International Symposium on Radioglaciology

Tübingen, 6–11 September 2026

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Poster Presentations

John Paden - A Unified Radiometric Calibration Procedure for Radar Depth Sounder Data Products

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Airborne radar depth sounders have imaged ice sheets and subsurface features for more than three decades but the data products remain without absolute radiometric calibration. This limits quantitative analysis and retrieval of englacial attenuation, basal-reflectivity, and basal conditions. The lack of calibrated data prevents consistent inter-season and inter-system comparison. This paper presents a unified, data-dependent calibration procedure to close the gap using two complementary constraint classes (crossovers and natural targets) already captured in the raw data. Building on our earlier work on crossovers (that provide a link between two flight paths) and smooth natural targets (that include sea-ice leads, polynyas, and melt water lakes), we solved the combined weighted least squares system. We addressed the problems of graph disconnections in the crossover network, row scaling between constraint types, and verified that the processing pipeline introduces no radiometric bias. For the NASA Operation IceBridge (OIB) 2017 Greenland P3 campaign, we report the first set of per-day-segment calibration coefficients with inter-segment offsets spanning approximately 2 dB, and validate the Open Polar Radar processing chain using a newly developed 3D full-signal-chain simulator (FullSim). The procedure is open-source and extensible to the full 30-year radar depth sounder archive.

Donglai Yang - Formalizing statistical signature of bed echo power as a framework for imaging subglacial variability

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The deterministic derivation of radar variables, e.g. attenuation rate and reflectivity, is subject to highly local and variable subglacial/englacial environments, and it adds significant uncertainty to our interpretation of the glacier dynamics. To mitigate the issue, we propose a stochastic framework, where we consider the statistics of bed echo power in a small region. Specifically, we formalize an analytical theory that relates the variance of bed echo power and its correlation with ice thickness, meanwhile accounting for the ice thermodynamics and topographic scattering.

Our theory shows that ice sheet acts as a nonlinear filter in its vast interior which amplifies the subglacial heat flux variability, resulting in highly uncorrelated bed echo power distribution. This explains the limitation of existing adaptive method in extracting attenuation rate, which assumes an identifiable linear correlation between ice thickness and bed echo power. The theory also enables us to map across the Antarctic Ice Sheet where the said method works and where it breaks down.

We further pose the theory as a novel formulation of geophysical inversion problem. By optimizing against the observed bed echo variance and correlation, we demonstrate its utility in simultaneously constraining the geothermal heat flux and geomorphology (through scattering). In concert with existing radiometric methods, the framework will serve as a powerful toolkit and sandbox to help substantially reduce the hypothesis space as we interpret the subglacial and englacial environment.

Antoine Hermant - Towards isochronal calibration of Ice Sheet Models

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The Antarctic Ice Sheet (AIS) preserves a unique archive of past climate, recording transient changes in the Earth system. The thermal state and age structure of the AIS is shaped by both external forcing (surface temperature, accumulation, geothermal heat flux) and internal dynamics (ice deformation, basal processes). Traced and dated isochrones (extracted from Radio-echo sounding) provide a powerful but underutilized constraint for ice sheet models, as their geometry reflects the integrated effects of these processes over time. Here, we use the thermomechanically coupled Parallel Ice Sheet Model (PISM) to simulate the AIS over the last 1 Ma, leveraging the available isochrone data.

Using ice core chronologies and isochrones, we calibrate the ice sheet model around deep ice core sites, constraining ice rheology, basal conditions, and external forcing to match observed isochrone geometries. Combining statistical and optimization methods, we disentangle the drivers of modeled ice temperature and age-depth profiles, enabling reconstruction of past surface temperature, accumulation rates, and geothermal heat flux. This yields both an isochronally calibrated ice sheet model around deep ice core sites and new paleo-climate reconstructions. As part of this work, we developed the AntADatabase, a publicly available, open-source database of dated isochrones for Antarctic ice sheet modeling.

This framework demonstrates the value of isochrones for constraining ice sheet models and provides a pathway toward isochronally calibrated, continental-scale simulations to improve future ice sheet projections.

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Chen Lv - Efficient Time-Domain Image Reconstruction of Ice-Sounding Data in Subsurface Medium with Quasi-Polar Plane

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Radio echo sounding (RES), a powerful remote geophysical technique, provides excellent insight into the characterization of englacial and subglacial environments. Time-domain back-projection integration has the benefit of naturally handling arbitrary aperture geometries, nonuniform sampling and irregular imaging grids. However, its direct implementation is computationally prohibitive for large-scale RES data reconstruction. Although several time-domain RES imaging methods have been developed, a generalized nonredundant Nyquist sampling criterion and a flexible wide-beamwidth processing framework remain insufficiently established. Therefore, we here propose a rigorous quasi-polar imaging plane that accounts for refractive ray bending and subglacial medium velocity under general geometries. By formulating RES imaging in this physically grounded plane, nonredundant sampling requirements, with substantially fewer samples than the Cartesian ones, and alias-free reconstruction can be achieved for efficient and accurate subglacial imaging. This focusing approach opens a practical pathway toward high-precision subglacial imaging through the efficient reprocessing of existing RES archives and facilitating investigations of complex basal topography and heterogeneous subglacial properties.

Leah Sophie Muhle - Depth-resolved radar attenuation rates and englacial temperatures over the Antarctic Ice Sheet

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Projecting the response of the Antarctic Ice Sheet to a warming climate requires knowledge of englacial temperatures, which exert strong control on ice rheology and hence ice dynamics. Direct temperature measurements from deep boreholes only provide point estimates and are logistically expensive, making indirect measuring techniques essential to map englacial temperatures over large scales. Here, radar-based methods play a pivotal role as radar attenuation rates serve as a proxy for englacial temperatures. Existing approaches, however, only yield depth-averaged attenuation estimates, leaving the vertical temperature structure unresolved.

Here, we present a method to infer depth-resolved attenuation rates and englacial temperatures from airborne radar data. Building on our recently proposed Bayesian machine learning framework developed for ground-based impulse radar systems, we extend the approach to continuous wave, airborne radar systems. We validate the method using 180-210 MHz wideband radar data acquired over ice core sites with available borehole temperature profiles. We then apply the method to produce the first map of depth-resolved englacial temperatures from available 180-210 MHz radar data. This dataset offers new observational constraints on the physical and rheological conditions of the ice sheet, providing critical inputs for subglacial hydrology and ice flow models.

Tong Hao - AI-Driven Characterization of the Antarctic Subglacial Environment: From Ice-Bed Interface Picking to Basal Wetness Prediction

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Accurately determining subglacial conditions—such as basal topography and material conditions—is crucial for understanding ice-sheet dynamics, mass balance, and contributions to sea-level rise. Traditional methods, including radar reflectivity analysis based on empirical thresholds and manual ice-bed interface picking, face limitations in automation, robustness against noise, and generalization across diverse regions. Artificial intelligence (AI) offers a promising avenue to overcome these challenges. In this presentation, we explore AI-based approaches for characterizing the Antarctic subglacial environment through two representative studies:

1. AI-Enhanced Ice-Bed Interface Picking: We developed PickFormer, an end-to-end framework that integrates edge detection with a frequency-space Transformer network. By leveraging global-local attention and fusing frequency-domain information, it significantly improves the continuity, noise resistance, and cross-regional generalization of interface extraction in complex subglacial settings.

2. AI for Discriminating Basal Wet/Dry Conditions: We proposed SSIGAN, an unsupervised anomaly detection framework that combines radar waveform similarity with geometrically corrected echo power to generate a composite "wetness" score. This method effectively distinguishes wet and dry beds, overcoming the inconsistencies of threshold-based reflectivity methods and their dependence on manual labels.

Collectively, these studies leverage AI's strengths in feature learning and pattern recognition to enable more accurate, efficient, and robust characterization of key subglacial elements. This work provides new methodological support for advancing our understanding of ice-sheet dynamics and their impact on sea-level change.

Oliver Pranis - Enabling Time-Lapse 3D Imaging of Subsurface Ice-Sheet Processes Using Large-Scale RF over Fiber Arrays for Adaptive Software Defined Radar Sounding

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Observations of dynamic subglacial processes are critical for improving models of current and future ice sheet behavior and sea level contributions. However, most subsurface observations are limited to a single "snap shot" with many ice penetrating radar surveys focused on expanding coverage into more sparsely observed portions of Antarctica or Greenland. In parallel, there has been a growing role of "1D" time-series sounding profiles collected by stationary systems like the ApRES. Expanding on initial field deployments of smaller (e.g. 16 - 40) arrays, we present the initial and ongoing development of a large-scale fiber-based radar system. By exploiting the low-losses and non-dispersive performance of fiber links, the low cost of both fiber switches and fibre-to RF transducers, our approach enables experiments with two-dimensional arrays deployed over multiple square kilometers. This will enable the collection of time-lapse images of the ice sheet volume and bed. We discuss some of the key design features and challenges (including link-budget, range, and frequency resolution for particular targets and experimental designs). We also discuss novel imaging and adaptive sensing approaches enabled by long-deployment, large-array observations of slowly-varying targets. Finally, we highlight how novel observations from this type of system stand to improve our understanding of basal sliding, ice-shelf melt, and subglacial erosion processes.

Kenichi Matsuoka - Unresolved Antarctic bed topography drives ice discharge uncertainties equivalent to 65% of ice sheet mass balance

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Predicting the timing, magnitude, and distribution of freshwater discharge from the Antarctic Ice Sheet and contributions to global sea level depends critically on subglacial topography in the coastal zone. Kilometer-scale features are crucial for tipping mechanisms and introduce substantial uncertainties, however, one third of the coastal zone is more than 5 km from the nearest measurement, and interpolation can mask substantial uncertainty, limiting confidence in estimates of ice discharge and future sea-level rise. We quantified bed elevation uncertainty using geostatistical simulations based on open data and find that uncertainty exceeds 400 m across some sectors of the East Antarctic grounding line, propagating this uncertainty into grounding-line flux calculations reveals discharge uncertainties of up to 15 Gt/yr in individual basins. Integrated around the entire ice-sheet margin uncertainty is 76 Gt/yr, or 65% of current Antarctic mass balance, exposing bed elevation as a dominant source of uncertainty. We also assessed the fraction of Marine-Ice-Sheet Stability-prone regions, provided bed topography maps that can be used to estimate the future project uncertainties, and developed an empirical relationship linking radar survey spacing to achievable bed uncertainty provides a quantitative framework to guide future Antarctic bed mapping.

Duncan Byrne - A Scalable and Coherent 3D Radar Sounder Simulator for Complex Glaciological Subsurfaces

Duncan Byrne [1], Dustin Schroeder [2], Mark Haynes [3], Matthew Siegfried [4], Sean Peters [5]

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Reliable 3D radar sounder modeling is an invaluable asset for quality interpretation of radar data captured from highly heterogeneous subsurfaces. These difficult environments are seen across the cryosphere of numerous planetary bodies, including Earth, Mars and Europa. Therefore, there is growing need for a fast, coherent, 3D radar sounder simulator capable of identifying how intricate surfaces and non-layered reflectors can alter radar echoes in large-scale radargrams. Existing finite-difference based simulators are computational expensive when operating over large domains; conversely, vector simulators can handle large domains but are restricted to simple layered subsurfaces, which prevents its application to advanced geometries.

We present a rapid, coherent, 3D and vector-based radar sounder simulator designed to operate even at kilometer scale. Our simulator leverages efficient software architecture centered around simulation of individual coherent subsurface point targets, which we accumulate to emulate advanced geometries beyond simple layers, such as crevasses. Using modern GPUs, the simulator can model fine surface and subsurface features in seconds, enabling quick hypothesis testing at relevant radar sounding frequencies.

We demonstrate our simulator's performance over a few test cases including variable-dip layering, as well as highly attenuative pockets with non-specular reflectors. We then replicated a 212 km long orbital radar sounder observation over an ice-filled crater on Mars. By using previously identified subsurface radar horizons, we validated earlier hypotheses through our simulator, as our synthetic results closely match the collected surface and subsurface observations.

The rapid nature of our simulator is directly relevant to terrestrial radioglaciology by enabling quick evaluation and iteration on hypotheses about englacial structures, the ice-bed interface, or non-layered targets that are not yet modellable with existing tools. By using this novel approach of data interpretation, glaciologists can improve models of the glacial interior, helping constrain theories about subsurface processes. We see substantial potential for this approach to accelerate the analysis of complex terrestrial datasets as well as support the design and interpretation of future radar surveys.

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Jonathan Hawkins - Autonomous UHF phase-sensitive radio echo sounder for snow, firn and near-surface glacial processes

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Firn – the intermediate material between snow and ice – acts to modulate the behaviour of meltwater on ice shelves and ice sheets. Understanding how firn properties vary spatially and change over time is vital to predict future contributions of glaciers to sea level rise. Firn properties can be measured with direct observations such as firn cores, ground-penetrating or airborne radar, seismics and spaceborne remote sensing. Repeat measurements can reveal temporal changes, but these are often limited by spatial resolution or revisit frequency. Autonomous ground-based radar (ApRES) has been used to obtain high temporal resolution timeseries of glaciological processes such as basal melt, firn densification and glacier hydrology. However, its applicability for monitoring near-surface processes is limited due to its vertical resolution (40 cm) and antenna footprint.

We present a UHF autonomous phase-sensitive radar with a 1 to 3 GHz chirp bandwidth to enable observations of near-surface processes such as firn densification, ice layer formation and temporal changes in firn hydrology. The UHF ApRES is designed to measure vertical radar profiles with a 4 to 6 cm resolution (in glacial ice and snow respectively) at hourly intervals over annual timescales. We describe the radar system architecture based on a direct digital synthesiser and 8x translation loop multiplier to achieve the wideband 2 GHz chirp. To improve dynamic range at the receiver, we implement an optional active filter before digitisation with a gain of 20 dB/dec. The transmitted chirp has a nominal output power of 15 dBm. The radar transmits and receives a linear frequency-modulated chirp through a quasi-monostatic configuration of two custom designed Vivaldi printed-circuit antennas, separated by 620 mm within a ruggedised plastic case (1200 x 450 x 200 mm).

Results from laboratory characterisation and initial data from field deployments in the Alps, Greenland, Alaska and Antarctica are presented to demonstrate the performance of the instrument in a variety of deployment scenarios. Based on these initial results, recommendations for future deployments and design improvements are then discussed.

Di Zhu - Ice Penetrating Radar and Thermal Profiler: Spaceborne Design and Airborne Validation

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Ice Penetrating Radar and Thermal Profiler (ICE PATH) is an active and passive combined microwave remote sensing instrument used for glacier detection. By measuring the backscattering and brightness temperature, many important parameters of glaciers such as internal structure, temperature profile, density, and dielectric constant can be inverted. ICE PATH consists of a P-band & L-band ice penetrating radar and an ultra-wideband radiometer. P-band ice penetrating radar is designed for deep sounding with penetration depth up to 3-4 km for ice sheets. L-band ice penetrating radar is designed for shallower detection with different response to firn compared with P-band. P- to L-band ultra-wideband microwave radiometer is designed for ice sheets and glaciers internal temperature profiling.

For Spaceborne payload design, ICEPATH employs a foldable parabolic antenna with a ~20 meters diameter and multi-channel feeds for radar and radiometer. A pulsed high power amplifier with peak power over 1000W is developed for deep ice sheets penetrating.

For airborne ICEPATH validation, the active-passive RF channel, digital unit, two quad-ridged horn are mounted on helicopter and accomplishes its first flight experiment to make combined active and passive microwave detection of Laohugou No. 12 glacier in Qilian Mountain, Gansu, China in October 2024. Then, the radiometer is sent to Zhongshan Station in Antarctica for ice sheet experiments, and the ice penetrating radar was sent to the Guliya Glacier in Kunlun Mountain, Tibet in November 2024. The ice depth result of airborne ICEPATH around ice core in Guliya Glacier agree well with the ice core measurement (~309.8 m). The ice temperature retrieval result agree with the in-situ observation from the temperature chain (10-20m, excluding seasonal layer). The trends and ranges of deep ice sheet temperature variations are shown to be reasonable (compared with ice sheet modeled results near flightpaths).

Laurent Mingo - An Operational Airborne Ice-penetrating Radar (AirIPR) System

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Over the last 40 years, the most common approaches used to acquire ice-penetrating radar data were with fixed-wing aircraft, and ground-based surveys. Small planes can cover large areas efficiently, but lack maneuverability that confines them to relatively higher-elevation flights compared to a mountain range's local scale. Except for large ice-caps or ice-sheets, surveys are limited to single longitudinal profiles that often lead to significant valley wall reflections. This negatively impacts data quality, and challenges bed interpretation. By contrast, ground-based surveys, conducted on foot, skis, or snow machines, are well adapted to smaller scale glaciers but are slow (foot, skis), and all constrained by surface conditions and topography and can quickly become ineffective. Helicopter-based surveys, more prevalent in recent years, seem to offer another approach beside these two established radio-echo sounding methods.

To explore their potential, we developed an airborne, helicopter-based, ice-penetrating radar (AirIPR) that was first deployed in 2021 in the St. Elias Mountains, Yukon, Canada, which has since covered thousands of kilometers in operational over glacier types as diverse as those found in Yukon, Alaska, Greenland, and Norway. Like comparable airborne impulse radars used in radioglaciology, AirIPR has two major components. The radar itself, and a carrier slung beneath the helicopter, whose primary role is to support the antennas' physical layout at the necessary geometrical scale. The goal is to maximize the potential operating wavelength while minimizing the carrier physical size for logistical practicality. On the radar side, the system builds on our ground-based IceRadar platform, incorporating both hardware and software improvements alongside a newer, purpose-built hardware and software new radar platform. In all cases, an above-ground-level (AGL) sensor to measure terrain clearance beneath the carrier is incorporated. From our own surveys, system performance to date across various ice regimes result in a maximum attainable ice depth of approximately 600–700 m in temperate settings, and clearly detectable returns in the 1000 m range in cold ice, with potential for greater depths in the latter. Despite challenges — from survey speed and weather constraints to valley-wall reflections, which manifest differently than in fixed-wing surveys — AirIPR has proven valuable when applied to the appropriate terrain and conditions.

Ange Haddjeri - Ice Temperature Sensitivity Analysis for the CryoRad Earth Explorer 12 Candidate Mission

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The CryoRad mission, an Earth Explorer 12 candidate, aims to bridge critical observational gaps in our understanding of the Earth's ice sheets. By deploying a space-based low-frequency wideband microwave radiometer (0.4 to 2 GHz), the mission seeks to improve assessments of ice sheet mass balance and stability by retrieving ice sheet temperature. This presentation details a forward model sensitivity study utilizing the Snow Microwave Radiative Transfer (SMRT) model to evaluate the satellite's anticipated performance and refine mission requirements.

To better characterize the response of different ice sheets and constrain temperature inversions, we simulated the satellite's response to various geophysical parameters, primarily temperature and density profiles. Our simulations confirm that both temperature and density significantly impact the microwave signal's penetration depth, allowing the signal to reach the base of the ice sheet. We observed a distinct frequency-dependent contribution to the brightness temperature: higher frequencies (2 GHz) are highly sensitive to the upper temperature profile, while lower frequencies (0.4 GHz) provide a unique window into deeper layers, offering crucial insights into basal temperatures. Our simulations also show strong sensitivity to ice permittivity uncertainties, stressing the need of new measurements.

Furthermore, we investigated the impact of density layering. After collecting in-situ density profiles and analyzing their deterministic and stochastic components, we developed a generator to produce realistic density profiles across the ice sheets. We then simulated the impact of this layering on brightness temperature using both incoherent and coherent models. This comparative approach is vital, as previous research [1] indicates that coherent models are particularly sensitive to density layering at low frequencies. Ultimately, the results of this sensitivity study confirm the mission's capability to deliver critical scientific data on ice sheet properties, highlighting CryoRad's potential to significantly advance our understanding of polar processes in a warming climate.

Reference: M. Leduc-Leballeur et al., "Modeling L-Band Brightness Temperature at Dome C in Antarctica and Comparison With SMOS Observations," in IEEE Transactions on Geoscience and Remote Sensing, vol. 53, no. 7, pp. 4022-4032, July 2015, doi: 10.1109/TGRS.2015.2388790.

Nicholas Rathmann - Inferring ice-crystal orientation fabrics from oblique polarimetric radar

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Downward-looking radar systems are widely used to infer the structure and basal conditions of glaciers and ice sheets. Oblique propagation, in contrast, is rarely considered even though polarimetric traveltime tomography is sensitive to the full crystal orientation fabric which exerts important viscous control on ice masses. I will present a polarimetric common midpoint (CMP) framework for ice sheets that accounts for the dielectric anisotropy arising from preferred crystal orientations and preferred bubble shapes in firn, including refractive bending due to density variations. Travel times are modeled along oblique ray paths using a Maxwell--Garnett effective medium formulation coupled to a single stage Herron--Langway density model with a power-law bubble eccentricity profile, validated against Antarctic firn cores from Dome Fuji. An optimization problem is proposed for simultaneously inferring the crystal fabric profile and bubble close-off depth of any firn--ice column, which is shown to be robust to noise in observed travel times and requires only a few CMP offsets. The inverse problem is applied to Ekström ice shelf, Antarctica, revealing a girdle-type fabric that strengthens with depth despite restricted range in CMP offset. Finally, future improvements are discussed, including how to best design CMP surveys aiming to infer crystal fabrics.

