InSAR Time Series Analysis of Seasonal Active Layer Dynamics in Low-Land Permafrost Terrain - Northwest Territories, Canada

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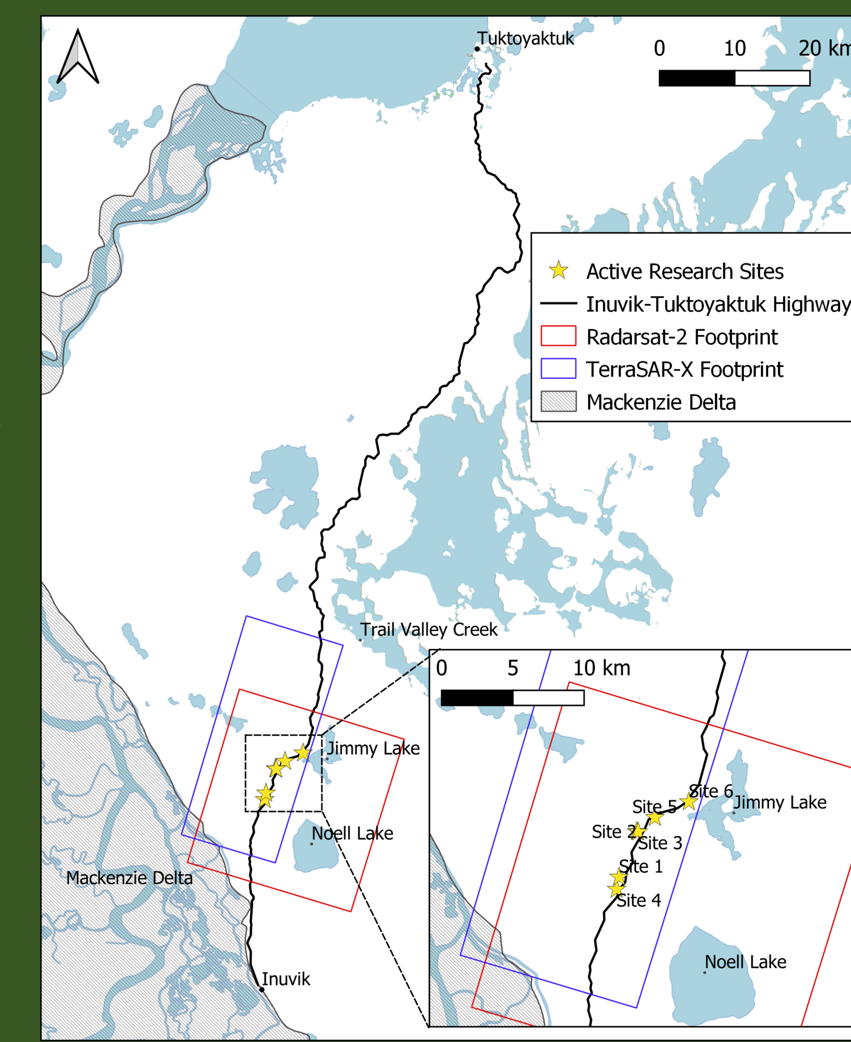


