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Author for correspondence:
Dustin M. Schroeder, E-mail: dustin.m.schroeder@stanford.edu

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Five decades of radioglaciology

Dustin M. Schroeder[1,2], Robert G. Bingham[3], Donald D. Blankenship[4], Knut Christianson[5], Olaf Eisen[6,7], Gwenn E. Flowers[8], Nanna B. Karlsson[9], Michelle R. Koutnik[5], John D. Paden[10] and Martin J. Siegert[11]

[1]Department of Geophysics, Stanford University, Stanford, USA; [2]Department of Electrical Engineering, Stanford University, Stanford, USA; [3]School of GeoSciences,University of Edinburgh, Edinburgh, UK; [4]Institute for Geophysics, University of Texas, Austin, USA; [5]Department of Earth and Space Sciences, University of Washington, Seattle, USA; [6]Alfred-Wegener-Institut, Helmholtz-Zentrum für Polar- und Meeresforschung, Bremerhaven, Germany; [7]University of Bremen, Bremen, Germany; [8]Department of Earth Sciences, Simon Fraser University, Vancouver, Canada; [9]Geological Survey of Denmark and Greenland, Copenhagen, Denmark; [10]Center for the Remote Sensing of Ice Sheets, University of Kansas, Lawrence, USA and [11]Grantham Institute, and Department of Earth Science and Engineering, Imperial College London, London, UK

Abstract

Radar sounding is a powerful geophysical approach for characterizing the subsurface conditions of terrestrial and planetary ice masses at local to global scales. As a result, a wide array of orbital, airborne, ground-based, and in situ instruments, platforms and data analysis approaches for radioglaciology have been developed, applied or proposed. Terrestrially, airborne radar sounding has been used in glaciology to observe ice thickness, basal topography and englacial layers for five decades. More recently, radar sounding data have also been exploited to estimate the extent and configuration of subglacial water, the geometry of subglacial bedforms and the subglacial and englacial thermal states of ice sheets. Planetary radar sounders have observed, or are planned to observe, the subsurfaces and near-surfaces of Mars, Earth's Moon, comets and the icy moons of Jupiter. In this review paper, and the thematic issue of the *Annals of Glaciology* on 'Five decades of radioglaciology' to which it belongs, we present recent advances in the fields of radar systems, missions, signal processing, data analysis, modeling and scientific interpretation. Our review presents progress in these fields since the last radio-glaciological *Annals of Glaciology* issue of 2014, the context of their history and future prospects.

Introduction

Five decades of radioglaciology (the use of radio waves to investigate ice masses of all types) since the first data were published have seen a progression of instruments and platforms, as well as data processing and analysis approaches applied to a growing data archive (e.g. Stern, 1930; Steenson, 1951; Robin, 1975; Gogineni and others, 1998; Dowdeswell and Evans, 2004; Allen, 2008; Turchetti and others, 2008). Radar-sounding (also known as ice-penetrating radar) data have been used to observe ice thickness, basal topography and englacial layers across Antarctica and Greenland, as well as many ice caps and glaciers. Major data-collection efforts started in the late 1960s and early 1970s, including a collaboration between the Technical University of Denmark, Scott Polar Research Institute, and National Science Foundation (TUD-SPRI-NSF) to map the bed of Antarctica. Other early surveys were also led by Russia, Germany, Iceland, Italy, China, and Canada (among others) across Antarctica and Greenland, as well as Iceland, Arctic Ice Caps, and mountain glaciers (e.g. Drewry, 1983; Bingham and Siegert, 2007; Björnsson, 2020; Popov, 2020). Planetary radar sounders have also been used, or are planned, to observe the subsurface and near-surface conditions of Mars, Earth's moon, comets and the icy moons of Jupiter (e.g. Seu and others, 2007; Jordan and others, 2009; Kofman and others, 2010; Bruzzone and others, 2013; Kofman and others, 2015; Patterson and others, 2017; Blankenship and others, 2018). Fully exploiting the valuable information from these data, such as ice-sheet bed topography, the distribution of subglacial water, the spatial variation of basal melt, the transition between frozen and thawed bed conditions, englacial temperature, histories of accumulation, flow, and the distribution of age in ice masses remains an active area of international research. In this review paper, and the thematic issue of the *Annals of Glaciology* on 'Five decades of radioglaciology' to which it belongs, we present recent advances in the field in the context of their history and future prospects. We include papers published in this issue, topics presented at an International Glaciological Society Symposium on the same theme hosted at Stanford University during the summer of 2019, and work added to the published literature since the last thematic Symposium and Annals issue focused on radioglaciology in 2014.

