Overview:

Quantarctica and QGreenland have rapidly become indispensable tools for the polar research community, making diverse data sets readily available to researchers. They are widely used in: the planning stages of field work, when the ability to see many different data sets in geographical context and in relation to each other is crucial; in the interpretation of results, where QGIS's existing plugins for exploring data shine; and in the creation of publication-quality figures. However, QGIS primarily supports data that is able to be represented in a 2D map view: data sets including ice thickness maps, surface velocities, lake locations, etc. are all well served by the existing technology.

Ice penetrating radar is a major category of data that is not currently supported – it is possible to see the locations of existing survey lines, and the ice thickness maps that have been interpreted from their data, but it is not readily possible to see the radargrams themselves in context with all of the other information. This capability is important because there is far more visual information contained in a radargram than simply its interpreted basal elevation or ice thickness.

We propose to develop software that will enable researchers to discover where available data exists and to view radargram images and interpreted surface and basal horizons in context with the existing map-view datasets in Quantarctica and QGreenland. This new QGIS plugin will include a cursor that moves simultaneously along the radargram and along the map view, making it straightforward to determine the precise geolocation of radar features.

Intellectual Merit:

The proposed software would be a science enabler for many currently-funded and future projects that use ice penetrating radar to study the Earth's ice sheets. The ability to easily access the original radargram data is relevant for work including: (1) generation of continent-scale bed elevation maps (e.g. BEDMAP3 and BedMachine); (2) site-selection for drilling projects (e.g. COLDEX); and (3) studying processes involved in ice sheet flow and ocean-driven melting (e.g. the Thwaites Glacier Collaboration). In addition to addressing bottlenecks in research workflows, the ability to readily access radargrams will improve the capabilities of reviewers to quality control the underlying data and evaluate interpretations.

Broader Impacts:

It is not sufficient for data to technically be openly available; it is still largely inaccessible until appropriate tools exist to facilitate its discovery and use.

This proposal is aligned with growing momentum in the research community that seeks to make radar data more FAIR: Findable, Accessible, Interoperable, and Reusable (e.g. the Open Polar Radar project, upcoming data releases from the British Antarctic Survey and the Alfred Wegener Institute). This proposal will help to address *findability*, by indexing data that is distributed across multiple international data centers, as well as providing *interoperability* between datasets from other disciplines and radar data in multiple formats via a QGIS plugin.

Beyond its utility to researchers who have already invested significant effort in learning to work with radargrams, our proposed tool will reduce barriers to interacting with radar data to the point that it will become accessible and visible to the interested public, whether they be high school students, artists, or members of the media. This has the potential to change not only how the data is used but also who is able to use it.

We will directly involve undergraduate students in this project, both as paid interns assisting with the development of this tool and via a collaborator's plan to use this software while teaching.

1 Introduction

Ice Penetrating Radar (IPR) has been a fundamental tool in understanding Antarctica ever since the first flights in the 1960's that were a collaboration between the Scott Polar Research Institute, the Technical University of Denmark, and the US National Science Foundation (Schroeder et al., 2019). It is crucial to our understanding of Antarctica's potential contribution to sea level rise and our understanding of past climate cycles. Since those first flights, many countries have developed the capability to collect this type of data, including: the United States (led by CReSIS (Arnold et al., 2020), LDEO (Tinto et al., 2019), and UTIG (Peters et al., 2007)), the United Kingdom (BAS (Vaughan et al., 2006)), Germany (AWI (Kjær et al., 2018)), Italy (Tabacco et al., 2008), South Korea (KOPRI, (Lindzey et al., 2020)), Russia (Popov, 2020), and China (PRIC (Cui et al., 2020)). Figure 1 shows the existing data coverage from all of these sources.