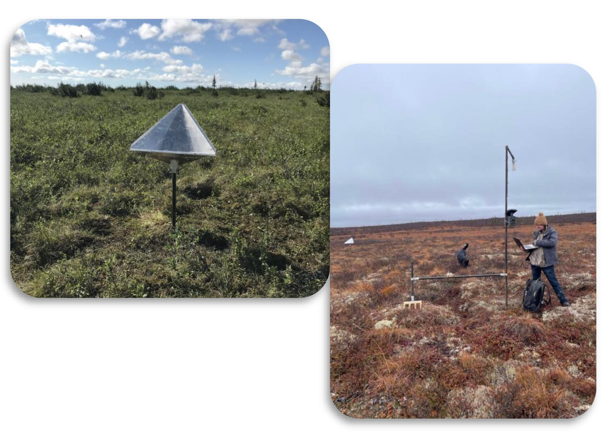
Abstract

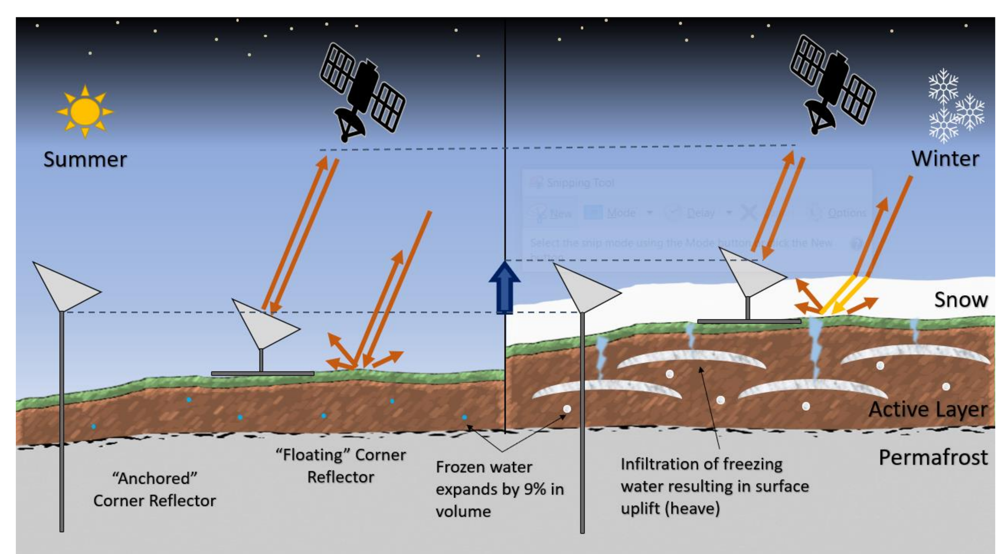
This study explores the seasonal dynamics of low-land permafrost terrain situated north of Inuvik, Northwest Territories. We perform a comparative InSAR displacement time series analysis of TerraSAR-X Stripmap and RADARSAT-2 Ultrafine data with in-situ field measurements. Specifically, we examine the onset of freeze-back in the fall, which initiates rapid seasonal frost-heave, followed by subsidence during the thawing season. Seasonal dynamics exhibiting amplitudes as high as 8 cm (as measured at our ground truthing sites) create phase wrapping challenges for the InSAR analysis that are not well compensated by existing temperature driven phase demodulation models of the active layer. Phase biases due to snow cover changes in winter additionally contaminate InSAR displacement measurements of the active layer if winter data are included. To measure the actual active layer deformation with high accuracy on the ground, to help improve phase demodulation methods and characterize the snow contribution to the phase, we have installed instrumentation with robust redundancy at multiple field sites (one of which is presented here), including inclinometers to measure vertical surface deformation, permafrost-anchored and surface-floating corner reflectors for reference as well as snow height gauges. The reflector reference phases are snow bias free due to use of Lexan covers. This setup allows us to unambiguously measure the thaw/heave displacement of the active layer, separate from changes in snow cover. By implementing a multi-faceted approach to exploit these ground measurements to de-bias InSAR time series analysis measurements and improve active layer models used for approximate phase demodulation we aim to contribute valuable insights to the scientific understanding of the seasonal dynamics of permafrost terrain.

Theory

DInSAR is a well-established method for monitoring surface displacement in permafrost terrain [1]; however, due to the effects of snow on the phase, analyses are limited to snow-free scenes, drastically reducing data availability and affecting overall measurement accuracy [3][4]. To overcome this limitation, corner reflectors (CRs) have been installed with Lexan covers, avoiding phase contributions due to snow.