Shuji Fujita - Extending the dielectric tensor method to the whole ice-sheet column: from firn structure to deep ice fabric within an integrated ice-core analysis framework

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Dielectric anisotropy in polar ice sheets originates from both crystallographic preferred orientation (COF) in deep ice and geometrical anisotropy of ice–air structures in firn. The dielectric tensor method (DTM) provides a unified framework to quantify these effects by measuring the bulk dielectric response of ice-core samples.

DTM has been successfully applied to the Dome Fuji ice core to characterize the development of COF and its relation to deformation and recrystallization in deep ice. Variations in dielectric anisotropy with depth reflect changes in fabric strength and ice-sheet flow regime. Importantly, the method is also applicable to firn, where stratification and metamorphism create anisotropic pore geometry and gas transport pathways near bubble close-off. Thus, DTM can detect both crystallographic and structural sources of anisotropy.

Measurements across the firn–ice transition and shallower ice demonstrate that DTM can continuously track the evolution of dielectric properties from porous firn to fully densified glacier ice. This makes the method uniquely suitable for studying the full vertical structure of ice sheets within a common physical framework.

From a radioglaciological perspective, dielectric anisotropy directly influences radar wave propagation, including birefringence, polarization-dependent reflectivity, and anisotropic scattering. DTM therefore provides valuable observational constraints for interpreting radar sounding data throughout the ice column.

A further advantage of DTM is its compatibility with established ice-core processing workflows. The prismatic samples used for DTM share preparation procedures with continuous flow analysis (CFA), enabling direct comparison with high-resolution records of chemical impurities, stable water isotopes, dust, and gas species. This common sampling strategy promotes efficient collaboration among multiple research groups.

We propose that DTM should be regarded not only as a fabric-analysis tool, but also as an integral component of multidisciplinary ice-core science linking electromagnetic, structural, and geochemical properties of ice sheets.

Carlos Martin - Beyond Coherence: New Matrix Based Inversions of Radar Polarimetry for Ice Fabric Reconstruction

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Radar polarimetry provides a powerful means to infer ice crystal orientation fabric in glacial ice. Ice fabric plays a central role in glaciology: it modifies ice mechanical properties and large scale flow, while also recording aspects of past climate through its links to impurity content, temperature, and deformation history. Radar based fabric inference therefore offers a scalable pathway to inform ice sheet modelling, ice core interpretation, and ice core site selection.

Current polarimetric approaches, notably coherence and co registration methods, infer fabric by linking it to variations in radar wave velocity between vertical planes of the ice. These techniques successfully estimate bulk fabric orientation, particularly at ice core sites, but are limited when fabric orientation varies rapidly with depth. In addition, they do not explicitly resolve anisotropic scattering, in which radar energy is scattered differently depending on propagation direction.

Here, we introduce two complementary methods to invert radar polarimetric data for ice fabric information, both based on the matrix based forward model of Fujita (2006). The first method, Striping, performs a layer by layer inversion of the scattering matrix from the surface to the bed. The second applies Ensemble Kalman Inversion (EKI), providing a probabilistic framework that is robust to observational noise and yields uncertainty bounds on inferred fabric parameters.

We apply these methods to polarimetric radar data from ice core sites (EPICA Dome C and the East Greenland Ice core Project) and from fast flowing ice at Rutford Ice Stream. At ice core sites, inferred bulk fabrics are broadly consistent with coherence and co registration estimates and available ice core measurements, while additionally revealing signatures of anisotropic scattering linked to rapid vertical changes in fabric. In fast flowing ice, Striping is sensitive to data noise, whereas EKI indicates greater fabric variability than inferred from conventional methods.

Together, these results show that matrix based and probabilistic inversions of radar polarimetry can extract richer ice fabric information from existing and future datasets and provide a flexible framework for ice core studies and anisotropic ice sheet modelling.

Duyi Li - Radar-Derived Ice Fabric Anisotropy and Anisotropic Scattering in Thwaites Glacier, West Antarctica

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Ice fabric birefringence and volume anisotropic scattering are two distinct mechanisms that influence radar signal propagation through ice sheets. Both are influenced by the crystal orientation fabric, which preserves the deformation history of ice sheets and influences present-day flow dynamics. Characterizing these mechanisms is essential for understanding ice sheet dynamics, particularly in fast-flowing ice streams such as Thwaites Glacier, West Antarctica, where complex stress and strain regimes can lead to strong and spatially variable fabric development. However, both ice fabric anisotropy and volume anisotropic scattering are poorly constrained in West Antarctica due to limited in-situ data and challenges in remote characterization.

Here, we analyze helicopter-borne, multi-polarized ice-penetrating radar data collected over Thwaites Glacier during the 2023–2024 and 2025–2026 Antarctic field seasons. From the multi-polarized measurements, we synthesize azimuthal co-polarized and cross-polarized radar responses, together with polarimetric coherence phase, to evaluate the directional dependence of radar power and phase through the ice column. Co-polarized azimuthal variations and coherence phase provide sensitivity to birefringence associated with bulk fabric anisotropy, whereas cross-polarized azimuthal responses provide complementary constraints on anisotropic volume scattering and englacial microstructure.

Preliminary results reveal spatially variable azimuthal radar responses across Thwaites Glacier, suggesting variations in both bulk ice fabric anisotropy and anisotropic scattering. By integrating power- and phase-based polarimetric observables, this study provides a framework for separating birefringence from scattering effects and offers new constraints on englacial structure, deformation history, and rheological anisotropy in one of Antarctica's most dynamically important glacier systems.

Clara Henry - The influence of fabric across ice-shelf flow regimes: Insights from phase sensitive radar and modelling

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Ice fabric both influences and is influenced by ice deformation. Patterns in the preferred crystal orientation of ice lead to a direction-dependent (anisotropic) viscosity, which facilitates deformation in certain directions by up to a factor of ~60. Although ice is inherently anisotropic, most continental-scale models continue to represent ice as an isotropic fluid, at best incorporating anisotropic effects only indirectly through enhancement factors.

Here, we present novel quad-polarimetric Autonomous phase-sensitive Radio-Echo Sounder (ApRES) observations along a central streamline and across a lateral shear margin of Ekström Ice Shelf, East Antarctica. In addition, we map the ice shelf grounding zone with high spatial coverage through autonomous rover-based data acquisition. These observations cover various flow regimes and are used to validate the fabric calculated by a 2D depth-integrated Shallow Shelf Approximation model and a 3D full Stokes model. The modelled anisotropic viscosity shows systematically harder lateral shear in the grounded areas than in the ice shelf. Similarly, the extensional viscosity is generally harder in the grounded area than the ice shelf. These spatial differences have consequences for grounding-line migration, ice-shelf buttressing and sea-level projections.

Tun Jan Young - Radar-Constrained Anisotropic Modelling of Ice Fabric and Flow Enhancement at the Thwaites Glacier Shear Margin

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Terrestrial ice naturally forms as hexagonal crystal sheets that deform more readily along the basal plane than perpendicular to it. Under applied stress, these crystals develop a preferred Crystal Orientation Fabric (COF), creating directionally dependent viscosity, known as viscous anisotropy. While anisotropic rheology is modeled extensively, it is under-constrained by in situ data. Recent radioglaciological advances permit the detection of anisotropic intensity. First, analysing two transects completely crossing the eastern shear margin of Thwaites Glacier, ApRES measurements are used to define a COF that forces a 3D flow model to determine the anisotropic impact on basal sliding parameters. Second, contemporary velocity and topography evolve the COF to a steady state, allowing a comparison between modeled anisotropy and radar-derived estimates. Forward-model results indicate that anisotropic rheologies outperform isotropic versions in replicating surface velocity and resolving the effects of basal topography. Together, these results show that radar-derived fabric signals in shear margins are systematically biased when fabric orientation departs from vertical, leading to an overestimation of flow enhancement if this geometry is ignored. Incorporating this geometric correction into anisotropic rheologies, particularly where shear plane fabrics dominate, will advance robust data–model integration and improve predictions of shear-margin strength and ice-stream dynamics.

Andrew Hoffman - Ice fabric determination from quad-polarimetric radar data collected in West Antarctica

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Glacier ice is a polycrystalline material with bulk properties that reflect the collective orientation of mechanically and dielectrically anisotropic ice crystals. The bulk alignment of crystal grains is known as the Crystal Orientation Fabric (COF). Because evolution of COF due to ice deformation also causes bulk dielectric permittivity anisotropy, polarization-dependent travel-time and phase differences in radar data provide a way to infer COF direction and strength. The radar-determined COF can then be used to estimate effective ice viscosity and infer the regional ice-flow history responsible for the observed COF development.

Here we present new quad-polarimetric radar measurements and polarimetric crossover analyses of legacy radar data with coincident multi-element 3D radar swaths across several different ice-flow settings in West Antarctica. Using an open source processing workflow implemented in the open polar radar toolbox, we co-register focused co-polarized radargrams, estimate the phase difference between orthogonal co-polarized returns, and use the unwrapped phase gradient to estimate bulk horizontal asymmetry of the fabric across West Antarctica. At Thwaites Glacier, Antarctica, polarimetric data suggest that strong horizontal fabric develops within the eastern shear margin, coincident with folded layers. Near the onset of the stagnating Kamb Ice Stream, fabric strengthens with depth, consistent with shutdown hypotheses for the Gould Coast Ice Streams. Together, these results show that polarimetric radar can resolve spatial variations in fabric that provide new constraints on ice rheology and flow history.

Rebecca Schlegel - Basal drag exerted on Thwaites Glacier flow, comparison of offshore and onshore data

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Thwaites Glacier is one of the most dynamically unstable glaciers in West Antarctica and a major contributor to present and future global sea-level rise, with the potential to trigger wider destabilisation of the West Antarctic Ice Sheet. However, its future evolution remains highly uncertain, largely due to limited knowledge of basal conditions that exert strong control on its retreat dynamics. One key uncertainty is bed roughness, which influences basal drag, ice flow, and grounding-line stability, yet remains poorly constrained due to the scarcity of direct subglacial observations.

Here, we present new observations of subglacial roughness derived from ground-based radar data collected as part of the GHOST project within the International Thwaites Glacier Collaboration (ITGC) during the 2022/23 and 2023/24 field seasons. Data were acquired over a 70x10km2 area approximately 70 km upstream of the grounding line. Our analysis reveals pronounced spatial variability in basal roughness along flow, which we link to variations in bedform dimensions and large scale topography, highlighting variations in bed composition and heterogeneous sediment availability.

We further compare these onshore radar-derived roughness estimates with offshore roughness inferred from multibeam bathymetric data. This comparison highlights contrasts between present-day subglacial conditions and geomorphic signatures of past ice flow. Integrating onshore and offshore datasets not only improves understanding of the evolution of ice dynamics at Thwaites Glacier but also provides a means to better calibrate offshore-derived roughness fields, which are widely used to inform large-scale ice-sheet models.

We propose that spatial patterns in basal roughness play a key role in organizing ice flow and may contribute to feedback mechanisms that influence glacier stability. In particular, the progressive erosion of softer, rough topographic highs could reduce basal resistance, facilitating grounding-line retreat and ice-shelf ungrounding. These findings underscore the importance of incorporating realistic representations of basal roughness into ice-sheet models to improve projections of future sea-level rise.

Peter Wray - Regional Ice Thickness Interpolation Approaches Using Measurements from a Novel V-dipole Helicopter-Borne Radar System

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The Yukon St. Elias Mountains contain one of the highest densities of surge-type glaciers in the world and have a paucity of ice thickness measurements and bed topography data. Models that predict bed topography from surface observations depend on the steady state assumptions of mass conservation, so do not work well for surge-type glaciers. Here we demonstrate that regional ice thickness measurements of thick valley glaciers can be collected and interpolated into high resolution bed topography models, using a 5 MHz, V-dipole, helicopter-borne, ice-penetrating radar system.

We have collected 1 km spaced transects over the 10 largest glaciers in Yukon, Canada, totalling ~ 2500 line-km of data. Bed reflections are detected or interpreted in over 90% of radar returns, with maximum ice thicknesses of ~900m. Detailed analyses of simulated radiation patterns and antiparallel transects confirm data is repeatable within the theoretical uncertainty limit of +/- 20 m, even through zones of low signal to noise ratio. Using these data we have produced bed topography models for select glaciers comparing different interpolation methodologies. Here, we discuss the preliminary results of the ice thickness interpolation intercomparison, and the key topographical results pertaining to surge-glacier dynamics. The regional-scale bed topography produced by this work will be one of the most extensive high-resolution data sets for surge-type glaciers globally.

Ole Zeising - Decadal evolution of a basal melt channel at the 79°N Glacier, Northeast Greenland, from ultra-wideband airborne radar sounding

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The 79°N Glacier is a major outlet of the Northeast Greenland Ice Stream and one of the few remaining glaciers with a floating ice tongue in Greenland. Over the past two decades, atmospheric warming has intensified surface meltwater production, driving adjustments in the subglacial hydrological system and altering basal melt patterns near the grounding line. Here, we investigate the long-term morphological evolution of a major basal melt channel using ultra-wideband (UWB) airborne radar data acquired during Operation IceBridge and Alfred Wegener Institute (AWI) campaigns between 2012 and 2024. Our results reveal a profound transformation of the ice base, with subglacial channels reaching heights of up to 500 m by 2024 and reducing the local ice thickness to as little as 100 m. We observed an upstream migration of the largest channel by approximately 4 km, located in the center of the glacier. Channel growth is characterized by pronounced short-term variability rather than steady-state expansion. Within 5 km downstream the grounding line, steep and spatially localized basal gradients exist, likely reflecting seasonally enhanced melt rates. We hypothesize that these channels are driven by increased seasonal subglacial discharge, pointing to a direct coupling between surface meltwater runoff and basal melting. Although the ice tongue near the grounding line is stabilized by lateral buttressing, the rapid development of large basal channels represents a structural weakening that could compromise the long-term stability of the floating ice tongue.

Knut Christianson - Radar imaging of basal ice for determining past ice flow and climate on Earth and Mars

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The deepest portions of the ice sheets remain one of the most mysterious environments on Earth. Direct sampling of the basal ice remains logistically challenging and costly, but it may be possible to generalize results from individual ice cores across ice sheets using spatially-distributed geophysical imaging (e.g., ice-penetrating radar). Until recently, radar imaging of basal ice was challenging due to few radar echoes near the ice-sheet bed. The lack of radar returns in this “echo-free” zone was hypothesized to be due to a lack of reflective horizons at these depths or technological limitations that prevented effective radar imaging of low amplitude reflections. Here, we present radar data from the flank of Dome A in East Antarctica that clearly images the basal ice. In these new data, the radiometric character and englacial geometric structure of the lower third of the ice column is clearly distinct from the meteoric englacial layering in the overlying ice. Using new radar imaging techniques, specifically profiling polarimetric radar and radar swath (3D) imaging of the englacial structure, we evaluate potential formation mechanisms for the “basal unit” observed on the flank of Dome A, including: (1) non-steady folding of deformed meteoric ice, (2) basal ice accretion and accompanying debris entrainment, and (3) decoupling of horizontal ice flow across an englacial interface due to a localized transition in the ice crystal-orientation fabric and ice grain size. We compare possible formation mechanisms for the Dome A basal unit to different formation mechanisms that have been proposed for basal units imaged by radar in Greenland. Our results have implications for understanding past and future ice flow, preservation of old ice, and interpretations of past climate from englacial stratigraphy and englacial structure. Finally, we discuss applications of our radar-analysis techniques for understanding past Martian environmental conditions through interpretation of the satellite-radar observed structures mapped deep in the ice in both the North and South Polar Layer Deposits on Mars.

Niels Peter Kirkegaard Christensen - Pan-Antarctic Mapping of Subglacial Meltwater Activity from Sentinel-1 SAR Interferometry

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Subglacial hydrology beneath the Antarctic ice sheet modulates ice flow, glacial run-off, and ice shelf stability, and is thought to be an important influence on ice mass balance and future sea level rise. Resolving this hydrological system could benefit flow models with improved estimates of subglacial water pressure and basal sliding. Yet located beneath kilometers of ice, the subglacial environment is not easily observed. Boreholes, radar sounding or seismic arrays provide the primary direct measurements, while satellite altimeters can detect localized vertical surface displacements - a tracer for changes in subglacial water pressure - but lack the spatial and temporal coverage to resolve the system at continental scale. In this study, we employ differential synthetic aperture radar interferometry (DInSAR) to achieve a pan-Antarctic mapping of subglacial meltwater activity. Transient displacements are isolated by forming double-differenced interferograms from ~160 terabytes of Sentinel-1 SAR data spanning 2014-2025. Processing this volume requires an automated TOPS-mode InSAR processing pipeline, including a supervised segmentation model trained on manually annotated Sentinel-1 interferograms. More than 4000 individual displacements have been identified from the first 17% (27 TB) of data. The high sensitivity and spatiotemporal resolution of the DInSAR time series allows us to observe both persistent subglacial lakes and rapid and long-term cascading drainage events, where subglacial water propagation is traced over tens or hundreds of kilometers, often terminating at glacier grounding lines. Individual displacements span hundreds of meters to tens of kilometers, while propagation pathways reach hundreds of kilometers. Fast-flowing outlet glaciers show most signs of dynamic subglacial meltwater transport, although sporadic activity is observed continent-wide, even hundreds of kilometers inland. These results suggest that subglacial hydrology below the Antarctic ice sheet is an active and dynamic system, raising questions about efficient versus inefficient drainage and potential local transitions between the two. Ongoing work includes robust magnitude estimation via phase unwrapping, with centimeter-scale sensitivity. The derived inventory of displacement events, including spatiotemporal extent and estimated magnitude, will be released as a dataset with a study region covering 6.4*10^6 km² (54%) of continental Antarctica.

Ursula Enzenhofer - Combining GPR and TEM to Study Subglacial Hydrology in Cold and Polythermal Glaciers, Svalbard.

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Subglacial hydrology in sediment-rich glaciers is strongly controlled by the thermal and hydrological state of subglacial till, but direct observations of frozen versus unfrozen conditions remain scarce. In this study, we present preliminary results from combined ground-penetrating radar (GPR) and transient electromagnetic (TEM) surveys on three Arctic glaciers, spanning marginal, ablation, and accumulation zones as well as cold based and polythermal thermal regime. We jointly analyse GPR backscatter energy and TEM-derived resistivity to investigate spatial patterns in subglacial till properties and to infer the presence of frozen and unfrozen conditions beneath the ice.

Our first results reveal regions interpreted as unfrozen till, including areas where frozen conditions might traditionally be expected. These observations suggest that subglacial sediments can maintain substantial liquid water contents over large areas, with implications for subsurface fluid migration, connectivity of subglacial drainage pathways, and glacier dynamics. The combined GPR, TEM approach demonstrates strong potential for constraining the thermal and hydrological state of subglacial environments and for improving process-based understanding of sediment-rich glacier systems.

Zachary Katz - Airborne Ice-Penetrating Radar Specularity Maps David Glacier Subglacial Water Routing

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Subglacial lakes—bodies of water beneath an ice mass—modulate basal hydrology and biogeochemical fluxes, playing an important role in glacier dynamics. Active subglacial lakes can be detected by satellite altimetry time series of changing glacier surface elevation, interpreted as filling and draining of the lake. However, active subglacial lakes are often hard to discern in ice-penetrating radar bed echoes, particularly compared to the clear fingerprint of stable subglacial lake radar returns. In preparation for clean hot-water drilling and access of active Subglacial Lake Cheongsuk on David Glacier, East Antarctica, airborne ice-penetrating radar surveys of the lake region were conducted in January 2017 and November 2018. We performed a bed specularity analysis using these surveys, showcasing the ability of the dense (1 km spacing) radar survey to detect active subglacial hydrologic system features. Along each radar transect, we computed the Doppler spectra in 750 m segments with 250 m overlap and used a thresholding algorithm to extract the Doppler spectra width, providing an estimate of the along-track scattering distribution of the ice-bed interface. The resulting Doppler widths are interpreted as a spectrum from a dry rough bed (wide Doppler spectrum) to a subglacial liquid layer (narrow Doppler spectrum). We compare Doppler widths to co-located satellite altimetry and seismic data, demonstrating the ability of our ice-penetrating radar specularity analysis to discern the active subglacial lake and surrounding hydrologic system. We compare between years of specularity data to assess time evolution of the subglacial hydrology. These results emphasize the ability for dense radar surveys to characterize subglacial features at subglacial lake scales, showcasing the fine-scale detail recorded and potential for future interpretation of subglacial hydrologic system extent and evolution from ice-penetrating radar data.

Steven Franke - Ice-Sheet-Wide Sediment Entrainment in the Antarctic Ice Sheet

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Ice-rafted debris in Antarctic shelf sediments has long signaled extensive sediment entrainment within the ice sheet, but the spatial distribution and mechanisms of entrainment on the grounded ice sheet remain poorly understood. Using Antarctic-wide airborne radar data, we map characteristic diffuse high-backscatter signals at the ice base, distinct from surrounding basal ice units, revealing that sediment-laden basal ice is far more widespread and volumetrically significant than previously recognized. These layers, concentrated along continental margins and alpine topographic settings, serve as observational markers of subglacial geology, basal thermal regimes, and ice flow dynamics. Our findings provide critical constraints for models of subglacial erosion, sediment transport, and Antarctic ice sheet behavior.

