Spaceborne transmitter/stationary receiver bistatic SAR retrieval over the Girose glacier

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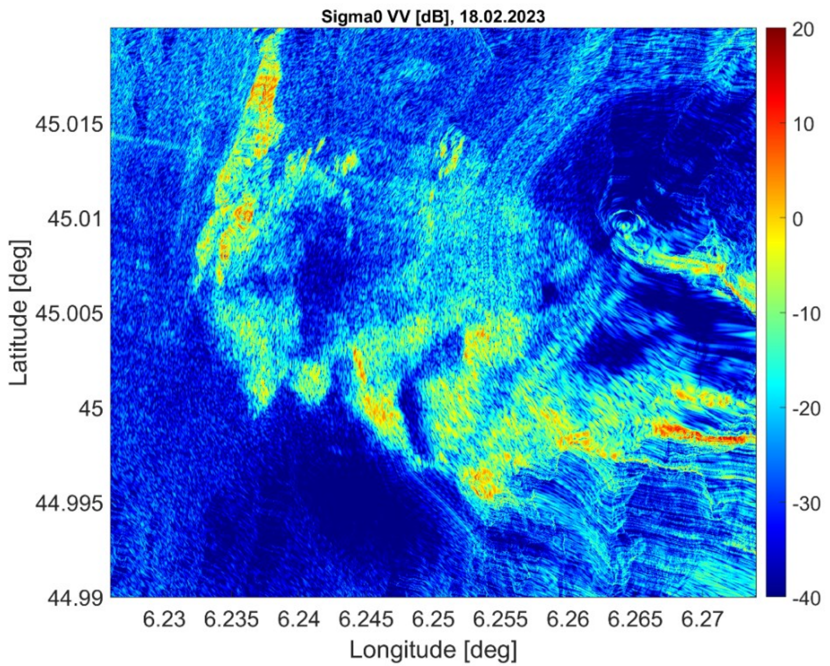
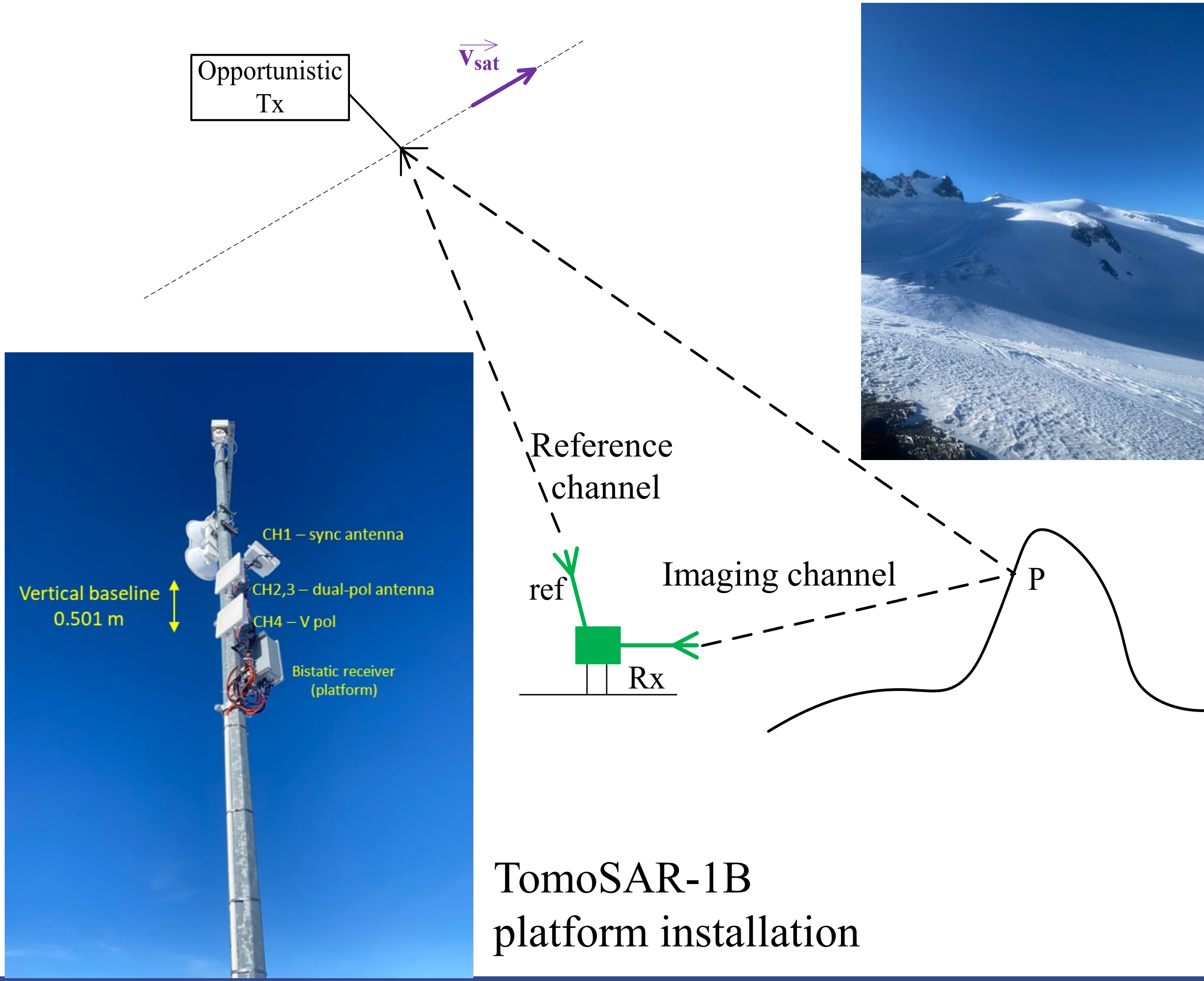


COBIS4Harmony Project

Main objectives:

- ✓ Acquisition of a time series of bistatic SAR data to retrieve vertical motion over the Girose glacier and study snow/firn penetration.
- ✓ Perform correlative ground-based measurements (meteorological parameters, glacier parameters, measurements on structural properties of the snow/firn volume).
- ✓ Testing and evaluating procedures for deriving the penetration-related elevation bias of InSAR-based DEMs from interferometric parameters and backscatter properties.
- ✓ Estimating the performance of the correction algorithm for InSAR penetration, considering specific features of the Harmony mission, comprising two receive-only SAR sensors using Sentinel-1 as illuminator.

