9.35 °C·day yr^{-1} in Alert during 2012–2018 and 8.17 °C·day yr^{-1} in Resolute Bay during 2003–2014, and 66.41 °C·day yr^{-1} in Repulse Bay during 2014–2019, respectively.

The ground surface underwent subsidence with increasing DDT in Alert, Resolute Bay, and Repulse Bay. At these three sites, the surficial materials are sandy soil and barely vegetated (Table 2). Due to the lack of an insulating organic layer, bare soil facilitates the heat transfer between the atmosphere and the ground. When the climate was warming, the transient layer (i.e., the layer between the active layer and long-term permafrost table and subjected to freeze and thaw seasonally to centennially (Shur et al., 2005)) started to thaw with ground ice melting and surface subsidence, such as that seen in Alert, Resolute Bay, and Repulse Bay, even though they have low ice content in near-surface permafrost (Table 2).

Liu and Larson (2018) obtained surface elevation changes during 2004–2015 at Barrow, Alaska by using GPS-IR, and found a subsidence trend of 0.26 ± 0.02 cm yr^{-1}. During the same time span, the thaw season in Barrow also had a warming trend with 4.79 °C·day yr^{-1}. The results of Liu and Larson (2018) are consistent with ours: warming thaw seasons lead to surface subsidence. These findings in Barrow and our sites indicate that permafrost in high latitudes were degrading and air temperature is the dominant driver.

5.3 Possible error sources of GPS-IR-measured surface deformation

GPS-IR measurements of surface elevation changes might be affected by the surrounding environment (e.g., troposphere, vegetation, and soil moisture) and instruments (including antenna and monument). In this section, we discuss the impact of these variables on GPS-IR measurements and their magnitudes.

GPS signals refract when they propagate through the troposphere, leading to changes of propagating velocity and direction. Such refraction effects change the geometry among the direct and reflected signals and the receiver antenna, then introduce bias to reflector height retrievals. Tropospheric bias mainly depends on the antenna height and atmospheric conditions at a given elevation angle (Williams and Nievinski, 2017). In our study, because (1) all sites are located in the Canadian Arctic characterized by a dry and cold climate, and (2) their antenna heights are ~ 2 m (Table 1), the tropospheric biases at these sites are expected to be limited. More quantitatively, we calculate the tropospheric biases at RESO in the thaw season in 2014 by using the astronomical refraction model of Bennett (1982), and present them in Fig. S3. The magnitudes of tropospheric biases are ~1.6 cm and keep relatively steady during the thaw season. As the magnitudes of biases are comparable to the uncertainties of GPS-IR measurements and we focus on the temporal variations of reflector heights, it is not necessary to correct for them.

Soil moisture also affects GPS-IR measurements of surface elevation changes through impacting phases of SNR series. For any given SNR series, soil moisture has slightly different influence on the phase of each point, i.e., ϕ in equation (1) is also a function of elevation angle. Taking ϕ as a constant in practice introduces bias. Such bias is called compositional reflector height, as it manifests itself by a part of reflector height (Nievinski, 2013). Liu and Larson (2018) simulated the compositional height and found that they are less than 2 cm and their variation range is less than 1 cm, given a variation range of soil moisture between 15% and 40%. In this study, the compositional heights and their variation range are expected to be limited, as the precipitation is light and limited due to the cold and dry polar climate. Moreover, as we focus on the temporal variations of reflector heights at interannual and multi-annual time scales, we expect negligible impact of compositional heights on our results and interpretation.

Regarding the vegetation, at the study sites, the biomes are Arctic desert or tundra. The ground is barely or sparsely vegetated, and the vegetation is short enough, i.e., less than the wavelength of L-band GPS signals. The vegetation is approximately transparent for GPS signals. The impact of vegetation on GPS-IR measurements is therefore negligible.

Antenna gain pattern also impacts GPS-IR measurements. As the GPS stations used in this study were installed originally for geodetic or ionospheric studies, the receiver antennas were designed to favor 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 span, the antennas are not replaced. The impacts of antenna gain patterns can be regarded as system biases, and barely impact the GPS-IR results.

As for the monuments of the identified CACS stations, their material is galvanized or stainless steel and aluminum. The coefficients of linear thermal expansion measured at 20 °C of steel and aluminum are 11~13 × 10^{-6} m·$(m·K)^{-1}$ and 23.1 × 10^{-6} m·$(m·K)^{-1}$, 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.

5.4 Limitations of GPS-IR measurements of surface deformation in permafrost studies

GPS-IR measured surface deformation has relatively large uncertainties, whose magnitudes are on the order of a few centimeters (i.e., ~2 cm in Resolute Bay). The uncertainties are mainly caused by the rugged surface, presence of vegetation, and other unexpected disturbances. Such uncertainties make it difficult to study the daily changes of surface elevation based on GPS-IR measurements, and even the seasonal changes if their magnitudes are comparable to those of seasonal subsidence. Resolute Bay is such a case, where daily and seasonal elevation changes cannot be obtained reliably. However, 12-years long measurements enable the interannual variability of end-of-thaw elevations and decadal linear trend to be obtained with high confidence.

Data gaps exist in GPS observations due to instrumental problems. GPS-IR measurements before and after the gaps are contaminated by the bias introduced by the replacement of instruments. The data gaps and bias hinder the study of permafrost with long-term, continuous, and consistent GPS-IR measurements.