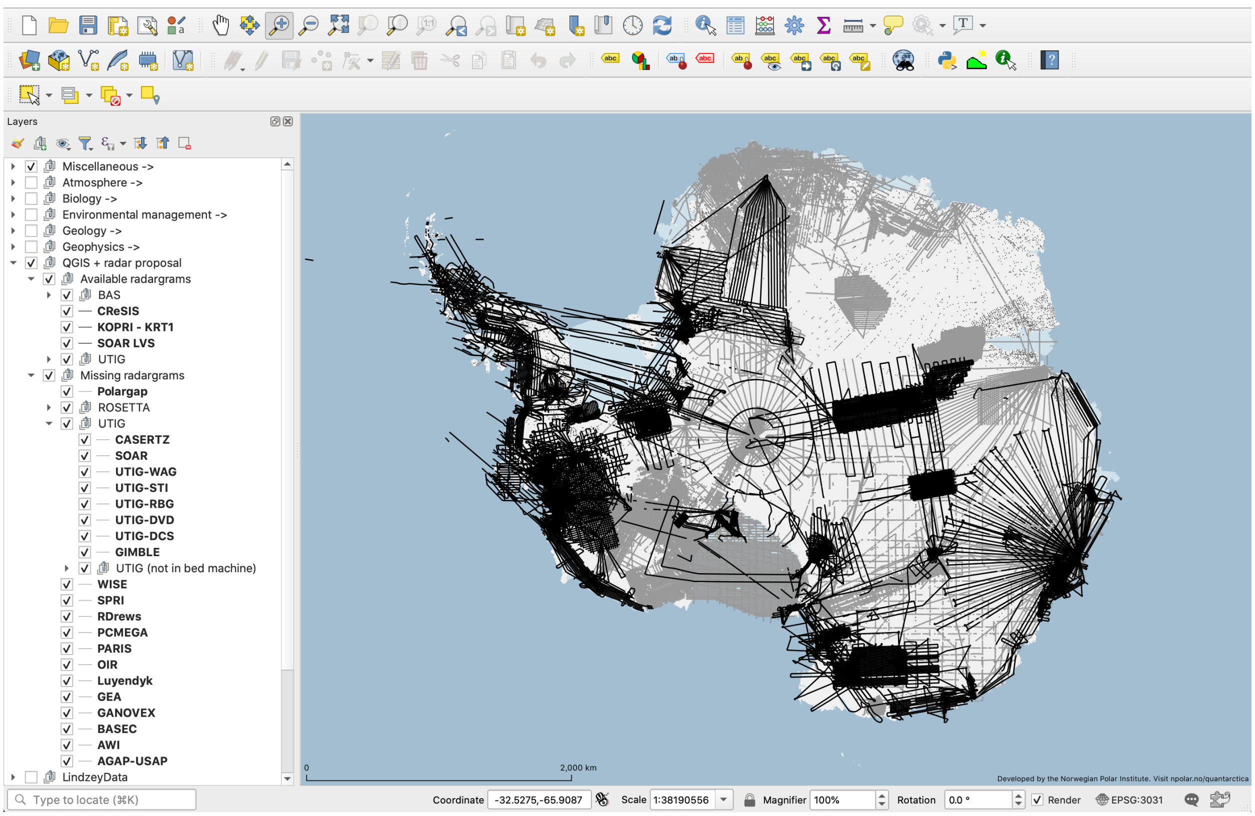

Figure 1: Existing ice penetrating radar data in Antarctica, displayed in QGIS. Survey lines that are known to have been released and that we propose to support are in black. Grey lines have either not (yet) been released, were not found in our searches, or are ground-based.

The US alone has spent many tens of millions of dollars on direct grants to enable the acquisition and analysis of radar data, and even more on the associated infrastructure and support costs. Unfortunately, much of these data is not publicly released, and even the data that has been released is not easily accessible. There is significant technical work involved in figuring out how to locate, download and view the data:

- There is no index of this data, and it has been posted at a variety of data centers and institutional websites.
- Each data provider releases data in a different format, so a user must figure out how to access

the data and plot the radargram.

- Finally, there is no standard interface or tool for georeferencing the data.

As such, only a handful of institutions in the US are really set up to use radar data, and often, only with the data that they themselves have collected or from a single major data creator.

We propose that all researchers need the ability to browse available radargrams and view them in context with other scientific data. A low-overhead tool for doing this will help make these data accessible beyond the groups that originally collected them or those with full time technical support staff. This accessibility is important both for evaluating existing results in the literature and in enabling broader participation in related research.

This proposal will make these data more broadly accessible by supporting the development of a QGIS plugin that:

- **Includes QGIS layers for Antarctica and Greenland that will serve as an index to all known ice penetrating radar survey lines**
- **Downloads publicly-available radargrams that have been released in a compatible format**
- **Provides a radargram viewer for georeferenced radargrams, tying the mouse position on the radargram to a cursor on map view, enabling precise geolocation of features.**

This proposal is aligned with the Directorate for Geosciences's Office of Polar Programs.

2 Project Motivation and Impact

2.1 Science-driven

There are increasingly more sophisticated analyses being performed that require access to full radargrams. Some are purely computational, while others require human interpretation of the images. Easier visualization of georeferenced radargrams would be beneficial for all of these applications, both on the side of the original researchers, but even more so for reviewers and later readers, who may not have already set up their own pipelines to handle radar data but still have a need to understand the data in context. Visualizing radargrams in context with other datasets is only becoming more important as the field becomes more interdisciplinary, and many of these relevant datasets have already been provided as QGIS layers by Quantarctica (Matsuoka et al., 2021) and QGreenland (Moon et al., 2021).

Englacial features: Some geologically and glaciologically interesting features are only observable in the radargrams themselves. For starters, there is a vast literature on using englacial layers for dating isochrons (e.g. Parrenin et al. (2017)) and inferring ice dynamics (e.g. Winter et al. (2015)).

