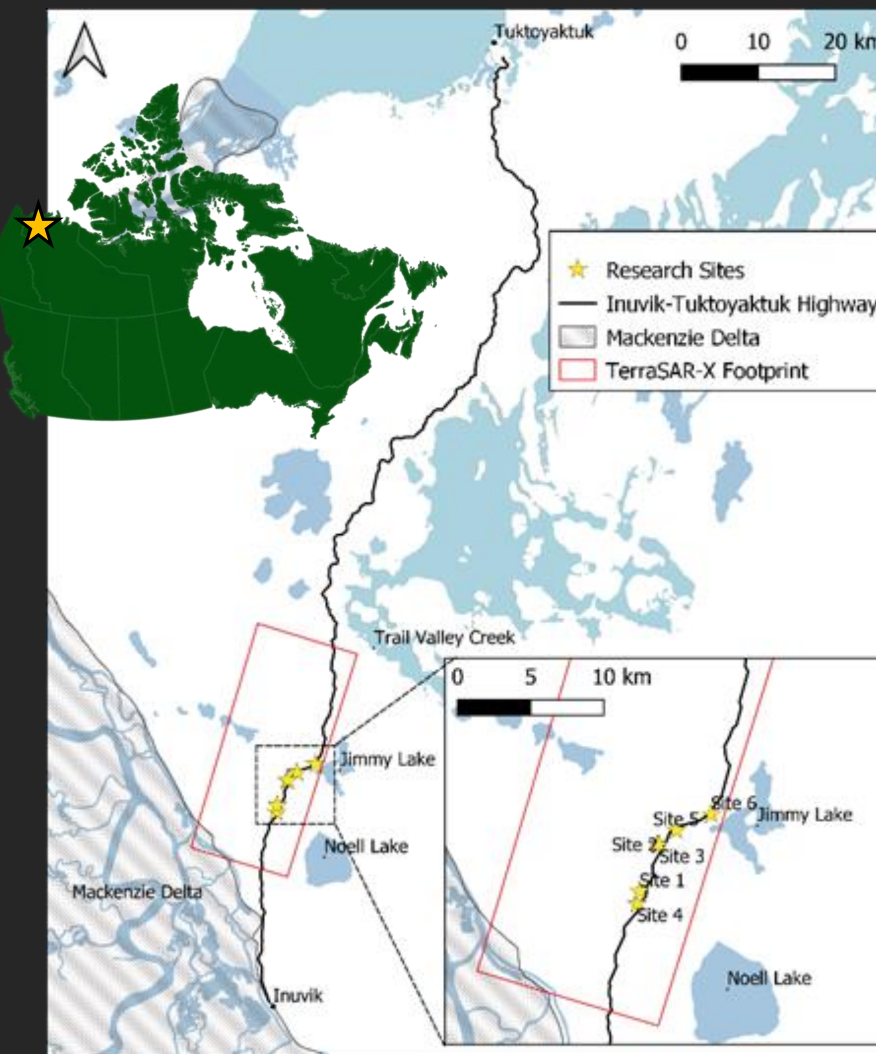
Analysis of a topographic-based InSAR SWE estimation technique for low-land permafrost terrain north of Inuvik, Northwest Territories

Allison Plourde, MSc. Candidate
Department of Engineering Science,
Simon Fraser University