The interpretation of GPS-IR measurements in permafrost areas needs ground observations, such as soil temperatures and moistures. However, these data are usually not available at GPS sites, as they were installed initially for tectonic and ionospheric research. Moreover, surface condition records are often brief or absent. This being the case, we usually only have GPS-IR measurements, and lack ancillary data such as ground temperature or soil moisture to help interpret the GPS-IR results.

These limitations indicate that, in the future, better location choices and maintenance of GPS stations and other ground measurement sensors are needed to exploit the full potential of GPS-IR observations in permafrost studies.

5.5 Potential of linking GPS-IR measurements to large-scale mapping from InSAR

Both GPS-IR and InSAR can measure surface elevation changes. In Table 4, we summarize their typical temporal and spatial samplings rates, advantages, and limitations. As we mentioned in Sect. 1, GPS-IR measurements are at daily intervals and local scales. In contrast, space-borne InSAR observations have much coarser temporal resolutions (the shortest to date being 6 days) and larger spatial scales (covering tens of kilometers), and also require a reference point with known surface deformation or assumed stable. These characteristics make GPS-IR and InSAR measurements complementary to each other. GPS-IR measurements could be used to overcome the limitations of InSAR observations. In particular, as GPS-IR measurements are continuously and at daily intervals over a few years to decades, they can provide baseline information for reference and can validate InSAR observations.

Several major research programs such as Arctic-Boreal Vulnerability Experiment (ABoVE), Next-Generation Ecosystem Experiments (NGEE), and European Space Agency Permafrost Climate Change Initiative (CCI) use remote sensing elevation changes (e.g., InSAR) to investigate permafrost dynamics. GPS-IR measurements can be used to calibrate and validate them and provide baseline information for historical, current, and future remote sensing measurements from air and space.

6 Conclusions

In this study, for the first time, we implement a framework for assessing useful GPS stations for GPS-IR studies in permafrost areas, and identify 12 useful GPS stations extensively distributed across the Canadian permafrost areas. Our framework can be applied to GPS networks in other regions and nations to identify more usable GPS stations. Our identified useful stations and the potential ones are also complementary to existing monitoring networks such as the CALM and GTN-P programs.

This study is also the first one using multiple GPS stations to study permafrost by GPS-IR. At the 5 identified CACS sites, we obtain their time series of elevation changes. The ground surface subsided in Alert by 0.61 ± 0.04 cm yr^{-1} during 2012–2018, in Resolute Bay by 0.70 ± 0.02 cm yr^{-1} during 2003–2014, and in Repulse Bay by 0.26 ± 0.05 cm yr^{-1} during 2014–2019. At the other two sites of Baker Lake and Iqaluit, the linear trends are not statistically significant. The trends at Alert, Resolute Bay, and Repulse Bay are negatively correlated to those of annual thaw indices, i.e., warming thaw seasons lead to surface subsidence. This finding indicates that frozen ground at the study sites is sensitive to air temperature changes.

In Resolute Bay, we also find a highly negative correlation between the end-of-thaw elevations and the square-root of thaw indices during 2003–2012 and suspect that it was possibly due to active layer thickening under the warming thaw seasons. And we also find that the end-of-thaw elevations were low even with cool summers in 2013 and 2014. Continuous and daily measurements reveal the complexity of frozen ground dynamics, i.e., the irregularity and inconsistency of seasonal surface elevation changes and the summer heave in Resolute Bay. To further investigate the dynamics and mechanisms of frozen ground changes, it is important to measure other variables such as ground temperature, soil moisture, and ground ice content.

Our discussion on error sources and limits of GPS-IR measurements recommends that better location choice and maintenance of GPS stations should be conducted to fully use the potential of those stations in frozen ground. The multi-year, continuous, daily GPS-IR measurements with intermediate spatial coverages can validate or calibrate remote sensing observations of elevation changes in permafrost areas.

Code and data availability

The software tools of GNSS Interferometric Reflectometry are available from https://www.ngs.noaa.gov/gps-toolbox/GNSS-IR.htm. The SNR observations of CACS GPS sites are available from https://webapp.geod.nrcan.gc.ca/geod/data-donnees/cacs-scca.php?locale=en. The air temperature and snow depth measurements are available from http://climate.weather.gc.ca/historical_data/search_historic_data_e.html. The borehole ground temperature measurements are available from http://gtnpdatabase.org/boreholes. The GPS-IR measurements of surface elevation changes at Alert, Resolute Bay, Repulse Bay, Baker Lake, and Iqaluit in Canada are available from https://doi.pangaea.de/10.1594/PANGAEA.904347.

Author contribution

JZ identified the useful GPS stations for GPS-IR studies, conducted data processing to obtain results of surface elevation changes, performed results analysis, and wrote the manuscript. LL helped interpret the results and revise the manuscript. YH guided using the software of GNSS Interferometric Reflectometry and assisted in data processing.

Competing interest

The authors declare that they have no conflict of interest.