Erik Schytt Mannerfelt - Glacier thickness, thermal regime, and subjective uncertainty from ground-penetrating radar of 25 Svalbard glaciers

Erik Schytt Mannerfelt [1], Ursula Enzenhofer [2], Satu Innanen [3], Jogscha M. Abderhalden [4], Karlijn Ploeg [5], Johannes Brunner [6], Mette K. Gillespie [7], Gabrielle E. Kleber [8], Jonathan Kolar [9], Geir Moholdt [10], Solveig Solem [11], Andrew J. Hodson [12]

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Glacier thickness and thermal regime control glacier dynamics and long-term evolution, but observations are sparse at regional scales. Both can be measured using ground-penetrating radar (GPR), which requires manual or automated interpretation. Interpretation often depends on more than signal waveform analysis alone, and this subjectivity has not been quantified before. We present 725 km of ground-based GPR data from 25 glaciers in Svalbard, and crowd-source glacier bed and cold- temperate transition surface (CTS) interpretations from 41 contributors. We find that subjective uncertainty is usually smaller than instrument uncertainties for the glacier bed, though notable exceptions exist from off-nadir reflections or occlusion by temperate ice. CTS interpretations have higher spreads and show qualitative disagreement in the required amount of scatter to be considered as temperate ice. Our thermal regime consensus estimates reveal a wide diversity in temperate ice extent and distribution between glaciers, including insights into the thermal structure of glaciers with surge-related histories. Our thickness consensus agrees with previous measurements, and we show that thickness inversion model performance is slightly dependent on thermal regime. All data are available to enable novel applications and improve subjectivity-aware automation.

Xueyuan Tang - Discriminating Basal Dry and Wet Conditions Along the Zhongshan–Dome A Traverse, East Antarctica, Using Multisystem Radar Basal Reflectivity

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Basal dry or wet conditions exert first-order control on ice-sheet dynamics. Radio echo sounding (RES) is widely employed to infer basal conditions; however, quantitative interpretation of basal reflectivity remains challenging, largely owing to the scarcity of closely overlapping survey lines acquired by different radar systems. In this study, we perform a systematic cross-comparison of three near coincident radar profiles collected along the Zhongshan–Dome A traverse in East Antarctica. To circumvent the lack of standardized detection thresholds for ground-based radar systems and to enable consistent identification of wet basal conditions across heterogeneous platforms, we develop a data-driven threshold calibration framework that uses highfidelity airborne observations as a spatial prior to derive platform specific reflectivity thresholds for ground-based systems. Our results reveal systematic differences in data completeness and reflectivity response among radar platforms, which are governed not only by radar hardware and signal processing strategies but also by observation geometry. Joint analysis further indicates that synchronous absence of basal echoes across multiple systems most likely signifies intrinsically complex basal or englacial environments, whereas asynchronous loss of basal signals primarily reflects platform-dependent limitations rather than true dry or wet conditions. These findings highlight the limitations of single platform RES interpretation and demonstrate that integrated multisystem observations provide substantially stronger geophysical constraints on basal conditions. The proposed framework offers a physically consistent approach for integrating heterogeneous radar datasets and enhances the reliability of subglacial water detection in data sparse regions of Antarctica.

Cyril Grima - Distribution of the Basal Conditions at Lake Vostok, Antarctica, from Radar Reflectometry

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Lake Vostok, East Antarctica, is a well-defined, quasi-sealed subglacial cavity dominated by baroclinic flow. Water circulation models indicate that active exchange processes primarily follow the gradient of the pressure-dependent basal melting point—favoring glacier ice melting in the north and lake water refreezing due to supercooling in the south.

The global pattern of mass balance at the ice–water interface governs the distribution of ice and oxygen fluxes through the entire lake lid. Understanding this pattern also provides a valuable analog for studying extraterrestrial subglacial water bodies, where ice–water exchange processes could contribute to habitability. However, the ice–water mass balance at Lake Vostok has mostly been inferred from water circulation models, which themselves rely on gravity-inverted cavity bathymetry with coarse spatial resolution.

Here, we present direct measurements of ice–water conditions at Lake Vostok using 60 MHz radar reflectometry from the 2000–01 U.S. Support Office for Aerogeophysical Research (SOAR) campaign. Our method applies statistical analyses of basal return strength to derive reflectivity descriptors. We use a combined ratio of these descriptors that is insensitive to englacial attenuation and primarily sensitive to roughness and volume scattering at the interface. Results indicate heterogeneous basal roughness, suggesting a revised distribution of melting and freezing zones. These findings could redefine the understanding of ice–water exchange at the lake lid and offer a new means of constraining water circulation models using independently measured basal conditions.

Jogscha Miriam Abderhalden - Geometry and Thermal Regimes of Storbreen, Norway: Relations to Transient Glacier Features

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Observations of glacier geometry and thermal regimes of mountain glaciers are known to be essential to gain a better understanding of their dynamics. In a changing climate, such observations are also a valuable basis to study glacier retreat patterns and future scenarios. In mainland Norway, most glaciers are assumed to be temperate or at least warm-based, but measurements are sparse. Storbreen is a glacier in central southern Norway and has one of the the longest ongoing mass-balance series in the world, starting from 1949. Located close to the main water divide, it is an ideal starting point for assessing climate change impacts on glacier structure and dynamics along a maritime-continental climate gradient. In this study, we use ground penetrating radar (GPR) to map glacier geometry and thermal regimes. Moreover, we use stake data, repeat LiDAR data, orthophotos and satellite imagery to map changes in glacier velocity, crevasse patterns and transient snowline over the last two decades. A thermistor string deployed in the ablation area of the glacier is used to validate GPR travel velocities and to assess the depth of seasonal signal on the ice temperatures. We present a first full GPR-based glacier geometry and bed topography map of the glacier including the distribution of cold ice. Our preliminary findings show a maximum measured ice thickness of ~240 m. The glacier has a polythermal structure with a persistent 5-100 m thick cold surface layer across most of the glacier's ablation zone with entirely cold-based areas towards the margins, while the accumulation zone (1.37 of 4.9 km2 in 2024) is mostly temperate, indicating active firn processes. This study of Storbreen will serve as a baseline for further planned investigations on glacier thermal regimes of Norwegian glaciers along an east-west precipitation gradient.

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Nicholas Holschuh - Property inference from diffuse scattering in basal ice using 3D radar volumes

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Beamforming techniques used for radar swath imaging generate three-dimensional (3D) radar volumes which describe variations in backscattering intensity as a function of instrument position, two-way travel time, and cross-track direction-of-arrival (Holschuh, Eisen, et al., 2026). These data volumes can be used to better understand the nature and sources of englacial scattering. Most energy returning from within the ice column is the product of specular reflection from meteoric layering, identifiable in 3D radar volumes by the restricted range of angles with measurable backscattering in each range shell. But, in deep ice in Northern Greenland, meteoric layering appears to abruptly transition to diffuse scattering, with backscattering targets visible across a wide range of look angles (Holschuh, Christianson, et al., 2026). In this work, we use several distinct beamforming techniques to quantitatively describe backscattering from these diffuse targets as a function of angle, documenting the spatial distribution and scattering characteristics of basal ice across Greenland. We also explore the use of a Dense Media Radiative Transfer Theory (DMRT) model (Picard et al., 2018) for scatterer property determination, with the explicit goal of distinguishing diffuse scattering from fabric transitions and diffuse scattering from debris laden ice. Together, data and scattering models can help us better understand the properties of basal ice, with implications for its development and role in modifying modern flow dynamics.

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Picard, G., Sandells, M., & Löwe, H. (2018). SMRT: an active–passive microwave radiative transfer model for snow with multiple microstructure and scattering formulations (v1.0). Geoscientific Model Development, 11(7), 2763–2788. https://doi.org/10.5194/gmd-11-2763-2018

Sinan He - The impact of along-track temperature profile variations on absolute and relative bed reflectivity signatures.

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Radar sounding bed echoes are widely used to infer the physical properties of ice sheets. However, bed echoes contain contributions from both bed reflectivity and englacial attenuation. From these echoes, researchers estimate bed conditions through bed reflectivity and infer depth-averaged temperature from the englacial attenuation rate. A typical interpretation of bed reflectivity relies on relative bed reflectivity, which is obtained by subtracting a background reflectivity signal. Each step in this process can introduce ambiguity, raising the possibility that some englacial attenuation effects to be misattributed to bed reflectivity variations or vice versa. One potential source of this ambiguity complex along-profile temperature profile variation. Here, we explore the effects of boundary-condition transitions, basal topography, and ice flow on along-profile temperature profiles, attenuation, and the interpretation of absolute and relative reflectivity signatures.

Kiera Tran - Radar-Derived Basal Melt Rates of the Ross Ice Shelf Reveal Underlying Basal Processes

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Ross Ice Shelf (RIS) plays a critical role in buttressing the Antarctic Ice Sheet, yet its basal mass balance remains poorly constrained. In this study, we use airborne radio echo sounding data from the ROSETTA-Ice survey (2015 - 2017) to estimate basal melting and refreezing. We develop a method that links radar-derived englacial attenuation to basal melt rates through ice thermal structure, based on a physics framework from Holland and Jenkins (1999) and a one-dimensional heat transfer model that includes horizontal advection. Our results show clear spatial contrasts between regions of high and low basal melting. Elevated melt rates occur near grounding lines in the western Ross Ice Shelf and along major flow paths on Siple Coast, as well as near the ice front, where warm water intrusions and subglacial discharge enhance melting. In contrast, lower melt rates dominate the eastern Ross Ice Shelf and interior regions, where colder cavity conditions limit ocean heat access. While overall patterns are consistent with previous studies, local differences show higher melting from lower attenuation signals. The patterns observed here highlight strong links between basal melt rates and basal processes created by subglacial hydrology, cavity circulation, and small-scale roughness. These results show that radar attenuation can resolve spatial variability in basal processes and improve estimates of freshwater fluxes, with implications for Southern Ocean stratification and ice shelf stability under future climate change.

Robert G. Bingham - Do radar surveys spaced by 14 years show dynamism at the bed of Thwaites Glacier?

Robert G. Bingham [1], Nicholas Holschuh [2], Felipe Napoleoni [3], Rebecca Schlegel [4], Helen Ockenden [5], Julien A. Bodart [6], Andrew O. Hoffman [7], Knut Christianson [8], John Paden [9], Reinhard Drews [10], Richard B. Alley [11], Andrew M. Smith [12], Alex M. Brisbourne [13], Sridhar Anandakrishnan [14], ITGC-GHOST Team [15]

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Potential dynamism of ice-stream beds is an important component of subglacial traction, till continuity and landform development, yet in very few instances have changes to the beds of contemporary ice streams been measured in situ. In Antarctica, previous geophysical surveys targeting the same locations spaced by several years have yielded contrasting results: at Rutford Ice Stream significant changes to the bed echo have been observed, in one case interpreted as the formation of a drumlin; but at Pine Island Glacier no detectable morphological change was picked up by radar surveys over the same sites surveyed each side of a 6-year interval.

Here, we present the results from a 14-year "repeat radar survey" of a ~50 km2 region of Thwaites Glacier ~120 km upstream of the grounding line. The region incorporates the western extent of "THW124", a region of ice-surface-elevation oscillation interpreted to represent a dynamic subglacial lake periodically draining and filling; and adjacent regions of streamlined topography overlying an interpreted geological transition between relatively hard and soft substrates. The radar data from 2009/10 were acquired by Twin Otter aircraft using the 6-element array of the US Center for Remote Sensing and Integrated Systems (CReSIS) Multichannel Coherent Radar Depth Sounder (MCoRDS/I) radar system; and the data from 2023/24 with the British Antarctic Survey (BAS) ground-based DEep-LOoking Radio-Echo Sounder (DELORES) as part of the International Thwaites Glacier Collaboration.

The greatest detectable changes across the region occur across the THW124 "subglacial lake" feature, where there is a ubiquitous change across the bed over the 14-year interval. Away from this region, changes to the bed morphology are not confidently discernible.

Riley Culberg - Radar Evidence for Englacial Over-Winter Water Storage in Greenland's Ablation Zone

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In the western Greenland ablation zone, most meltwater is understood to drain to the bed of the ice sheet through moulins or hydrofractures, leading to surface mass loss and seasonal ice velocity increases. However, there is a growing body of work on slow and partial depth hydrofracture, which could store meltwater englacially for longer periods of time. If widespread, this process would reduce total surface mass loss from the ablation zone, delay or reduce meltwater delivery to the subglacial system, and warm the ice through latent heat release, thus modulating all aspects of glacier mass balance.

Here, we investigate a spatially extensive, non-conformal englacial radar reflector observed in Operation IceBridge ice-penetrating radar data collected in the springs of 2011-2017 in the Paakitsoq region of the western Greenland ablation zone. Radar coherence and phase statistics suggest that this horizon is produced by volume scattering rather than quasi-specular reflection. We develop and apply a multi-frequency Mie scattering model that accounts for radar parameters and sounding geometry to test the hypothesis that this horizon represents entrained liquid water pockets within the ice. Our joint inversion of radar reflectivity and attenuation in data collected at 195 MHz and 750 MHz demonstrates that this signature is consistent with scattering from liquid water pockets 1.5-2 m in diameter within a water-bearing layer 40-80 m thick. We also investigate temporal variations in bulk radar attenuation through this horizon on a flight line with seven years of repeat flights. We show that interannual variations in bulk attenuation, a proxy for total liquid water storage, are well correlated with interannual variations in total surface melt in the summer preceding each spring radar observation. Together, we interpret our results as showing that surface melt which drains into surface crevasses during the summer is routinely retained over-winter in englacial water pockets that form as the dry portion of the crevasse closes by creep after the melt season. This suggests that englacial water storage may play a more important role in ice temperature and surface mass balance in the ablation zone than previously assumed.

Parrenin Frédéric - age_flow_line-1.0: a fast and accurate numerical age model for a pseudo-steady flow tube of an ice sheet

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Numerical age models are useful tools for investigating the age of the ice in an ice sheet. They can be used to date ice cores or to interpret isochronal horizons which are observed by radar instruments. Here, we present a new numerical age model for a flow line of an ice sheet. The assumption here is that the geometry of the flow line and the velocity shape functions are steady (i.e. constant in time). A time-varying factor can only be applied to the surface accumulation rates and basal melting rates. Our model uses an innovative logarithmic flux coordinate system (π , θ), previously published, which is suitable for solving transport equations because it tracks ice trajectories. Using this coordinate system, solving the age equation is simple, fast and accurate, because the trajectories of ice particles pass exactly through the nodes of the grid. Our numerical scheme, called Eulerian-Lagrangian, therefore combines the advantages of Eulerian and Lagrangian schemes. We present an application of this model to the flow line going from Dome C to the Beyond EPICA Little Dome C drill site and show that horizontal flow is a non-negligible factor which should be considered when modelling the age-depth relationship of the Beyond EPICA ice core. The code we developed for age modelling along a flow tube is named age_flow_line-1.0 and is freely available under an open-source license.

Joseph MacGregor - Revisiting the onset of the Northeast Greenland Ice Stream

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Since its discovery more than three decades ago, the 700-km-long Northeast Greenland Ice Stream (NEGIS) has been studied extensively to understand the nature of its anomalous fast flow, which extends deep into the interior of the Greenland Ice Sheet. These studies have clarified the sensitivity of the NEGIS to downstream forcings, its englacial and subglacial rheology, and its Holocene evolution. However, what – if anything – initiates the onset of faster flow at NEGIS remains controversial. Here we revisit the NEGIS onset region using the wealth of satellite and aerogeophysical data that have been collected since its discovery, focusing on its ice dynamics, englacial radiostratigraphy, subglacial topography and geology. Using multiple radiostratigraphically-constrained ice-flow models, we confirm that apparent basal melting is widespread in the NEGIS onset region, which lies along the western flank of the eastern subglacial highlands. While the origin of this apparent basal melting remains unclear, geophysical data synthesis indicates anomalous subglacial geology there. Further, recent compilations of field observations and discoveries in eastern and northeastern Greenland demonstrate that the extreme subglacial heat flow needed to generate significant basal melting beneath the NEGIS onset region may not be unique to that region.

Shuji Fujita - An overview of the layered structure of the polar ice sheet based on crystalline textural properties of the Dome Fuji summit ice core, Antarctica

Shuji Fujita [1], Tomotaka Saruya [1], Atsushi Miyamoto [1], Kumiko Goto-Azuma [1], Motohiro Hirabayashi [1], Akita Hori [2], Yoshinori Iizuka [3], Takao Kameda [2], Hiroshi Ohno [2], Wataru Shigeyama [1], Shun Tsutaki [1]

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This study provides an overview of the layered structure of Antarctic ice sheets, focusing on the crystalline textural properties and deformational regimes in the Dome Fuji ice core. Polar ice sheets consist of layers with diverse rheological characteristics, shaped by depositional processes such as atmospheric aerosol deposition. Layer thickness varies from millimeters (annual layers) to thicknesses spanning glacial-interglacial periods, with the initial ice fabric forming during firnification.

Key factors influencing the rheology of ice include ion content (e.g., Cl^-, F^-, NH_4^+) and insoluble particles such as salts and dust. Ions can substitute within the ice crystal lattice, affecting dislocation density, viscosity, and deformation behavior. These influences persist from firnification to the basal layers of the ice sheet. Notably, salt inclusions have larger volume fractions than dust particles, significantly impacting microstructure evolution.

The ice sheet's deformation can be divided into two regimes: the upper 80% of the ice sheet, characterized by lower strain and temperature gradients, and the lower 20%, where higher temperatures and strain induce complex recrystallization processes. Four primary factors drive the evolution of crystal orientation fabrics and microstructures: (i) temperature conditions, (ii) strain configurations, (iii) insoluble particle effects, and (iv) dynamic recrystallization, including grain boundary migration and the formation of new grains. These processes result in a deformational history unique to each layer, spanning up to one million years.

Understanding these layered structures has significant implications. For ice sheet modeling, they provide constraints on strain values and inform models of vertical thinning. For ice core sciences, the layered structure highlights the importance of drilling sites. Dome summit sites preserve continuous, undisturbed records of ancient ice, while locations away from domes risk basal disturbances, including folding, faulting, and layer mixing.

This research enhances our understanding of ice sheet dynamics and supports the development of improved dating models, contributing to studies of Earth's climate history over millennia.

Annie Cheng - Effect of anisotropic melt and air inclusions on the radar permittivity of bulk ice

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Interpretation of ice-penetrating radar data is intrinsically reliant on the assumed electrical permittivity of the ice itself. The permittivity of ice is known to vary with temperature, salinity, and crystal orientation fabric; however, bulk ice existing in terrestrial sea ice and ice sheets, or planetary ice shells, may additionally possess water or air inclusions that can further influence ice-penetrating radar measurements. Here, we explore the effects of anisotropically distributed water and air inclusions on bulk ice permittivity through the application of effective medium models. We find that melt anisotropy at the bed may be capable of producing radar reflectivity comparable to that of an ice-water interface, such as subglacial lakes. We additionally find that melt anisotropy within an ice column may produce significant attenuation depending on orientation relative to radar polarization. Furthermore, we find that both anisotropic melt and air inclusions -- existing in temperate ice or firn, respectively – are capable of producing birefringence signals at beat wavelengths of similar magnitude to that of crystal orientation fabric. This offers a potential new avenue of interpretation for existing polarimetric and beat-frequency observations, as well as a way to quantify firn porosity or melt fraction in temperate ice. We will further discuss methods of reducing uncertainty in inclusion anisotropy and distribution through the combination of effective medium models with polarimetric radar surveys, modelling, and laboratory experiments.

Julien Bodart - Proxy-constrained modelling of the Amundsen Sea sector using radar isochrones places Holocene retreat rates in the context of present and future ice-sheet evolution

Julien Bodart [1], Johannes Sutter [2], Duncan Young [3], Donald Blankenship [4], Vjeran Višnjević [5], Antoine Hermant [6], Emma Spezia [7]

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Whilst our understanding of the past ice-sheet extent of the Amundsen Sea Embayment (ASE) at the Last Glacial Maximum (LGM) is relatively well known, the subsequent retreat of Pine Island and Thwaites glaciers during the de-glaciation and through the Holocene is less well constrained. Of equal importance is the uncertainty of future retreat rates of these glaciers, and whether their histories can help inform our understanding of their current and future projected retreat. Here, we employ the three-dimensional PISM ice-sheet model to reconstruct the evolution of this sector since the LGM and throughout the next centuries. We first explore a large parameter space using Latin Hypercube sampling, and further constrain our best sets of paleo simulations using available proxy data. Central to our novel calibrating approach is our use of spatially extensive (2D) isochrones imaged by radars and dated at several snapshots throughout the Holocene, including a newly available dataset of four deep isochrones over THW (4.7 - 24.9 ka). Together with this new record, we also employ more traditional 1D proxies such as ice-surface elevation change from boulders recovered on nunataks; surface-elevation change from ice cores; and sediment cores offshore recording both past fresh-water discharge and ice-sheet extent, to provide a new high-resolution and well-constrained paleo evolution of this sensitive sector of the ASE. We first show that isochrones are essential for assessing the transient evolution of paleo simulations, particularly in off-divide areas of the ice sheet, and that calibrating ice-sheet models solely on 1D proxies does not guarantee a well-constrained model. We then calculate paleo retreat rates along key flowlines over Pine Island and Thwaites glaciers, which average ~15 m a-1 (min: 0, max: 170 m a-1). Restarting from the end of our best paleo-constrained ensemble member, which is well calibrated against proxies offshore and inland throughout the last 20ka, but also produces a strong match to present day observables, we then model the future evolution of the ASE using both conservative (RCP 2.8) and worst-case (SSP-5.8.5) climate scenarios to the year 3000. We find that the upper ends of our calculated retreat rates in SSP-8.5 are approximately two orders of magnitude greater than our calculated paleo retreat rates, and point to the rapid and unprecedented changes these large ice-streams could experience in the absence of measures to limit GHG emissions.