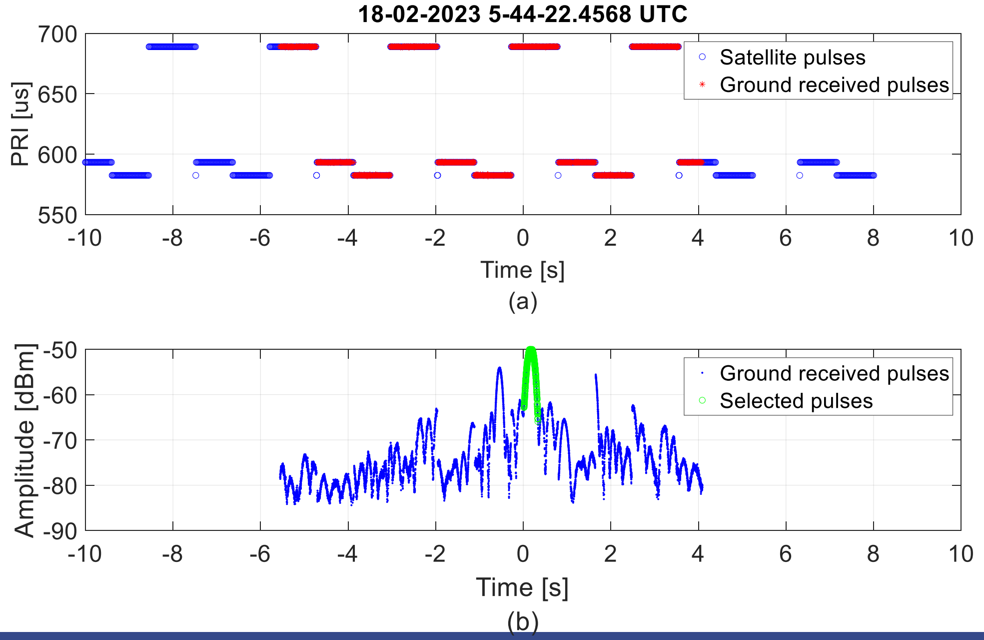


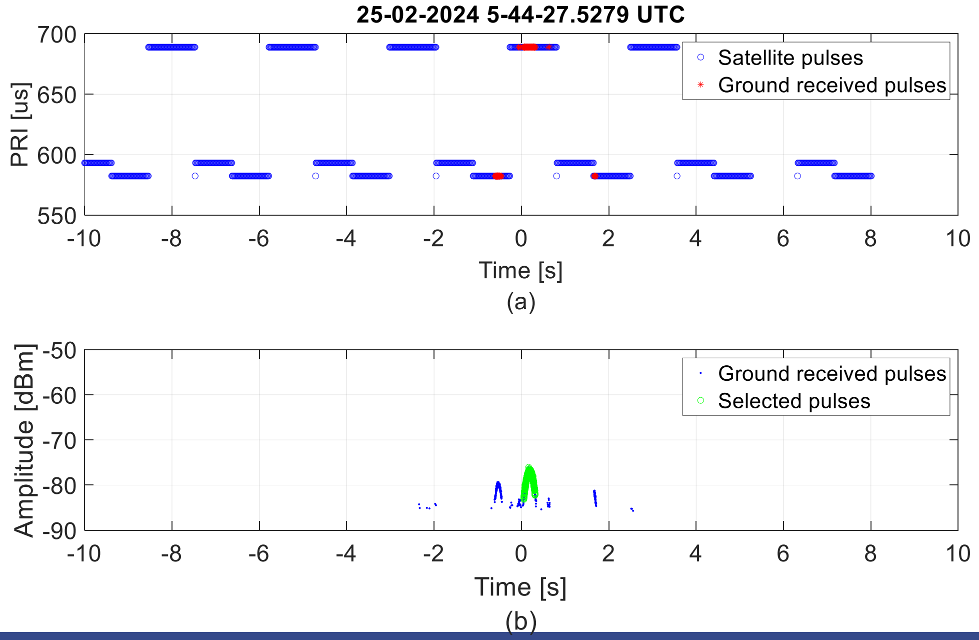
Imaged scene

TomoSAR-1B platform installation

Bistatic data acquisitions

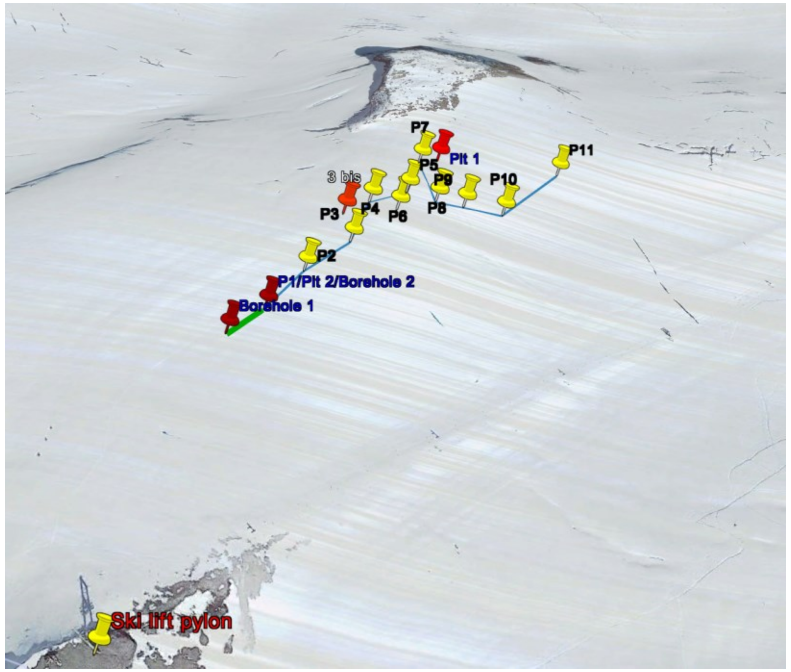
- ✓ Acquired and processed 52 datasets (from all the visible orbits) in 2023 as follows:
  - Orbit 139 (main orbit): 18 datasets between 18.02.2023 – 29.08.2023
  - Orbit 037: 16 datasets between 30.01.2023 – 22.08.2023
  - Orbit 066: 18 datasets between 1.02.2023 – 24.08.2023
- ✓ Acquired and partially processed (image focusing, InSAR DEM generation) 10 datasets (from the main orbit) in 2024 between 01.02.2024 – 19.05.2024.





In-situ measurements

- ✓ Performed 2 firncores and 2 snowpits under the surface (reaching a level of up to -11.6 m at the date of the core) to investigate the physical properties of both annual and multi-annual snow layers.
- ✓ The thickness of the snow layer was measured in 11 probing points to determine the snow layer spatial and temporal variation.