Data

The data collected by radar surveys in the last five decades have transformed our appreciation of glacier and ice-sheet beds and how ice flows over them. Prior to this era, such information was gained from seismic data, taking orders of magnitude longer to acquire. Early radar

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surveys witnessed significant improvements in survey design, instrument capability (e.g. the Technical University of Denmark System), platforms (e.g. the US Hercules LC-130) and coastal airstrips, leading to systematic surveys of the Greenland and Antarcticice sheets (Sorge, 1933; Robin, 1958; Gudmandsen, 1975; Drewry, 1983). In the case of Antarctica, the TUD-SPRI-NSF collaboration collected over 400 000 line-km of data during the 1970s and, in some regions, these data provide the only measurements ever taken. By the early 1980s, those first long-range airborne radar surveys had ended, giving way to regional studies collected by, for example, Russian and German programs and the US Support Office for Aerogeophysical Research (SOAR) in Antarctica (Blankenship and others, 1993; Behrendt and others, 1994; Bell and others, 1998; Hempel and others, 2000; Masolov and others, 2006; Dean and others, 2008; Turchetti and others, 2008). Other examples include surveys of glaciers and ice caps in Iceland, Alpine glaciers, Svalbard and the Russian and Canadian Arctic (e.g. Dowdeswell and others, 1986, 2002, 2004; Björnsson and others, 1996; Fürst and others, 2018; Pritchard and others, 2020).

In the early 2000s, the Bedmap Consortium produced a new compilation of radar data from Antarctica for which the TUD-NSF-SPRI data still formed by far the most significant contribution, with dozens of other regional-scale surveys that form a patchwork coverage of parts of the ice sheet while other regions remained completely free of data (Lythe and Vaughan, 2001). Bedmap2 followed a decade later, including additional regional surveys as well as long- and medium-range airborne studies returned in 2008 by the US–UK–Australia–China–French ICECAP project and NASA's Operation IceBridge (OIB) (Holt and others, 2006; Vaughan and others, 2006; Bell and others, 2011; Young and others, 2011; Ross and others, 2012; Fretwell and others, 2013). However, several regions remained free of data (Pritchard, 2014). Other compilations are now due that will incorporate new data that have been acquired to fill many of Bedmap2's gaps, including, for example, across Marie Byrd Land, West Antarctica, the Recovery Basin/South Pole, the Dome F region and Princess Elisabeth Land, as well as newly remastered TUD-NSF-SPRI film data and updated thickness measurements for the Ross Ice Shelf (Tang and others, 2016; Young and others, 2016; Popov, 2017; Humbert and others, 2018; Jordan and others, 2018a; Karlsson and others, 2018; Morlighem and others, 2019; Paxman and others, 2019; Schroeder and others, 2019; Tinto and others, 2019). Compared to Antarctica, surveys of Greenland starting in the 1990s by the University of Kansas as part of NASA's Program for Arctic Regional Climate Assessment (PARCA) and later OIB have led to relatively abundant and mutually interpretable observations of the ice-sheet bed and englacial properties (Bamber and others, 2013; Gogineni and others, 2014; MacGregor and others, 2015a; Morlighem and others, 2017).

In addition to the collection of radar sounding profiles, interpolation is a critical component of producing bed topography maps. Previous approaches focused on grid interpolation techniques such as spline interpolation or kriging (e.g. Fretwell and others, 2013). However, in many regions, this gridded topography falls short of capturing topography at the scales most critical for resolving ice-flow processes (Durand and others, 2011; King and others, 2016; Bingham and others, 2017; Kyrke-Smith and others, 2018). For this reason, other approaches, such as mass-conservation modeling or geostatistical approaches, which can provide multiple observation-consistent realizations, provide improved interpolations of bed topography (e.g. Rasmussen, 1988; Warner and Budd, 2000; Goff and others, 2014; Morlighem and others, 2017; MacKie and others, 2019).

Future surveys are unlikely to resemble those conducted previously since ice-sheet models require that data are collected with strategies optimized for their purpose, including flowlines for process interpretation, ground-based time-series for local process monitoring, and repeat flights (Kingslake and others, 2014; Nicholls and others, 2015; Chu and others, 2016; Khazendar and others, 2016; Holschuh and others, 2017; Davies and others, 2018; Schroeder and others, 2018; Young and others, 2018; Bartlett and others, 2020). These process- and site-specific surveys can also take advantage of systems with wider bandwidths and larger antenna arrays that provide enhanced performance, but with more limited range (e.g. Rodriguez-Morales and others, 2013; Kjær and others, 2018). Ultimately, new platforms, such as rovers, drones and satellites stand to transform the way radar-sounding observations are made (Jezek and others, 2006; Koh and others, 2010; Arcone and others, 2016; Freeman and others, 2017; Dall and others, 2018; Carrer and others, 2018; Gogineni and others, 2018; Culberg and Schroeder, 2019; Arnold and others, 2020).

