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Paths forward in radioglaciology

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Letter

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Abstract

Ice-penetrating radar sounding is a powerful geophysical tool for studying terrestrial and planetary ice with a rich glaciological heritage reaching back over half a century. Recent years have also seen rapid growth in both the radioglaciological community itself and in the scope and sophistication of its analysis of ice-penetrating radar data. This has been spurred by a combination of growing datasets and improvements in computational resources as well as advances in radar sounding instrumentation and platforms. Together, these developments are transforming the field and highlight exciting paths forward for future innovation and investigation.

1. Recent progress in data analysis

The collection and exploitation of radiometric and geometric information in ice-penetrating radar data has transformed our knowledge of the subsurface conditions and processes of ice in the polar regions and across the solar system. In 2019, the International Glaciological Society hosted a symposium and published an associated issue of the Annals of Glaciology focused on *Five Decades of Radioglaciology* (Schroeder and others, 2020). The work presented in these venues included scientific investigations of ice-sheet and glacier bed conditions, radio-wave attenuation, englacial structure, interpretation and the growing of the field of planetary radioglaciology. Those advances and work undertaken since have transformed the analysis of radar sounding data from an activity primarily focused on measuring ice thickness, bed topography and radiostratigraphy to a rich source of geophysical information about a diverse range of glaciological conditions and processes. This transformation was made possible by exploiting the scattering, reflection, attenuation and reflectivity signatures in radar sounding data (Fig. 1). This paper presents selected recent progress in radar sounding data analysis since 2019 with a particular focus on work in the areas of near-surface processes, crystal orientation fabric, subglacial hydrology, basal thermal state and bed morphology and material.

For much of its history, the analysis of radar sounding data has focused on relatively deep subsurface interfaces (e.g. internal layers or the ice/bed interface), however there has been a growing body of work looking at the surface and near surface (e.g. surface roughness, accumulation, firn properties, ice slabs, firn aquifers) (e.g. Case and Kingslake, 2022). For example, recent work has used radar sounding data to assess the impact of extreme melt seasons in Greenland on the production and growth of reduced-permeability ice layers which can affect the infiltration runoff of surface melt in subsequent seasons (Culberg and others, 2021). Additionally, the analysis of the radar signature of near-surface fractures also highlights their potential to enable investigations into the physical processes that underpin their formation and impact on ice-sheet evolution (Altenburg and others, 2022; McLeod and others, 2022).

An area of intense recent activity is the observation and investigation of ice-sheet crystal orientation fabric (COF). The COF of ice, which can affect and encode information about the viscosity of ice flow, can be measured using polarimetric radar sounding data (Jordan and others, 2022). As a result, recent work has focused on the rapid observation of that signature using ground-based, stationary phase-sensitive radar sounding systems (Young and others, 2021; Ershadi and others, 2022) as well as the development of approaches to constrain the birefringent COF signature in more abundant single-polarization radar sounding (Young and others, 2021). In addition to the effect of COF on contemporary ice rheology, this method has also been used to investigate flow around ice divides and ice domes as well as the history and stability of ice streams (Lilien and others, 2021; Young and others, 2021; Ershadi and others, 2022). Across these studies, creative and challenging approaches to analyzing data are shedding light on hard-to-observe conditions occurring at scales far below the intrinsic resolution of radar systems (at the scale of ice crystals) but which can affect and encode macroscopic ice-sheet behavior.

Subglacial water bodies (e.g. subglacial lakes and rivers) were some of the earliest, most common and most distinctive observables investigated in radar sounding data, but have also been the subject of significant recent work (e.g. Napoleoni and others, 2020; Rutishauser and others, 2022). For example, cross-system calibration of overlapping radar surveys collected by different radar systems enabled the analysis of subglacial water flow beneath and between the Thwaites and Pine Island Glaciers (Chu and others, 2021). In a similar vein, geostatistical modeling of basal topography revealed by ice-penetrating data showed that subglacial drainage pathways are sensitive to topographic information below the typical interpolated resolution of bed topography datasets (MacKie and others, 2021). In other work, ice-sheet models have been used to reproduce the along-flow transition from a distributed to channelized basal water