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Table 1. Basic information of the identified GPS stations

ID	Site name	GPS network	Lat & Lon (°)	Permafrost zonation	GPS antenna Monument	Monument foundation type and depth	Data time span	Azimuth range used by GPS-IR	Antenna height (m)	Footprint radius (m)
ALRT	Alert	CACS	82.49, -62.34	Continuous	Galvanized steel pipe	Bedrock, 6 m	2012–2018	270°–360°	1.9	61
RESO	Resolute Bay		74.69, -94.89	Continuous	Steel pipe	Bedrock, 3 m	2003–2014	0°–90°	2.3	67
REPL	Repulse Bay		66.52, -86.23	Continuous	Aluminum pillar	Bedrock, 1.5 m	2014–2019	150°–250°	2.0	61
BAKE	Baker Lake		64.32, -96.00	Continuous	Stainless steel pillar	Bedrock, N.A.	2010–2017	0°–90°	1.2	49
IQAL	Iqaluit		63.76, -68.51	Continuous	Aluminum cylinder	Bedrock, 1 m	2010–2019	30°–120°	1.7	57
PONC	Pond Inlet	CHAIN	72.69, -77.96	Continuous	Mounted on buildings	N.A.	2008–2018	150°–240°	4.5	102
HALC	Hall Beach		68.77, -81.26	Continuous			2008–2018	180°–360°	3.7	90
IQAC	Iqaluit		63.74, -68.54	Continuous			2008–2018	200°–320°	4.0	94
RANC	Rankin Inlet		62.82, -92.11	Continuous			2014–2018	300°–150°	3.8	91
FSIC	Fort Simpson		61.76, -121.23	Discontinuous			2014–2018	150°–330°	3.9	93
FSMC	Fort Smith		60.03, -111.93	Sporadic			2014–2018	30°–120°	3.9	93
SANC	Sanikiluaq		56.54, -79.23	Discontinuous			2008–2018	135°–225°	3.4	85

Table 2. Regional background of the study sites

	Canadian Forces Station Alert	Resolute Bay	Repulse Bay	Baker Lake	Iqaluit
Biome	Polar Desert	Polar Desert	Tundra	Tundra	Tundra
Landcover[a]	Mainly silts, sands, and shattered rocks filled with ice, ranging from 2.4 to 4 m thick (Taylor, 1982)	Rounded or sub-angular gravels and shelly and fine-grained sands (Cruishank, 1983)	Sands and silts ranging from 1 to 10 m thick (Dredge, 1994)	Coarse gravels and sands with low ice contents underneath a peat layer (Throop et al., 2010)	A thin till veneer with fairly well-developed soil, with sparse vegetation (Throop et al., 2010)
Ground ice content of near-surface permafrost[b]	None[e]	Negligible wedge ice and low segregated ice	None	Negligible wedge and segregated ice	Low wedge, segregated, and relict ice
MAAT[c] (°C)	-18.0	-15.7	-12.1	-11.8	-9.8
MAGT[d] (°C)	-11.1 – -14.4 (2007–2011)	-11.9 (2008–2012)	-8.2 (2009–2013)	-7.9 (2006–2007)	-5.6 – -7.1 (2003–2004 & 2011–2012)

a. The landcover information is for the areas around the boreholes, which are close to the identified GPS stations.

b. The ground ice contents are surficial material unit-based, which are simulated with surficial geology, deglaciation, paleo-vegetation, glacial lake and marine limits, and modern permafrost distribution (O'Neill et al., 2019).

c. MAAT refers to Mean Annual Air Temperature during 1981–2010 (Environment Canada, http://climate.weather.gc.ca/climate_normals/index_e.html).

d. MAGT refers to Mean Annual Ground Temperature at or near the depth of zero annual amplitude, except Repulse Bay (Smith et al., 2013). MAGT at Repulse Bay was at the depth of 15 m (Ednie and Smith, 2015).

e. Note that it is contrary to the field observations (Taylor, 1982) that found ground ice exists in the active layer and near-surface permafrost in Alert.

Table 3. Basic statistics of annual DDT at Alert, Resolute Bay, and Repulse Bay

Site	Data time span	Mean (°C·day)	Trend (°C·day yr^{-1})	Trend of surface deformation[a] (cm yr^{-1})
Alert	2012–2018	255.85	9.35	-0.61 ± 0.04
Resolute Bay	2003–2014	319.03	8.17	-0.70 ± 0.02
Repulse Bay	2014–2019	518.63	66.41	-0.26 ± 0.05

a. Negative means subsidence, vice versa.

Table 4. Comparing GPS-IR and space-borne InSAR for measuring surface elevation changes in permafrost areas

	GPS-IR	Space-borne InSAR
Temporal sampling	daily	6 days to months
Spatial coverage	Local, site-specific (about 1000 m^2)	Large scale (typically tens to hundreds of kilometers)
Need reference of known deformation	No	Yes
Advantages	Daily and continuous; Free of reference; Free of solid earth movement	High accuracy (The magnitude of uncertainty is on the order of a few millimeters)
Limitations	Surface should be relatively flat and smooth.	Coarse temporal resolution; Loss of coherence; Requiring a reference point.