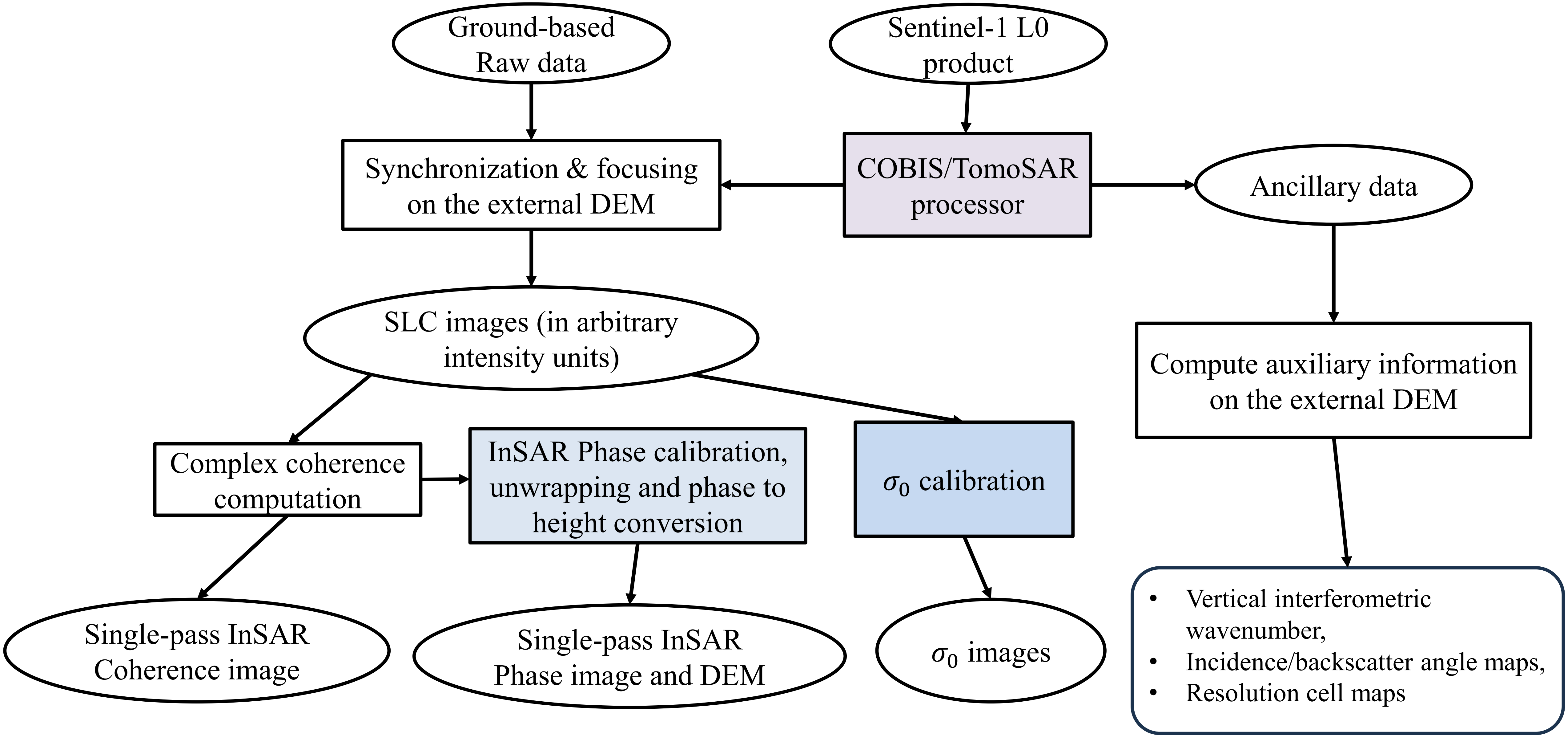
<u>3 probing campaigns:</u>

13-14 February 2023

04-05 April 2023

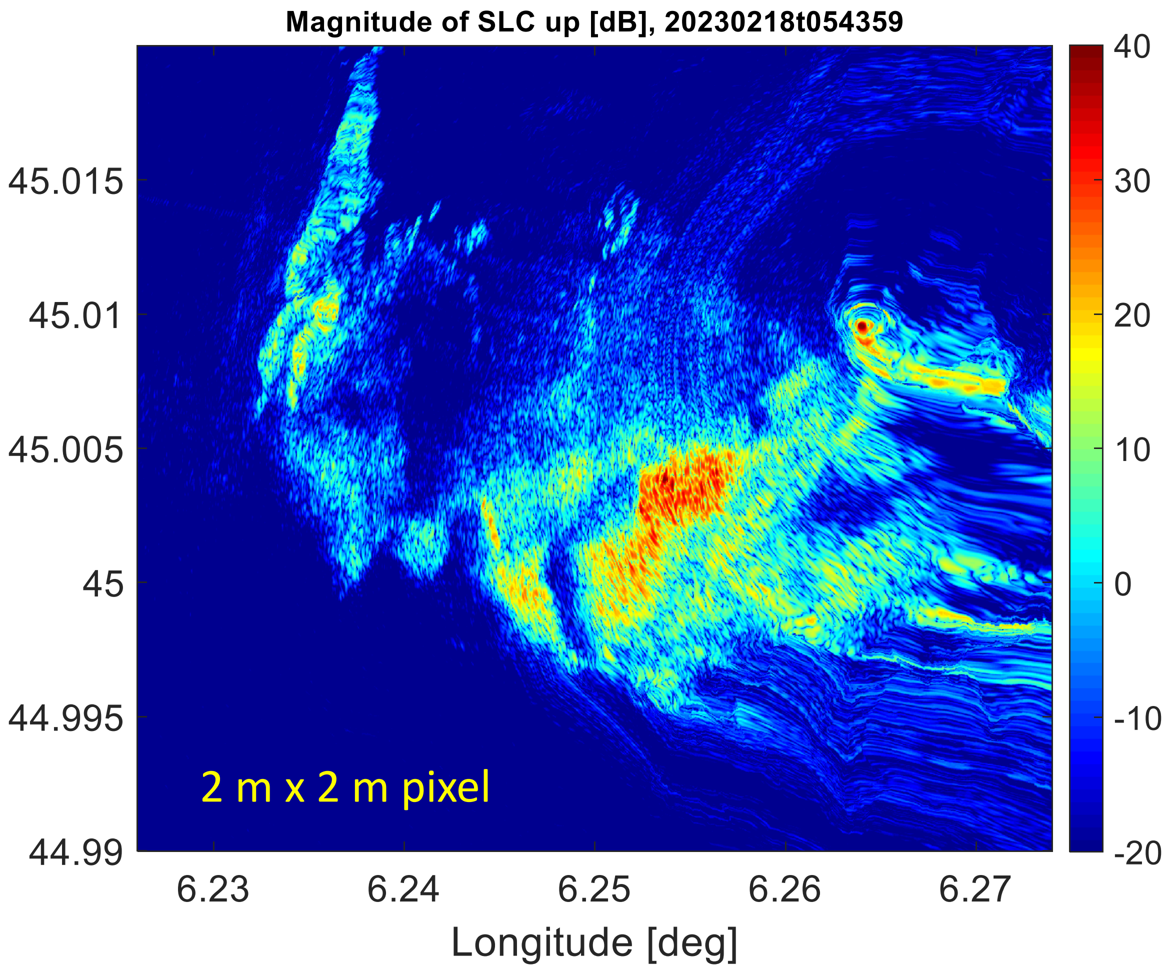
12 April 2024

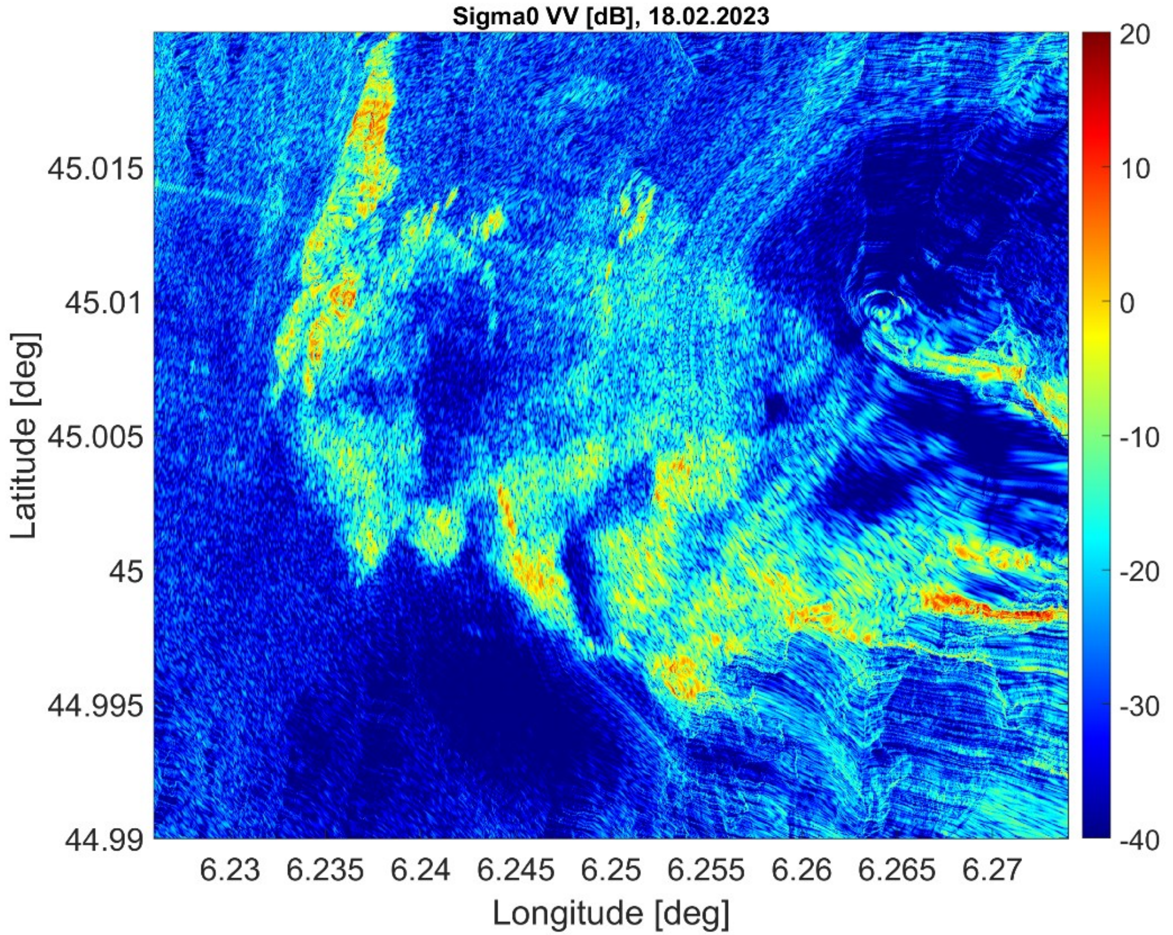
Bistatic data processing



Sample bistatic products

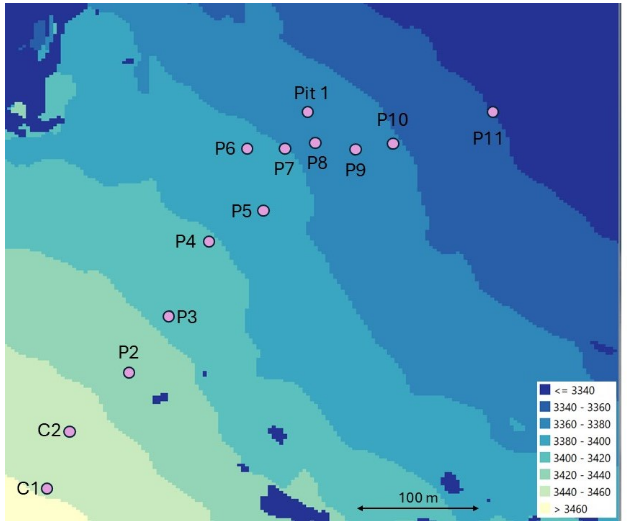
February 2023



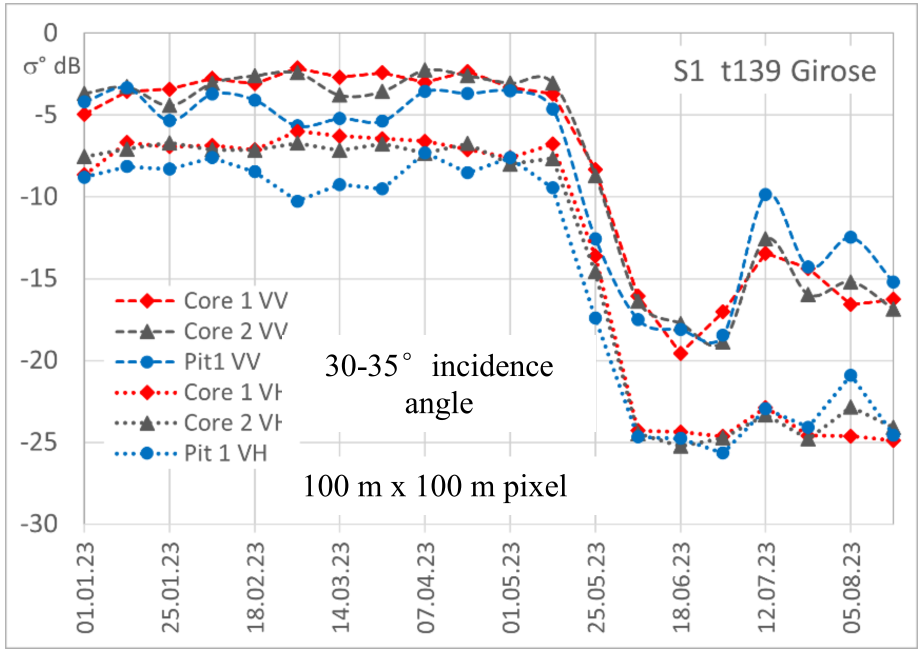


Monostatic/bistatic σ_0 time series

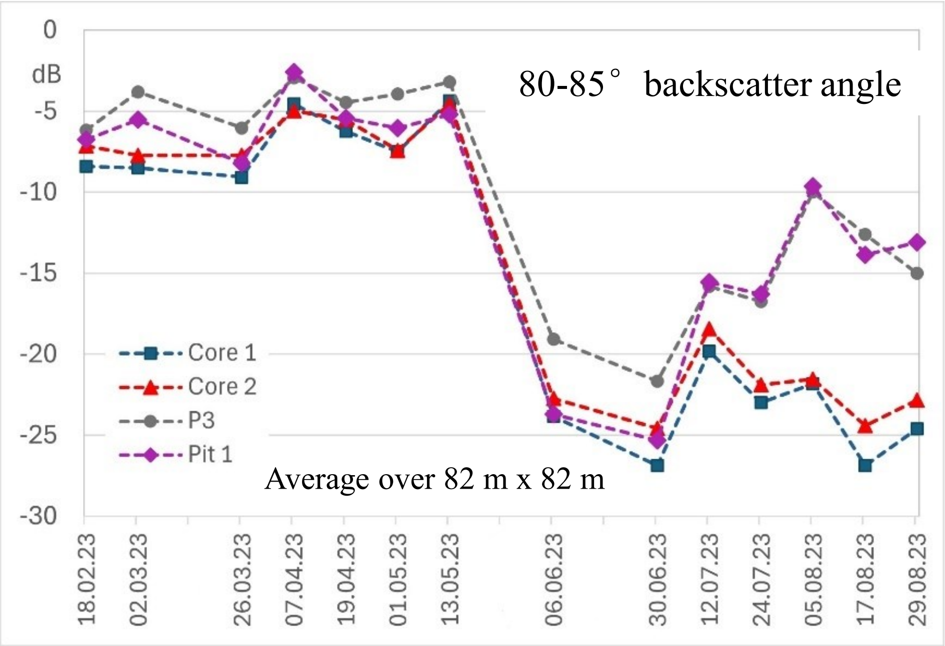
Section of the Girose glacier DEM with in-situ measurement points.



