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Multi-Frequency Satellite Approaches for Snow on Sea Ice

Polar+ Snow on Sea Ice (PSSI)



Deliverable 6.1:
Scientific Roadmap (SR)





FMI



UNIVERSITY OF LEEDS

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1 Executive summary

This document outlines the scientific roadmap for the Polar+ Snow on Sea Ice (PSSI) project. It synthesizes the improvements in satellite altimetry achieved through the development of novel multi-frequency snow products, assesses their impact on operational applications such as shipping and forecasting, and positions these efforts within the broader landscape of international snow on sea ice research.

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2 Review of Altimetry Improvements (WP 6.1)

2.1 Transitioning from Climatology to Satellite Observation

The primary scientific advancement of the PSSI project is the transition from static climatology to dynamic, satellite-derived observations.

Limitations of Warren 99 (W99): Historical retrievals relied on the W99 climatology, which is based on drifting station data from 1954–1991. W99 fails to capture inter-annual variability and is biased towards Multi-Year Ice (MYI), often misrepresenting the snow distribution on First-Year Ice (FYI) which now dominates the Arctic.

Novel Product Capabilities: The project developed "KuKa" (dual-frequency radar) and "Laku" (laser/radar fusion) products. These products successfully capture regional and seasonal variability that climatology misses, providing a more realistic representation of the snow load on dynamic ice covers.

2.2 Quantified Improvements in Sea Ice Thickness (SIT)

The Impact Assessment Report (IAR) and Validation Reports (VR) quantified the specific benefits of these new products:

Bias Reduction: Validation against Upward Looking Sonar (ULS) and airborne data (IceBridge/CryoVEx) confirms that PSSI products (specifically the Laku variants from LEGOS and UiT) significantly reduce the bias in sea ice thickness retrievals compared to W99.

Accuracy: The Laku methodology demonstrated superior performance, with higher correlations (R^2) and lower Root Mean Square Errors (RMSE) against validation datasets than single-frequency or climatological approaches.

Volume Estimation: The application of these snow products results in significantly different sea ice volume estimates. In regions like the Canadian Arctic Archipelago, satellite-derived snow depths revealed lower ice volumes than previously estimated by W99, correcting for the climatology's inability to account for recent thermodynamic changes.

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3 Operational Applications and Future Missions (WP 6.2)

3.1 Facilitating Operational Applications

Accurate snow data is critical for the implementation of the Polar Operational Limit Assessment Risk Index System (POLARIS). Thick snow increases friction, potentially exceeding ice friction in specific regimes. The project demonstrated that using monthly satellite snow products instead of climatology could change the calculated Risk Index Outcome (RIO) for vessels in the Kara Sea. This improvement could allow for safer and more efficient route planning for different classes of ice-strengthened vessels.

Forecasting and Numerical Modelling. Assimilation experiments (e.g., using NEMO-LIM3) demonstrated that initialization with PSSI snow products leads to significant changes in simulated freshwater release. Differences in sea ice volume initialization resulted in freshwater flux variations comparable to the total annual melt of Arctic glaciers (~1500 km³). Improved snow thickness data also better constrains the insulating effect of snow in forecast models, leading to more accurate predictions of ice growth rates and ocean-atmosphere heat exchange.

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3.2 Future Mission Requirements (State of the Art)

The results of the PSSI project provide a clear scientific justification for upcoming satellite missions:

CRISTAL (Copernicus Polar Ice and Snow Topography Altimeter): The PSSI "KuKa" experiments proved that retrieving snow depth via differential radar penetration (Ku-band vs. Ka-band) is viable. However, current results are limited by the imperfect collocation of separate satellites (CryoSat-2 and AltiKa). The roadmap strongly endorses CRISTAL, which will carry both frequencies on a single platform, eliminating temporal latency and spatial mismatch errors, and providing the definitive solution for snow depth retrieval.

CIMR Synergy: The roadmap highlights the necessity of fusing active altimetry with passive microwave data from the future Copernicus Imaging Microwave Radiometer (CIMR). This synergy allows for the resolution of snow depth across different scales, combining the high vertical accuracy of altimetry with the broad spatial coverage of radiometry.