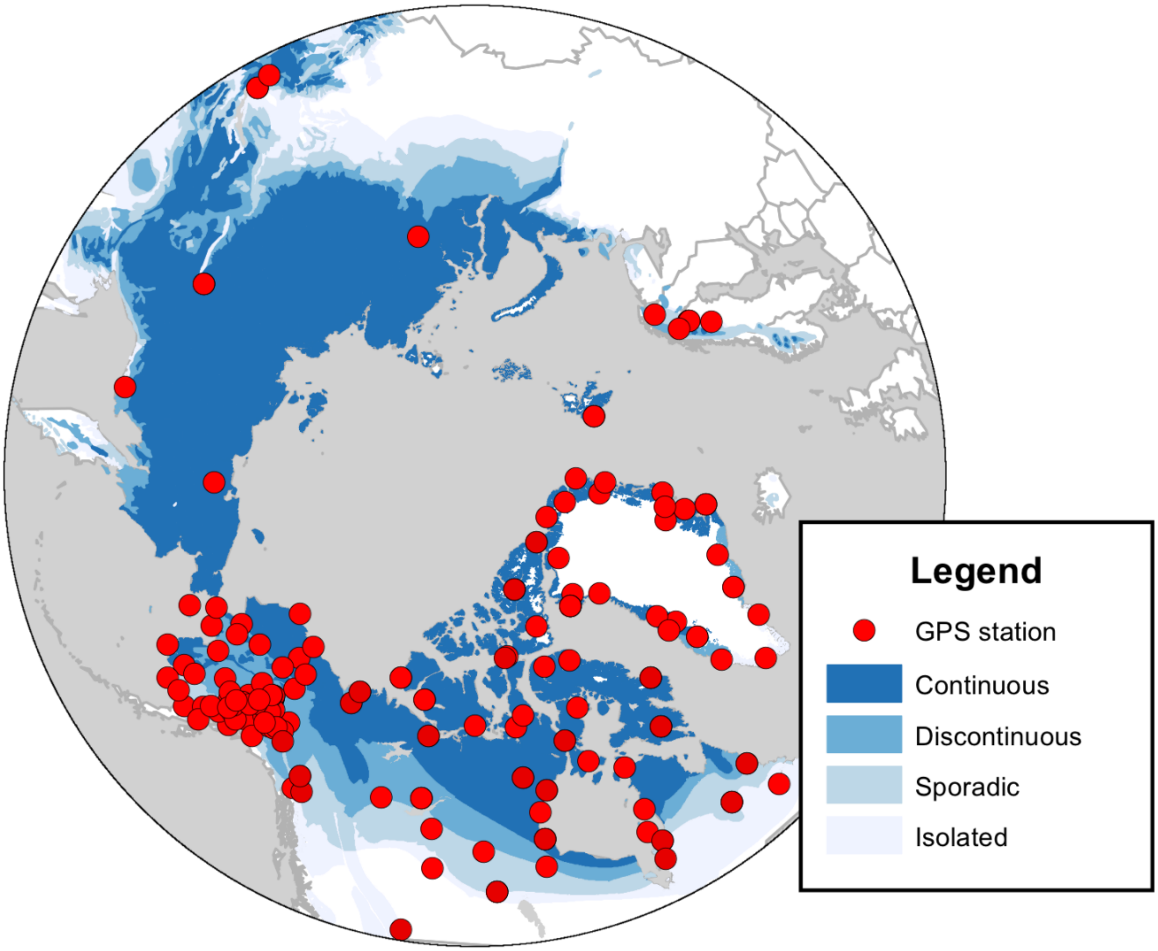


Figure 1: Locations of continuously operating and open-data GPS stations in the permafrost areas north of 50°N. The permafrost zonation, represented by various colors, is based on Brown et al. (1997).