Systems

Early radar sounding systems spanned a range of frequency, bandwidth, power and array configurations including both short mono-pulse and chirped-waveform systems (Allen, 2008; Gärtner-Roer and others, 2014). However, until the 1990s (and the availability of faster and lower-cost electronics) the data recorded remained 'incoherent', limiting the azimuth resolution and processing gain below that achievable with phase-coherent stacking and Synthetic Aperture Radar (SAR) processing (Musil and Doake, 1987; Hamran and Aarholt, 1993; Leuschen and others, 2000; Legarsky and others, 2001; Hélière and others, 2007; Peters and others, 2007). For stationary ground-based systems, a similar gain in the achievable post-processing signal tonoise ratio (SNR) and range-estimate precision has been achieved by coherent 'phase-sensitive' frequency-modulated continuous wave (FMCW) radars (Nicholls and others, 2015).

Just as coherent radar sounders enabled improved along-track resolution and processing gain, the development of systems with multi-channel cross-track arrays improved cross-track resolution, processing gain, clutter discrimination and swath mapping (Gogineni and others, 1998; Paden and others, 2010; Wu and others, 2011; Rodriguez-Morales and others, 2013; Castelletti and others, 2017; Holschuh and others, 2020; Scanlan and others, 2020). This is also true for ground-based multiple input, multipleoutputimplementations of the 'phase-sensitive' FMCW radars mentioned above (Young and others, 2018). While these multi-channel sounders do achieve some diversity in viewing angle and englacial propagation, true bistatic observations and tomographic inversions can be exploited to provide much richer constraints on subsurface properties including, for example, using commercial pulsed ground-penetrating radar (GPR) systems in common mid-pointor borehole configurations to achieve wider (though coherence-limited) offsets (e.g. Kofman and others, 2015; Holschuhand others, 2016; Patterson and others, 2017; Church and others, 2019).

The evolution of distinct radar sounding systems has resulted in a diversity of frequencies, spanning HF (3–30 MHz), VHF (30–300 MHz), UHF (300 MHz–3 GHz) and higher frequency bands (Gudmandsen, 1975; Paden and others, 2005; Hélière and others, 2007; Peters and others, 2007; Allen, 2008; Shi and others, 2010; Hindmarsh and others, 2011; Rignot and others, 2013; Rodriguez-Morales and others, 2013; Dall and others, 2018; Yan and others, 2018). Although, this diversity can make it challenging to compare or combine distinct datasets, it also offers the opportunity to probe the radio-frequency responseof the ice sheet to constrain conditions and processes with greater fidelity (e.g. Carrer and Bruzzone, 2017; Winter and others, 2017).

In addition to systems capable of recording amplitude, phase and channel information, radar sounder development has also

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included systems that record multiple polarizations (e.g. Vaughan and others, 2006; Dall and others, 2010). These systems allow for the analysis of crystal-fabric orientation from polarization information (Doake and others, 2002; Fujita and others, 2003; Matsuoka and others, 2003; Eisen and others, 2007; Drews and others, 2012; Li and others, 2018; Wang and others, 2018; Jordan and others, 2019). This information can be used to constrain the depth distribution of the crystal orientation fabric along survey lines, enabling the investigation of processes occurring in ice masses, comparison to ice-dynamic models, and interpretation of particle-astrophysical observations (e.g. Jordan and others, 2019, 2020a,b; Shoemaker and others, 2020).

Technical advances in available hardware have also allowed the development of stationary systems designed for long-term (several months to years) autonomous operation with repeated observations over cycles ranging from minutes to days, targeting the temporal evolution of a particular site (Nicholls and others, 2015; Kendrick and others, 2018; Mingo and others, 2020; Vankova and others, 2020). To further address the power demands of generating an active radar signal (particularly in the extreme resource constraints of planetary missions) passive radar sounding is also being developed as a new radioglaciological technique to exploit Jovian radio noise, or that from the Sun, as sources for radio echo detection, with the promise to enable pervasive monitoring of subsurface conditions by low-cost, low-power sensor networks (Romero-Wolf and others, 2015, 2016; Schroeder and others, 2016b; Peters and others, 2018).