Robert G. Bingham - A combined update on AntArchitecture and Bedmap

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AntArchitecture and Bedmap are international programmes in radioglaciology, coordinated through the Scientific Committee for Antarctic Research, that respectively concern the internal structure and basal boundary of the Antarctic Ice Sheet. This presentation will reflect on recent achievements of, complementarities between, and visions of both programmes looking ahead to the International Polar Year 2032-33 and beyond.

Bedmap has existed for three decades as a collaborative community project, with an ongoing mission to bring together datasets of Antarctic ice thickness and bed topography for the international community. Milestone outputs have comprised successive maps and datasets of gridded Antarctic subglacial topography released in 2001 (BEDMAP), 2013 (Bedmap2) and 2025 (Bedmap3), with each release fundamentally improving upon data volume and interpolation techniques between decreasing (but still in some regions significant) data gaps between geophysical (primarily radar) surveys. As a project Bedmap has also evolved and expanded its remit to acting as a repository and portal for managing and standardising radar datasets. We envisage that in its next phase Bedmap will continue to ingest and manage further Antarctic ice thickness surveys, but also manage a more dynamic system of interpolating the data using recent advances in surface-to-bed inversion and artificial intelligence, and a more dynamic system of releasing more frequent and versioned interpolated products.

AntArchitecture has existed for the last decade and focusses on internal ice structure imaged by many of the same datasets that are curated in Bedmap. Its most significant activity over the last decade has comprised tracing internal-reflecting horizons across different parts of the Antarctic Ice Sheet, demonstrating the existence of pervasive horizons linked to volcanic or dust deposition events which act as chronostratigraphic markers of ice age-depth across the ice sheet. Many of these have now been compiled into a single database that forms a proto pan-Antarctic age-depth model. These datasets are now forming calibration data for ice-sheet modelling of past behaviour. We envisage that in its next phase AntArchitecture will continue to expand Antarctica's radiostratigraphy, and other ice-internal properties, increasingly using artificial intelligence tools, across further regions, and develop further radiostratigraphy as an integral calibration tool for ice-sheet modelling.

Dustin Schroeder - Waveform Choice in Ice Penetrating Radar

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There is a growing collection of ice penetrating radar systems being used in a variety of glaciological settings to collect a body of data that is expanding in its scale, diversity, and information-richness.While there are nuanced differences among particular instruments, there are three main classes of radars systems used to observe the subsurface of ice sheets and glaciers: chirped airborne sounders, impulsive snowmobile-borne systems, and stationary continuous-wave systems.While these classes are often treated as fundamentally different instruments with distinct communities and literature, in this paper, we seek to re-frame them as choices on a continuum of potential waveforms. In particular, we focus on the tradeoff between achieving large coherent processing gains and mitigating side-lobes from strong echoes at shorter delays as key limiting factors for subsurface target detection.

We discuss the glaciological settings in which different waveform choices perform best as well as potential avenues this raises for new instrument and experiment designs.

Duncan Young - An englacial climate signature in Antarctic ice penetrating radar data

Duncan Young [1], Kieran Herman [2], Heidi Jackson [3], Shivangini Singh [4], Shuai Yan [5]

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It has long been known that the change in glacial-interglacial dust content in Greenland ice changes the radar expression of englacial radar horizons in the Greenland ice Sheet. Due to the much lower glacial dust loading in the Antarctic ice Sheet, this climatic effect is not seen in Antarctic ice penetrating radar data.

However, here we show a correlation between englacial broadly scattered radar energy (detectable through delay doppler techniques) in MARFA 60 MHz airborne ice penetrating radar data and estimated snow accumulation at Dome C, East Antarctica with a strong detection of the enhanced accumulation of the Last Interglacial period, as well as earlier interglacials. This signal (independent of the strong coherent radar horizons optimized by processing and usually mapped) may allow for dating of the englacial structure of Antarctica where ice core constraints are limited.

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Marguerite Shaya - Understanding ice flow from messy data: Towards reliable ApRES measurements of near-zero vertical velocities in blue ice areas

Marguerite Shaya [1], T.J. Fudge [2], Michelle Koutnik [3], Carlos Martín [4], John-Morgan Manos [5], Howard Conway [6], Annika Horlings [7], Benjamin Hills [8]

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In Antarctic blue ice areas (BIAs), wind scour and sublimation drive net ablation that, together with slow ice flow up steep bedrock topography, preserves the oldest ice on Earth recovered to date. Observations of englacial velocities are key to understanding the past and present dynamics of BIAs and to predicting their age structure. We present the first interferometric Autonomous phase-sensitive Radio Echo Sounder (ApRES) survey of englacial vertical strain rates from the Allan Hills BIA, where NSF COLDEX supported four years of ground-based geophysical measurements. Spaced along a present-day flowline, the 16 ApRES sites span the transition from a snow-covered surface to exposed blue ice. Ice thicknesses range from 1200-300 m, thin enough that attenuation is minimal and the near-bed signals remain coherent. These data provide a new perspective on ApRES survey design and analysis in BIAs, to meet the challenges of measuring very slow (order 1 cm/yr) vertical velocities that change direction depending on the accumulation or ablation forcing and the steep bedrock slopes. Because of the slow deformation, subtle inconsistencies in the radar setup between field seasons create significant "apparent velocity" signals. We show that small changes to the antenna spacing distance dominate the near-surface (<200 m depth) results, while small variations in the antenna rotation relative to the ice fabric can introduce oscillations superimposed on the mean signal at all depths. In addition, the interferometric profiles capture both 1-D vertical velocities from surface mass balance and other ice dynamic processes and 2-D vertical deformation from horizontal flow over a sloping bed. To understand the signal, we optimize a kinematic model based on ice incompressibility that partitions between these flow components. Using measured bedrock topography and surface horizontal velocities, the model can fit much of the ApRES relative vertical velocity profiles, including some strain rate reversals with depth, corroborating those observations. Some structure in the englacial velocities – especially of the deepest ice – cannot be explained, either due to measurement artifacts or to complicated basal flow that exceeds the model capabilities. The model-data comparisons provide a framework for interpreting ApRES profiles within the context of other geophysical constraints and for investigating ice flow in regions of low surface mass balance and steep topography.

Jonathan Kolar - Directly validating 3D GPR images of englacial conduits using in-situ LiDAR mapping

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Englacial conduits play a key role in routing meltwater toward the glacier bed and thereby influence basal hydrology and glacier dynamics. Ground penetrating radar (GPR) is widely used to detect such features, yet interpretation is a challenge due to the limited opportunities for validation via direct in situ observations. Here we present a unique high resolution three-dimensional (3D) dataset acquired on Glacier de la Plaine Morte (Swiss Alps), combining 3D radar measurements with detailed in situ mapping of an englacial cave system.

The dataset was acquired using an uncrewed aerial vehicle (UAV)-mounted GPR system, enabling spatially dense coverage over a section of the glacier that includes multiple moulins connected to the englacial conduit network. In parallel, this cave system was accessed using speleological techniques and surveyed from within using a hand held LiDAR scanner to depths of up to 60 meters, producing a detailed 3D map of the conduit geometry. The latter provides rare ground truth for direct comparison with the radar volume.

The GPR data clearly image the surveyed cave system, with conduit locations well aligned with the direct LiDAR mapping. Beyond the mapped tunnels, the GPR volume also reveals a network of strong radar responses, suggesting the presence of additional englacial conduits.

The direct correspondence between the LiDAR-derived conduit geometry and the GPR volume provides a rare basis for linking englacial structures to their radar response. This dataset therefore offers a benchmark for interpreting 3D GPR observations of glacial hydrological systems.

Kirk Scanlan - ARCTEX: Combining observations to improve our understanding of extreme events in an integrated Arctic system

Kirk Scanlan [1], Daniele Fantin [2], Louise Sandberg Sørensen [3], Malcolm McMillan [4], Anna Hogg [5], Kate Briggs [6], Anders Kusk [7], Renée Fredensborg Hansen [8], Jack Landy [9], Amber Leeson [10], Jennifer Maddalena [11], Robbie Mallet [12]

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Radar and microwave techniques are a pillar of polar remote sensing and have been for decades. Multiple observational time series provide objective evidence for the long-term effects of decadal-scale climate warming. At the same time, owing to the on-going development and diversity of radar- and microwave-based Earth Observation (EO) sensors and data products, it is now possible to also investigate spatially- and temporally-extreme events along with teleconnections that occur within an integrated climate system.

In this context, the European Space Agency (ESA) Arctic Extremes (ARCTEX) project focuses on three Arctic case studies; i) Nioghalvfjerdsfjorden (79N Glacier) and Zachariae Isstrøm and ii) the Austfonna ice cap in Svalbard, and iii) the ice cap on Crown Prince Christian Land, commonly referred to as Flade Isblink. Of cross-cutting interest for all case studies are the intersections and feedbacks that occur at the critical boundary between land ice (i.e., ice caps and glaciers) and sea ice, which have been conventionally treated within separate thematic domains. These intersections include extreme events, such as accelerated dynamic mass losses experienced during periods of glacial surge and rapid changes in surface topography associated with active subglacial hydrology systems, as well as broader teleconnections, such as relationships between sea ice buttressing and melange conditions with marine terminating glacier flow velocities, and open water polynyas and ice cap surface mass balance.

The interconnected nature of these key processes means they cannot be completely captured by a single observation, and they can occur rapidly such that they can be lost in the generation of stable, long-term climatic time series. It is only by leveraging the diversity and fidelity of state-of-the-art satellite radar and microwave systems that it becomes possible to interrogate them. To that end, the main EO data products incorporated within the project include ice surface elevation change and surface properties from radar altimetry, ice surface velocities and deformation from synthetic aperture radar, polynya characteristics from the combination of satellite altimetry and passive microwave radiometry, and sea ice thickness from radar altimetry. Supported by state-of-the-art climate reanalysis products and novel analysis approaches, these observations open a window into the complex interactions occurring between Arctic land and sea ice.

Johannes Noll - The Potential of Wideband Synthesis in Firn Studies Using Software-defined Radar

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In radioglaciology, different radar systems are used depending on the required resolution and penetration depth to image the target of interest. Software-defined radars offer a solution to this specialization, as their flexibility in waveform design allows a single system to address multiple objectives. However, this flexibility often comes at the cost of lower instantaneous bandwidth, which limits resolution. We overcome this limitation by transmitting multiple chirps at different center frequencies and synthesizing them into a wideband waveform, thereby increasing resolution.

The approach is demonstrated in a near-surface firn study on Aletsch Glacier, Switzerland, using a modified subset of the radar system MAPPERR, developed by the Stanford Radioglaciology group. We perform a common midpoint measurement, combining four 84 MHz chirps to span a total frequency range of 225–531 MHz. We compare it to a similar measurement with the Autonomous phase-sensitive Radio Echo Sounder which uses a chirp spanning 200–400 MHz. Results show that the synthesis of chirps increases our resolvability in depth and our detectability of layers. The resolution is similar to that of a nearby 500 MHz impulsive radar survey, while our system additionally captures phase information. We leverage this information to invert for subsurface signal velocities without manual layer picking. Using these velocities, we compute a density profile of the firn, which can be used to better constrain firn densification models.

Since MAPPERR has previously demonstrated deep ice sounding, this is another step towards a single radar system for both deep and shallow sounding, with the capability to adjust the waveform in the field based on the respective scientific target.

Anna Siebenbrunner - Glacier-Spanning UAV-Based Ground-Penetrating Radar (cryoGPR): A New Reference Method for Ice Volume Determination in the Eastern Alps

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Ground-penetrating radar (GPR) is the established standard for glacier ice thickness measurement, yet systematic, glacier-spanning surveys remain constrained by terrain inaccessibility, safety hazards, high time investment, and limited repeatability. Unmanned aerial vehicle-based GPR (UAV-GPR) has emerged as a promising alternative, but its application to complete glacier-scale surveys has to date been largely unexplored. Here we present the first systematic, glacier-spanning UAV-GPR surveys — conducted with our purpose-built cryoGPR system — across ten benchmark glaciers in the Eastern Alps. The study covers the full spectrum of regional glacier morphologies, including cirque, debris-covered, and valley glaciers distributed across Austria and Germany. These surveys directly address a critical source of uncertainty in glacier volume assessments, where sparse thickness data propagate into substantial volumetric errors under existing interpolation approaches.

System reproducibility is quantified through repeated surveys on three glaciers, confirming low intrinsic measurement uncertainty. Absolute thickness retrievals are independently validated at four sites against geodetic mass balance estimates and direct ice-drilling records. In addition to volumetric results, we define an operational best-practice framework, specifying optimal flight velocity, terrain-following altitude, and spatial sampling strategies for reliable ice thickness retrieval.

Our results demonstrate that glacier-spanning UAV-GPR is a viable and high-resolution reference method for ice volume determination. The approach enables surveys of previously inaccessible or hazardous glacier terrain, provides robust calibration targets for thickness inference models, and delivers high-fidelity boundary conditions for next-generation glacier evolution simulations.

Johanna Klahold - Imaging Seasonal and Interannual Evolution of Glacier Drainage Using UAV-Based 4D GPR

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Meltwater transport through englacial and subglacial drainage systems plays a key role in regulating glacier motion, water availability, and associated hazards. However, direct observations of the geometry and temporal evolution of these systems remain limited. Here, we use high-resolution, uncrewed aerial vehicle (UAV)-based four-dimensional (4D) ground-penetrating radar (GPR) to characterize drainage evolution at the Otemma Glacier (Swiss Alps) across seasonal to interannual timescales.

We conducted repeated, high-density 3D GPR surveys during four field campaigns (August 2022; June, August, and October 2023), allowing detailed comparison of subsurface structures over time. A dedicated processing workflow combines reflection-based imaging of the glacier bed with coherence-based diffraction analysis to resolve both subglacial channels and englacial features. The GPR results are complemented by dye tracing experiments, UAV photogrammetry, time-lapse imagery, and targeted validation using steam drilling.

The results reveal a drainage network comprising both persistent and transient components. At the glacier bed, one major channel persists across surveys and shows signs of increasing hydraulic efficiency, while another is partly rerouted toward the glacier margin. Englacial features show partial spatial persistence, with some consistently detected in similar locations across surveys, whereas others are short-lived. Clear seasonal changes are observed, along with evidence for coupling between englacial and subglacial systems through co-evolving structures.

Our results highlight glacier drainage systems as hybrid networks, in which persistent pathways coexist with ongoing reconfiguration. This study demonstrates the potential of UAV-based 4D GPR to resolve these processes and provides new constraints for models of meltwater routing and glacier dynamics in a warming climate.

Mukta Mani Maurya - Sentinel 1 SAR data based experimental study for assessment of 2D deformation of glacier in Western Himalaya using Phase Wrapping - Unwrapping, DInSAR and Offset Tracking Techniques.

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The recent accelerated climate change has led to loss of snow and ice from the global cryosphere at higher rate than the earlier. The Himalayan cryosphere more adversely affected than the other area in the world. Most studies on glacier-lake dynamics rely on remotely sensed optical data. The use of Sentinel 1 SLC data for glacier deformation is limited in the Hindukush Himalaya. This paper examines the 2025 deformation of Bara Shigri glacier and eleven nearby glaciers in Western Himalaya using DInSAR and Offset Tracking to analyse melt and post-snow melt season changes. Six images from both ascending and descending orbits with VV polarization are used. East-west, vertical, and 3D deformation were calculated to understand glacier deformation. Phase wrapped was unwrapped into line-of-sight displacement, then east-west using an equation in SNAP. Calculating 3D deformation needs three variables. As Offset Tracking results were unsatisfactory, it wasn't included, making the result 2D. Analyzing east-west displacement, north and northwestern glaciers move east, while most south and southwest glaciers go west. The lower middle of the Bara Shigri glacier shows low or no displacement. The September and December images show 0-12 cm east displacement, except the middle Bara Shigri glacier moves west 12 cm. Between May and September, glaciers subsided, while the lower Bara Shigri and upper parts of other glaciers uplifted. The lowest Bara Shigri glacier shows less subsidence than the lower middle and headwalls. The lower south-eastern glaciers show 0 to 5 cm uplift, except at the Bara Shigri glacier headwall, where uplift exceeds 30 cm. 2D deformation shows glacier movement horizontally and vertically, giving a true deformation picture. Deformation differences between May-September and September-December show changes post-melt season. Offset Tracking results with a four-month gap are erroneous, preventing azimuth calculation. The gap might disturb the cohort but still indicates regional deformation. Coherence for generating interferogram was poor, ranging from 0 to 0.5, affecting interferogram quality. Despite the not being satisfactory result, it shows the deformation pattern of debris - covered glaciers. Techniques like DInSAR and Offset Tracking might be beneficial if the images are at six-day interval for continuous monitoring. 3D deformation of glacier might help understand ice loss and future lake formation.

Zhuo Wang - New radio-echo sounding observations of Swedish and northern Greenland glaciers: ice thickness, thermal structure, and subglacial hydrology

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Recent radio-echo sounding (RES) datasets acquired between 2024 and 2025 through field campaigns conducted by the Tarfala Research Station and the GEOEO Scientific Party provide new information on glacier structure in Arctic environments. The datasets cover two research efforts: Swedish glaciers and marine-terminating glaciers in northern Greenland.

For the four Swedish reference glaciers (M√•rmaglaci√§ren, Storglaci√§ren, Rabots glaci√§r, and Riukojietna), RES observations are integrated with ice-thickness modelling to derive high-resolution ice thickness distributions and subglacial topography. In addition, englacial reflections are analysed to identify cold‚Äìtemperate transition surface (CTS), which represents the pressure-melting point. This study marks the beginning of systematic investigations of Swedish glaciers using modern ice-penetrating radar system and provides updated glacier boundary conditions, as well as new insights into their thermal structure.

In parallel, RES datasets collected around the grounding zones of Petermann Glacier, Ryder Glacier, and C.H. Ostenfeld Glacier in northern Greenland are used to investigate ice thickness and grounding zone dynamics. Notably, a previously unreported sub-ice-shelf channel is identified in Ryder Glacier, corresponding to a supraglacial channel and the subglacial hydrology modelling results. These observations contribute to an improved understanding of glacier-ocean interactions.

Together, these studies demonstrate the capability of RES to investigate glacier geometry, thermal structure, and subglacial hydrology across different glaciological settings, and highlight recent contributions from Sweden to radioglaciology and Arctic cryosphere research.

Satu Innanen - Long-term GPR observations of firn thickness and perennial firn aquifers on Austfonna ice cap, Svalbard

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Firn (multi-year, compacted snow) plays a crucial role in the mass balance of glaciers by storing meltwater in both liquid and refrozen forms. Perennial firn aquifers are bodies of meltwater that percolate into the firn and remain liquid year-round. These aquifers are primarily detected using airborne or surface-coupled ground-penetrating radar (GPR) and have been identified in regions ranging from Greenland to Svalbard and Antarctica.

Here we present results from repeated GPR surveys conducted on Austfonna, the largest ice cap in Svalbard, covering the period from 2004 to 2026. We analyze changes in firn thickness and properties, investigate the thermal regime, and examine the spatial and temporal variability of firn aquifers. In addition, we present results from common mid-point surveys that provide further insight into the structure and characteristics of firn aquifers.

Akash Patil - Annual firn pack variations in the context of the climate settings: Example from the Grosser Aletschgletscher using multi-year radar observations

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The glacier mass balance and hydrology are driven by processes such as meltwater percolation, refreezing, and runoff, which are triggered by warming high Alpine regions, producing surface meltwater, increased firn temperature, and liquid water content. All these processes are functionally related to the temporal changes in firn density under regional climatic conditions. In our study, we used multi-year indirect geophysical observations, such as the ground-penetrating radar-based (GPR) common midpoint (CMP) method, complemented by direct measurements (firn cores) at the Aletsch glacier's accumulation area. We estimated temporal changes in firn density and compaction rates within the identified 9-13 annual layers using the available internal reflection horizons (IRHs) from CMP measurements. Our results suggest that the change in firn density over a year decreases with depth and age, with the highest (~130 kg/m^3) at the surface at both CMP locations of the accumulation area. Similarly, the estimated compaction rate (~0.3 m/a) at the lower elevation also decreases with depth and age. Additionally, the deep firn core-derived density-depth profile complements the CMP-derived results, illustrating the CMP measurements as a possible alternative for the invasive and laborious glaciological observations. We also estimated spatial changes in firn density and accumulation along the GPR transect. The comparison of repeated radargrams from winter 2024 and 2025 measurements reveals the possible effect of glacier dynamics on firn stratigraphy, further helping to trace the spatial extent of firn body by locating the Equilibrium Line of Altitude (ELA). We demonstrate how processes such as meltwater percolation, refreezing, and overburden stress influence firn density and compaction rate over spatial and temporal scales.