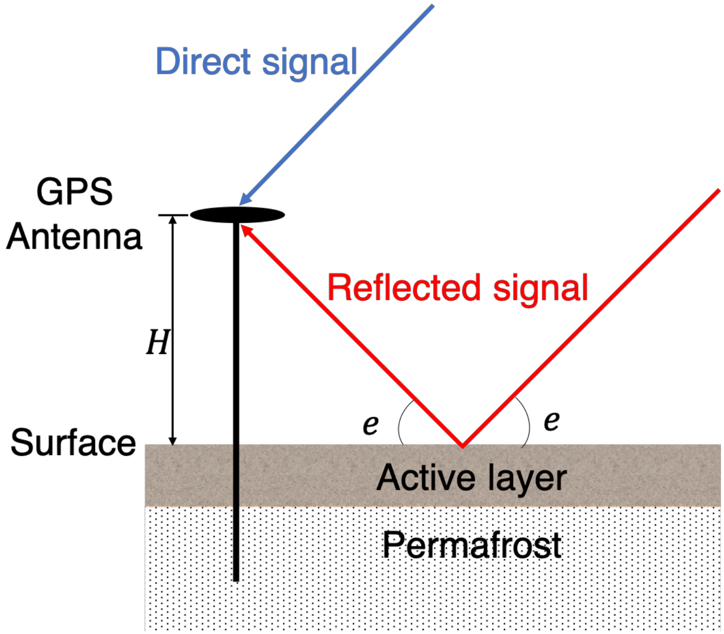
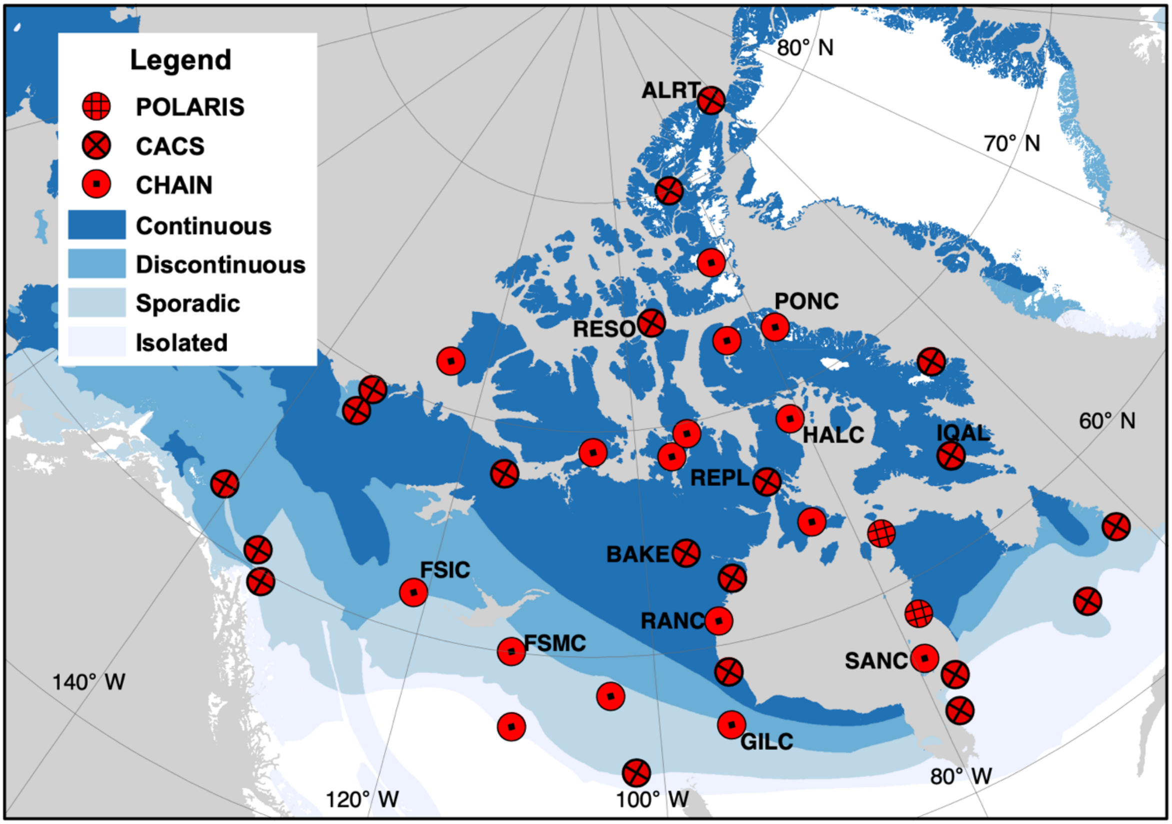


Figure 2: Schematic diagram showing the geometry of the GPS antenna, GPS signals, and the ground surface in permafrost area. *H*, or reflector height, is the vertical distance between the GPS antenna and the surface, and *e* is the satellite elevation angle.



545 **Figure 3: Locations of GPS stations in the Canadian permafrost areas. The identified stations are labeled by their four-character IDs.**