Processing

Processing radar-sounding data turns low-SNR, low-resolution, high-clutter raw data into usable radargrams. With the exception of a subset of short-pulse systems such as commercial GPRs and some legacy sounders still in use today nearly all radar sounder processing begins with pulse-compression of a chirped waveform using some windowing function for range-sidelobe suppression, some amount of on-board pre-summing to increase SNR and moderate data-rates, and filtering (e.g. Peters and others, 2007; Booth and others, 2010; Lilien and others, 2020; Wang and others, 2020). For coherent radar-sounding data, along-track SAR focusing is also nearly ubiquitous to improve the SNR, signal to clutter ratio and azimuth resolution (Legarsky and others, 2001; Hélière and others, 2007; Peters and others, 2007). Additionally, azimuth processing that evaluates along-track coherence, multiple apertures, large coherent apertures, layer-specific phase histories, or squinted processing, enhance layer resolution or provide information about the scattering function and fine-scale geometry of the bed (e.g. Oswald and Gogineni, 2008; Schroeder and others, 2014a; Heister and Scheiber, 2018; Castelletti and others, 2019; Ferro, 2019). For multi-channel sounders, cross-track processing can considerably increase the level of resolution, with large benefits for tomographic swath imaging of the ice bottom and internal structure, in particular of irregular disturbances of basal ice, such as folds or entrained matter (e.g. Paden and others, 2010; Wu and others, 2011; Rodriguez-Morales and others, 2013; Castelletti and others, 2017; Young and others, 2018).

In addition to the instantaneous or single-survey coherence required for focusing and array processing, modern high-stability and low-noise systems make it feasible to perform repeat-pass interferometric analysis on sounding data from ground-based platforms (Kingslake and others, 2014; Nicholls and others, 2015). While point-based observations of phase changes over time periods, ranging from months to years, are now widespread, for example, to deduce basal melt rates of ice shelves and vertical velocities in ice sheets, its spatial application to large airborne surveys is relatively recent and, as yet, rarely applied (e.g. Corr and others, 2002; Castelletti and Schroeder, 2017; Stewart and others, 2019).

Another critical area of innovation in radioglaciological data processing and analysis is automatic methods for radargram image interpretation. These include algorithms for layer tracking, bed and surface mapping and basal feature categorization (Sime and others, 2011; Crandall and others, 2012; Ferro and Bruzzone, 2012; Ilisei and Bruzzone, 2015; Panton and Karlsson, 2015; Carrer and Bruzzone, 2016; Rahnemoonfar and others, 2017; Berger and others, 2018; Donini and others, 2019). Success of these approaches is a prerequisite to be able to cope efficiently with the data volume of future surveys and effectively exploit their information content.

Ice sheet and glacier bed conditions

Five decades of radioglaciology have produced a diverse array of information pertaining to subglacial conditions. The vast majority of surveys have been motivated by the primary imperative of locating the bed reflector either to estimate the total volume and sea-level potential of the major ice sheets or to map basal topography (e.g. Bailey and others, 1964; Gudmandsen, 1969; Bamber and others, 2013; Fretwell and others, 2013). In the last two decades, the emphasis has expanded to the investigation of the geometric, thermal and material properties of the basal interface, by using the sounder-appropriate radar equation to solve for either basal reflectivity or echo character (Peters and others, 2005; Oswald and Gogineni, 2008; Schroeder and others, 2013; Grima and others, 2014b; Haynes and others, 2018b; Haynes, 2020).

Radar sounding data encode a range of information about the roughness of the basal interface. The most common glaciological definition of roughness is the extent to which terrain varies vertically over a given horizontal distance (Rippin and others, 2014). As mapped across a number of regions of Antarctica and Greenland, roughness variations at the multi-kilometer scale inform us about present and past ice-stream and ice-stream tributary locations (Siegert and others, 2004; Bingham and Siegert, 2007, 2009; Rippin and others, 2014; Frank and others, 2020). Additionally, basal roughness at the wavelength-scale can affect the character of the reflected echo including its specularity (or spread in Doppler), waveform abruptness, statistical distribution of echo amplitudes, as well as the radar-derived topography itself (Goff and others, 2014; Grima and others, 2014a; Rippin and others, 2014; Schroeder and others, 2014a; Jordan and others, 2017; Heister and Scheiber, 2018; Eisen and others, 2020; Franke and others, 2020; King, 2020). Principles from these studies have also been translated to paleoglacial landscapes and have also been compared to contemporary bed morphology and lithology (Gudlaugsson and others, 2013; Schroeder and others, 2014c; Falcini and others, 2018; Cooper and others, 2019; Muto and others, 2019; Holschuh and others, 2020).

In radioglaciology, although reflectivity is used as an umbrella term encompassing all methods used to interrogate variations in the magnitude of the bed echo, it most commonly and appropriately refers to changes in the material properties (and therefore Fresnel reflection coefficient) of the ice–bed interface (Peters and others, 2005). While there are challenges in correcting or constraining attenuation or surface roughness losses, the basal thermal state (frozen or thawed and the presence or absence of water) fundamentally affects the reflection coefficient (Peters and others, 2005; Matsuoka, 2011; Schroeder and others, 2016a). The reflection coefficient can provide a constraint on where the bed is frozen or thawed, the reach and character of ocean water at the grounding line, and basal conditions of ice streams (Peters and others, 2005; Jacobel and others, 2009; Ashmore and others, 2014; Christianson and others, 2016). The presence and volume of inferred basal water bodies have also

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been used to place constraints on the basal thermal state and/or geothermal flux, while layer drawdown has also been used to constrain basal melt rates and geothermal flux (Fahnestock and others, 2001; Catania and others, 2006; Buchardt and Dahl-Jensen, 2007; Schroeder and others, 2014b; Rezvanbehbahani and others, 2017, 2019; Seroussi and others, 2017; Jordan and others, 2018a,b).

