Responses to SC1

We thank Dr. Felipe G. Nievinski for his insightful and constructive comments. We have addressed all of them in the revised version of our manuscript. Our point-by-point replies are given below. As the reviewer may not be able to read our revised manuscript at this stage of The Cryosphere's review process, the line numbers refer to the previously submitted discussion paper, aiming to point out where the discussion paper has partly addressed the reviewer's comments.

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 the 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 (*Lines 251–252*). 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.

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 parts 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.

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.

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	2012–2017	https://webapp.geod.nrcan.gc.ca/geod/datadonnees/cacsscca.php?locale=en
RESO	ASHTECH UZ-12	ASH700936A_M	NONE	2003–2014	

REPL	TRIMBLE NETR9	TRM59800.00	NONE	2014–2017	
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	2010–2017	
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	

We have included the table R1 into the revised manuscript as supplementary.

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 angels (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.

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.

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

Response: We have revised the units of thawing index to °C·day.

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.

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.

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

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

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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, Boul- der, 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