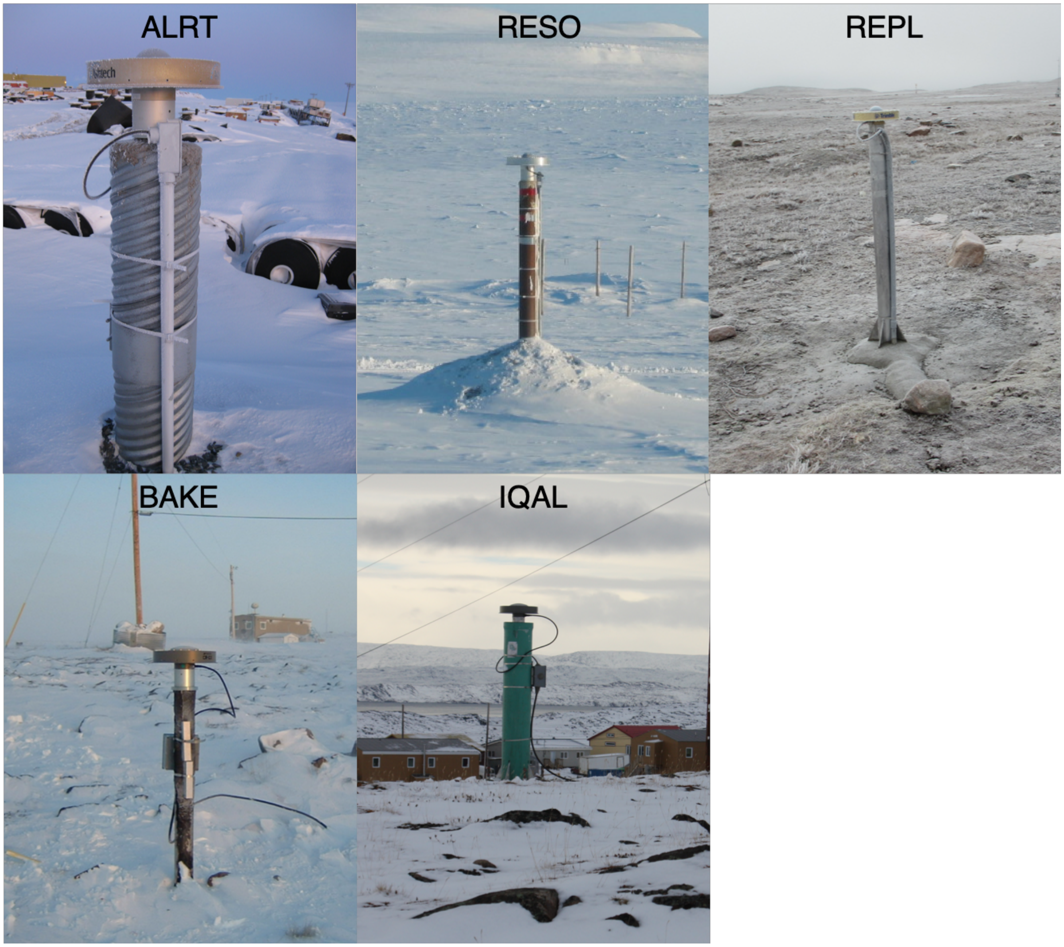


Figure 4: Ground photos of the identified CACS GPS stations. Source: https://webapp.geod.nrcan.gc.ca/geod/data-donnees/cacs-scca.php?locale=en

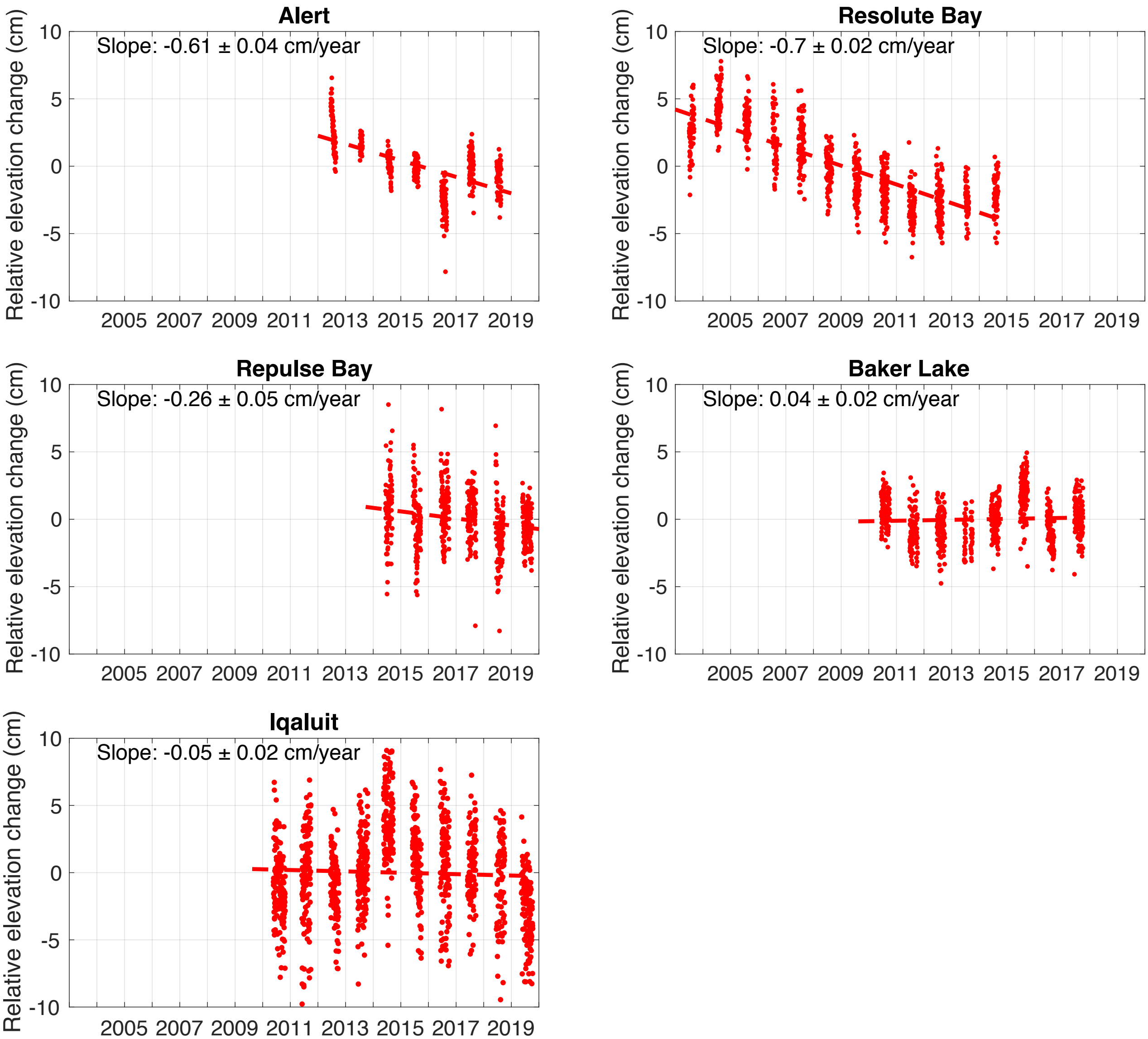


Figure 5: Time series and the best linear fit dashed lines of surface elevation changes in thaw seasons at the five CACS sites. For clarity, we do not show the error bars. For the y-axis, 'relative' means that the presented elevation changes are referenced to the mean value of the entire records at each site.