Other examples include investigation of basal accretion structures (e.g. in the Gamburtsev Subglacial Mountains, (Wolovick et al., 2013; Wrona et al., 2018)) and comparing historical volcanic ash plumes captured in the ice with modern seismic records to study volcanism in Marie Byrd Land (Lough et al., 2013).

Reinterpreting basal picks: Published basal horizons are subject to interpretation, and the original picker's choice may not be appropriate for a given question. The typical labeling policy attempts to enforce consistency over absolute correctness, and requires the pickers to label the first bright return as the bed. In areas with steep basal slopes, this can result in off-nadir returns being labeled, and an underestimate of the actual ice thickness.

As one consequence of this, automatic identification of lakes is often not possible from the bed picks alone. For example, there are lakes near the South Pole that are in steep valleys where the first return is due to an off-nadir return from the valley wall (Carter et al., 2007).

Ice shelves can also be challenging to interpret, particularly in regions with significant basal crevassing that creates bright off-nadir reflectors. These regions can be of interest for e.g. studying basal ice shelf channels and their linkage to inferred subglacial hydraulic networks (Le Brocq et al., 2013). Additionally, any attempt to use IPR data to confirm grounding line locations should be using the full radargram (Greenbaum et al., 2015).

Operational needs: Finally, a number of operational and survey planning use cases benefit from easy access to georeferenced radargrams. For example, when selecting a location to install a coordinated surface weather station and borehole-deployed oceanography package it is important to know whether the proposed site is in an area of sub-ice shelf melting or refreezing. Similarly, this type of data has been used when targeting under-ice-shelf AUV missions to study particular regions of accretion.

2.2 Available Datasets

There are decades of publicly-funded ice penetrating radar datasets, ranging from single experiments consisting of hundreds of line-kilometers to multi-season campaigns with tens of thousands of line-kilometers. While gridded datasets are broadly available and widely used, and interpreted bed elevations / ice thickness profile datasets are also often released, there are comparatively fewer datasets that include the complete radargram.

Figure 1 shows all IPR survey lines that we are aware of, based on data from BedMachine (Morlighem et al., 2020), BEDMAP2 (Fretwell et al., 2013), ROSETTA (Tinto et al., 2019), and CHINARE (Cui et al., 2020). Black lines indicate airborne surveys where full radargrams have been released. This is likely to be an underestimate of data availability by the end of the project: as part of the BEDMAP3 effort, BAS is releasing additional surveys; and the currently-funded Open Polar Radar (OPoRa) project has an explicit goal of standardizing radargram data formats across major US institutions and re-releasing old data in this format.

The following surveys are known to be available:

- CReSIS's (Arnold et al., 2020) full history of data is available through their website in a Matlab file format.
- BAS has released data from most of their surveys via their Polar Data Center in segy and netCDF formats (e.g. Corr et al. (2021), Nicholls et al. (2021), Ferraccioli et al. (2021a)).
- UTIG has released data from their ICECAP-IPY (Young et al., 2011), ICECAP-OIB (Greenbaum et al., 2015), ICECAP-EAGLE (Roberts et al., 2018), and OIA (Young et al., 2017) surveys split between NSIDC and AADC, both in a netCDF format (Blankenship et al. (2017a,b, 2018), Young et al. (2021)). The AADC requires email-based interaction in order to download data. The AGASEA survey radargrams (Holt et al., 2006) are available from USAP-DC in a netCDF format (Chu et al., 2021), though accessing them requires an emailed request and waiting for multi-GB files to be uploaded to Google Drive. Earlier data, including the dense grids in West Antarctica, are currently available only as gridded ice thicknesses.
- LDEO has released radargrams from their AGAP-GAMBIT survey (Bell et al., 2011) through their website in Matlab, netCDF and segy formats (AGAP-GAMBIT, 2021), though we only found ice thicknesses and PNGs of the radargrams for their ROSETTA (Tinto et al., 2019)

survey.

- KOPRI released their survey of the David Active Lakes (Lindzey et al., 2020) in a netCDF format via zenodo (Lee et al., 2020), but it is all in a single 9.4 GB tar file, preventing line-by-line download.
- SOAR released data from their Lake Vostok survey (Studinger et al., 2003) in segy format via USAP-DC (Studinger and Bell, 2020), but the individual files are protected with a CAPTCHA preventing scripted download.

Notably, each institution has chosen a different data center or hosting strategy, creating a significant barrier to findability. Even knowing what data center hosts the data, we have found it difficult to locate many of the radargrams. Additionally, while there are three main file formats used – matlab, netCDF and segy – the actual data fields within that format are not standardized across groups.