Perhaps the most widely and successfully studied basal feature with radar sounding data has been subglacial water bodies, particularly subglacial lakes in Antarctica using the principle that subglacial water results in reflections brighter than surrounding bed echoes in radar data (Oswald and Robin, 1973; Peters and others, 2005; Wright and Siegert, 2012). Because of the coherent specular character of subglacial water, small fractional areas can dominate the echo both in terms of reflectivity and geometric spreading (Haynes and others, 2018b). This has been exploited to automatically detect lakes in radar sounding data (Carter and others, 2007; Ilisei and others, 2018). Additionally, lake-bottom echoes have been used to probe water thickness and conductivity (Gorman and Siegert, 1999). Surface altimetry data have also been used to infer active lakes around Antarctica where the ice surface has been observed to rise and fall, yet, surprisingly, these lakes typically do not have higher reflectivities than their surroundings in radar data, showing that we still have much to learn about Antarctic subglacial lakes (Carter and others, 2007; Smith and others, 2009; Siegfried and others, 2016; Carter and others, 2017; Siegert, 2018). This is also emphasized by different observations with different systems of the same regions, leading to contrasting interpretations (e.g. Bell and others, 2007; Humbert and others, 2018). Recent advances in the analysis of subglacial hydrology from radar sounding data has focused on subglacial water systems beyond Antarctic subglacial lakes (e.g. Young and others, 2016). This includes utilizing bed-echo strength and character to investigate water body geometry and dynamic configuration, catchment-scale drainage systems and grounding zones (Schroeder and others, 2013, 2014a; Ashmore and Bingham, 2014; Christianson and others, 2016). In Greenland, a range of studies has investigated the distribution of subglacial water, including lakes, topographically controlled seasonal storage and gradients in water near the onset of fast flow (Oswald and Gogineni, 2008; Palmer and others, 2013; Chu and others, 2016, 2018b; Jordan and others, 2018b; Oswald and others, 2018; Bowling and others, 2019). Hypersaline lakes have also been identified beneath Devon Ice Cap in Arctic Canada (Rutishauser and others, 2018).

Radio-wave attenuation

Laboratory analyses of radio-wave absorption in ice, as well as radar sounding data from the field, have revealed that while relatively homogeneous ice is a very low-loss medium for radio-waves at VHF frequencies, there is a loss of returned power englacially due to dielectric absorption of radiowaves in ice. Dielectric absorption is proportional to the electrical conductivity of the ice, which is related to ice temperature and the presence of impurities (Glen and Paren, 1975; Johari and Charette, 1975; Moore and Fujita, 1993; Stillman and others, 2013; Pettinelli and others, 2015). Without sufficiently distinct basal echo signals (e.g. relative changes that delineate sharp boundaries, such as ice stream shear margins) or sufficiently effective corrections, uncertainty in englacial attenuation can obfuscate the interpretation of basal reflectivities (Matsuoka, 2011; Siegert and others, 2016; Schroeder and others, 2016a).

Empirical methods for estimating englacial attenuation using bed echoes range from simple linear fitting to adaptive or model-informed fitting (Jacobel and others, 2009; Wolovick and others, 2013; Ashmore and others, 2014; Jordan and others, 2016; Schroeder and others, 2016c). Englacial layers themselves have also been used to derive attenuation (Matsuoka and others, 2010; MacGregor and others, 2015b). These approaches can also be intercompared or combined (e.g. Hills and others, 2020; Jeofry and others, 2020). Additionally, investigating attenuation with variable offset can constrain englacial, attenuation, though there is a limit on the maximum offset achievable with commercial GPR systems (Holschuhand others, 2016). These empirical attenuation values can either be used to correct losses to enable reflectivity interpretation or interpreted themselves as a proxy for englacial temperature.

In addition to applying empirical methods that estimate and correct for attenuation, attenuation rate can also be modeled (Matsuoka and others, 2012). This approach can be used when correcting attenuation effects or constraining the bed conditions using layer power (MacGregor and others, 2015b; Chu and others, 2018b). Modeled attenuation can be compared to observations to constrain englacial temperature, parameterize basal conditions to match surface velocities or to quantify englacial water from persistent firn aquifers (Forster and others, 2014; Schroeder and others, 2016c; Chu and others, 2018a; Holschuh and others, 2019).