Monostatic



COBIS Bistatic

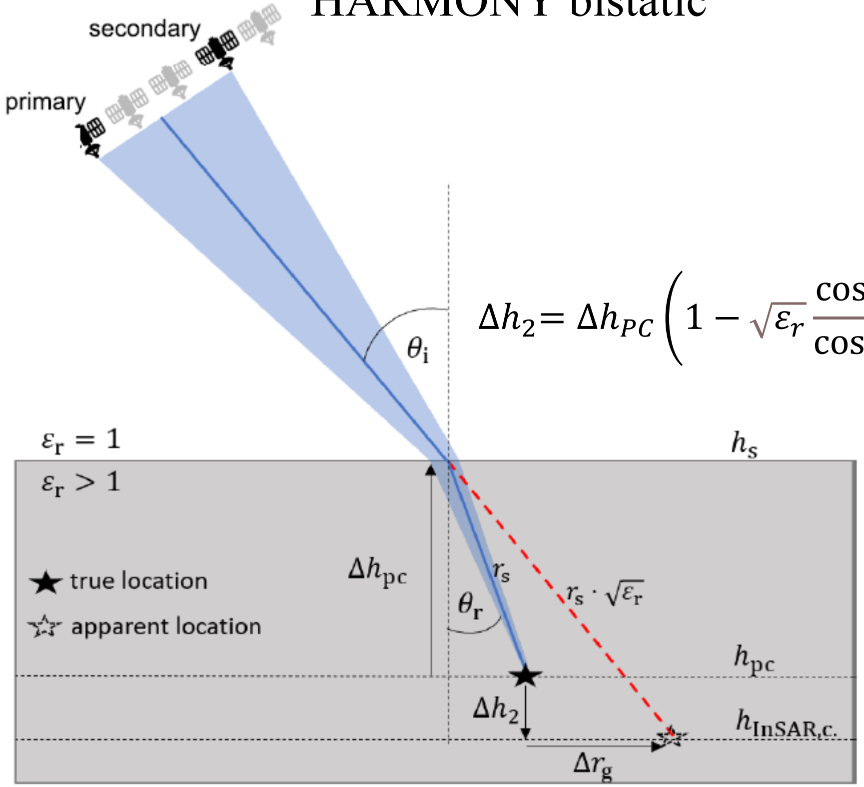


- Up to early May there is no indication for surface melt (high backscatter, small co- to cross polarized backscatter ratio and there is no significant temporal trend even though the average depth of seasonal snow increased between February-April with over 2.5 m).
- Snow surface melting in May caused a drop of σ_0 by about 15 dB (monostatic) and 20 dB (bistatic).
- The lowest backscatter values were observed in June, an indication for snow with high liquid water content and smooth surfaces.
- The rise of σ_0 during summer can be explained by increasing roughness of wet snow surfaces, and later on by the increasing exposure of glacier ice with rough surfaces.

COBIS Bistatic InSAR Elevation Bias

- The apparent and real InSAR phase centers should have the same propagation delay, which translates in the same *bistatic range* (i.e., same $|\vec{r}_{sat} - \vec{r}| + |\vec{r}_R - \vec{r}|$) for both phase centers.