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4 Synergies with Existing International Efforts

4.1 Alignment with other projects and community working groups

SIN'XS (Sea Ice-thickness product iNter-comparison eXerciSe): A flagship ESA Polar Science Cluster project (2022–2025) led by NOVELTIS with AWI, LEGOS, and UCL. Relevance: SIN'XS aims to reconcile the differences between various satellite sea ice thickness (SIT) products. PSSI contributes directly to this by providing improved snow depth inputs, which are often the largest source of uncertainty in SIT retrieval. The project will define a "reconciled" SIT estimate for the community (*SIN'XS Project Team, 2023*).

CRYO2ICE: A dedicated orbital resonance campaign (ESA/NASA) aligning CryoSat-2 and ICESat-2 tracks. This campaign provided the coincident "KuLa" data used in this project, proving the value of fusing radar and laser altimetry for snow depth retrieval.

Cryo-TEMPO: Cryo-TEMPO delivers state-of-the-art CryoSat products to a broad range of users, particularly those new to CryoSat data. Thematic products allow quick and easy access to CryoSat's unique, long-term satellite record of global ice and water spanning 15 years.

ESA Sea Ice Climate Change Initiative (CCI): While broader in scope, this ongoing European initiative enhances satellite-based climate data records for sea ice concentration and thickness in both the Arctic and Antarctic. Better sea ice datasets support understanding of snow effects indirectly by improving thickness and mass balance estimation, for which snow cover is an important factor.

IASK: IASK has set up a Working Group on Compilation and Standardization of Snow on Sea Ice Data (2025-2029) with a view to compile existing snow on sea ice data, develop standardized snow-data tools and advanced querying interface in a data portal.

CRiceS - how sea ice and snow affect our climate future. The EU project CRiceS that just ended had for objective to map the role of polar sea ice and snow in the global climate system.

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MOSAIC Expedition: The project utilized the unprecedented year-round in-situ data from the MOSAiC drift to validate the seasonal evolution of snow products, addressing the historical "spring bias" in validation data. This remains an invaluable source of data for years to come.

NASA SnowEx & IceBridge: PSSI aligns with NASA efforts to bridge the gap between airborne campaigns and satellite calibration, ensuring cross-agency product consistency. The data collected as part of these campaign remain essential for snow product validation.

ESA CryoVEx: Continued reliance on ESA’s dedicated validation campaigns remains a priority for checking the stability of multi-frequency retrievals.

IACS & WCRP CliC: The project contributes to the World Climate Research Programme's goals by providing "Climate Data Record" (CDR) quality snow products that are essential for long-term climate monitoring.

4.2 Integration with Modelling Efforts

Recent and ongoing modelling efforts already provide a strong foundation for integrating snow-on-sea-ice products into both research and operational systems.

Advanced Snow Stratigraphy and Microstructure Modelling: To resolve the complex vertical stratigraphy that introduces biases in satellite altimetry, the community is increasingly turning to sophisticated physical modelling frameworks. A primary example is SNOWPACK (Wever et al., 2020), an open-source (LGPL v3) physical model that simulates the temporal evolution of the snowpack based on meteorological forcings (derived from reanalyses, forecasts, or Automatic Weather Stations). By modeling the detailed microstructure, density layering, and thermodynamic interactions—specifically the mass and energy exchanges between the atmosphere, snow, and the underlying sea ice—SNOWPACK provides the necessary stratigraphic profiles to drive radiative transfer models (such as SMRT). This high-fidelity modelling is essential for moving beyond bulk density assumptions, allowing for a mechanistic understanding of how snow metamorphism drives radar penetration and scattering variations throughout the winter season.

Snow radiative transfer modelling: Sandells et al (2025) produce the ISSI Science Team Meeting Report on Development of a Reference-Quality Model for Snow and Sea Ice Surface Microwave Emissivity and Backscatter. Fourteen members of an International Space Science Institute team—from America, Asia, and Europe and with backgrounds in radiative transfer modeling, data assimilation, remote sensing, field campaigns, space agencies, and instrumentation—met to identify a strategy for development of a reference-quality model for snow and sea ice emission and backscatter

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Lagrangian Tracking: Lagrangian snow evolution models, such as SnowModel-LG, NESOSIM-Lagrangian variants, and trajectory-based applications of CICE, are increasingly used to simulate the full life cycle of snow on drifting sea ice. These models explicitly represent snow accumulation, redistribution, compaction, and melt along ice trajectories and therefore provide a physically consistent, time-evolving benchmark for satellite snow depth retrievals. Continued use and expansion of these approaches is strongly encouraged to evaluate satellite products under realistic dynamical conditions rather than point-based or climatological comparisons.