Englacial structure

The study of radar-derived englacial properties dates back almost to the beginning of radioglaciology (e.g. Harrison, 1973; Gudmandsen, 1975; Paren and Robin, 1975). The englacial information that radar data contain has the potential to provide insights into ice-flow processes as well as climatic forcings. The layers have thus been widely used with models for ice-core site selection, stratigraphic control and inferring accumulation histories (see below) (e.g. Jacobel and Hodge, 1995; Cavitte and others, 2016; Parrenin and others, 2017). In recent years, the radioglaciological community has seen an increase in the retrieval of such information from radar data although barriers remain to the widespread usage of englacial stratigraphy. This is due to the fact that a substantial amount of manual work is generally needed to convert the stratigraphic information into, for example, dated isochrone surfaces that can readily be used by ice-flow models. Attempts to overcome this obstacle include methodologies focusing on quantifying the slope of the stratigraphy and extracting information from slopes instead (Panton and Karlsson, 2015; Holschuh and others, 2017; Castelletti and others, 2019). Studies focusing on the reorganization of ice flow often avoid tracing isochrones and take a qualitative approach. For example, imprints of shear margin migration or change in flow direction are typically identified based on the amount of stratigraphic disruption. Examples include studies showing changes in ice-flow structure or folded stratigraphy in Greenland and entrained debris in a glacier in Patriot Hills, West Antarctica (Catania and others, 2006; Martín and others, 2009; Dahl-Jensen and others, 2013; Bell and others, 2014; Bingham and others, 2015; Kingslake and others, 2016; Winter and others, 2019; Ross and Siegert, 2020). Advances in processing radargrams to extract ice-sheet structure make it possible to interpret these features in regions of complex flow (Elsworth and others, 2020).

The tracing of englacial isochrones in the radar data acquired over Greenland between 1993 and 2013 by the University of Kansas Center for Remote Sensing of Ice Sheets and OIBis a vital step forward in the efforts to make englacial stratigraphic information readily available (Gogineni and others, 1998, 2001; MacGregor and others, 2015a; Arnold and others, 2018). The resulting data archive has increased the availability of traced isochrones by orders of magnitude. Derived results include evidence of Holocene deceleration of the Greenland ice sheet, and improved constraints on its internal temperature (MacGregor and others, 2015b, 2016). In Antarctica, no such large-scale synthesis has been undertaken, but the SCAR AntArchitecture

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project has the potential to address this critical gap. Several studies have successfully linked isochrones between deep ice-core sites: the interior Antarctic ice-core sites are now linked from Dome Concordia through Vostok to Dome Argus, and Dome Fuji has been linked to the EPICA-DML (European Project for Ice Coring in Antarctica Dronning Maud Land) ice-core site (Cavitte and others, 2016; Winter and others, 2019). These efforts will play a key role in identifying optimal drill sites for the Oldest Ice (ice older than 1.5 million years, Fischer and others, 2013).

Other important derived products from traced isochrones are the past accumulation rates and patterns (e.g. Eisen, 2008). Recent work in this area has been carried out on time-scales ranging from annual to centennial to millennial (Eisen and others, 2008; Medley and others, 2014; Nielsen and others, 2015; Grima and others, 2016; Karlsson and others, 2016; Koenig and others, 2016; Koutnik and others, 2016; MacGregor and others, 2016; Lewis and others, 2017; Cavitte and others, 2018; Karlsson and others, 2020; Montgomery and others, 2020). Efforts to automate layer tracing continue, which include methodologies that use seed points to initiate semi-automatic tracing routines as well as fully automatic schemes. In parallel, the extra-terrestrial radar community has been working toward automatically extracting layer information from the Martian orbital radar sounders (Ferro and Bruzzone, 2012; Onana and others, 2015; Xiong and others, 2018; Xiong and Muller, 2019). Delf and others (2020) (this issue) present some strategies for assessing automated algorithms inherited from both terrestrial and planetary work.

Interpretation

The history and dynamics of glaciers and ice sheets are written into radar-sensitive properties of these ice masses. Interpretation of radar data may be qualitative or quantitative, with the latter facilitated by process-based models in particular. In its most common form, however, interaction between radioglaciology and models is often limited and one-directional: radio-echo sounding of ice depth furnishes the basal boundary condition for ice-flow models (e.g. Fretwell and others, 2013). While gaps in our knowledge of basal topography have spurred model development, radar studies have produced a trove of other data and discoveries, including, for example, evidence of retreat, past flow, basal accretion, firn-aquifers and ice-shelf conduits, that remain under-exploited by theory and models (Conway and others, 1999; Siegert and others, 2004; Bingham and Siegert, 2007; Bell and others, 2011; Morlighem and others, 2011; Forster and others, 2014; Bons and others, 2016; Drews and others, 2017; Jordan and others, 2018a; Leysinger Vieli and others, 2018; Holschuh and others, 2019; Langhammer and others, 2019).