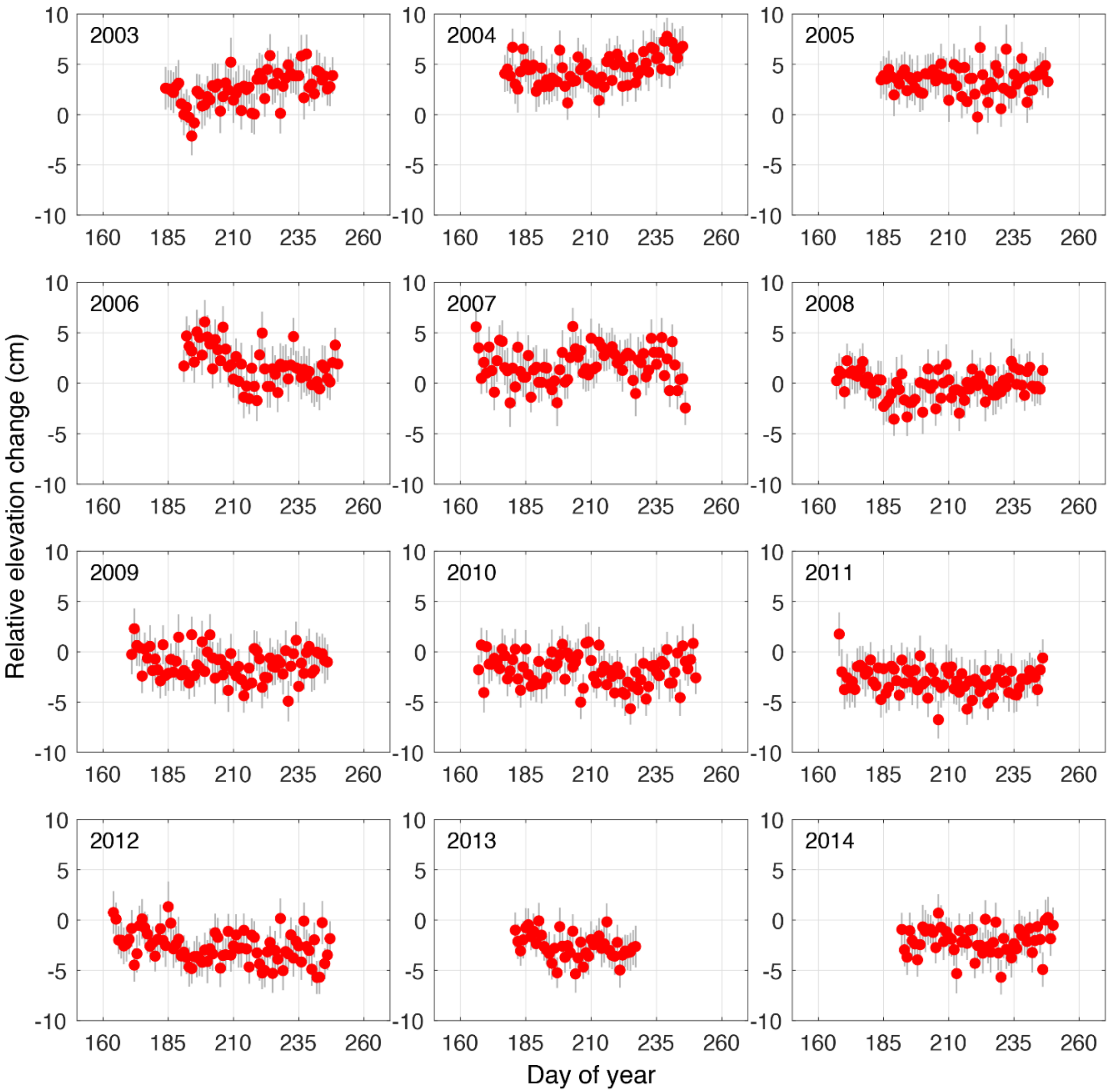


Figure 6: Surface elevation changes in each thaw season in Resolute Bay during 2003–2014. Red dots denote the measurements in the thaw seasons. Grey error bars denote the uncertainties. The mean value of the measurements has been removed. The shorter thaw season in 2013 was due to the late thawing onset on DOY 181 and early freezing onset on DOY 227, estimated from air temperature and snow depth records.