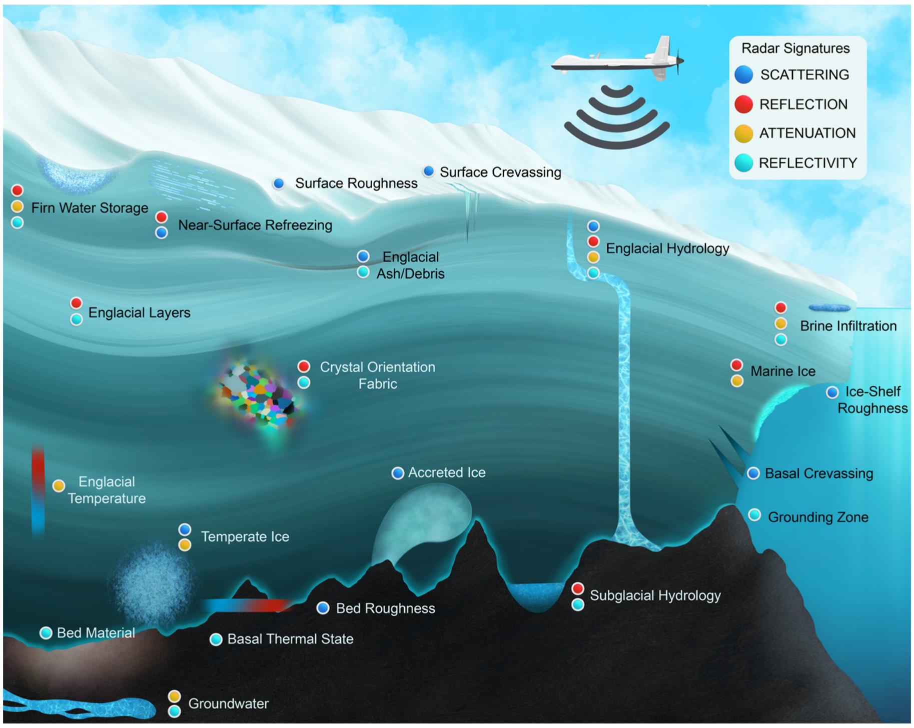

Fig. 1. Advances in the analysis of ice-penetrating radar data have demonstrated the capacity to interpret signatures of radar scattering, reflection, attenuation and reflectivity to observe a growing range of near-surface, englacial and subglacial processes.

system beneath Thwaites Glacier, which had been previously detected using radar bed echo specularity (Hager and others, 2021). Finally, analysis of ultra wide band (UWB) radar sounding data collected using a CReSIS (Center for the Remote Sensing of Ice Sheets) radar operated on an AWI (Alfred Wegner Institute) aircraft over Hiawatha Glacier, Greenland were used to analyze echoes from a groundwater system beneath the bed of the glacier and to determine that the bed above the groundwater table was either frozen or drained (Bessette and others, 2021). Taken together, the studies highlighted here show how radioglaciology continues to improve understanding of subglacial water movement and how it impacts ice-sheet processes.

A related, but distinct, subsurface condition is the basal thermal state of the ice sheet. The strong temperature dependence of the englacial attenuation rate and strong reflectivity contrast between frozen, thawed and wet basal interfaces encode information about the thermal state of the ice sheet into the radiometric signal of radar sounding data. This has been exploited to identify an area of frozen bed in the upper catchment of the eastern tributary of Thwaites Glacier which may play a key role in the routing of ice flow from the Byrd Subglacial Basin into Pine Island Glacier (Chu and others, 2021). If frozen patches like this (or others closer to the coast) thaw, they have the potential to reshape catchment boundaries and mass loss projections (Dawson and others, 2022). Radar observations of the ice-sheet thermal state can also constrain the stability of subglacial lake systems as well as poorly constrained ice-sheet boundary conditions like accumulation rate, melt, advection and geothermal flux (Wolovick and others, 2021; Zeising and Humbert, 2021; Hills and others 2022a, 2022b).

Recent work has also improved the characterization of the material and morphology of ice-sheet beds. Detailed analysis of wide-band and swath-imaging radar systems have revealed fine scale morphology of features on the bed which impacts basal sliding and ice flow (Franke and others, 2021, 2022; Hoffman and others, 2022). As have dense ground-based surveys (Schlegel and others, 2022). This finer-scale, sliding-governing, geologically diagnostic morphology falls (far) below the resolution of typical bed topography data products. Advances in the geostatistical characterization of bed topography have also enabled the representation of that kind of information at the catchment to ice-sheet scale (MacKie and others, 2020). Recent work has also highlighted the potential for geologic properties of the bed to be encoded in the reflectivity signature of the bed echoes (Tulaczyk and Foley, 2020). This kind of higher-fidelity analysis of the geologic and geophysical sources of radar sounding echo strength signatures highlights the need for corresponding advances in both radioglaciological laboratory studies and electromagnetic modeling.