Theoretical work has established relationships between the architecture of internal layers and ice-sheet accumulation, topography, rheology and dynamics (e.g. Nereson and Waddington, 2002; Siegert, 2003; Hindmarsh and others, 2006; Parrenin and others, 2006; Martín and others, 2009; Felix and King, 2011). Internal layers have been integrated with models to determine ice rheology and to understand flow history, including migration of ice streams, divides and domes (e.g. Nereson and Raymond, 2001; Ng and Conway, 2004; Catania and others, 2006; Gillet-Chaulet and others, 2011; Pettit and others, 2011; Drews and others, 2015; MacGregor and others, 2016). The discovery of deep internal structures that do not conform to the bed has prompted new model exploration of englacial and basal processes including interpretation of their radar scattering character, with implications for interpreting ice-sheet dynamics and the climate archive (e.g. Bell and others, 2011, 2014; Dahl-Jensen and others, 2013; Wolovick and others, 2013; Wrona and others, 2017; Kjær and others, 2018; Goldberg and others, 2020).

In addition to englacial layers, radar sounding data have been used to detect channels under ice shelves that have also been the focus of a suite of model investigations (e.g. Jenkins, 2011; Le Brocq and others, 2013; Sergienko, 2013; Drews, 2015; Alley and others, 2016). Theory and observation are yielding new insight into ice–ocean interactions and real-time geomorphic processes in grounding zones, the influence of topography on channel position and formation, and the uncertain relationship between channels and ice-shelf stability (e.g. Gladish and others, 2012; Greenbaum and others, 2015; Khazendar and others, 2016; Drews and others, 2017; Gourmelen and others, 2017; Jeofry and others, 2018).

With so much radioglaciological data, the advent of resources such as ice-sheet-wide radiostratigraphic archives should help operationalize data–model integration (MacGregor and others, 2015a). But how are such archives best exploited? Inverse methods present a natural approach, although the persistent problem of non-uniqueness demands care in defining the problem, choosing the tools and incorporating constraints (e.g. Waddington and others, 2007; Eisen, 2008; Gudmundsson, 2011; Koutnik and Waddington, 2012; Nielsen and others, 2015; Koutnik and others, 2016). Computational costs of large-scale models further demand attention to efficiency, for example, by the use of adjoint methods (e.g. Hascoët and Morlighem, 2018). Consideration should also be given to the information content of different variables, including those sensitive to basal processes, as well as to the limitations of rendering 3-D effects in 2-D data (Leysinger-Vieli and others, 2007; Holschuh and others, 2017; Young and others, 2018). While we must devise modeling strategies to make best use of the data, this is far from a case of models simply lagging observations. Challenges remain in combining disparate datasets, conditioning data for comparison with modeling and utilizing radiometric, interferometric and polarimetric information in modeling (e.g. Hindmarsh and others, 2009; Schroeder and others, 2016c; Castelletti and others, 2017, 2019; Winter and others, 2017, 2019; Chu and others, 2018b; Jordan and others, 2019). Finally, data–model interaction is a two-way street: testable hypotheses produced by theory and models may suggest new observational targets or provide new reasons to tap the rich radioglaciological archive (e.g. Raymond, 1983; Arthern and others, 2015).

Planetary radioglaciology

The bulk of extra-terrestrial ice-sounding data stems from the planet Mars, specifically from the two orbital radar sounders: MARSIS (Mars Advanced Radar for Subsurface and Ionospheric Sounding) onboard the European Space Agency's Mars Express, and SHARAD onboard the Mars Reconnaissance Orbiter launched by NASA (National Aeronautics and Space Administration, USA) (SHAllow RADar, Seu and others, 2007; Jordan and others, 2009). The difference in frequency between the two sounders allowed for different penetration depths and thereby different insights into the planet's ice bodies (MARSIS operated at 1.3–5.5 MHz in its subsurface sounding mode while SHARAD used 15–25 MHz). Although both instruments are now inactive, analysis of the data is ongoing and continues to contribute to our understanding of water ice on Mars. The results from the radar sounders documented the high water content of the Martian water-ice reservoirs (e.g. Grima and others, 2009). These have now been supplemented by more detailed studies of the composition of the polar ice bodies, the immediate subsurface of the north pole, and the mid-latitude water ice reservoirs (Guallini and others, 2018; Mirino and others, 2018; Petersen and others, 2018; Putzig and others, 2018; Nerozzi and Holt, 2019). In addition, the radar sounding has confirmed areas on