Harry Davis - High-Resolution Firn Deformation Monitoring at the REWIND Ice-Core Site Using a Novel UHF ApRES System

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Ice-core interpretation requires knowledge of the present and past flow conditions and changes in the geometry of the area. One reason for this is the dynamics of ice flow influence annual layer thickness that in turn affects our interpretation of past changes in snow accumulation, and it is critical to date the deepest sections of the ice core, where annual layer counting is not possible. Additionally, changes in ice thickness affect some proxies, in particular stable isotopes, and affect our interpretation of past changes in temperature.

To constrain ice-flow conditions and ice thickness at the REWIND ice-core drilling site (Palmer Land, Antarctic Peninsula) we collected a set of phase-sensitive radar observations that complement other geophysical observations at the site. We deployed a new UHF autonomous phase-sensitive radar with a 1 to 3 GHz chirp bandwidth designed to measure high-resolution near-surface vertical radar profiles. We show this instrument is able to sound the firn layer at hourly intervals for over a month and from this calculate time series of vertical deformation and strain. Using these data, we constrain a 1-dimensional ice-flow model to reconstruct time series of surface density and accumulation directly from UHF ApRES data. We analyse these timeseries alongside automatic weather station data, other geophysical data collected at REWIND (ground-penetrating radar and ApRES), and preliminary measurements derived from the ice core.

Nicolas Jullien - Deciphering changes in Antarctic Ice Sheets Surface Mass Balance rates since the Last Glacial Maximum using Airborne Radar data.

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The mass balance of the Antarctic Ice Sheet (AIS) reflects the balance between mass input from snowfall in the interior and mass output at the margins through ocean-induced melting and iceberg calving. Reconstructing the mass input, defined here as Surface Mass Balance (SMB; the annual net accumulation or ablation of snow) from the Last Glacial Maximum (LGM) to the present remains a first order unknown in Glaciology. This reconstruction is crucial because (a) SMB histories are required to initialise ice-sheet models used to project the AIS contribution to future sea-level rise and (b) spatiotemporally resolved SMB fields are needed to resolve the contrasting signals reported in several regions of the AIS, where both SMB-driven mass gain and loss are observed. Furthermore, although SMB may increase in a warming climate, the extent to which this increase could buffer or offset ice-sheet mass loss – and thus mitigate sea-level rise – remains uncertain, and recent trends lack observational constraints.

Firn cores provide excellent local SMB reconstructions at the drill location, but they cover different time intervals and integrate over limited spatial areas. Atmospheric reanalysis could in principle provide broader coverage, but they currently lack observations with sufficient spatiotemporal frequency for robust calibration. Geophysical radar surveys are a well-established technique that can provide this coverage by extending firn core data spatially using the isochronous firn stratigraphy. Recent technical advances in airborne radioglaciology now enable the resolution of the near-surface stratigraphy at the continental scale.

Here, we present how latest airborne radar surveys can be used to reconstruct SMB rates across the AIS since 1800 to determine whether increasing snowfall accumulation is offsetting the contribution of the AIS to sea-level rise. These findings can be placed in a longer-term context by reconstructing SMB since the LGM. Overall, observational constraints of SMB rates provide the basis for evaluating the ability of regional climate models to simulate the AIS SMB, with the goal of improving model capacity to project future Antarctic contributions to sea-level rise.

Pierre Zeiger - A direct monitoring of Greenland percolation zone extent and dynamics using SMOS

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The percolation zone of the Greenland ice sheet (GIS) is a key buffer to sea level rise through the refreezing of meltwater in available firn pore space. It is also an increasing source of runoff due to the expansion of near-surface impermeable ice slabs preventing meltwater percolation in the firn. Understanding these processes and the percolation zone response in a warming climate is key to better constrain the projected GIS sea level rise contribution. We present a new Ice Lens Index (ILI) based on the spaceborne multi-incidence measurements from the Soil Moisture and Ocean Salinity (SMOS) L-band radiometer, which is used to map the percolation zone extent and its dynamics. An implementation of ice lenses and ice pipes simulators in the Snow Microwave Radiative Transfer (SMRT) model supports the ILI definition and allows for a physically consistent interpretation of SMOS measurements on the GIS. The ILI shows a strong sensitivity to the transition from ice slabs to percolation facies, and from percolation facies to dry snow, at the lower and higher boundaries of the percolation zone. The 16+ year SMOS time series allows to follow the recent evolutions of the GIS percolation zone, its non-linear inland migration and ice accretion into impermeable slabs, at unprecedented spatio-temporal scales.

Winnie Chu - Spectral and Electromagnetic Characterization of Firn Aquifer Radar Returns at Helheim Glacier

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Firn aquifers store liquid water within porous firn, influencing meltwater retention, runoff, and englacial-to-subglacial hydrology pathways. However, their spatial extent and persistence remain difficult to constrain because direct observations are sparse and radar signatures can be ambiguous. Here, we present a spectral and electromagnetic analysis of ground-based PulseEKKO data from Helheim Glacier, southeast Greenland, collected over the 2025 and 2026 field seasons. We combine spectral ratio analysis of 100 MHz radar profiles with electromagnetic forward modeling of plausible firn dielectric contrasts. Spectral amplitude shifts above and below picked reflectors yield trace-by-trace estimates of attenuation along the transect, with firn grain size considered as an additional control on scattering loss. In parallel, effective-medium mixing of ice, air, and water across a range of porosities and saturations is used to compute Fresnel reflection coefficients at candidate interfaces, with grain size further influencing effective permittivity through inclusion geometry. Comparing modeled reflection magnitudes to the observed aquifer return reveals lateral variability in reflection strength consistent with a patchy, partially saturated aquifer rather than a uniform saturated layer. Together, the spectral attenuation structure and dielectric modeling provide complementary constraints on aquifer geometry and saturation state and demonstrate the utility of frequency-domain radar methods for mapping firn aquifers and improving quantitative interpretation of englacial hydrology.

Falk M. Oraschewski - ApRES as a Tool for Firn Water Monitoring and Runoff Quantification

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Surface meltwater runoff accounts for half of the Greenland ice sheet mass loss with increasing rates over recent decades. Its future trajectory will be decisive for the ice sheet stability. How runoff evolves is strongly dependent on the hydrological processes in the percolation zone, where runoff is buffered by meltwater percolation and refreezing in the porous firn. Increasing melt rates can exhaust this retention capacity and lead to the formation of impermeable ice slabs that promote subsequent runoff. Together, these processes govern the inland migration of the runoff limit and, ultimately, total runoff from the ice sheet. However, monitoring liquid water in firn throughout the melt season remains a challenge, leaving percolation zone processes underconstrained in regional climate models (RCMs) and causing strong divergence in runoff projections.

The Autonomous phase-sensitive Radio-Echo Sounder (ApRES) can fill this observational gap. We present hourly ApRES observations acquired over three melt seasons (2023–2026) adjacent to four GC-NET automatic weather stations across Greenland's percolation zone (KAN_U, DYE-2, Crawford Point and Camp Century). These data provide continuous time series of total liquid water amount in the near-surface firn, i.e. the top few meters beneath the antennas. We quantify runoff rates through a joint analysis of the ApRES data and the GEUS firn model. Comparison with runoff simulations from three RCMs highlights deficiencies in their runoff parametrizations in terms of the timing, location, and magnitude. Our results demonstrate the potential of ApRES firn water monitoring to improve RCM representations of Greenland's percolation zone and narrow uncertainties in Greenland ice sheet mass balance projections.

A free byte for lunch: Long-term observations of glacier properties using wireless sensors, and bonus insights from changes in received signal strength - Lisa Craw

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Collecting long-term observational data in and around glaciers is difficult due to challenging environmental and weather conditions. In many cases, field sites are only accessible during the summer months, and harsh weather, limited daylight, rapid ice movement, and disturbance by local wildlife can all lead to data loss through instrument damage or power failure.

Recent advances in affordable satellite airtime, alongside more efficient battery and solar power systems, have enabled the development of wireless instrumentation capable of delivering near real-time data from remote environments over multi-year timescales.

We have developed a suite of wireless sensors, primarily the “Cryoegg” and “Cryowurst”, which transmit measurements of water pressure, temperature, electrical conductivity, and orientation from within and beneath glaciers via radio link. Using Cryoegg, we have obtained continuous hourly data from the subglacial hydrological system over an 18-month period, while a network of Cryowürste has been reporting englacial and basal data at half-hourly intervals since mid-2024.

Beyond improving robustness for long-term deployment in dynamic environments, the use of radio link also enables investigation of how glacier properties influence radio wave propagation through ice. We present observations of azimuthal variations in signal strength associated with strong ice anisotropy in the Northeast Greenland Ice Stream, as well as the influence of weather and subglacial hydrological activity on received signal strength over a melt season in a mountain glacier.

These preliminary datasets demonstrate the potential of wireless sensors as a tool for in situ studies of radio wave propagation in ice.

An inverse approach to inferring crystal orientation fabric anisotropy from polarimetric radar data - Niels Nymand

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The crystal orientation fabric (COF) of glacial ice strongly influences its mechanical properties and evolves with flow. Large-scale ice flow models currently neglect COF evolution, but including it is becoming increasingly feasible. However, observations are still very sparse and often depth-averaged or point measurements. Radars, and especially polarimetric radars, are sensitive to the COF due to the birefringence of ice and provide a relatively easy and cost-effective way to collect observations that can be used to infer the anisotropy and orientation of the COF. In this study, we formulate the problem of inferring the COF from polarimetric radar data as an inverse problem to derive depth-resolved horizontal COF anisotropy. The method relies on an iterative linearization of the Fujita radio-wave depolarisation matrix model to estimate COF orientation and scattering anisotropies. It also employs a linear maximum likelihood solution to derive eigenvalue differences from travel-time anisotropies. The method is applied to polarimetric radar data from the Northeast Greenland Ice Stream and Dronning Maud Land, both characterised by a relatively strong anisotropy that has challenged previous inference approaches.

Antarctic subglacial specularity content mapping for ice sheet models - Duncan Young

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The distribution of basal slip parameters are a critical component of understanding ice sheet sensitivity to change (eg Zhao et al. 2025). These have often been inverted for from surface and ice thickness observations. However, additional information on basal conditions can be inferred from the radar echo itself. Direct inference of subglacial water from echo strength is complicated by variable englacial attenuation, basal material properties and small-scale roughness. Radar basal specularity content (S_c, Schroeder et al., 2014) maps out regions of smooth basal interface, potentially allowing the identification of regions of basal melting. S_c has its own complications, with basal roughness anistropy and false water positives due to very smooth bedrock in some regions.

S_c has been used as a constrain for local ice sheet models (Dow et al., 2020, Huang et al. 2024, Kerr et al. 2026), as an indicator of melt or sediments. We have been funded to expand and optimized Antarctic-wide specularity content grids as a boundary condition field for use in ice sheet models.

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ApRES interferometry to measure deformation in blue ice areas with steeply dipping internal layers - Marguerite Shaya

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Interferometric Autonomous phase-sensitive Radio Echo Sounder (ApRES) measurements use the phase differences between two co-registered acquisitions to calculate vertical strain rates across the ice column, providing valuable constraints for ice flow modeling and depth-age predictions. Previous ApRES studies assume that englacial layers are flat and specular. Here, we explore extensions of ApRES interferometry to the steeply dipping layers of the Allan Hills, Antarctica, Blue Ice Area (BIA), where the NSF Center for Oldest Ice Exploration has recovered the oldest ice on Earth to date. At the Allan Hills, surface ablation exposes blue ice, while a submerged bedrock ridge which sometimes outcrops as a nunatak slows the ice flow to near-zero velocity. Electrical conductivity measurements (ECM) in the upper portion of two shallow (90 and 186 m) ice cores drilled to bedrock reveal steeply dipping (~28° and 69° from horizontal) englacial layers. ECM analysis on basal ice from these cores predicts that the layering near the bed result from integrated basal material. To assess the nature of radar reflections at these two sites, we collected repeat ApRES acquisitions separated by one year with radar tilt angles that varied between 0-35° and 0-60° from horizontal. Tilting the radar setup to be parallel to the ice core layering (as opposed to aligning the radar with the surface) results in stronger reflections but no change in the two-way travel times, consistent with expectations for reflections off steep and specular scattering horizons. Because the backscattered energy does not arrive from nadir, interferometric profiles at these sites measure deformation along an off-vertical axis. With knowledge of the englacial layering structure, we can correct for the measurement frame, although the errors are large. Understanding how to infer vertical strain rates when layers are steeply dipping may also inform interpretations of basal flow and stratigraphic continuity at a proposed Allan Hills intermediate depth (~1000 m) ice core site located down-flow from a 200 m high bedrock bump.

Bed mapping of southern Greenland outlet glaciers using helicopter-borne ground penetrating radar (AIRETH) - Ilaria Santin

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We present the first deployment in southern Greenland of the redesigned Airborne Ice Radar of ETH Zürich (AIRETH), a helicopter-borne ground-penetrating radar system developed for glaciological applications. In March 2025, we acquired 348 km of radar profiles over three outlet glaciers near Narsarsuaq: Qooqqup Sermia, Eqalorutsit Kangilliit Sermiat, and Sermilik Bræ. Basal reflections were identified along 102 km of the profiles (29%), with most successful detections occurring in shallower marginal sectors, while thicker and more heavily crevassed central glacier zones often remained uninterpretable. The effective penetration depth of the current 25 MHz configuration is approximately 300 m, with a maximum detected ice thickness of about 340 m.

The surveyed glaciers are in narrow, high-relief outlet settings where existing regional datasets remain sparse or weakly constrained. We therefore compare AIRETH-derived bed elevations with collocated Operation IceBridge radar soundings and BedMachine v5 estimates. At many crossings, AIRETH and Operation IceBridge show broadly consistent bed elevations, although outliers of up to approximately 600 m occur in localized areas. The comparison with BedMachine also reveals substantial and more spatially widespread local mismatches, in some cases reaching several hundred meters. These differences likely reflect the limited direct observational constraints available in complex marginal terrain, where gridded products rely strongly on inversion and interpolation.

Our results show that terrain-following helicopter-borne GPR can provide valuable, targeted ice-thickness constraints in geometrically complex outlet-glacier corridors that are difficult to resolve with conventional regional airborne surveys. At the same time, they define the practical limits of the present AIRETH setup in temperate, crevassed ice. The AIRETH system will be deployed again in Greenland during the CASCADES expedition, planned for August 2026, using a 12.5 MHz antenna configuration. The aim is to test whether the lower-frequency setup can increase radar penetration beyond the current 25 MHz limit, at the cost of reduced vertical resolution. Preliminary results will be briefly presented if available.

Capabilities of new airborne NZArC-CReSIS ice-penetrating radar on Windracers ULTRA UAV - Charlotte Carter

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Miniaturisation of radar technology and improving size, reliability and range of platforms means that the future of airborne radio-echo sounding is moving towards the use of uncrewed aerial vehicles (UAVs). UAVs have key advantages as logistical challenges (fuel placement and cost), and environmental considerations (CO_2 emissions) come to the fore in polar research. The Windracers ULTRA UAV is a platform hosting the newly developed NZArC-CReSIS radar system, consisting of 4 H-polarised under wing antennas and 3 dual-polarised fuselage antennas, with 2 transmitting and 8 receiving channels. The radar has a centre frequency of 300 MHz (bandwidth of 250-350 MHz) and up to 1 kW peak power. The UAV platform has a wingspan of 10 m, speed of 30 m/s, and a flight range of 1000 km, and can co-host magnetometer and optical camera systems. Here, we present preliminary test results demonstrating the capabilities of the radar system conducted offshore in the UK. Ultimately the system will include deep-ice sounding, polarimetric, and swath-mode radar capabilities. The system will be deployed in Greenland at Petermann Glacier during the 2027 summer season, as part of the ARIA GIANT project. This will focus on the grounding zone of the glacier with a closely spaced swath-mode survey, as well as a 1 km spaced wider survey from the ice shelf front to 50 km inland.

Classification of ice sheet dry-wet surface status using passive microwave satellite - Pierre Zeiger

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Passive microwave satellite observations are commonly used to detect liquid water in the snowpack on the ice sheet. The typical algorithm yields a binary dry-wet indicator limiting the information. However, recent theoretical analyses demonstrated that these dry-wet indicators are representative of different depths in the snowpack depending on the microwave frequency: from the surface to ~0.2 m at 37 GHz, from the surface to ~1 m at 19 GHz and from the surface to depths exceeding 1 m at 1.4 GHz. Building on this finding, our study combines multiple frequencies to support a deeper understanding of melting and refreezing processes in Antarctica. For this, we propose an empirical method that combines several binary dry-wet indicators computed at three frequencies (1.4, 19, and 37 GHz) and for two satellite acquisition time-period (afternoon / night). We obtaine 10 qualitative classes describing multiple "snowpack status" such as fully dry, fully wet, wet with night refreezing occurrence, or remnant liquid water at depth with a dry surface.

The classification captures the expected seasonal melt evolution: night refreezing is frequent at the beginning of the melt season, while sustained melting is observed in the middle of the summer, and remnant liquid water at depth features the end of the melt season. This new classification offers deeper insights in melt processes for investigating extreme events and climate variations compared to previous binary indicators. This opens great prospects for a potential use for the Copernicus Imaging Microwave Radiometer (CIMR), which is scheduled for launch in 2029.

Contrasting internal dynamics at two Antarctic ice rises from vertical velocity profiles and polarimetric fabric measurements - Katrin Lindbäck

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Ice rises are grounded features that pin ice shelves and record past and present ice-sheet dynamics in their internal stratigraphy. Understanding their flow regimes, particularly whether the Raymond effect is active and how accumulation has varied over time, is critical for interpreting ice cores drilled at their summits and for assessing their role in ice-shelf stability. We present repeat phase-sensitive radio echo sounding (pRES) measurements at Djupranen and Leningradkollen ice rises, Dronning Maud Land, collected one year apart. Fitting the Lliboutry vertical velocity function to phase-derived displacement profiles at sites across each divide yields the surface vertical velocity, the flow-law shape parameter p, and ice-equivalent accumulation. Despite comparable geometry and proximity, the two ice rises display strikingly different dynamics. At Djupranen, p falls to low values at the divide, consistent with a well-developed Raymond effect, and rises towards Glen-type values at the flanks. Leningradkollen shows no evidence for a sustained Raymond effect: p indicates plug-like flow at every site along the transect, including the divide, and the flanks are asymmetric, with no clear p gradient on the northern side. Differences in surface and bed topography between the two ice rises are a likely control on this contrasting dynamic behaviour. We compare accumulation rates inferred from the velocity profiles with multi-decadal radar-derived surface mass balance at both ice rises. Preliminary polarimetric pRES analysis indicates differences in crystal fabric between the two sites. These findings highlight that neighbouring ice rises within the same climatic and regional setting can exhibit markedly different flow characteristics and internal properties. This has important implications for the interpretation of ice-rise stratigraphy, the selection of ice-core sites, and the reconstruction of past ice dynamics in coastal Antarctica.

Deep Learning-Based Semantic Segmentation of Polythermal Glacier Structure from Ground-Penetrating Radar Data – Jaime Roas

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The internal temperature field of polythermal glaciers, and in particular the geometry of the cold-temperate transition surface (CTS), is a key element to understand their dynamics. Ground-penetrating radar (GPR) has been shown to be an effective technique for mapping the CTS, given the dielectric contrast between cold ice and water-rich temperate ice. However, conventional interpretation remains manual, labour-intensive and poorly scalable to large datasets. Here we present a deep learning framework for the automatic semantic segmentation of GPR radargrams into three classes: cold ice, temperate ice and bedrock. The model is based on a convolutional neural network following a Feature Pyramid Network (FPN) architecture. The model has trained on an extensive multi-campaign dataset acquired across glaciers in Svalbard (Sabine Land, Nordenskiöld Land, Wedel Jarlsberg Land and Nordaustlandet) between 2008 and 2022, using GPR systems with central frequencies of 20–25 MHz. To address data scarcity, we evaluated two dataset expansion strategies: forward modelling of electromagnetic wave propagation to generate synthetic radargrams, and data augmentation techniques. Segmentation performance was quantified using conventional metrics for semantic segmentation tasks. Our results for the Intersection over Union (IoU) metric reaches values of 68.7%, 76.7% and 98.2% for cold ice, temperate ice and bedrock, respectively. Data augmentation consistently outperformed synthetic data generation as a strategy for improving model generalisation, suggesting that diversity in real acquisition geometries and glaciological conditions is a stronger driver of performance than dataset expansion through simulation.

This research was funded by grants PID2020-113051RB-C31 and PID2021-128362OB-I00 from Agencia Estatal de Investigación. UL was supported by grant PRE2021-100049 financed by MCIN/AEI/10.13039/501100011033 and by FSE+.