Due to the rapid onset of freeze back and subsequent thawing, the phase at the beginning of each freezing and thawing season is highly wrapped. Thus, a model is required to unwrap the phase. Two such models are explored, the first is derived from the in-situ measurements. The second model is derived using a modified version of the Stefan equation.



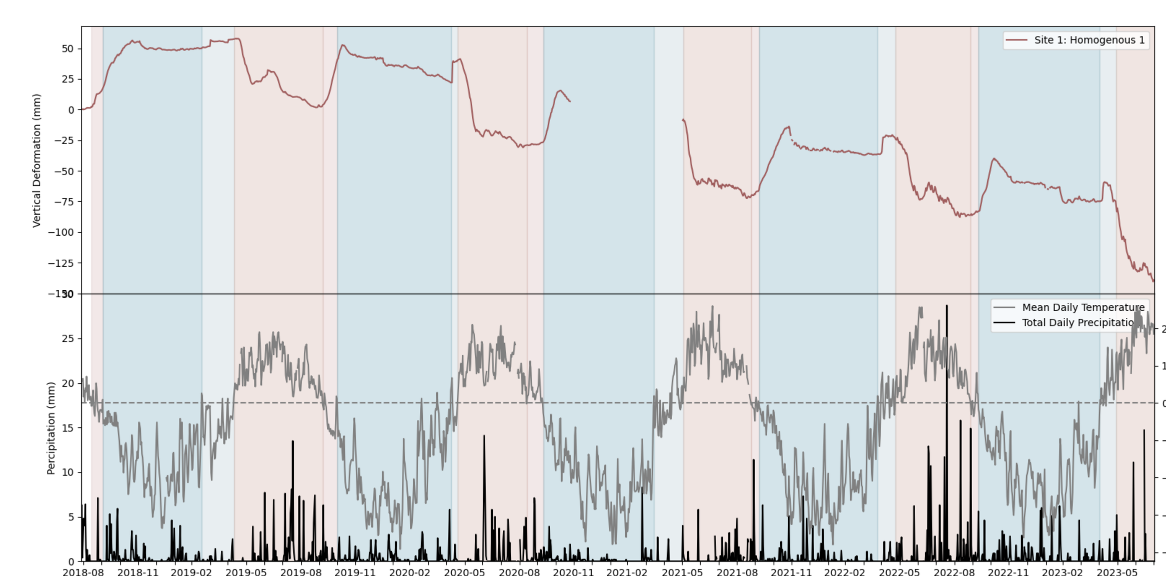


- Floating Corner Reflector measures line-of-site displacement
- Anchored Reflector serves as a stable reference point

$$\phi_{LOS\ surf.disp.} = \phi_{cr_a} - \phi_{cr_f}$$

- Where ϕ_{cr_a} and ϕ_cr_f is the interferometric phase of an InSAR pair for the pixel corresponding to each corner reflector

Research sites have been instrumented with inclinometers from which vertical surface displacement can be derived [2]. Periods of sustained thaw (coral) and sustained freeze (grey) are highlighted along with transition periods between the states. Climate data is taken from the Environment Canada climate station at Inuvik, NWT. Given the rapid, high-amplitude changes at the beginning of each period, the InSAR phase is expected to be highly wrapped.



Method

1. Registration to master scene
2. Generation of sequential interferometric pairs
3. Topographic phase removal with TanDEM-X digital elevation model.

InSAR Processing with Gamma Software

Phase Correction with Anchored Corner Reflector

- Line-of-site displacement calculated to be the complex conjugate of the anchored and floating corner reflectors

$$\phi_{LOS} = \phi_{cr_a} - \phi_{cr_f}$$

- Timeseries derived from cumulative sum of the phases

In-Situ Measurements

- Inclinometer measurements are converted to equivalent phase, ϕ_{tilt}

$$\phi_{tilt} = \frac{4\pi}{\lambda} z \cos(\theta_{inc})$$

- Where z is the measured displacement, λ is the radar wavelength and θ_{inc} is the incident angle of the beam.
- Relative differences for each InSAR pair are calculated to determine where phase wraps are expected to occur in the InSAR data.
- Correction factors of $k\pi$, where k is an integer corresponding to the magnitude of phase wrapping, are applied to the InSAR data