2. Future directions in technology

The 2019 IGS Symposium and Annals of Glaciology issue also addressed the data, systems and processing upon which such studies are based (Schroeder and others, 2020). Crewed, fixed-wing aircraft (e.g. MacGregor and others, 2021) have been the backbone of radar sounding surveys for the field's entire history, however recent advances in instrumentation, platforms and experiments are reshaping how radar sounding data are collected. This transformation is enabling a shift from collecting profiles in order to explore new areas with a single system to ecosystems of distinct and complementary sensors, platforms and observations (Fig. 2). These ecosystems can include, variously, satellite and UAV platforms, multi-static, multi-frequency, polarimetricand radiometric systems instruments, and repeat-pass, interferometric and in situ sensor network experiments.

Given the transformative impact of surface-observing satellite remote-sensing data (e.g. velocity, imagery, altimetry) and the centrality of ice-penetrating radar as a geophysical tool in the field of glaciology, the idea of collecting radar sounding data from orbit is understandably appealing. As a result, a range of Earth-orbiting mission concepts building on the heritage of planetary radar sounders been put forward (Bruzzone and others, 2021; Gogineni and others, 2021; Haynes and others, 2021; Heggy, 2021). Such missions stand to produce more uniform coverage of both bed topography and internal layers, which are currently observed by a patchwork of surveys and systems, and increase the potential for repeat observations (especially during winter). However, the terrestrial clutter environment can pose a

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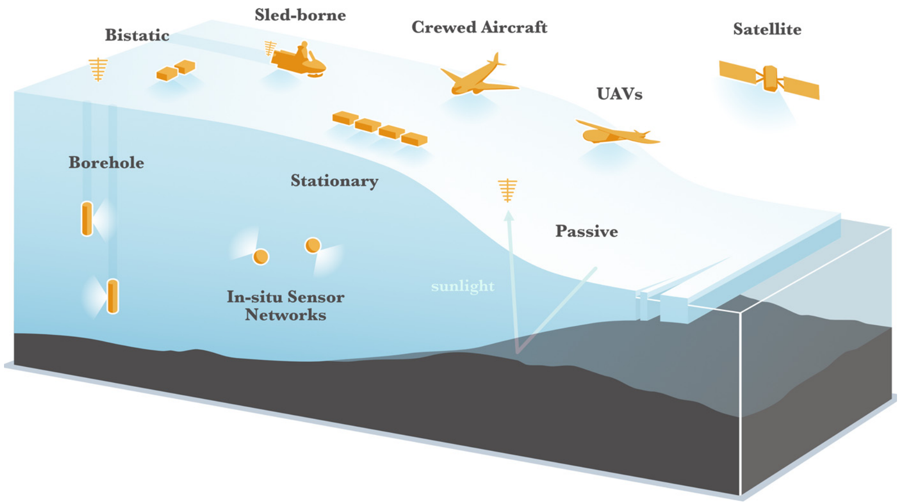

Fig. 2. Developments in instruments and platforms are enabling radioglaciology to transition from a relatively data poor field typified by sparse profiles and point measurement to field richer spatial, temporal, geometric and signal coverage.

significant obstacle, leading many mission concepts to include multi-element and multi-satellite arrays (Culberg and Schroeder, 2020; Bruzzone and others, 2021; Gogineni and others, 2021; Haynes and others, 2021; Altenburg and others, 2022). Additionally, Earth-orbiting radar sounders face challenges from Earth's ionosphere, a more regulated radio emission environment, and dramatically higher temperature-dependent attenuation rates than planetary settings. In this scenario, ice shelves have among the most favorable link budgets for orbital radar sounder detection (Schroeder and others, 2021).

Other promising, novel platforms for collecting radar sounding data are uncrewed aerial vehicles (UAVs) (e.g. Arnold and others, 2020). UAVs offer some of the same potential benefits as satellites (e.g. increased opportunity for repeat, regular and winter observations), but operate in a lower cost, range and altitude envelope. Their lower altitude and greater flexibility in managing energy budgets generally allows UAV-borne sounders to achieve more favorable link budgets and azimuth resolutions. Similarly, their operation below the ionosphere and from remote field sites offers greater flexibility in frequency and transmit power choices. Perhaps most uniquely, UAVs have the capacity to adaptively modify their flight plans to optimize specific scientific goals (Teisberg and others, 2022). This stands to be particularly impactful for time-series observations and topographic bed mapping with interpolation (e.g. kriging, mass-conservation, geostatistics or ML-based methods) which can exploit information in radar echo character or survey geometry to improve bed representation (e.g. Leong and Horgan, 2020; Rahnemoonfar and others, 2021; Teisberg and others, 2021; Liu-Schiaffini and others, 2022). For example, UAV flight-plans can be dynamically optimized to minimize the method-specific post-interpolation uncertainty in bed topography or modeled sea level contribution. As the availability, performanceand price of these platforms continue to evolve, UAVs stand to become increasingly attractive and impactful as sounding platforms.

