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Progress in Cryosphere Applications using Innovative SAR Techniques

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The cryosphere, which includes permafrost, snow, glaciers, and ice sheets, is a vital component of the Earth's climate system. Monitoring these environments is essential for assessing the effects of climate change. SAR (Synthetic Aperture Radar) is a powerful tool for cryosphere research because it can provide large-scale information on both surface and subsurface properties, as well as track dynamic changes over time. Innovative SAR techniques such as polarimetry, interferometry, PolInSAR, and tomography are particularly valuable. Polarimetry allows for detailed analyses of scattering mechanisms, interferometry enables precise measurements of surface deformation, PolInSAR combines both polarimetry and interferometry to estimate vegetation or ice layer height, and tomography provides three-dimensional imaging of subsurface structures. Together, these techniques offer a comprehensive view of processes in the cryosphere, enabling more accurate monitoring and analysis of these sensitive environments.

Currently, we primarily focus on airborne campaigns conducted with DLR's F-SAR sensor. Typically, we obtain multi-frequency datasets over specific test sites within the Arctic and Alpine glaciers. This approach allows us to apply innovative SAR techniques to high-resolution data, enabling the refinement of existing algorithms, the exploration of their applicability across different test sites, and deeper insights into scattering processes with the goal of deriving physical parameters or achieving an improved glaciological understanding of the test site. To validate and enhance the accuracy of our SAR-derived measurements, we compare them with a range of complementary datasets, including spaceborne SAR observations, optical data, LiDAR for height accuracy, and ground measurements.

SAR has the capability to penetrate snow and ice, with the depth of penetration determined by the radar frequency and the permittivity of the ground. Higher frequencies are ideal for capturing surface and near-surface snow properties, such as snow density and snow-water equivalent. In contrast, lower frequencies enable deeper penetration, allowing for detailed exploration of firn and ice, revealing subsurface structures like internal layers and ice-bed interfaces. Consequently, a multifrequency approach provides a more complete and nuanced understanding of the test site, offering insights across different snow and ice layers.

In Greenland, we are currently studying glaciers and ice sheets across various glacial zones. In the percolation zone, we focus on investigating firn structures to uncover snow accumulation and compaction processes, ultimately deriving accurate density profiles of the area [1]. In the ablation zone, we analyze heterogeneous backscatter variations to better understand surface and subsurface characteristics and their glaciological implications [2]. To achieve this, we employ a combination of SAR techniques, particularly polarimetric and interferometric methods integrated with tomographic techniques, to capture a detailed 3D representation of the scattering processes at the test site, providing a comprehensive view of the region's complex dynamics.

In our snow studies, we monitor Snow Water Equivalent (SWE) changes using repeat-pass SAR interferometry, which estimates SWE variations through the analysis of phase differences between acquisitions [3]. A multifrequency approach is employed to improve the accuracy of DInSAR SWE retrievals, reducing single-frequency uncertainties. Furthermore, interferometric and polarimetric variables are combined in a joined PolInSAR SWE retrieval.

In permafrost studies, we use airborne SAR data to analyze SAR signal penetration into frozen soils during winter. Permafrost environments pose challenges for SAR due to mixed signals from soil, vegetation, and snow [4]. We address this by combining polarimetric and interferometric SAR with PolInSAR to better separate and analyze these contributions.

Our integrated approach of different innovative SAR techniques improves the accuracy and reliability of observations in the cryosphere, offering critical insights into the physical processes driving changes in these environments. By leveraging the unique capabilities of SAR, our work advances cryosphere science and contributes to better monitoring, modeling, and prediction of climate change impacts on these vulnerable regions.

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[2] Schlenk, P., Fischer, G., Pardini, M., & Hajnsek, I. (2024). Multi-modal SAR reveals complex scattering structure in the ablation zone of the Greenland ice sheet. In Proceedings of the European Conference on Syn-

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[4] Saporta, P., Alonso-González, A., & Hajnsek, I. (2024). Analysis of Pol-InSAR coherence region parameters over a permafrost landscape. In Proceedings of the European Conference on Synthetic Aperture Radar (EUSAR), pp. 88-92. ISBN 978-3-8007-6286-6, ISSN 2197-4403.

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