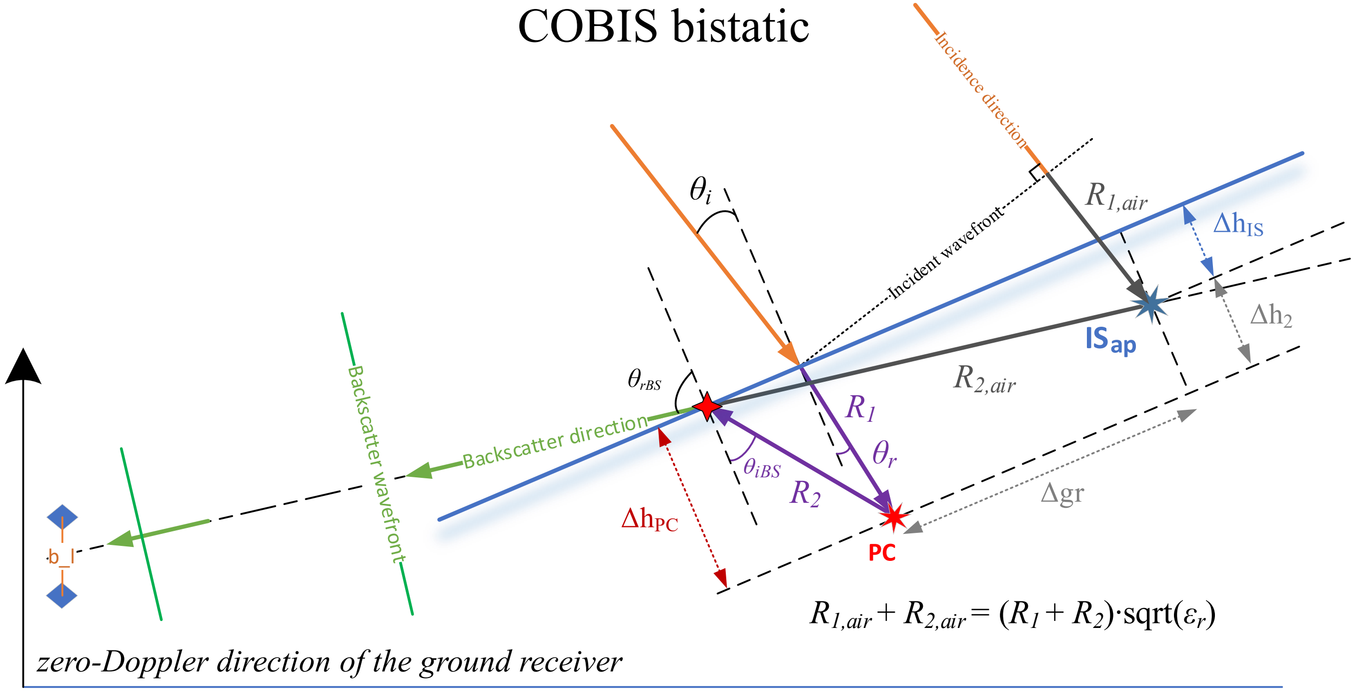
HARMONY bistatic



$$\Delta h_2 = \Delta h_{PC}\left(1 - \sqrt{\varepsilon_r}\frac{\cos\theta_i}{\cos\theta_r}\right)$$

[*] A. Benedikter, M. Rodriguez-Cassola, P. Prats-Iraola, G. Krieger and G. Fischer, "On the Processing of Single-Pass InSAR Data for Accurate Elevation Measurements of Ice Sheets and Glaciers," in *IEEE Transactions on Geoscience and Remote Sensing*, vol. 62, pp. 1-10, 2024, Art no. 4300310

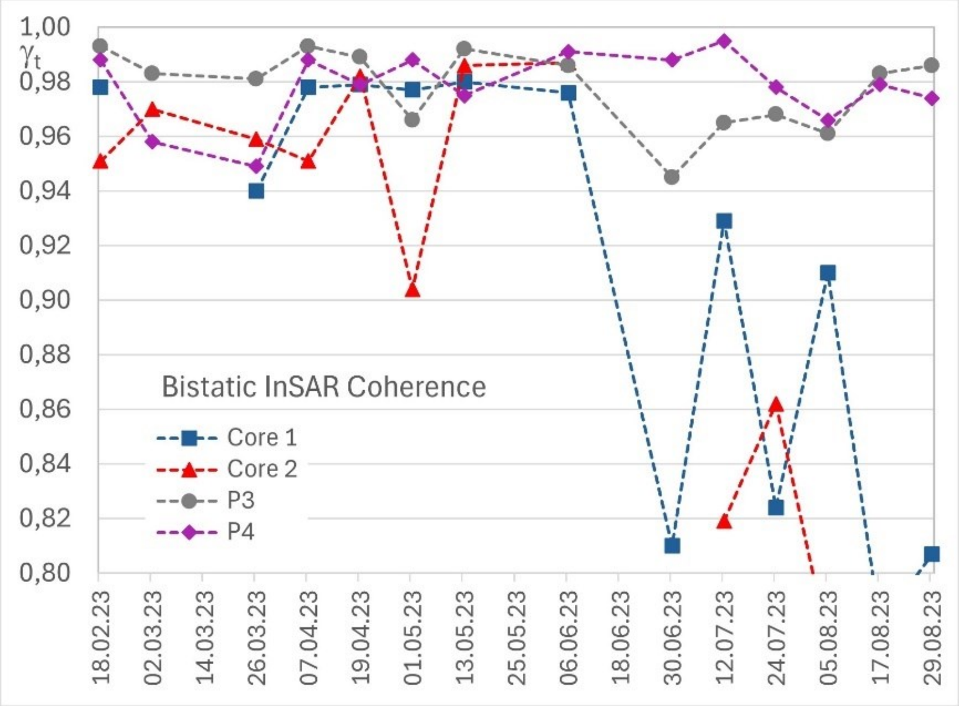
COBIS bistatic



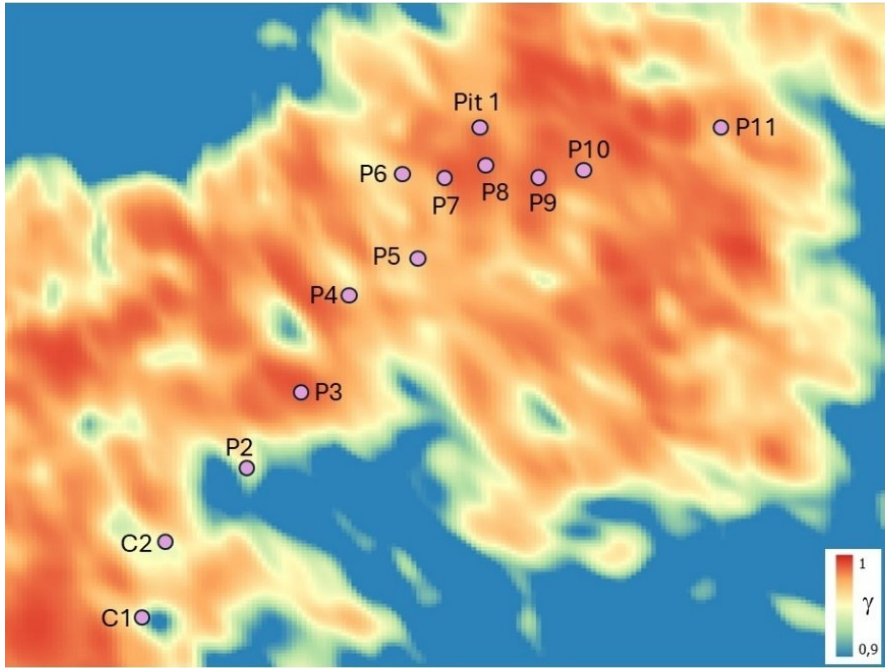
$$\Delta h_2 = \Delta h_{PC}\left(1 - \frac{\sqrt{\varepsilon_r}\left(\frac{1}{\cos\theta_r} + \frac{1}{\cos\theta_{iBS}}\right) + (\tan\theta_{iBS} - \tan\theta_r)\sin\theta_i}{\tan\theta_{rBS}\sin\theta_i + \cos\theta_i + \frac{1}{\cos\theta_{rBS}}}\right)$$