Easy come, easy go? More than a decade of firn volume fluctuations on the Juneau Icefield, AK and implications for climate sensitivity - Mikaila Mannello

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Glaciers in Alaska represent a major and ongoing source of sea-level rise outside of the continental ice sheets. Juneau Icefield is representative of this broader trend, including the well-studied T'aakú Kwáan Sít'i (Taku Glacier). Important to this contribution is the role of meltwater storage both in and under these temperate glaciers. Firn, or the intermediate material between snow and glacial ice, plays a critical role in glacier mass balance, as it has the capacity to store liquid meltwater, delaying transport to the glacier bed as well as buffering melt contribution to sea level rise. T'aakú Kwáan Sít'i, the main outlet glacier for the southern portion of Juneau Icefield, transitioned from an advancing to a retreating glacier within the span of our study period, 2012 – 2025. To quantify firn volume, we collected 400 MHz ground-penetrating radar glacier centerline profiles in 2012, 2015, 2021, 2023, 2024, and 2025 along T'aakú Kwáan Sít'i and Matthes Glacier (~25 km). We constrained these data with in-situ measurements of relative permittivity from firn cores. Between 2012 and 2021, we observed a firn volume loss of more than 50 percent. Conversely, from 2023 to 2025, firn volume increased and nearly returned to 2012 levels. Our observations appear to reflect a lag in firn volume response to the glacier's mass balance in preceding years. The data suggest the residence time of firn here is short (< 10 years) and responsive to annual variability of precipitation and temperature. These findings highlight the importance of better quantifying the role and variability in firn so that we are able to more accurately constrain the impact of increasing temperatures on temperate glacier mass balance and contribution to sea-level rise.

Effect of coherent subglacial water area on basal reflectivity - Sunme Zhao

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Ice-penetrating radar is our best tool for observing subglacial water in Antarctica at the glacier to continent scale. However, the non-unique interpretations of basal reflectivity make it challenging to use basal reflectivity to robustly constrain amounts of subglacial water. In this work, we model the effect of subglacial water on reflectivity by treating the bed as Fresnel zone with a mixture of coherent and incoherent patches for a range of bed materials. We find that water covering as little as 10% of the bed can cause as much as 20 dB increase in reflectivity. We also make estimates for the subglacial water volume needed to cover this fraction of the bed, and we show that this quantity is highly sensitive to local bed topography. Lastly, we discuss implications of using relative and absolute reflectivity for detecting subglacial water in Antarctica.

Effects of basal debris on radar signals: a lab experiment - Rebecca Schlegel

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Imaging of boreholes and ice-shelf bases reveals that debris (sediment) is commonly incorporated within basal ice layers. Such basal debris influences ice rheology and glacier flow dynamics by modifying deformation rates and basal sliding behaviour, while also complicating the interpretation of radar reflectivity at the ice–bed interface due to its effects on wave propagation and attenuation. Despite its importance, reliable methods to quantify debris content in basal ice remain limited, restricting robust inference of subglacial properties.

Here, we present results from lab experiments to examine how debris and water content within basal ice impact radar response, with a particular focus on dielectric properties. Measurements were conducted using a custom built parallel-plate capacitance bridge designed specifically for icy samples. Samples were constructed in which debris content varied between 0-50 % by volume. Basal sediments deposited by the Laurentide Ice sheet were used in all samples. Measurements were collected across frequencies from 50 Hz – 50 kHz and over a controlled temperature range (–20 °C to 0 °C), enabling analysis of both the static dielectric constant and frequency-dependent polarization mechanisms.

Initial results indicate that even small amounts of debris, and particularly the presence of water, in basal ice can significantly influence radar signals. Future work will focus on the quantitative incorporation of these findings into analyses of basal properties across different locations to better assess the reliability of such interpretations. These results have important implications for glacier flow modelling and the remote sensing of subglacial environments, especially in debris-rich and warm-based glacier systems.

Eqip Sermia Basal Ice: Analysis of Surface Change and Ice Sheet Deformation - S. Isabel Cordero

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The Eqip Sermia catchment, in West-central Greenland, contains a 30 km long basal ice unit that is similar in form to freeze-on units identified in East Antarctica. Analysis of 2008-2019 Operation IceBridge repeat survey lines reveals the basal unit is moving downslope at ~100m/yr. Emerging from the stoss side of a ridge, the large basal unit extends downstream to a region where surface elevation and surface velocity data suggest the bed is deforming. The distinct bulbous downstream margin of the basal ice unit indicates if freeze-on produced the 20-600m thick basal ice, the accretion to the ice sheet base began within the last ~300 years. The basal melt in the Eqp catchment is insufficient to support this observed basal ice thickness, pointing towards a major contribution from surface melt water. We hypothesize the basal ice forms as surface water refreezes over the ridge due to a combination of surface temperatures conducted through thinner ice and the reduced pressure melting point.

Coincident with this newly resolved englacial movement, the ice surface is lowering more slowly than expected. At the leading edge of the basal ice unit, the surface of the unit is moving upward at ~1m/yr. The modest (100-150m/yr) surface velocities over the unit could be accommodated by internal shear or basal sliding, both of which could be affected by the presence of sediments entrained in the ice. Synthetic glacier modeling shows that a moving basal ice unit with a different rheology or basal traction, possibly due to its debris-rich nature, can produce dynamic surface elevation change in broad agreement with the observations. Downstream of the basal unit, the ice surface is relatively stable, but exhibits episodic rapid thinning at rates of 2-3m/year over shorter 2-4 year periods. These ice surface changes are characteristic of ice changes over draining subglacial lakes, indicating the bed of the ice is temperate downstream and the subglacial hydrology complex. The nature of the underlying bed will influence this system through varying geothermal flux and sediment distribution.

This integrative analysis of unusual changes in surface elevation, coincident with an actively moving basal unit imaged in repeat radar profiles, points toward the formation and evolution of basal ice that may be fundamentally impacting local ice sheet behavior.

Estimating instrument performance for high-altitude radar sounders using open radar data - Thomas Teisberg

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To collect data at scale, radar sounders are often deployed on conventional aircraft over Antarctica and Greenland. Due to the remoteness of these ice sheets, these aircraft deployments are expensive and logistically complicated. Weather often limits the number of flights that can be completed, further increasing costs and limiting data collection volume. Emerging autonomous, solar-powered stratospheric aircraft represent a compelling alternative that could both reduce the cost per unit of data collected and bypass the weather constraints that limit data collection. While stratospheric platforms are logistically appealing, uncertainties remain about instrument requirements for a stratospheric radar sounder.

Prior work has widely identified signal-to-noise and signal-to-clutter ratios as the primary obstacles to high altitude radar sounders. We use the extensive catalog of airborne radar sounder data available through Open Polar Radar to put data-driven constraints around the unknown quantities in these instrument performance models. Using this framework, we discuss the feasibility of a validation mission and reasonable target instrument parameters.

Estimation of ice thickness using Ground Penetrating Radar (GPR) of the Shallap glacier in the Cordillera Blanca, Peru - Camila Granados Quispe

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This research aims to estimate the ice thickness of the Shallap Glacier, located in the Cordillera Blanca, Ancash Department, Peru, using Ground Penetrating Radar (GPR). The goal is to generate detailed geophysical information about its internal structure and contribute to the understanding of glacial dynamics in the tropical Andes. The study was conducted in the glacier's ablation zone, where longitudinal and transverse profiles were acquired to identify the ice-rock interface and calculate ice thickness.

The methodology comprised three main stages: (i) field data acquisition using high-altitude GPR, including transect planning and georeferenced recording; (ii) preprocessing and processing of radargrams in the REFLEX software, applying zero-time correction, dewow, bandpass, and background removal filters, as well as gain adjustments to optimize the signal; and (iii) manual identification (picking) of the reflection corresponding to the bedrock to convert the double propagation times into ice thickness measurements. Subsequently, the results were integrated into a Geographic Information System for spatial representation and interpolation.

As a result, 228 point thickness measurements were obtained, distributed along the surveyed profiles. The estimated values ranged from 25 m to 179 m, with propagation times between 302 and 2,134 ns, demonstrating a marked spatial heterogeneity of glacier thickness. The generated map shows greater thicknesses toward the central sectors of the glacier tongue and lower values at the evaluated margins.

The results confirm the effectiveness of ground-penetrating radar (GPR) as a non-invasive geophysical technique for estimating glacier thickness in tropical mountain environments, constituting a relevant input for future analyses of ice volume, glacial dynamics, and water availability in Peru.

Evidence for Phase Signal in the Antarctic Echo-Free Zone - Hannes Staehlin

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Autonomous phase-sensitive radio echo sounding (ApRES) is a powerful tool for measuring vertical ice deformation and basal melt rates. However, existing ApRES methods cannot be applied in the lowest regions of the ice, known as the Echo-Free Zone (EFZ), where traditional amplitude peak-tracking algorithms fail due to the absence of continuous specular layers. This limits ApRES-based studies to observe and model ice sheet basal dynamics and sliding for inclusion in ice sheet models and sea level projections. Since velocities near the bed are usually extrapolated from hundreds of meters above, the uncertainties in processes and conditions near the ice sheet bed are especially large.

In this work, we demonstrate that the EFZ is not an information void. By shifting the focus from amplitude tracking to interferometric phase coherence, we reveal that coherent phase signals persist deep within the highly deformed basal unit. To extract this obscured signal, we present a novel data-processing approach that uses phase signals and localized filtering. This approach pools phase information across depth windows, enabling us to recover vertical velocity signals from the complex radar return, independent of detectable amplitude peaks. We applied this methodology to a 312-day ApRES record taken above a subglacial lake beneath the Mercer Ice Stream. We estimate the full-column velocity profile and discuss observational constraints on the signal's origin. Ultimately, this methodology offers a way to extend layer-based ApRES velocity estimates to unlock full-column deformation from stationary radar time series.

Focussing of ice-penetrating Synthetic Aperture Radar by propagation based on diffraction to correct defocussing by refraction - Alvaro Arenas-Pingarron

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To improve the Synthetic Aperture Radar (SAR) image focussing for englacial ice sounding, we introduce a radar signal propagation model based on ray-tracing by diffraction. In glaciology, SAR imaging is applied for profiling englacial stratigraphy and estimating ice thickness. In SAR, the radar is on board of a platform that moves while the radar operates. After the data processing (focussing), the SAR image consists of the vertical englacial profile (range) along the coordinates of the moving platform (along-track). For a correct along-track or SAR focussing, the propagation delay of the radar signals must be known. In airborne or spaceborne SAR, the path travelled by the electromagnetic waves is assumed to be by refraction at the air/ice interface and across the ice thickness. However, with the refraction model in highly crevassed ice streams, we observed the SAR image was severely defocussed. For example, for ice at 1 km depth, the horizontal defocussing was greater than 400 m. This defocussing was even greater than the raw, unprocessed image during the radar data acquisition. To improve the image quality, we tested several electromagnetic propagation models, and the model based on diffraction was the one which better captured the signal dispersion in the along-track domain. We include results from data collected in Recovery Ice Stream and Thwaites, Antarctica, during two airborne campaigns with the British Antarctic Survey PASIN2 radar at 150 MHz. We compare images by both refraction and diffraction, showing the degradation with the refraction model, and the focussing by diffraction. Our model improves the focussing farther than 140 km upstream from the grounding zone. To assess focussing quality in the stages of raw data, processed by refraction, and processed by diffraction, we represent the SAR images with the RGB Doppler Decomposition method.

Frequency-Dependent Polarimetric Analysis of Snow on Sea Ice Using Airborne UWB FMCW Radar - Luisa Wagner

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Snow-covered sea ice presents a complex radar scattering regime in which contributions from surface roughness, snow volume scattering, and subsurface interfaces overlap within the radar response. Understanding these scattering mechanisms is essential for robust snow thickness retrieval from echo-sounding ultra-wideband (UWB) frequency-modulated continuous-wave (FMCW) systems, as well as for improving the physical understanding of snow properties and processes.

Generally, polarimetric radar observations are well suited to distinguish scattering mechanisms. However, their interpretation in airborne nadir-looking UWB systems remains limited and has seen little application over snow-covered sea ice. This limitation arises because, in nadir geometry, the polarisation orientation relative to the plane of incidence becomes geometrically inaccessible, whereas polarisation conversion remains observable.

We therefore investigate whether nadir-looking full-polarimetric UWB FMCW radar measurements can provide physically meaningful information on scattering processes when combined with frequency-dependent analysis. We use full-polarimetric data acquired with a 2–18 GHz UWB FMCW snow radar during Arctic winter campaigns conducted by the Alfred Wegener Institute.

A processing workflow is developed to derive frequency-dependent polarimetric descriptors from full-bandwidth and subbanded data, including phase relations, channel symmetry, covariance and coherence matrix statistics, and eigenstructure-based measures. Subbanding reduces bandwidth and thus range resolution, but enables the analysis of frequency-dependent scattering behaviour, which, through frequency-dependent penetration, provides insight into depth-dependent variations within the snowpack. Initial results suggest that lower-frequency subbands retain stronger sensitivity to coherent subsurface interfaces, whereas higher-frequency subbands increasingly capture surface-related scattering and small-scale heterogeneity.

By combining polarimetric, frequency-dependent, and geometry-aware descriptors, the analysis expands the feature space available for distinguishing scattering regimes beyond conventional intensity-based interpretation. This provides a basis for evaluating which components of the polarimetric response remain informative under nadir viewing and how they may support more robust snow-on-sea-ice retrieval algorithms.

Greenland surface accumulation from ice-penetrating radar: interannual variability and comparisons with weather station observations - Nanna B Karlsson

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Accurate estimates of snow accumulation over the Greenland ice sheet are critical for quantifying the mass balance of the ice sheet and ultimately its contribution to sea level rise. Ground-penetrating radar provides a means for retrieving large-scale spatial accumulation patterns that significantly extend point-based in-situ measurements. Here, the accumulation rates in the interior of the Greenland Ice Sheet are investigated using ice-sounding radar data acquired by CReSIS (Center for Remote Sensing and Integrated Systems) during surveys in 2014, 2016, 2017, and 2018. The radar acquisition lines intersect the GC-Net automatic weather station sites Summit and NASA-East, enabling a direct comparison between radar-derived accumulation rates and in situ observations.

Annual layers from 2002, 2004, 2012, and 2014 are identified and traced, and subsequently converted to water-equivalent estimates using information on firn density. The resulting estimates are compared against GC-Net weather station measurements and outputs from the MAR 3.10 regional climate model. As expected, accumulation rates decrease with increasing surface elevation and with increasing distance from the west coast. No significant change in annual accumulation is detected at Summit over the 2002–2014 period. The point-based weather station measurements are found to be only locally representative, as substantial local variability in accumulation is observed in the vicinity of Summit and NASA-East from the traced radar data.

Ice-sheet evolution in Aurora Subglacial Basin modelled using isochrones and a 3D ice-sheet model - Clara Nyqvist

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Aurora Subglacial Basin is one of three major marine basins that underlies the East Antarctic Ice Sheet. The basin is drained by several marine-terminating glaciers, and one of these, Totten Glacier, is currently experiencing the highest rates of both ice thinning and discharge of all outlet glaciers in East Antarctica. This has led to recent research relating to if, and to what extent, Totten Glacier and Aurora Subglacial Basin may be vulnerable to marine ice-sheet instability, both in the past, and under future anthropogenic climate change. Here, we use a three-dimensional thermomechanical ice-sheet model (The Parallel Ice Sheet model, PISM) to model ice-sheet evolution in Aurora Subglacial Basin over the last two glacial-interglacial cycles. To calibrate the model, we use datasets of internal reflection horizons (isochrones), previously mapped from airborne radio-echo sounding datasets, and dated at intersections with ice cores. With this, we investigate the basin's exposure to marine ice sheet instability during the last glacial-interglacial cycle and attempt to assess Last Interglacial/Holocene grounding line dynamics from direct comparison between modelled and observed isochrone geometry. Our results also indicate where we potentially require more measurements of internal stratigraphy to adequately constrain past ice sheet evolution in the region.

Improved subglacial boundary conditions near Dome C, Antarctica, through rigorous integration of multi-campaign radar data and an ensemble stochastic simulation approach - Kenichi Matsuoka

Calvin Shackleton [1], Kenichi Matsuoka [2], Brett Fraysher [3], Joohan Lee [4], Jørgen Dall [5], Allain Rapadas [6], Prasad Gogineni [7], Drew Taylor [8], Hyeontae Ju [9], Changhyun Chung [10], Anders Kusk [11]

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Subglacial bed topography is a fundamental boundary condition for ice-sheet flow, basal thermal regimes, and the preservation of palaeoclimate records, yet it remains highly uncertain across Antarctica. We use stochastic simulation methods to generate an ensemble of gridded (500 m) ice thickness and bed elevation near Dome C, and map bed elevation uncertainty accounting for impacts of data availability and basal roughness. New airborne radar measurements uncover previously undocumented sectors of the ice-bed interface and we integrate these with existing data using a rigorous approach to ensure nearby measurement compatibility. Our simulated bed shows improved representation of basal roughness between survey profiles, revealing regional roughness over 50 % higher than previous interpolations. We apply the ensemble to investigate uncertainty in meltwater routing, identifying well-constrained drainage away from the Dome C Plateau but poorly constrained outflow from Concordia Lake and parts of the Belgica Highlands. Topographic focussing of geothermal heat predicts local anomalies up to ±30 % relative to the regional value, and several ice core drill sites are in a zone of 12 % locally-reduced geothermal heating which is favourable for deep ice layer preservation. This work demonstrates that the critical subglacial bed boundary condition is better represented by ensemble-based, stochastic simulations based on strictly cross-validated data rather than single deterministic interpolations, and simulated beds can improve the reliability of analyses with robust consideration of uncertainties in data-sparse regions.

Inferring Greenland Dry Snow Zone Depth-Density Profiles from Open Polar Radar Data - Siyu Xue

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A good understanding of the firn densification process is critical for estimating ice sheet mass change from altimetry measurements as well as the age of gases trapped in ice cores. For any firn densification model to be realistic and generalizable, a large set of high-resolution firn depth-density profiles is indispensable for model calibration and validation.

This study aims to retrieve such profiles from airborne radar data collected by the Center for Remote Sensing of Ice Sheets (CReSIS) during NASA Operation IceBridge. The current work focuses on the Greenland dry snow zone for the years 2010–2014, 2017, and 2018.

We first estimate depth-averaged near-surface density from Accumulation Radar surface reflectivity using Radio Statistical Reconnaissance (RSR). For radiometric scaling, we perform absolute calibration using data collected over open water and the known reflectivity of seawater. We then apply relative calibration across flightlines using flightline crossover points.

The retrieved surface density serves as a boundary condition for the subsequent inversion of the full firn depth-density profile. Using six high-resolution firn core records from the Greenland dry snow zone, we empirically identify three critical density points which are identifiable in radar profiles based on the intrinsic relationship between firn density and density variability, which governs the firn layer reflectivity. These three critical densities provide three data points relating density to two-way travel time (TWTT) and are considered universal across the dry snow zone. An additional density-to-TWTT data point is obtained from the solid-ice layer observed in radar depth sounder data. With these data points, we invert for the full firn depth-density profile using the steady-state Sorge's Law.

Once we complete the inference of all depth-density profiles, we assess the potential systematic bias by evaluating the inferred profiles at flightline crossover points and by comparison with firn core records. The resulting depth-density product provides a large observational dataset for studying firn compaction and improving firn densification models.

Interpreting ice fabric in the South Pole - Dome A sector - Shivangini Singh

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Ice fabric anisotropy can lead to birefringent electromagnetic wave propagation in polar ice characterized by distinct but periodic phase fringes. This phenomenon has been observed previously across known fast flowing shear margins in Antarctica and Greenland. However, phase fringing is also observed in the interior of the East Antarctic Ice Sheet where ice flow is moderately sluggish but punctuated by a transient network of diffuse faster flowing tributaries.

We devise a framework to use phase fringing to test ice fabric formation hypotheses in regions characterized by ice flow reorganization through time. Our approach is (i) to utilize the grid design of our NSF COLDEX airborne radar surveys1 of central East Antarctica to extract bulk fabric character using the inherent polarimetric information at the intersections of these survey lines and (ii) to trace the location and morphology of these phase fringes across the entire survey to test the hypothesized fabric imprint of flow reorganization for both slow and fast flowing regimes of central East Antarctica. The validity of these results will be demonstrated through reconciliation with the established englacial architecture across the sector2.

1: Hills, Benjamin H., Matthew R. Siegfried, Duncan A. Young, John D. Paden, Shivangini Singh, Donald D. Blankenship, and Dustin M. Schroeder., A birefringence correction for multi-frequency radar sounding, IGARSS 2025-2025 IEEE International Geoscience and Remote Sensing Symposium, pp. 25-30. IEEE, 2025.

2: Singh, Shivangini, Young, Duncan A., Yan, Shuai, Buhl, Dillon, Ng, Gregory, Kempf, Scott D., Kerr, Megan, Blankenship, Donald D., Englacial Stratigraphy at the Southern Flank of Dome A, Antarctica Derived Using Airborne Radar-Sounding Surveys: A COLDEX Perspective, AGU Fall Meeting Abstracts 2024 (1), C44B-1

Isolating effects of fabric and fractures across Antarctic ice shelves - Athene Demuth

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Fabric, fractures, temperature, grain-size and impurities affects large-scale ice flow, which is crucial for assessing changes in ice sheet mass loss and their contribution to the global sea-level rise. Fabric and fractures are both features that can influence the ice viscosity by orders of magnitude, but are poorly constrained from observations.

Using a recently-proposed fabric model that includes recrystallization, we provide an overview of how modelled horizontal anisotropy compares with recent radar data from ice shelves and ice streams in Greenland and Antarctica. Fabric fields are determined from a depth-averaged finite element model under a steady state shallow shelf assumptions and uses surface velocities inferred from satellites. By implementing a scalar enhancement factor (CAFFE method) we compare the fabric-induced flow enhancement of the ice shelf to the assumption of isotropic ice. Across all areas we see both regions with hardening and some significant softening of the ice due to anisotropy.