InSAR (Interferometric Synthetic Aperture Radar) is a well-established method for measuring small-scale surface deformations over large regions; however, contaminating effects of snow cover on the InSAR phase prevents the use of (usually less noisy) winter InSAR data, limiting the accuracy of comprehensive measurement of seasonal dynamics in permafrost terrain. In this study we investigate if a previously developed topography-based approach for estimating the contribution of the Snow Water Equivalent (SWE) from repeat pass InSAR phase is accurate enough to correct the displacement phase of the winter data. We use a stack of TerraSAR-X strip map data covering several winters over a study region located in low-lying permafrost north of Inuvik, Northwest Territories. In the study region several ground truth sites have been instrumented with (1) an inclinometer to measure vertical surface deformation due to active layer dynamics of the permafrost, and (2) an ultra-sonic range finder to measure snow-depth. Our analysis found a high uncertainty in the topographic SWE estimates around our ground-truth sites due to insufficient variation in terrain preventing us from evaluating the method directly against the ground truth. Estimates for other areas with higher terrain variability further away from our ground truth sites, however, showed more promising results in terms of error estimates from the topographic SWE estimation being small enough to correct the phase of winter InSAR data to allow their use for comprehensive permafrost active layer displacement measurements.



Theory

The radar signal is refracted by dry snow. To estimate SWE, the method exploits variations in topographic slope Eppler et al. (2022) according to:

$$\xi \doteq \frac{d\Phi_{SWE}}{dSWE} = \frac{4\pi}{\lambda\rho}\cos\alpha\left(\sqrt{\epsilon(\rho) - \sin^2\theta} - \cos\theta\right)$$

ξ: phase sensitivity to changes in SWE
Φ_{SWE}: relative phase due to changes SWE
SWE: relative Snow Water Equivalent
λ: radar wavelength
ρ: density of the snowpack
α: terrain slope angle
ϵ: permittivity of the snowpack
θ: local radar incidence angle θ

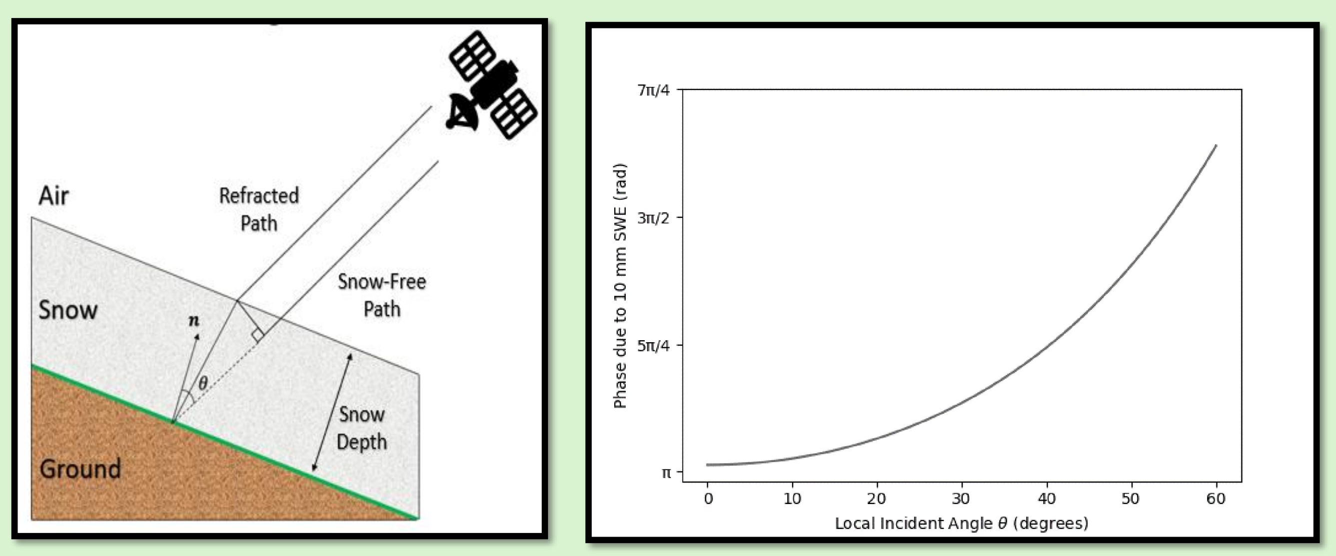


Figure 1. The radar path is refracted by dry snow, thus invoking a phase change proportional to the Snow Water Equivalent (SWE) and varies with topographic slope and the local radar incidence angle

Methods

- TerraSAR-X: 30 interferograms (Nov–Mar) where snowfall would be present and surface heave would be negligible.
- ~15 m ground resolution
- In-situ data collected at 6 research sites

Figure 2. (Left) Area with high variability in topographic slope. (Right) Inclinometer and snow depth sensor at one of the six sites.