As advances in platforms increase the abundance of radar sounding data, survey designs are increasingly able to expand from mapping the bed to observing the temporal evolution of the entire ice-sheet subsurface. In the relatively few areas where repeat radar sounding observations have been collected, they have produced new insights into subsurface conditions and processes across timescales from hours to decades. For example, repeat profiling has revealed seasonally evolving englacial water systems in mountain glaciers and multi-year refreezing water sills in Greenland (Church and others, 2020; Culberg and others, 2022). At shorter timescales, repeat-pass sounding can measure vertical displacements which can add a vertical component to the horizontal ice-surface velocities measurements routinely collected by satellites (Miller and others, 2020; Castelletti and others, 2021; Summers and others, 2021). Repeat-pass radar sounding also has the potential to dramatically improve bed topography with swath imaging (e.g. Hoffman and others, 2022). This survey-dependent data richness is particularly well suited to the adaptive and target-specific surveying capacity of UAVs and for feeding data-rich empirical approaches (e.g. physics-informed neural networks; Teisberg and others, 2021).

In addition to the advances in the platforms, acquisition and analysis described above, technical advances are occurring in the radar sounding instruments in and of themselves. This includes UWB systems and systems operating at higher center frequencies (Rodriguez-Morales and others, 2020, Yan and others 2020a; 2020b). Beyond the improved geometric resolution that these systems offer, their frequency diversity is deferentially sensitive to subsurface glaciological observables. For example, recent work has shown that multi-frequency, narrow-band sounding spanning three order of magnitude has the potential to disambiguate the potentially confounding contributions of basal roughness and material properties to the bed reflectivity signal (Broome and Schroeder, 2022). Additionally, polarimetric systems have been developed which can constrain and correct the effect of birefringence on observed bed echo power (Dall, 2020). Recent work has also shown that polarimetric systems are sensitive to subglacial water geometry and orientation (Scanlan and others, 2022). Finally, both active radar sounders and passive microwave radiometers are sensitive to ice-sheet temperatures (Broome and others, 2021; Johnson and others, 2021). Recent work has shown that wide-bandwidth UHF radar sounding data can been used in combination with radiometer data to correct near-surface effects in model-based radiometer temperature retrievals (Xu and others, 2020). Further, other work has shown that radiometer data can be combined with VHF sounder data to exploit their complementary sensitivity to temperature to improve both temperature profile retrievals and to correct for attenuation in bed echo reflectivity (Broome and others, 2021). Taken as a whole, these advances in the information richness of data collected by new radar sounding instruments stand to enhance the range and quality of studies analyzing it.

Recent and ongoing developments in radar sounding systems are also enabling new acquisition and experimental designs including repeat surveys (e.g. Miller and others, 2020) and ground-based deployments (e.g. Li and others, 2022). For example, recent work on developing a ground-based bi-static radar sounding system with direct-path synchronization has enabled the acquisition of data with large and variable offsets

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(up to several ice thicknesses and beyond) which is not achievable with commercial GPR systems (Bienert and others, 2022). These large offsets allow tomographic analyses that can yield improved constraints on englacial attenuation/temperature signals and the complex permittivity of the bed. The application of this type of system to study, for example, the configuration and evolution of englacial water systems stand to further enable the adaptation of variable-offset and array-based analysis approaches from exploration seismology to problems in glacier hydrology. Similarly, the successful and growing deployment of stationary, phase-sensitive radar systems are enabling the collection of time-series observations (with unprecedented temporal sampling) which go beyond measurements of vertical advection, basal melting and englacial water storage to include horizontal ice-flow and crevasse-formation processes (Summers and others, 2021; McLeod and others, 2022). This shows the power of in situ, time-series and extended-deployment radar sounding experiments and paves the way for in situ radio sensor networks that can integrate the advantages of both the temporal sampling of the stationary phase-sensitive systems and the geometric sampling of multi-static systems. The realization and success of these kind of sensor networks will be greatly aided by the experience and innovation involved in creating robust in situ probes currently being deployed beneath and within ice sheets (Prior-Jones and others, 2021). Similarly, the recent development and demonstration of passive radio-sounding systems for ranging and imaging (which exploit existing signals of opportunity rather than transmitting their own signal) have the potential to drive down the resource envelope required for both planetary and terrestrial radar sounding sensor networks (Peters and others, 2021). Whether active or passive, muti- or mono-static, in situ radar sounding sensor networks stand to be an increasingly important tool for radioglaciolgy.

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