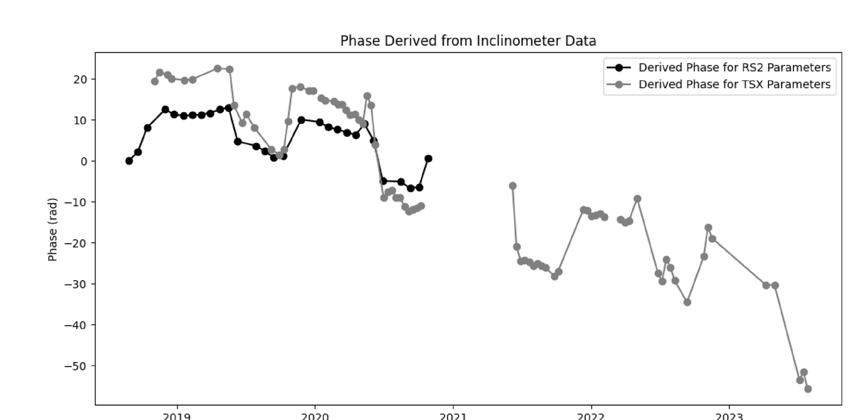
Modified Stefan Model [2]

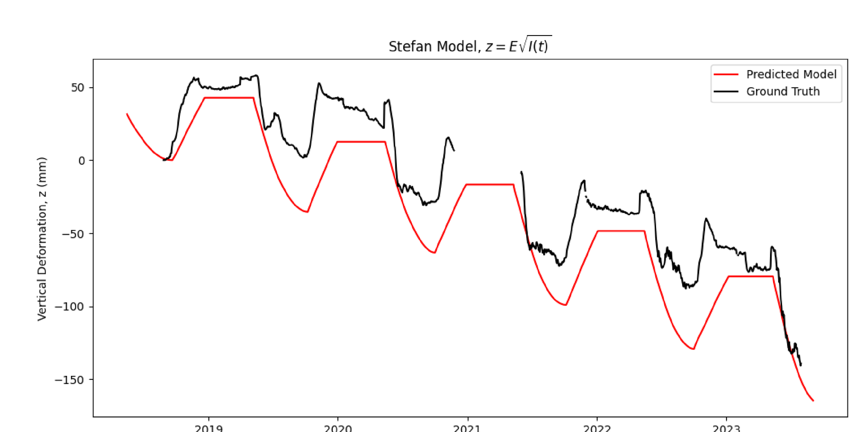
- Stefan Equation for deformation

$$z \propto \sqrt{I(t)}$$

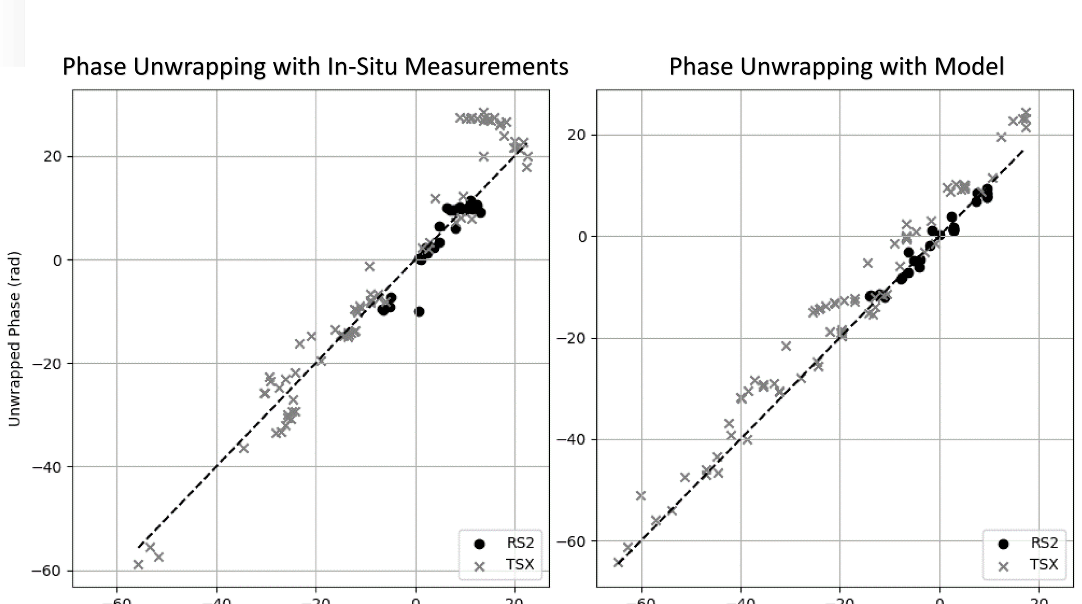
- Where z is the vertical displacement, and I is the thawing/freezing index calculated as the cumulative some of positive/negative daily temperatures for a given thawing/freezing period
- The model is clipped such that the heave due to freeze-back does not exceed the level of subsidence.
- The model is scaled using in-situ measurements from the inclinometer. The average scaling factor for the freezing and thawing periods is applied to the dataset.