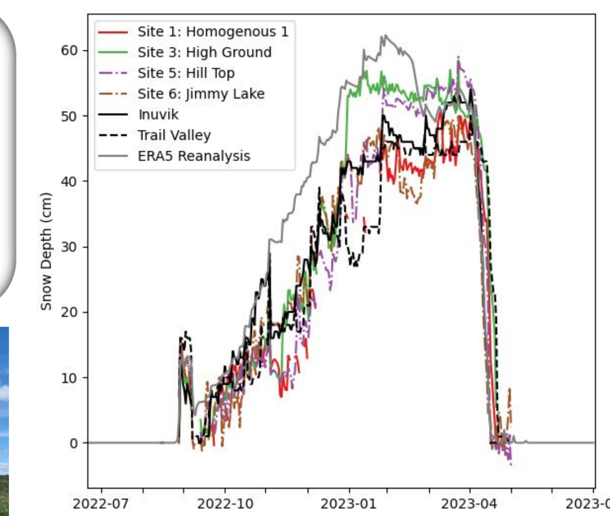


Figure 3. Snow depth measurements from 4 research sites along with Environment Canada data from nearby climate stations and ERA-5 Reanalysis.

Map generated using a local DEM shows phase sensitivity due to SWE; areas with high sensitivity (yellow) correspond to regions where the radar will have the shallowest incidence angle

A Quality map indicating regions with high variability (green) is generated to determine regions for which the method would be most suitable

Incidence angle masks is used to mask regions where the local incidence angle is below 25º (thus, the radar path is too steep to create noticeable change.)