Fracture maps derived from both optical and radar satellite data can be compared to results from viscosity inversions, where the effect of anisotropy has been removed, in order to gauge where damage might induce rheological weakening. The ice softness is inferred from inversions using the ice flow model Úa, that can invert for both basal slipperiness and the isotropic Glen softness parameter. Comparison between the residual flow enhancement and fracture maps reveals no consistent trend, suggesting that many fractures may not be rheologically active.

Making Glacial Radar Research Accessible with the Open Radar Code Architecture (ORCA) - Nicole Bienert

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The Open Radar Code Architecture (ORCA) is a community-formed initiative to make glacial radar-sounding research accessible through open-source code, instruction manuals, and forums, enabling teams to use low-cost Software-Defined Radios (SDRs) as ice-penetrating radars. This effort not only aims to make radar tools more accessible to glaciologists but also to streamline radar technology development by minimizing repeated efforts, reducing the barrier to entry, and promoting shared innovation.

Software-defined radios are a compelling alternative to traditional radar hardware due to their low cost, small form factor, and reconfigurability for fast prototyping or real-time functionality adjustments. Despite their potential, SDR adoption has been hindered by the high startup costs (time, personnel, expertise) of writing the code from scratch to make an SDR operate as a radar. While multiple research groups and companies have confidential SDR radar code, open-source code was not available until ORCA's original release in 2024.

Here, we present updates to ORCA, targeting improved accessibility, that the CU HI-SNR lab has introduced over the last two years. The codebase has been overhauled and reorganized for improved clarity and organization. Automatic unit tests and code commit protocols have been introduced to facilitate community code contributions, cross-device compatibility, and easy code maintenance. A plethora of new documentation and instructions were added, and their efficacy was validated with undergraduate freshmen who used ORCA to assemble and program an SDR radar system and take distance measurements. We will continue to expand the accessibility, functionality, and devices supported by ORCA.

We invite all radar users and developers to join our community at https://orca.hisnr.com/.

Mapping Ice Slab Front Geometries in Greenland Using Polarimetric Satellite Radar Backscatter - Ellen Mutter

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The growth of ice slabs influences both the spatial extent and the rate at which the Greenland Ice Sheet's wet snow zone transitions from storing meltwater in firn, to exporting it as surface runoff. These changes reorganize meltwater storage and flow pathways, shaping the ice sheet's contribution to sea level rise. In this work, we combine Sentinel-1 (S1) C-band satellite radar mosaics with Operation IceBridge (OIB) airborne radar profiles to produce a decade long annual time series of ice slab expansion in Greenland. We compile Interferometric Wide and Extra Wide Swath data acquired during boreal winters to produce annual co-polarized (HH) and cross-polarized (HV) backscatter mosaics and then apply a logistic regression model to optimize ice slab detection thresholds and to quantify classification uncertainty. Our time series reveals pronounced differences in ice slab expansion behavior between north and southwest Greenland. Isolated OIB radargrams also suggest marked differences in ice slab geometry between these two regions. To capture these contrasting ice slab front geometries, we develop a refined classification scheme to map thick and thin ice slabs across the Greenland Ice Sheet using S1 backscatter thresholds. In regions with available ALOS-2 L-band coverage, we explore dual-frequency approaches to constraining ice slab front geometry and develop insight into methods that could be applied to anticipated ROSES-L observations. The observed spatial and temporal patterns in ice slab geometry point to regions where atmospheric forcings and percolation zone firn conditions have restricted meltwater infiltration depth, accelerating shallow ice slab growth and altering the near-surface hydrologic regime.

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MIDAS: A Miniaturised Drone-Based Altimeter System for Surveying Sea Ice

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"Remote sensing is critical for long-term monitoring of the cryosphere. Historically satellites have been employed to monitor the polar regions, including Arctic sea ice, due to the extensive spatial coverage they provide. However, the spatial and temporal sampling of satellite observations is inadequate for synoptic assessments of sea ice conditions and there is also an ongoing need for the calibration and validation of satellite measurements. This sparsity in validation data is a limiting factor when developing novel methodologies for improving sea ice records.

Although airborne observations have also been used to compliment and validate satellite measurements owing to their improved spatial resolution and temporal revisit time, their high exploitation costs, lack of operational infrastructure and increased risk are each limiting factors. Unmanned Airborne Vehicles have consequently emerged as a low-cost, flexible and safer tool for studying the cryosphere at higher spatiotemporal resolution. Although the application of drone-based sensors for cryosphere research is becoming more common, these systems are still relatively large and expensive. Take-off weights generally remain on the order of several kilograms, which introduces stricter operational regulations and reduces usability. The miniaturised drone-based altimeter system (MIDAS) presented here is a low-cost and lightweight sensing system, developed from Commercial Off-The-Shelf products, that can be deployed on a sub-250g drone.

The prototype system currently includes two different payload versions: a 60 GHz (V-Band) frequency modulated continuous wave (FMCW) radar payload, and a 24 GHz (K-Band) FMCW radar payload. Both payload types are additionally equipped with a near-infrared time-of-flight laser. The performance of the prototype architecture is characterised through the ground-based calibration of each of the sensors, an indoor airborne validation test and the results from a set of preliminary field experiments. For the preliminary field experiments, surveys with the K-Band payload were conducted over snow-covered lake ice, fjord ice and water. As part of these field tests, the use of the system for surface classification was investigated, with preliminary results indicating that the system can distinguish ice and water surfaces using the NIR laser and through radar pulse peakiness. Preliminary results on radar penetration depth in snow are also presented."

Mitigating Mountain Glaciers Melt with Geoengineering - Feiteng Wang

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Accelerated retreat of mountain glaciers under ongoing climate warming poses severe risks to regional water security, ecosystems, tourism, and natural hazard management. Small and mid-sized glaciers are particularly vulnerable due to their limited thickness and high sensitivity to albedo changes and atmospheric warming. While global mitigation efforts primarily focus on emission reduction, the delayed climate response highlights the need to explore proactive, local intervention strategies.

This study evaluates the effectiveness of micro-geoengineering approaches—specifically geotextile surface covering and artificial snowmaking—through integrated field experiments and numerical modeling on Dagu Glacier No. 17 and Urumqi Glacier No. 1 in western China. These representative continental-type glaciers provide well-established observational records and logistical accessibility for controlled experiments.

In August 2020, a 500 m^2 geotextile protection zone was deployed on Dagu Glacier, followed by a 200 m^2 experiment on Urumqi Glacier No. 1 in 2022. Field observations, UAV photogrammetry, terrestrial laser scanning, and automatic weather station data were combined with surface energy-balance modeling (COSIPY). Results show that surface covering reduced glacier melt rates by 34–70%, primarily through increasing surface albedo (from ~0.48 to ~0.62) and decreasing net shortwave radiation by ~35 W m^{-2}, thereby lowering melt energy by approximately 27%. Protected zones maintained up to 0.8 m greater surface elevation, with up to 68% of ice preserved relative to adjacent uncovered areas. Increased geotextile thickness further enhanced preservation efficiency.

Artificial snowmaking simulations indicate that a 30-day annual snow production rate of 0.1 m d^{-1} can delay glacier disappearance by approximately 20 years. Extending snowmaking to 60 days per year at medium (0.15 m d^{-1}) or high (0.2 m d^{-1}) intensity can sustain positive mass balance and potentially promote glacier development.

Our results demonstrate that targeted micro-geoengineering interventions can substantially reduce ablation at local scales and provide a feasible adaptation pathway for vulnerable mountain glaciers, especially those of touristic or hydrological significance. Although not a substitute for emission reduction, such strategies may serve as complementary measures to preserve critical glacier resources in rapidly warming regions.

Multidimensional glacier velocity retrieval in the Himalayas using interferometric Sentinel-1 SAR Data - Shubham Bhattacharjee

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Understanding glacier dynamics in the Himalaya remains challenging due to steep topography, extensive debris cover, persistent cloud cover, and the geometric limitations of conventional remote sensing approaches. While Interferometric Synthetic Aperture Radar (InSAR) enables all-weather glacier motion monitoring, conventional line-of-sight (LOS) measurements capture only a single projection of the true displacement vector, often resulting in substantial underestimation of glacier motion in complex mountain terrain. This study develops a multidimensional InSAR framework for reconstructing complete glacier surface velocity fields in a glacierized region of the Himalaya using Sentinel-1A/C SAR observations. The azimuth displacement components were derived using sub-aperture interferometry. Finally, the full East-North-Up (E-N-U) glacier velocity components and a resultant multidimensional velocity field were retrieved. The results reveal strong spatial variability in glacier flow dynamics, with multidimensional velocities typically ranging between 0.07 and 0.15 m/day along major glacier trunks and tributaries. In contrast, conventional LOS-derived velocities commonly remain limited to 0.01,Äì0.06 m/day due to projection effects. The multidimensional approach successfully resolves continuous-flow pathways, cross-flow motion, and localized high-velocity tongues that are suppressed in single-component estimates. Statistical assessment demonstrates high reliability of the reconstructed velocity field. Quality assurance analysis further confirms systematic underestimation of LOS and improved consistency of the multidimensional solution. The integration of LOS and azimuth observations significantly enhances glacier motion retrieval in high-relief Himalayan terrain and provides a more physically realistic representation of glacier dynamics. The proposed framework demonstrates the potential of multidimensional SAR interferometry for improved glacier monitoring, cryospheric hazard assessment, and understanding climate-driven glacier changes in complex mountain environments.

Multiparametric glacier dynamics in the western Himalayas, India, using integrated SAR and optical remote sensing - Munizzah Salim

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The present study investigates the dynamics of the Samudra Tapu Glacier in the Western Himalayas, India, from 2018 to 2023, using an integrated approach of multisource remote sensing datasets. The study employs advanced geospatial techniques, including Synthetic Aperture Radar (SAR) and optical data from Sentinel-1 and Sentinel-2, to assess key glacial parameters such as snout fluctuations, ice velocity, ice thickness, and mass balance. Results indicate a significant snout retreat of approximately 39 meters and an increase in proglacial lake area from 1.41 sq. km to 1.82 sq. km over the study period, indicating increased recent melting and dynamic shifts over the research period. These findings show the glaciers' short-term reactions and can point to new patterns that need longer-term verification. Ice velocity varied spatially, with higher rates near the equilibrium line altitude (ELA) and reduced movement near the snout, while a decrease in velocity was observed in tributary zones. Ice thickness decreased from 420 m to 390 m in the tributaries, hinting at potential disintegration due to climatic impacts. Mass balance analysis revealed positive rates in the accumulation zone and negative rates in the ablation zone, indicating mass loss near the snout and lower tributary areas. Unlike conventional studies that focus on specific glacier parameters, this study provides an integrated, process-based paradigm that combines ice velocity, thickness, and mass balance to explain glacier behaviour. The primary novelty is the discovery of tributary breakdown using integrated geographic information and its association with proglacial lake development. This approach goes beyond descriptive research to provide new insights on glacier instability and associated hazard potential in the Himalayas.

On the evolution of the hydrothermal structure of polythermal glaciers in Svalbard - Francisco Navarro

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Polythermal glaciers consist of cold and temperate ice layers, with viscosity depending on temperature and liquid water content, respectively. Knowing their hydrothermal structure (i.e. its internal spatial distribution of cold and temperate ice) is fundamental to understand and model their dynamics, and how these glaciers will evolve under a warming climate. This is particularly relevant for Svalbard, as 57% of the archipelago is glacierized and most of its glaciers are polythermal, and it is among the fastest warming regions on Earth, with mean air temperatures rising several times faster than the global average. In this contribution we focus on 1) describing the main processes operating within the polythermal glaciers and how these processes can affect the evolution of the hydrothermal structure; 2) showing how the hydrothermal structure can be inferred from ground-penetrating radar (GPR) data, including examples in which the evolution of the cold-to-temperate transition surface (CTS) over periods of ca. 10 years can be observed; and 3) describing how this evolution can be modelled using thermomechanical models. The latter is illustrated using the Instructed Glacier Model (IGM), an open-source, Python-based glacier model that integrates climate-driven surface mass balance, ice-flow and heat transfer processes. IGM employs physics-informed machine learning and GPU acceleration to efficiently resolve high-order ice-flow dynamics, enabling large-scale simulations at high spatial resolution. The rich set of Svalbard GPR measurements provides ample opportunities for model calibration and validation. Some preliminary results for Svalbard glaciers are presented.

Preliminary Inversion Algorithm for Detecting Basal Conditions Using Multi-Frequency Radar - Christopher Barbarie

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Understanding the behavior of the Antarctic and Greenland ice sheets is crucial for improving ice sheet models and sea level rise predictions. Basal material, hydrology, and roughness exhibit first order controls on basal sliding and ice sheet evolution yet remain poorly constrained due to an inability to estimate these properties at sufficient scales and accuracy. Single-frequency radar surveys cannot simultaneously determine basal roughness and material composition due to their similar effect on the received radar power. Therefore, these surveys require geophysical knowledge or assumptions about the material composition of the bed to estimate the basal roughness. As a result, these survey types are limited to locations where the basal material composition has already been determined via in situ measurements or can be assumed with strong confidence. Multi-frequency radar surveys present a solution to disambiguating material composition and roughness. Since these parameters have differing responses to changes in frequency, measurements across multiple frequencies may enable simultaneous quantitative estimates of the basal roughness and material composition without the need for prior knowledge or assumptions about the geophysical properties of the bed. However, no methods currently exist to estimate these parameters from multi-frequency radar data.

We develop a preliminary inversion method that uses synthetic multi-frequency radar data and show that it can be used to simultaneously estimate the material composition and roughness of the bed. We simulate radar data at three frequencies of 2 MHz, 22 MHz, and 330 MHz. The developed inversion algorithm estimates the small-scale root-mean-square roughness and the volumetric content of water, till, and rock of the bed. We find that a signal-to-noise ratio of 25dB is required to estimate the volumetric content of water within 10% error. While this is a simplified model, it confirms that a multi-frequency radar system can quantitatively estimate basal water content and small-scale roughness without geophysical assumptions and can be used regardless of survey location. This shows that such a system can solve the degeneracy between the basal roughness and material composition that limits existing systems. The primary use cases of this system will be to field-validate sliding laws, hydrology investigations, and point estimates of basal friction to inform ice sheet models and improve sea level rise predictions.

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Quantifying Water Content, Density, and Structur Changes of Snowpack on the Juneau Icefield Through Group Penetrating Radar - Eleanore Allan-Rahill

Eleanore Allan-Rahill [1], Seth Campbell [2], Mikaila Mannello [3], Owen Power [4]

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Glaciers store about three-quarters of Earth’s fresh water and have widespread impacts on human and environmental health, and their ongoing melt threatens Earth's freshwater resources. Quantifying glacier water storage is challenged by technological limitations; however, Ground Penetrating Radar (GPR) is a promising method for understanding meltwater storage and glacial water resources.

This study analyzes the two-way travel time, density, and relative permittivity (ε) of the snowpack at two locations on the Juneau Icefield (JIF) during July 2025. Repeat GPR surveys were conducted using a 400 MHz GPR along 30-meter transects on Taku and Vaughan Lewis Glaciers to compare trends in geophysical responses over time. Weather data were collected to examine linkages between atmospheric temperature and snow water content.

The results of this study confirm trends of increasing density with depth, and relative permittivity (ε) values consistent with those expected in a wet snowpack. These data support the idea that liquid water inclusions in snow reduce the depth of radar penetration. This further supports the need for in situ ground truthing to verify the accuracy of GPR data. Additionally, results reveal relatively consistent derived velocity and associated ε values, suggesting that surveys provided reasonable approximations of these values on the JIF.

Radar-derived constraints on basal temperature and rheology in the echo-free zone - Neosha Narayanan

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Basal sliding is a critical boundary condition on the motion of ice sheets and glaciers, as it can account for half or more of ice deformation at fast-flowing glaciers. However, the difficulty of observing basal conditions makes inferring basal slip parametrizations challenging. Developing a better understanding of ice temperature and rheology profiles throughout the ice column can help us constrain the relationship between surface and basal velocities and internal ice deformation. Recent modeling work (Law et al. 2023) has shown that when realistic basal roughness is included in ice sheet simulations, deformation heating at basal ice can lead to a layer of temperate ice at the bed. In this work, we combine CReSIS airborne radar data at an outlet glacier in Greenland with geostatistical simulation (MacKie et al. 2023) and ice sheet modeling to investigate deformation heating zones and their radar signatures. We apply a spectral ratio method (Dawson et al. 2026) to differentiate radar attenuation in basal vs. overlying ice and investigate the feasibility of determining basal temperature and rheology within the echo-free zone of airborne radargrams.

Recent estimates of ice thickness across the Juneau Icefield from 1 MHz ground-based radar - Renée Clavette

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Alaskan glaciers are losing mass faster than any other mountain glacier region on Earth, and this trend is expected to continue throughout the current century. To constrain modeled future ice loss, we require present ice thickness estimates, which are challenging to obtain due to sparse data coverage and large measurement uncertainties. The Juneau Icefield (JIF) is a temperate icefield, covering ~4,000 km2, that is currently experiencing rapid mass loss. Several prior studies (seismic, gravity, airborne radar, ground-based radar, and numerical modeling) have attempted to quantify ice thickness across the JIF. Most of these studies have focused on estimating thickness across its thickest section, on T'aakú Kwáan Sít'i (Taku Glacier), with seismic results suggesting the ice reaches depths of up to ~1500 meters, among the deepest temperate ice ever measured. Prior icefield-wide attempts at quantifying ice thickness include airborne radar, which did not produce clearly identifiable glacier bed echoes over the majority of flight lines, and numerical modeling, which has uncertainties in ice thickness up to hundreds of meters. To estimate ice thickness and compare with existing datasets across a larger area on the JIF, we collected an extensive dataset (~250km) of 1MHz common-offset ground-penetrating radar, targeting cross-flow profiles. From our data, we interpret bed depths at or greater than ~1000 meters across significant tributary branches of Taku Glacier. Our results indicate deeper ice than suggested by modeling, and also reveal interpretable bed horizons in regions that have not been imaged previously. These results emphasize the need for better constrained ice thickness estimates for a regional-scale understanding of present ice mass and thus projected loss.

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Reconciling Subglacial Lake Detection: A Physics-Informed Radar Framework for Quantifying Antarctic Basal Hydrology - Mandala Pham

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Antarctic subglacial lakes play a critical role in ice sheet dynamics by modulating basal friction and driving ice stream initiation. These water bodies form part of an interconnected drainage network in which changes in surface elevation or ice thickness can trigger cascading shifts in basal hydrology and ice velocities. Despite their importance, detection methods — including seismic surveys, laser altimetry, radar sounding, and InSAR — frequently yield inconsistent results regarding lake locations and extents at well-studied systems such as the Whillans Ice Stream and Victoria Land, limiting quantitative assessment of their hydrological and dynamic influence.

To address these inconsistencies, we present a physics-informed radar reanalysis framework for improved detection and volumetric quantification of subglacial water bodies. The framework applies the spectral ratio method (SRM; Dawson et al., 2025) to derive englacial attenuation from changes in radar signal frequency content between shallow and deep reflectors — enabling attenuation mapping across regions where conventional time-domain techniques struggle, such as areas with near-uniform ice thickness or disrupted radiostratigraphy. SRM-derived attenuation corrections feed a geologically-constrained basal reflectivity inversion that explicitly incorporates spatially varying bed geology via Fresnel reflection coefficients, distinguishing between the dielectric contrasts expected for soft sedimentary beds versus hard crystalline substrates. We implement dual radiometric constraints, analyzing both dielectric loss and reflectivity anomalies, and apply Bayesian methods to probabilistically discriminate subglacial lakes, saturated sediments, and frozen bed conditions, replacing binary lake inventories with uncertainty-aware basal water maps.

Relating Seasonal Variations in Basal Slipperiness to Runoff, Surface Topography Changes, and Subglacial Conditions at Kangerlussuaq Glacier, Greenland - Majbritt K. Eckert

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Kangerlussuaq Glacier (KG) in Central East Greenland is one of the largest contributors to dynamic mass loss from the Greenland Ice Sheet (GrIS). Seasonal variations in ice surface velocity are well observed but the underlying changes in basal conditions driving the dynamics are poorly constrained. Here we invert seasonal surface velocity observations from the PROMICE satellite product for basal slipperiness using the finite element ice flow model Úa with seasonally varying surface topography from the PRODEM series. We recover 21 seasonal slipperiness maps spanning summer 2019 to summer 2024, revealing distinct spatial and temporal patterns of basal slipperiness. With a k-means clustering analysis we identify three modes of slipperiness response: a summer decrease consistent with efficient subglacial drainage, a summer increase suggesting inefficient distributed drainage and rising water pressure, and minimal seasonal variability. The spatial distribution of these clusters correlates with bed topography and basal friction regime, where hard-bed regions show the strongest direct response to runoff. Seasonal changes in slipperiness extend inland beyond the spatial extent of surface runoff, indicating that basal signals are dynamically transmitted upstream. Changes in surface topography alone explain only a minor fraction of velocity variation. Transient forward simulations forced with the inverted for slipperiness maps show that even small differences in basal conditions produce diverging committed mass loss, with a spread of at least 25% of total mass loss after 100 years of constant atmospheric forcing. These results demonstrate that seasonal changes in basal slipperiness are a key control on the dynamics of KG. By upscaling our seasonal inversion series to the whole GrIS and including radar based observations we want to improve the representation of subglacial condition variability in projections of future mass loss.