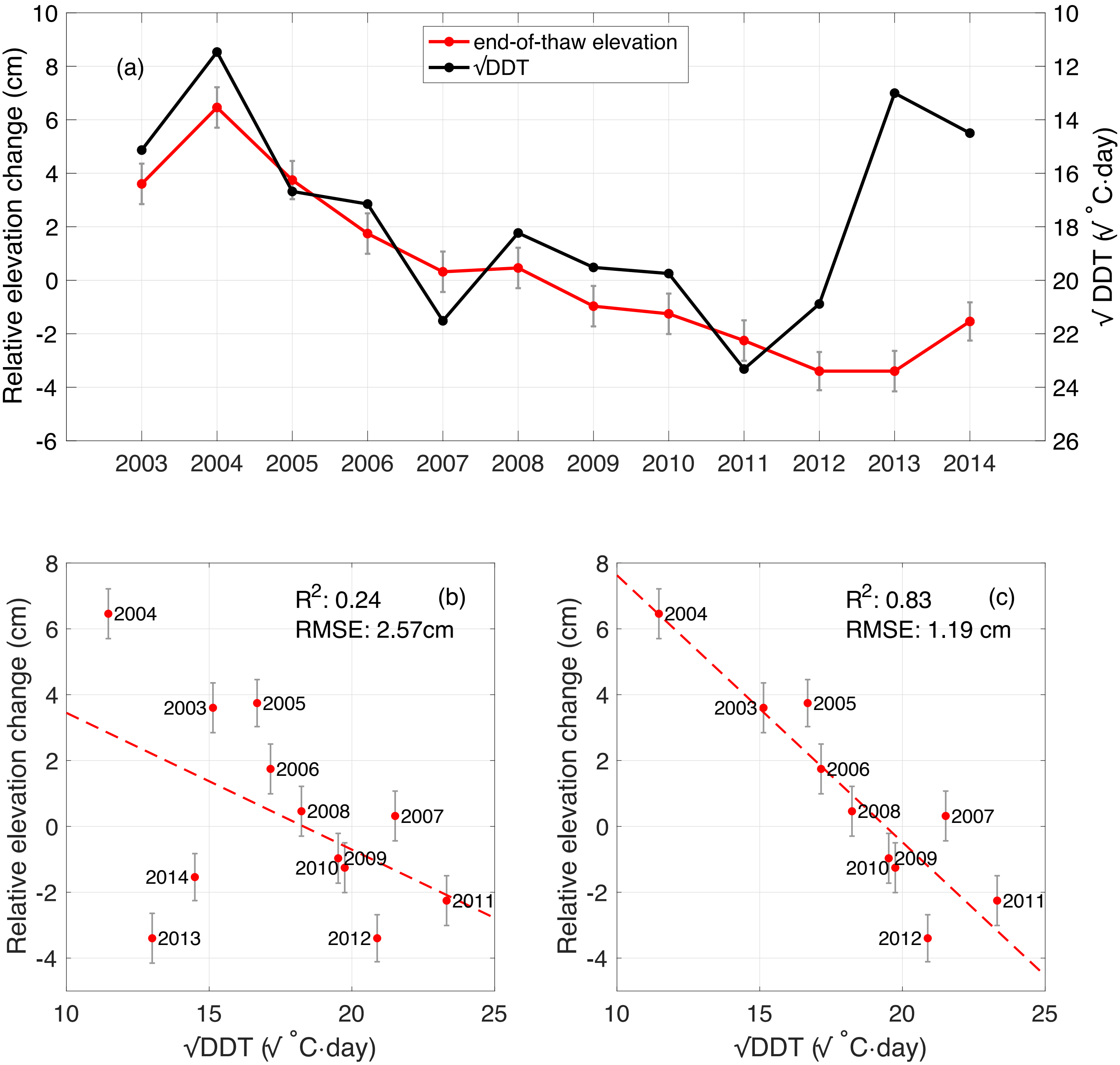


Figure 7: (a) Time series of the end-of-thaw-season elevations and $\sqrt{DDT}$ during 2003–2014. The right vertical axis for $\sqrt{DDT}$ has been reversed to show the correlation between $\sqrt{DDT}$ and the end-of-thaw elevations. (b) Scatter plots of the end-of-thaw elevations versus $\sqrt{DDT}$. The red dashed line is the best linear fit line. (c) Scatter plot and the best linear fit line of the end-of-thaw-season elevations vs $\sqrt{DDT}$ after removing the measurements of 2013 and 2014.

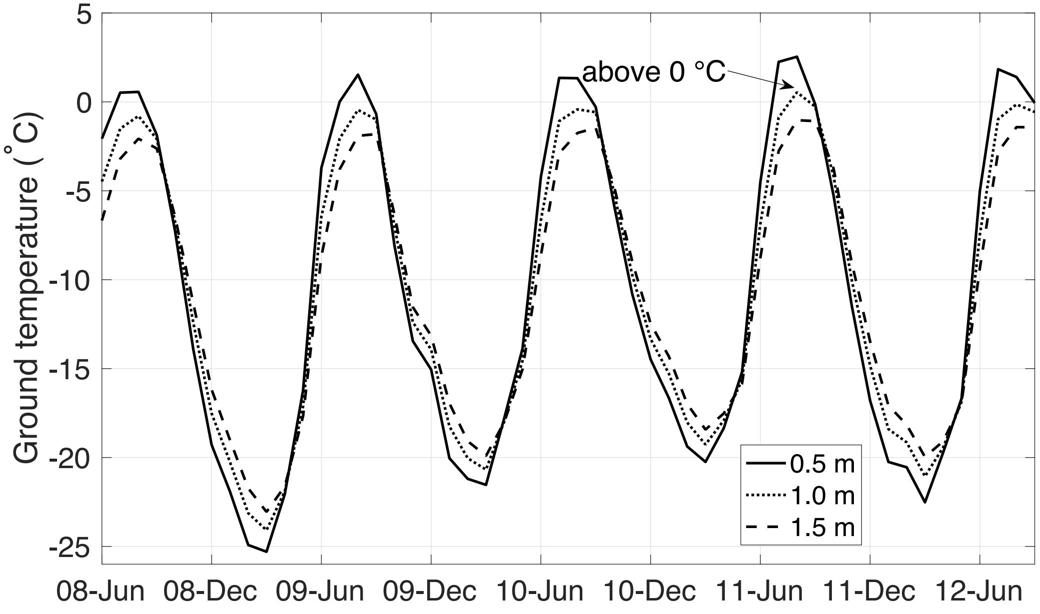


Figure 8: Time series of monthly ground temperatures at depths of 0.5 m, 1.0 m, and 1.5 m from June 2008 to September 2012 (Ednie and Smith, 2015). In August 2011, the ground temperature at 1.0 m depth was above 0 °C.