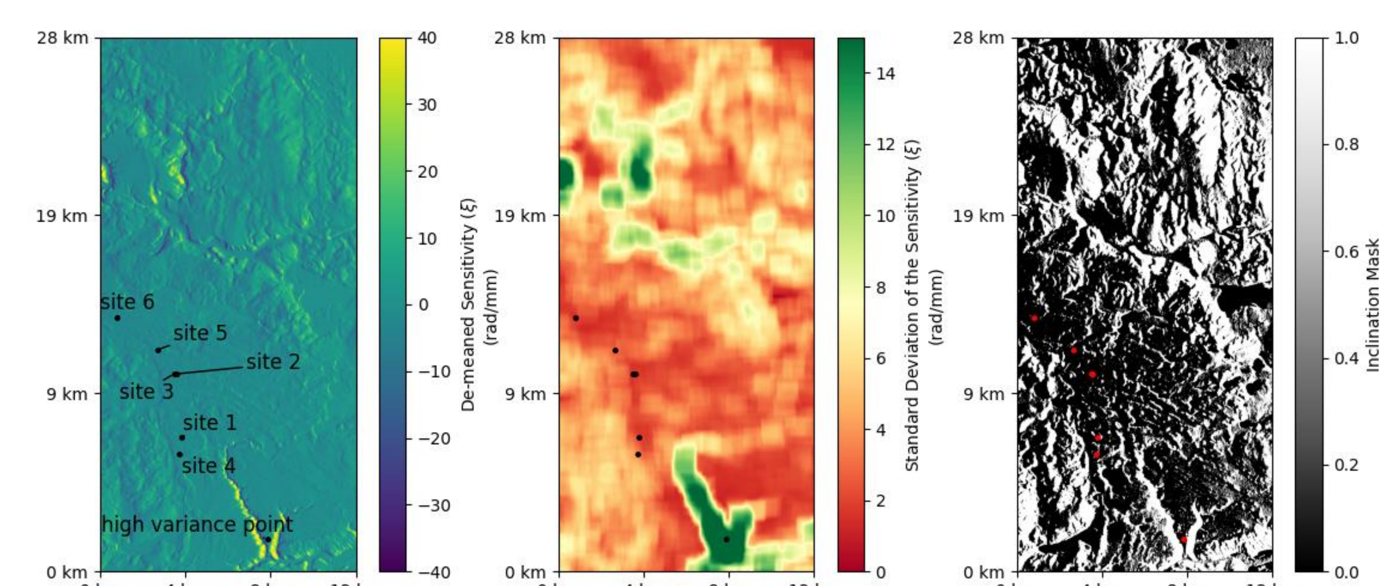


Figure 4. (Left) SWE sensitivity, (middle) quality map, (right) inclination mask

Results

- Majority of the study area shows low variability in topographic slope, making the estimation unreliable, including where the in-situ research sites are located
- In regions with high variability, estimates show some consistency with other regional snow depth estimates

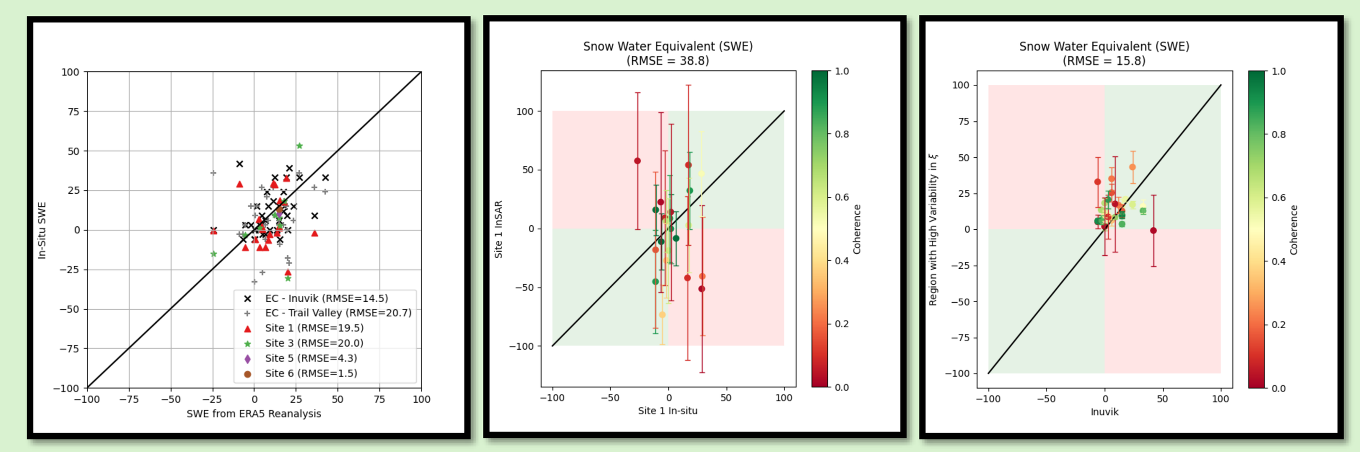


Figure 5. Comparing InSAR SWE estimates to in-situ data.