Bistatic InSAR coherence for phase center depth retrieval

Coherence at sites in the Girose firn area



Map of total coherence magnitude (mean values of 5 dates with dry snow/firn)



Relation between scattering phase center depth and volumetric coherence for a homogeneous scattering medium:

$$\Delta h_{PC} = \frac{1}{k_{zVol}} \arctan\left(\sqrt{|\gamma_{vol}|^{-2} - 1}\right)$$

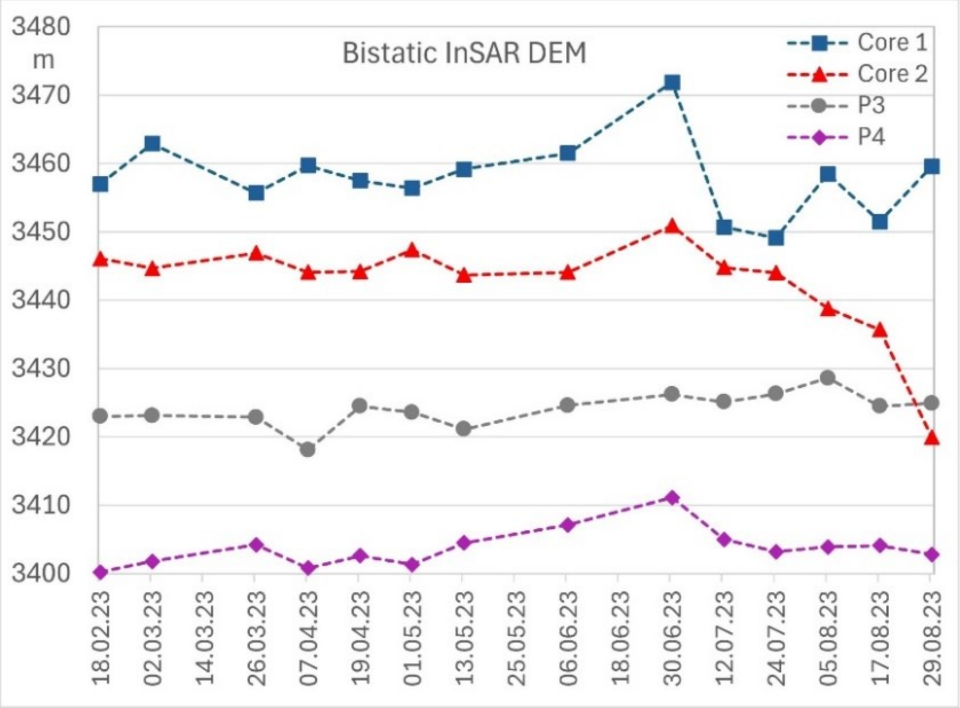
- Probing point P3 (θ_{bs} =80.4°) shows a consistent coherence time series during the dry snow period with mean γ_{tot} = 0.985.

Δh_{PC} = 11.2 m → Δh_{IS} = 5.4 m

[*] J. Dall, "InSAR Elevation Bias Caused by Penetration Into Uniform Volumes," in *IEEE Transactions on Geoscience and Remote Sensing*, vol. 45, no. 7, pp. 2319-2324, July 2007

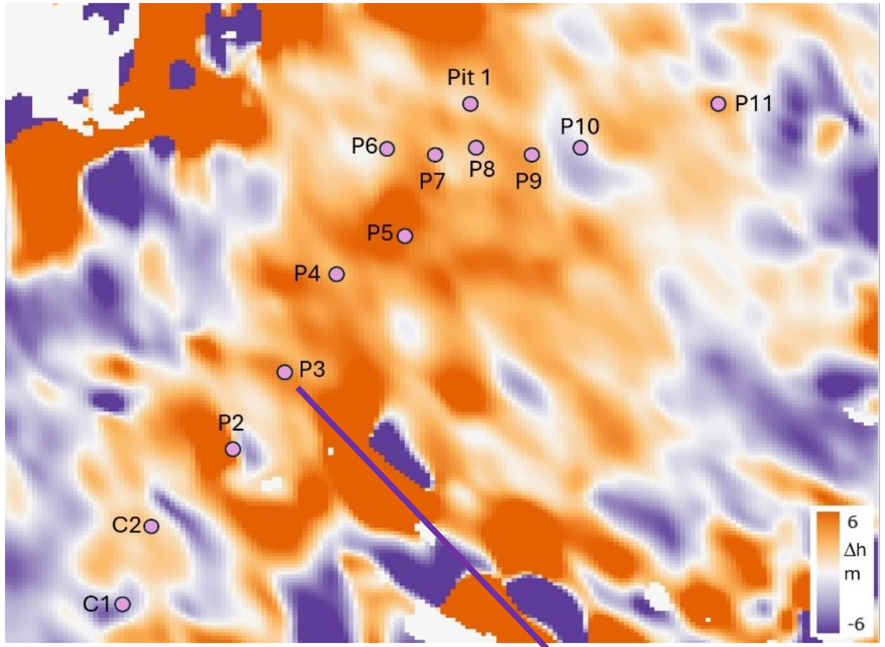
Bistatic InSAR elevation

Elevation at sites in the Girose firn area



Map of InSAR DEM elevation difference

$\Delta h_{IS,wd} = h_{IS,wet} - h_{IS,dry}$



random spatial pattern (gradual changes expected)

- Comparing the InSAR DEM surface elevation over melting snow with the apparent elevation in dry snow cases is an option for checking the performance of coherence-based penetration estimates.
- InSAR DEMs of the early melting phase used as reference for the snow surface elevation (wet snow DEM is the average of the InSAR DEMs of 06-06-2023 and 12-07-2023).
- The dry snow period DEM is the average of four InSAR DEMs (26-03-2023, 07-04-2023, 19-04-2023, 01-05-2023).