Phase Unwrapping



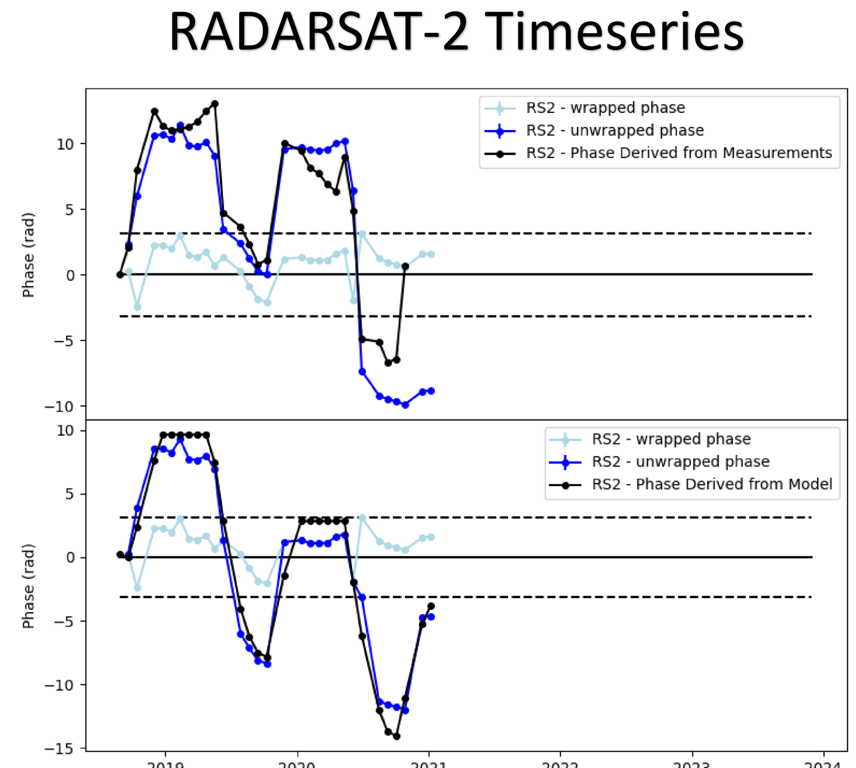


Results

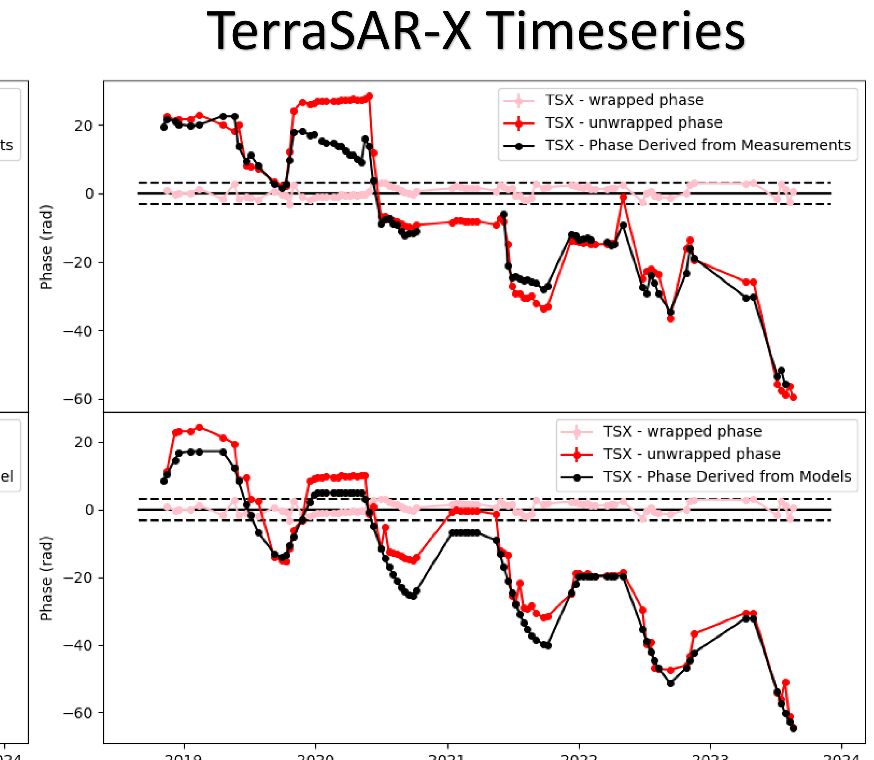


- Timerseries show the wrapped and unwrapped phase for each sensor
- Dashed lines indicate $\pm\pi$ from the zero line
- Stefan model overestimates subsidence due to lower-than-average subsidence in the first thaw period
- Periods of subsidence during the winter months may be due to consolidation of the soil as a result of hummock dynamics; the flatter phase trend measured by the InSAR is likely more representative of the overall terrain
- Unwrapping errors are still present; the unwrapping algorithm could be improved by looking at residuals and adjusting the InSAR phase accordingly
- The InSAR phase, as theorized, is significantly more stable in the winter periods than in the summer and so could be an improved metric for measuring long-term trends in subsidence.

RADARSAT-2 Timeseries



TerraSAR-X Timeseries



Conclusions

- 12-Day temporal resolution of TerraSAR-X allows for measurement of short-term anomalies not captured by 24-day RADARSAT-2 interferograms.
- The higher X-band frequency of TerraSAR-X exacerbates phase ambiguities during periods of significant and rapid displacement
- (With proper demodulation) TerraSAR-X and RADARSAT-2 produce consistent findings
- Lower than average subsidence in the first thawing season resulted in an overestimation of subsidence for subsequent years in the modelled deformation.

References:

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[2] Gruber, S., Link to external site, this link will open in a new window, 2020. Ground subsidence and heave over permafrost: hourly time series reveal interannual, seasonal and shorter-term movement caused by freezing, thawing and water movement. The Cryosphere 14, 1437–1447. https://doi.org/10.5194/tc-14-1437-2020

[3] Liu, L., Zhang, T., Wahr, J., 2010. InSAR measurements of surface deformation over permafrost on the North Slope of Alaska. Journal of Geophysical Research: Earth Surface 115. https://doi.org/10.1029/2009JF001547

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