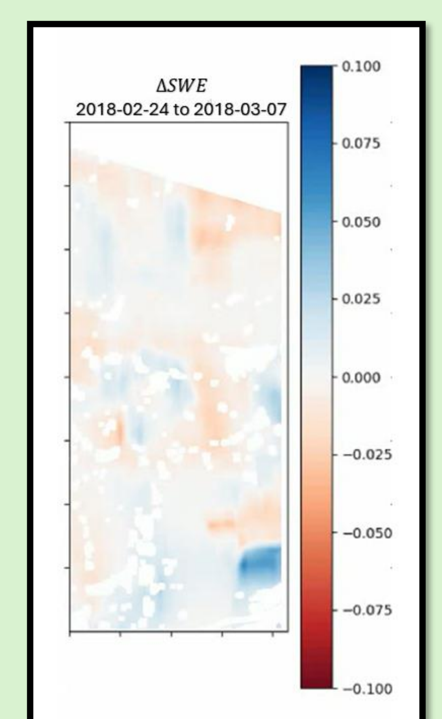
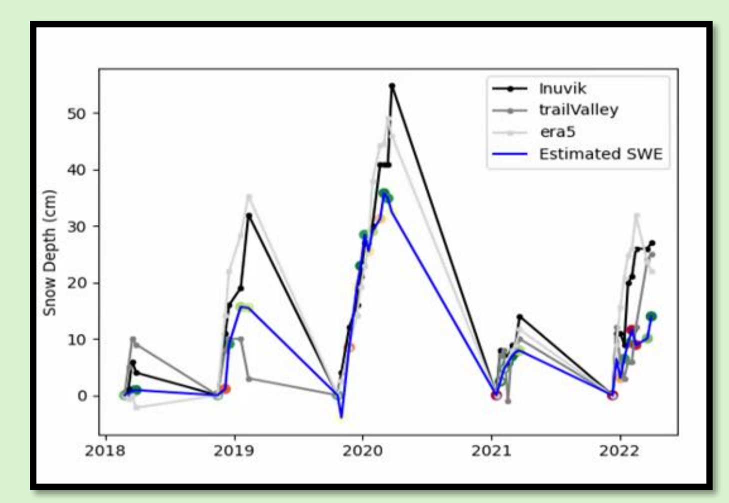


Figure 6. (Left) Sample SWE estimation map.
Figure 7. (Bottom) multi-year time series for estimated snow-depth averaged over the entire scene compared to nearby weather stations and ERA-5.

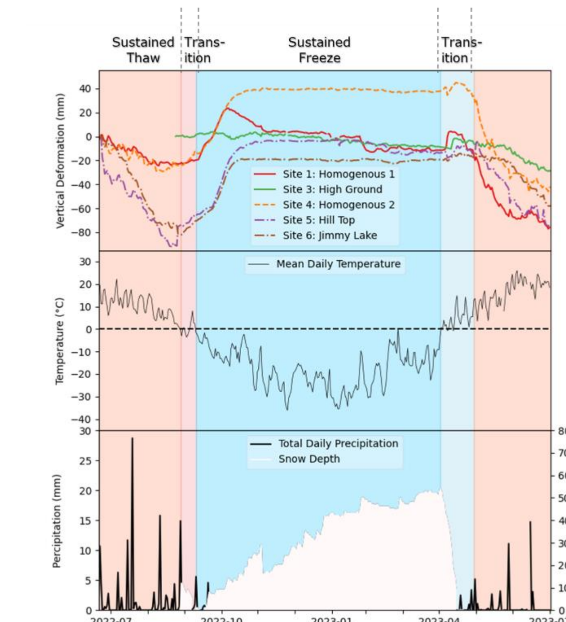


Conclusions

•**Study Focus**: Investigated the application of a method by Eppler et al. (2022) to estimate snow water equivalent (SWE) by leveraging topographic slope variations.
•**Limitation Identified**: Method found potentially ineffective for InSAR phase correction in regions with minimal topographic variability.
•**Incidence Angle Consideration**: Noted that TerraSAR-X's steep incidence angle (~24º) may not be optimal for detecting SWE changes due to less modulation effect on the phase at sharper angles.
•**Data Analysis Challenges**: Difficulty in making robust comparisons due to low terrain slope variability and limited availability of suitable interferometric pairs.

Future Work

Sentinel-1, with its shallower incidence angle, may be suitable for this area. Once SWE estimations can successfully be made, snow 'phase screens' can be generated to remove the phase due to snow which can allow for the long-term (year-to-year) degradation of the permafrost to be measured.



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