The InSAR DEM difference for P3

$\Delta h_{IS,wd} = 3$ m

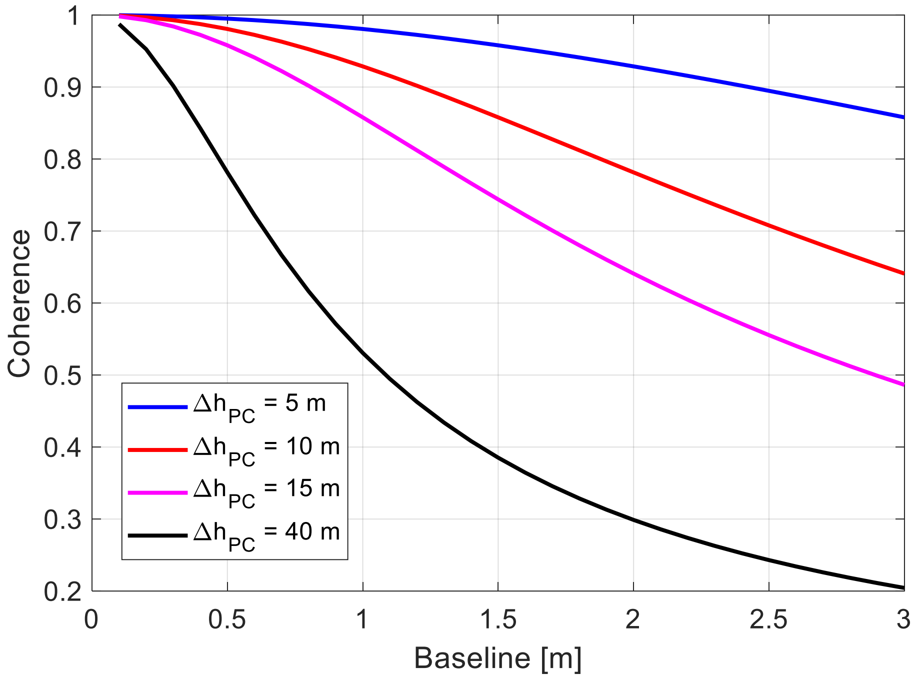
Volumetric coherence vs. vertical baseline

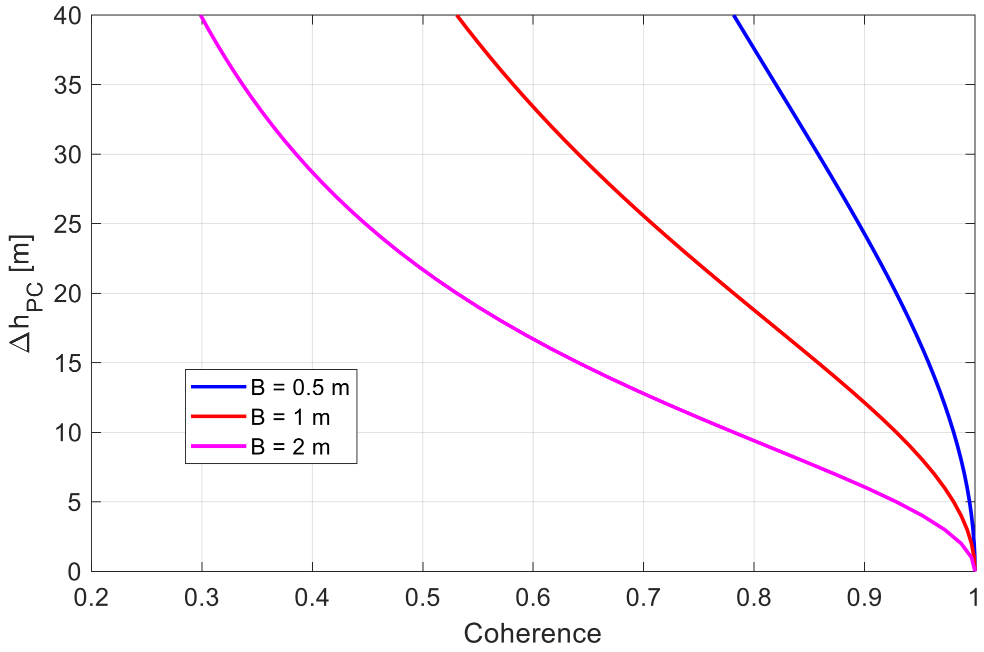
$$k_z = \frac{2\pi B}{\lambda R\left(\overline{\text{Baseline unit versor}} \cdot \overline{\text{Local normal}}\right)}$$

$$k_{zVol,b} = k_z \frac{\sqrt{\varepsilon_r}\left(\frac{1}{\cos\theta_r} + \frac{1}{\cos\theta_{iBS}}\right) + \sin\theta_i\left(\tan\theta_{iBS}\cos\alpha - \tan\theta_r\right)}{\tan\theta_{rBS}\sin\theta_i\cos\alpha + \cos\theta_i + \frac{1}{\cos\theta_{rBS}}} \propto B$$

$$\gamma(B, \Delta h_{PC}) = \frac{1}{\sqrt{1 + \left(k_{zVol,b}(B) \cdot \Delta h_{PC}\right)^2}}$$

Plots for typical angles on the Girose glacier transect.





- A higher baseline would provide higher sensitivity of volumetric coherence in respect to Δh_{PC} (larger $\partial |\gamma_{Vol}| / \partial \Delta h_{PC}$).

Conclusions & Outlook

- COBIS bistatic measurements on Girose glacier were performed at high backscatter angles (> 80°) due to terrain constraints.
- The averaged bistatic σ_0 time series vary in a similar fashion as the Sentinel-1A σ_0 time series, but with a higher variance.
- The InSAR coherence over the glacier is higher than 0.9. At high backscatter angles the accuracy requirements regarding volumetric coherence for phase center depth retrieval are challenging (better than 0.01).
- InSAR phase calibration was performed using an external DEM and a stable periglacial area as height reference (*without* an artificial target placed in the scene).
- The spatial pattern of the wet-dry difference DEM is quite noisy, dominated by positive values for the elevation difference of wet snow minus dry snow as expected, but showing locally also some negative values.

➢ For future studies on InSAR penetration in glacier snow and ice and related InSAR DEM correction algorithms it is recommended to focus on backscatter angles covering the expected main range of Harmony observations over glaciers (e.g., by placing the bistatic receiver on a stationary drone).

➢ The InSAR baseline should be chosen such that the sensitivity of coherence in respect to the phase center depth is higher.

Thanks for your attention !!!