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the planet also contains significant volumes of buried water ice (Bramson and others, 2015; Stuurman and others, 2016). One of the most prominent findings is the discovery of a signal that shares similarities with those of a liquid water body (Orosei and others, 2018). In the MARSIS data, this proposed 'subglacial lake' has characteristically bright and specular reflections and was found 1.8 km below the South Polar Layered Deposits. The salt content and/or heat flux necessary to form and sustain such a lake is, however, still debated (Sori and Bramson, 2019). In addition to these findings, the radar data have successfully been utilized to gain insights into the glaciological and climatological processes on the planet, including the deformational properties of Martian water ice, and the past climate history and accumulation patterns of both the North Polar Layered Deposits and the South Polar Layered Deposits (Karlsson and others, 2015; Parsons and Holt, 2016; Smith and others, 2016; Whitten and others, 2017; Nerozzi and Holt, 2018; Lalich and others, 2019; Schmidt and others, 2019). The radar data have also been used to reconcile observations from visual imagery with the radar-imaged englacial stratigraphy (Christian and others, 2013; Lalich and Holt, 2017).

Moving further afield, two radar sounders are now under preparation to probe the subsurface of the Jovian system. Two instruments have been selected for upcoming missions to Ganymede and Europa: the 9 MHz frequency Radar for Icy Moons Exploration (RIME) instrument on board the European Space Agency's Jupiter Icy Moons Explorer (JUICE) and the 9 and 60 MHz frequency Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON) instrument on board NASA's Europa Clipper (Bruzzone and others, 2013; Pappalardo and others, 2015; Lorente and others, 2017; Blankenship and others, 2018). These sounders are designed to probe the moons' interiors and have penetration depths which are functions of surface roughness, volume scattering, ice-shell thermal structure, chemistry and the character of the ice/water interface (Moore, 2000; McKinnon, 2005; Blankenship and others, 2009; Bruzzone and others, 2011; Schmidt and others, 2011; Berquin and others, 2013; Grima and others, 2014b; Pettinelli and others, 2015; Di Paolo and others, 2016; Grima and others, 2016; Aglyamov and others, 2017; Heggy and others, 2017; Kalousová and others, 2017; Campbell and others, 2018; Gerekos and others, 2018; Michaelides and Schroeder, 2019; Culha and others, 2020). The addition of a dual-channel VHF band on REASON also allows for characterization of the European ionosphere, altimetric investigation of Europa's shell and tides, and dual-frequency or interferometric clutter discrimination (Grima and others, 2015; Carrer and Bruzzone, 2017; Castelletti and others, 2017; Haynes and others, 2018a; Steinbrügge and others, 2018; Scanlan and others, 2019). Finally, the ability of both instruments to record strong Jovian emissions raises the possibility of using those emissions to probe the ice shell using passive radio sounding (Romero-Wolf and others, 2015; Schroeder and others, 2016b; Peters and others, 2018).

In addition to Mars and the icy Jovian Moons, radar sounding is also being deployed to investigate ice on other planetary bodies. For example, NASA's Lunar Reconnaissance Orbiter was equipped with a radar sounder in the gigahertz frequency range in order to search for water ice on Earth's moon (Nozette and others, 2010). The data reveal the existence of large deposits of relatively clean ice in the polar regions (Spudis and others, 2013). Unfortunately, measurements temporarily discontinued after an instrument failure in 2011, but have resumed in a bi-static configuration (Patterson and others, 2017). Additionally ESA's Rosetta mission included the bistatic CONSERT experiment (COmet Nucleus Sounding Experiment by Radiowave Transmission), which performed the first tomographic imaging of the interior of a comet (Glassmeier and others, 2007; Kofman and others, 2015).

Conclusions

More than 50 years after the first collection of radioglaciological observations, radar-sounding data are being acquired over ice sheets, glaciers, ice shelves and ice shells across the solar system at unprecedented scales and rates. Terrestrially, this ever growing data volume, along with re-mastery of archival data, is enabling multi-temporal investigations of subglacial and englacial processes at the spatial and temporal scales relevant to ice-sheet and sea-level change. Recent advances in radar-sounder systems now allow for the acquisition of multi-frequency, multi-offset, polarimetric and interferometric data that can provide rich new information about conditions within and beneath the ice. At the same time, advances in data analysis, interpretation and modeling have paved the way for using that rich new information to investigate the fundamental physical processes that control the past, present and future evolution of ice masses. Additionally, recent progress in sensor and platform technologies is making it possible to move from mapping to monitoring approaches in radar-sounding surveys by exploiting low-cost radar-sounder sensor networks, autonomous rovers and drones, or even orbital sounding. Finally, planetary ice/water systems are only growing in their appeal and feasibility as targets of radio-echo sounding. After half a century, radioglaciology may just be entering its golden age.

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