Sensitivity of ice flow to bed reconstruction in Grenzgletscher - Cristina Gerli

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Grenzgletscher, a polythermal glacier in the Swiss Alps, has cold-bedded ice in the accumulation zone and temperate-bedded ice downstream. We build a full-Stokes ice flow model with Elmer/Ice to reproduce observed surface velocities under varying basal conditions, testing the sensitivity of modeled velocities to basal topography derived from new ground-penetrating radar surveys conducted between 2024 and 2026. We perform perturbation experiments in which the basal topography is progressively smoothed or modified from a mass-conservation-type representation toward a more radar-constrained bed geometry. These experiments allow us to disentangle the relative contributions of basal traction, basal topography, englacial deformation, and thermal regime to observed surface velocities.

Simulation-based inference of crystal orientation fabric from polarimetric radar measurements - Johannes Noll

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Knowledge of the crystal orientation fabric (COF) of ice sheets is important for reconstructing past ice flow and projecting ice flow into the future. COF induces mechanical anisotropy in the ice, which exerts strong control on ice dynamics and rheology. As the COF simultaneously introduces dielectric anisotropy in the ice, it can be probed using polarized radio waves. However, existing polarimetric radar methods are limited to inferring a subset of COF properties such as the difference between horizontal eigenvalues or require site-specific tuning, limiting their generalizability across field sites.

We present a novel method capable of inferring all three COF eigenvalues and the ice fabric orientation angle, applicable across diverse field sites. Our approach leverages simulation-based inference, a Bayesian machine learning framework in which an inference network is trained on paired model parameters and forward simulations to learn their probabilistic relationship. Concretely, we simulate polarimetric radar responses across a wide range of COF eigenvalue combinations and fabric orientations and train a network to invert these simulations. When confronted with polarimetric field observations, the trained network returns the posterior probability distribution over COF parameters and naturally quantifies parameter uncertainty.

We demonstrate the method's validity for nadir-looking radar measurements under the assumption that one COF eigenvector is vertical, a standard approximation for ice sheets with moderate deformation history. Additionally, our workflow could be transferred to obliquely incident radar waves, which would allow to relax the assumption of one vertical eigenvector and could enable COF retrieval in dynamically complex settings.

Spatiotemporal variability in surface mass balance from radar stratigraphy in Dronning Maud Land, East Antarctica - Alexandra M. Zuhr

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Understanding temporal changes in surface mass balance (SMB) and their potential links to environmental factors is key to determine uncertainties in Antarctica's contribution to sea level rise. Climate models predict that a warming atmosphere could enhance SMB over the East Antarctic Plateau through increased snowfall, yet this region remains sparsely covered by observations, limiting our ability to evaluate if such changes have already occurred and if so with which magnitude.

In this study, we use near-surface radar stratigraphy (tens of meters depth) to investigate past accumulation variability, bridging the gap between point-scale firn cores and coarse-resolution reanalyses. Building on earlier airborne radar surveys from western Dronning Maud Land, we extend spatial coverage with 4,000 km of newly acquired ultra-wideband microwave radar profiles collected in December 2025 around Kohnen Station. This combined dataset enables tracing of internal reflection horizons across multiple spatial and temporal scales with decadal resolution for the past ~250 years, providing a consistent basis for reconstructing SMB and assessing temporal variability preserved in the upper 30 m of the firn column.

Preliminary results indicate relatively stable SMB prior to the mid-20th century, followed by increases of up to 20% over the last five decades since the 1970s. The analysis of the 2025 radar profiles will test whether similar temporal patterns or distinct regional SMB variations are evident in the Kohnen area for the late 20th and early 21st centuries. This work aims to refine spatially distributed SMB reconstructions and their temporal evolution, advancing our understanding of accumulation variability and the processes shaping East Antarctica's mass balance in a changing climate.

Structural persistence and connectivity of englacial drainage pathways in an Alpine glacier revealed by 4D UAV-based GPR - Mélissa Francey

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The configuration and temporal evolution of meltwater routing systems are critical determinants of glacier dynamics, yet direct observations of these internal networks remain limited. Recent high-resolution radar imaging at Otemma Glacier characterized the drainage system as a hybrid network comprising both persistent pathways and transient components that undergo interannual reconfiguration. However, the extent to which these findings are representative of other Alpine glaciers, particularly where ice geometry and pre-existing structural heterogeneities exert dominant control, remains an open question.

To address this, we investigate Findelen Glacier (Swiss Alps) using repeated, high-density, uncrewed aerial vehicle (UAV)-based 3D ground-penetrating radar (GPR) surveys acquired during the 2022 and 2023 ablation seasons, together with a survey conducted in early spring 2023 under winter snow conditions. Adopting the 4D GPR processing framework established in previous studies, we utilize 3D amplitude analysis to characterize the geometry and connectivity of internal conduits and voids.

The englacial system at Findelen consists of a series of elongated pathways aligned with ice flow. These structures define a partially connected network of interconnected and isolated elements and remain spatially stable across all surveys, including winter conditions, indicating limited geometric reorganization over seasonal to interannual timescales. Several englacial pathways are observed to connect to a single subglacial channel present in all acquisitions, suggesting persistent coupling between englacial and basal drainage.

Overall, meltwater routing appears to be organized within a limited number of fixed structural pathways rather than a dynamically evolving network. This suggests dominant control by pre-existing structural heterogeneities, with variability expressed mainly through hydrological activity rather than geometry. In addition, a persistent feature immediately above the ice-bed interface is interpreted as a zone of recurrent basal water accumulation, potentially linked to localized surface-to-bed recharge through crevasse fields. These results highlight the capability of repeated UAV-based 3D GPR to resolve internal hydrological network in Alpine glaciers.

Subglacial conditions estimated from unsupervised clustering analysis of radar bed-echo shape - Matthew Siegfried

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Constraining subglacial conditions in ice-stream systems, particularly through methods that mitigate the impact of uncertain englacial properties (e.g., temperature gradients, impurities), offers new insights into how basal processes influence multi-decadal ice-stream evolution. Here, we demonstrate a new framework to characterize ice-sheet basal conditions using a basin-scale (>10,000 line-km) airborne radio-echo sounding (RES) survey collected in the 2013-14 austral summer over Whillans Ice Plain, Crary Ice Rise, and Ross Ice Shelf. We train a batched, unsupervised K-Means clustering algorithm to group 1-D scattering profiles at the ice-bed interface, targeting similarities in their shape (as opposed to amplitudes). We additionally explore the effects of the transmitted beam and survey design on cluster outcomes. Interpreted basal environment characteristics from the clustered RES survey reveal spatial heterogeneity in material entrainment and inferred basal friction across Whillans Ice Plain. We use simulations of frozen fringe development informed by observations of multi-decadal ice-surface velocity and ice-thickness change to evaluate the spatial patterns of debris-entrainment from our RES clustering and assess the thermomechanical conditions required to generate the inferred pattern. Our bed-echo pre-processing and clustering workflow offers a radar attenuation-independent approach for identifying basal processes under ice sheets, where uncertainty in path effects makes interpreting scattering phenomena challenging, and holds broad potential for application in multi-mission, repeat-track, orbital, and multi-decadal RES surveys.

Supraglacial Lake Drainage and Hydrological Connectivity under Thick Ice Conditions - Tamara Gerber

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The delivery of surface meltwater to the bed of the Greenland Ice Sheet modulates ice flow through transient changes in basal lubrication. Supraglacial lake drainages can rapidly transfer large volumes of water to the subglacial system, with the resulting ice-dynamic response depending on drainage efficiency: inefficient subglacial drainage sustains high water pressures and enhanced sliding, whereas efficient systems promote rapid water evacuation and flow deceleration. While these processes are relatively well understood in the ablation zone, it remains unclear whether meltwater can access the bed beneath >1 km thick ice, and whether efficient drainage can develop under high overburden pressure and low hydraulic gradients typical of the ice-sheet interior.

These processes are also poorly constrained in models, particularly with respect to time-varying englacial and subglacial connectivity and associated water storage. Improved observational constraints are needed to better parameterize key quantities such as the englacial void ratio, to which subglacial hydrology models are highly sensitive.

We present preliminary results of field observations along the K-transect in southwest Greenland targeting two supraglacial lakes at ~1450 m a.s.l. (ice thickness ~1300 m) and ~1600 m a.s.l. (~1420 m), both inferred to be underlain by thawed beds. Four Autonomous phase-sensitive Radio-Echo Sounders (ApRES) were deployed around the lakes, complemented by a network of continuous GNSS measurements and time-lapse imagery.

Using ApRES-derived vertical strain rates and internal reflections, we aim to detect englacial and subglacial water input, constrain the timing of drainage events, and quantify how quickly water is evacuated. These results will help improve the representation of hydrological processes in ice-sheet models and their predictions of dynamic response to increasing surface melt.

Terrestrial Radar Interferometry as a dual tool for glacier and atmospheric dynamics - Christian Wild

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Ice-surface velocity is a key observable for understanding glacier dynamics, yet its measurement is often complicated by environmental noise and method-specific limitations. Terrestrial radar interferometry (TRI) provides exceptional spatial and temporal resolution, but atmospheric phase delays can obscure true glacier motion and introduce spurious ice-flow variability.

Here we present a novel approach to disentangle atmospheric effects from ice-flow signals by exploiting principles of double-differential interferometry to suppress steady ice motion. Using a classical geophysical inversion framework, we reconstruct time-resolved atmospheric phase screens and apply them to correct individual interferograms across a range of temporal baselines.

We evaluate the method using TRI observations of Grenzgletscher, Switzerland, acquired in autumn 2023 and spring 2024. The correction reduces apparent velocity fluctuations by about 70%, revealing a seasonal acceleration of the icefall of about 25% relative to its spring velocity of roughly 150 m/yr. In addition, the retrieved atmospheric phase screens exhibit coherent spatiotemporal patterns, highlighting the untapped potential of TRI as a dual-purpose tool for both glaciological and atmospheric research.

The Grenzgletscher at 3700 m: Results from a seismic survey complemented by GPR measurements - Emma Chizzali

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The Grenzgletscher, located in the Valais Alps near Zermatt, spans an altitude difference of roughly 2000 meters and is one of the largest glaciers in the Alps. Due to its relatively low accumulation rate and being frozen to the bed at high altitudes (Colle Gnifetti, 4450 m), it is often used as a natural laboratory, emulating polar conditions. Moreover, it is known to be temperate in the ablation zone; hence, it experiences at least one transition from a frozen to a temperate bed. While the glacier has been extensively studied in its upper part, particularly around the Colle Gnifetti, and at lower elevations, it has not been investigated at intermediate-to-high altitudes. As part of the ERC-funded project PHAST, several geophysical surveys have been conducted at a plateau at 3700 since 2024, aimed at characterizing its thermal structure and identifying the location of the frozen-to-temperate basal transition.

This contribution focuses on the seismic component of those field campaigns, particularly on the results of an active seismic study of two ~240-meter-long lines in the center of the 3700 m plateau, in- and across-flow direction, which complement large-area GPR surveys. Besides determining the ice thickness, the study also reveals information on the interglacial and basal conditions in this zone. By combining those findings with insights from GPR measurements along the same lines, the ice-bed interface can be fully characterized with respect to its thermal state, location, and other properties. This information is crucial for upcoming field campaigns to study the physics of sliding, particularly in the subtemperate regime — a primary objective of the PHAST project.

Topographic 3D Post-Stack RTM for UAV-Based GPR Surveys - Linan XU

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Unmanned aerial vehicle (UAV)-based ground-penetrating radar (GPR) has revolutionized the surveying of hazardous and inaccessible glacial environments. However, the resulting datasets often feature highly irregular acquisition surfaces and strong 3D topographic variations that severely compromise conventional migration techniques. To overcome these imaging challenges, we employ a 3D post-stack RTM workflow for GPR acquisition over rugged terrain. Based on a finite-difference time-domain (FDTD) solution of Maxwell's equations, our approach explicitly models wave propagation and directly extrapolates the GPR wavefield from the true acquisition coordinates, thus bypassing the need for error-prone re-datuming.

We validate the algorithm's robustness using complex 3D synthetic models, demonstrating precise structural reconstruction even in the presence of steep dips and strong lateral topographic variations. Furthermore, we apply the workflow to a dense drone-based GPR dataset acquired over a structurally complex surface collapse feature on the Rhône Glacier, Switzerland. The 3D RTM results show excellent focusing of out-of-plane energy, continuous delineation of the rugged glacier bed, and allow for resolution of intricate englacial features such as meandering subglacial channels. These findings demonstrate that explicitly accounting for 3D topography and acquisition geometry via RTM is essential for the reliable interpretation of complex subsurface structures in drone-borne GPR surveys.

Towards a new high-resolution bedrock topography map of the upper part of Grenzgletscher (Switzerland) - Helene Hoffmann

Helene Hoffmann [1], Christoph Mayer [2], Astrid Lambrecht [3], Andreas Bauder [4], Gabriela Racz [5], Mélissa Francey [6], Daniel May [7], Dustin Schroeder [8], Joachim Wassermann [9], Steven Franke [10], Cristina Gerli [11], Emma Chizzali [12], Elisa Mantelli [13]

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A thorough understanding of ice stream formation, evolution and dynamics is crucial to investigate changes in ice sheet discharge and thus sea level change in the future. Within the PHAST project, exploring ice stream dynamics and especially subtemperate sliding, we present first results from new ice-penetrating radar surveys on the model region of Grenzgletscher (Monte Rosa Massif, Switzerland). Using both ground-based and airborne (helicopter and drone) radar systems we obtain a glimpse into the ice at high spatial resolution at Grenzgletscher's accumulation zone. There are only sparse investigations in this glacier zone so far, yet it is a crucial region to understand the flow regime of the whole glacier body. The results from the radar surveys will be used to derive the subglacial topography and to identify potential (subtemperate) sliding zones. These findings will subsequently be used to provide better input data for a full stokes model of glacier flow, thus improving the understanding of mechanisms at the ice base related to glacier flow and sliding.

Tracking meltwater infiltration and refreezing in Greenland firn with UHF ApRES time-series observations - Anja Rutishauser

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Surface melting on the Greenland ice sheet has intensified in recent decades, with direct implications for sea level rise. Firn, a layer of compacted multi-year snow, acts as a critical runoff buffer by retaining meltwater through refreezing within the pore spaces and as discrete ice layers. However, repeated melt-refreeze cycles progressively reduce pore space and form thick, impermeable ice layers that block further percolation and promote lateral runoff, ultimately diminishing the firn's buffering capacity. These processes remain poorly constrained due to a lack of high-resolution in situ observations that capture firn-meltwater processes over full melt-refreeze cycles.

Stationary autonomous phase-sensitive radio echo sounders (ApRES) can derive the firn's bulk liquid water content continuously over a full annual melt-refreeze cycle, but the range resolution of conventional systems (300 MHz center frequency) is insufficient to resolve the vertical distribution of meltwater in near-surface firn. Here, we present hourly time-series observations from a UHF ApRES deployed at Dye-2 in the Greenland percolation zone over the 2025 melt season. Dye-2 experiences annual melt-, percolation-, and refreezing cycles that have produced a heterogeneous firn column with numerous ice layers. The UHF system operates at a 2 GHz center frequency, providing a 4-6 cm vertical range resolution in firn, a substantial improvement over conventional ApRES.

We examine the potential of this dataset to characterize the depth and timing of meltwater infiltration events in firn, derive depth-resolved liquid water content profiles across melt-refreeze cycles, and identify the formation of new ice layers upon refreezing. The radar observations are interpreted alongside atmospheric data and firn temperature profiles from the co-located GC-Net weather station and validated against firn cores and ground-penetrating radar surveys from before and after the melt season.

Using Combined Radar and Seismic Observations to Constrain Subglacial Properties Across the Eastern Shear Margin of Thwaites Glacier - Daniel May

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Radar and seismic methods are both widely used to investigate glacier structure and basal conditions, yet rigorous joint interpretation of radar and seismic reflectivity in glaciological settings remains relatively underexplored. These techniques provide complementary constraints: radar reflectivity, governed by dielectric contrasts, may be more sensitive to thin basal layers and small-scale variations in permittivity due to the short wavelengths of radio waves in ice, whereas seismic reflectivity depends on contrasts in acoustic impedance and, owing to the longer wavelengths of seismic waves, integrates over larger lateral and vertical scales, providing sensitivity to bulk sediment properties and deeper structure. Here, we use forward models to quantify how layered subglacial configurations, including water films, variably saturated sediments, and crystalline bedrock, affect both radar and seismic reflection amplitudes. By exploring combinations of layer thickness and material properties, these models provide a framework for interpreting co-located radar and seismic reflectivity in terms of subglacial thermal and hydrologic conditions. We apply this framework to observations collected across the eastern shear margin of Thwaites Glacier as part of the Thwaites Interdisciplinary Margin Evolution (TIME) project within the International Thwaites Glacier Collaboration (ITGC). We focus on radar reflectivity data derived from the British Antarctic Survey PASIN2 airborne system, as well as seismic reflection profiles acquired during the 2023-24 ground-based field campaign. The eastern shear margin of Thwaites is of particular interest due to its potential for migration and its influence on the future evolution of the West Antarctic Ice Sheet. By comparing modeled and observed amplitudes, we assess spatial variations in basal material properties and thermal state across the shear margin. This provides constraints on the geologic and hydrologic setting of the margin and offers insight into the processes governing its stability and potential evolution, while developing analysis techniques that can be applied to other areas where both radar and seismic data are collected.

Using isochrones in a 3D ice sheet model to reconstruct past ice sheet evolution in the Wilkes Subglacial Basin - Johannes Sutter

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The Wilkes Subglacial Basin (WSB) in East Antarctica features a sea level rise potential rivaling that of the West Antarctic Ice Sheet. It's exposure to the marine ice sheet instability (MISI) in the past and future has been studied only recently, with marine sediment records and modelling indicating periodic episodes of grounding line retreat during past interglacials (Wilson et al., 2018; Sutter et al., 2020; Blackburn et al., 2020) and collapse in future high-emission or idealized scenarios (Mengel et al., 2014; Wang et al., 2024). Whether it's current decline is a harbinger of future collapse is unclear as current ice sheet model- and scenario uncertainties prevent a conclusive projection of ice sheet evolution. Here we calibrate a 3D thermomechanical ice sheet model against a newly traced and dated data-set of internal layers in the region (Bodart et al., 2026). We show the dynamic behaviour of the WSB throughout glacial interglacial cycles and assess the potential and limitations to use internal layers as a direct constraint on past marine ice sheet instabilities.

Using phase-sensitive radar to investigate the Raymond effect in Antarctic ice rises - Marie-Axelle Gillain

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The Raymond effect within ice rises and underneath ice divides of ice sheets arises from the non-linear rheology of the ice and steady-flow conditions. The resulting Raymond arches are usually observed in internal stratigraphy on radargrams and have recently been associated with crystal orientation fabric and ice anisotropy, both detectable with phase-sensitive radar (pRES). Crystal orientation fabric can be inferred through inverse modelling of pRES data by estimating the orientation tensor. The tensor describes the distribution of crystal orientations and is derived from the dielectric properties of ice encoded in the radar backscatter signal.

pRES point measurements were collected along two transects across two ice rises, Hammarryggen and Lokeryggen, both located in Dronning Maud Land, Antarctica. Of the two ice rises, the rheology of Hammarryggen ice rise has previously been investigated (Ershadi et al., 2025). Despite their proximity and similar geometric characteristics, Raymond arches are observed at Hammarryggen but seem absent at Lokeryggen. A possible explanation for this contrast is the more irregular bedrock topography at Lokeryggen, which is investigated in this study.

Combining pRES data with inverse modelling, we compared the rheology of both sites and evaluated the role of bedrock geometry in controlling the presence or absence of Raymond arches. Results indicate weaker anisotropy and reduced crystal alignment at Lokeryggen, consistent with a weaker development of the Raymond effect and suggesting sufficiently strong control of bedrock topography on the local flow regime. These results highlight the importance of bedrock geometry in controlling anisotropy development and demonstrate the potential of inverse modelling of pRES data to constrain ice rheology in ice rises.

Where are Greenland's Grounding Lines? A Bayesian and Open Science Approach for Automated Grounding Line Detection - Michael Shahin

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The grounding line position, where grounded ice first loses contact with the bed, exerts a first-order control on glacier dynamics by influencing the force balance that governs ice flow and the connection between up- and down-flow processes. It is therefore a critical parameter for glacier response in ice sheet models. Identifying the grounding line location is challenging, especially in Greenland, where echograms are noisy due to heavily crevassed terminus regions, and floating ice regions are generally short (2-5 km) compared to Antarctic counterparts. As a result, the grounding line and the more-easily mapped terminus position are often assumed to be co-located for Greenland tidewater glaciers. In response to these challenges, we developed an open framework based on online Bayesian change-point detection, a probabilistic method for detecting changes in time series, with xOPR, a Python package to easily access Open Polar Radar echogram data. Our Bayesian approach strongly agrees with satellite-derived synthetic aperture radar grounding zones for floating ice tongues in North Greenland and can detect the grounding line for heavily crevassed glaciers such as Helheim Glacier. We aim to generate the first-of-its-kind, reproducible Greenland-wide grounding line map, questioning the common assumption that Greenland's tidewater glaciers are grounded at their termini.