Assimilation: At the operational level, several coupled ocean–sea ice forecasting systems already include snow as an integral part of their thermodynamic schemes (e.g. NEMO-LIM, NEMO-SI³, CICE). Future efforts will focus on the routine assimilation of Level-4 merged snow products into these systems, particularly within Copernicus Marine Service (CMEMS) and related Arctic forecasting frameworks (e.g. TOPAZ, ECMWF IFS). Assimilating snow depth and snow mass is expected to improve sea ice thickness estimates, freeboard interpretation, and short-term forecast skill.

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5 Future Outlook: Towards Multi-Frequency and AI-Driven Snow Retrievals

The retrieval of snow thickness on sea ice is rapidly evolving from simple empirical assumptions to sophisticated multi-sensor inversions. Future initiatives will increasingly rely on the synergy between active and passive microwave sensors, physical modelling, and artificial intelligence to resolve the complex vertical structure of the snowpack.

5.1 Advancing Multi-Frequency Radar Approaches

The legacy of the "KuKa" (Ku- and Ka-band) approach, validated but also challenged by early and recent field and airborne work (*Willatt et al., 2011; Stroeve et al., 2020; de Rijke-Thomas et al., 2023*), is expanding into broader spectral domains.

Airborne & Future Satellite Systems: Beyond the established Ku/Ka pairing (CRISTAL), new concepts could explore the integration of C-band and L-band data. Missions like TerraSAR-X (X-band), NISAR (L/S-band), and ROSEL (L-band) offer the potential to characterize surface roughness and volume scattering at deeper penetration depths.

SWOT Synergy: The SWOT mission provides a unique opportunity to combine its wide-swath Ka-band interferometry (KaRIn) with along-track Ku/C-band altimetry. This setup allows for a 2D assessment of the scattering horizon, potentially separating snow surface scattering from the ice interface over broad spatial scales (*Kacimi & Kwok, 2025*).

CRYO2ICE Campaigns: Recent analyses of coincident CryoSat-2 and ICESat-2 orbits have demonstrated the capability to retrieve snow depth by differencing radar and laser scattering horizons. This "KuLa" approach is now being refined to account for dynamic snow densities and roughness biases (*Landy et al., 2025*). Additionally, a study explored the use of ICESat-2 photon scattering distributions to infer snow depth directly from spaceborne lidar, independent of radar data (*Hu et al., 2022*).

5.2 Roughness and Radiative Transfer Modelling

Understanding the physical interaction of radar waves with the snowpack is critical for reducing retrieval biases.

Roughness Proxies: Innovative approaches are using C-band SAR imagery as a direct proxy for ice surface roughness, reducing the reliance on static assumptions. Similarly, MISR multi-angle optical data has been successfully trained with lidar to characterize the roughness of the *top* of the snowpack (*Johnson et al., 2023*), providing a crucial boundary condition for retrieval algorithms.

Radiative Transfer: To resolve vertical biases in radar altimetry, detailed modelling of snow stratification is essential. Coupling snow evolution models (e.g., SnowModel <https://snowpack.slf.ch/>) with radiative transfer codes like SMRT (*Picard et al., 2018*) allows for the quantification of scattering losses and velocity delays caused by specific snow microstructures (*Nab et al., 2025*).

Waveform Simulation: Direct numerical simulations using physical retracers like LARM (Lognormal Altimeter Retracker Model) are enabling the inversion of snow properties (density, thickness) directly from the radar echo shape (*Landy et al., 2024; Zhou et al., 2025*).

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5.3 Innovative Inversion and other ideas

The future of snow retrieval lies in the simultaneous processing of multiple data streams.

Bayesian Inversion: New statistical frameworks are emerging to retrieve snow and ice thickness jointly. By combining multi-frequency altimetry inputs within a Bayesian inversion scheme, it is possible to retrieve probability distributions for snow depth rather than single deterministic values (*René-Bazin et al., 2025*).

Passive-Active Synergy: Combining high-resolution altimetry with the broad spectral coverage of passive microwave radiometry helps constrain snow water equivalent and internal snow properties. Work with Sentinel-3 has shown that this synergy can significantly improve retrieval accuracy, paving the way for the joint inversions planned for CRISTAL (*Nelson et al., private communication.*).

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