We will endeavor to support all of the major surveys listed, though not all of the data is published at a data center that enables automated access or is provided in per-servey-line files. For the SOAR Lake Vostok, KOPRI KRT1, and all data hosted at AADC, we will provide instructions on how to manually download and import the data.

The ideal case is that this tool is an index to *every* available polar radar profile; however, we will not have the resources to add custom code for every format and source. Instead, we will provide clear documentation about: (1) preferred data formats and providers, (2) adding new lines to the QGIS layer, and (3) modifying the software to support a new format or data center.

2.3 Innovation

The U.S. Antarctic Program strongly encourages the submission of proposals that do not rely on field work. Our proposed tool will aid in reviving old datasets and by making them easily explorable by groups outside of the original collectors.

This proposal is aligned with growing momentum in the research community that seeks to make radar data more FAIR: Findable, Accessible, Interoperable, and Reusable. Numerous groups are working to make more of these data *accessible*, including upcoming data releases from the British Antarctic Survey and the Alfred Wegener Institute. The Open Polar Radar project is working on both *interoperability* via plans to standardize radar processing pipelines and *accessibility* by plans to re-release old data in the new format, including currently unavailable datasets.

Findability is currently hampered by data being split across data centers in multiple countries, as described in Section 2.2. This fragmentation is at least in part required by the various funding agencies' policies. Some individual organizations have been working to improve findability for their own data via improved web portals (e.g. CReSIS, BAS), but there is as yet no mechanism to achieve this across the entire research community. Our project involves creating an index to all available data, in order to generate the QGIS layer that shows available datasets. In addition to enabling human interaction via QGIS, we will also release this index in a machine-parsable format, which will allow other computational projects to obtain relevant radar data in an automated manner.

Interoperability is the key focus of this proposal – the polar community has made many important data sets interoperable by releasing them as QGIS layers, and there is demand for radargrams to be included in that ecosystem. Our tool would provide a way for users to visualize radargrams in context with these datasets and to seamlessly interact with radar data that was originally provided in varying formats.

3 Cyberinfrastructure Plans

3.1 Related Work

While there are a number of excellent data analysis tools already available, we believe that our proposal fills a critical gap for anybody who needs a low-overhead way to interact with radargrams.

3.1.1 CReSIS OpenPolarServer

The most closely related publicly available project to this proposal is CReSIS's excellent online radargram viewer OpenPolarServer (Purdon, 2014). They provide a web portal with a map view of every line, and make it possible to see a generated PDF for each radar segment before downloading the data. It is even possible to plot the flight lines on top of a variety of basemaps. However, this tool is designed as a way to determine which radargrams to download from the CReSIS servers, and thus does not provide features that would be useful for scientific analysis.

The key extensions that our proposal provides are:

- **Extensible** to support any publicly-available data.
- **Georeferencing:** We add a cursor linking a trace in the radargram to the corresponding geographic coordinate in the map. This makes it trivially easy to match up features between the radargram and other datasets.
- **GIS interoperability:** our tool will enable direct comparison between radargrams and any dataset imported as a QGIS layer.
- **Full resolution data**: After downloading the transect, our tool will enable exploration of the full-resolution radargram, rather than being limited to a lower-resolution generated PDF.
- **Offline Access:** its implementation as a plugin to a desktop application supports offline use by researchers in remote locations.

3.1.2 Radar (& Seismic) Tools

A number of existing desktop applications provide solutions for processing seismic data, and these are often repurposed for radar (e.g. Landmark, OpendTect, MOVE, and Kingdom). These excel when trying to perform analysis of an entire dataset (e.g. tracing layers) but require significant work to configure the system and ingest data; Landmark lease costs are also prohibitively expensive for many research groups.

We see our proposal as a complement to these heavier-weight tools – rather than providing significant analysis and interpretation functionality, we will provide a lightweight way to explore data within QGIS, a tool that is already broadly used by the Antarctic research community.

3.1.3 MARSIS/SHARAD viewer

The MARSIS/SHARAD viewer (Cantini and Ivanov, 2016) was a QGIS plugin developed by EPFL that allowed download of SHARAD radargrams and then displayed them in a second window within QGIS. In addition to providing a link between the base map and the visualized radargrams, it supported a few types of Mars-specific analysis. However, it has not been maintained and will not run with the current version of QGIS.

3.1.4 Deva

This proposal is a continuation of a project that PI Lindzey worked on while a graduate student. Deva (Figure 2) is a linked basemap and radar viewer that enables easy browsing of any radargram that UTIG has collected, as well as BAS, CReSIS, KOPRI and PRIC datasets. UTIG still uses the associated radar viewer for all of their surface and bed picking. Deva served as a proof-of-concept of the utility and viability of a project like we are proposing, but its reliance on a custom basemap implementation meant it wasn't interoperable with other datasets, and its tight integration with UTIG's internal database and server limits its portability.

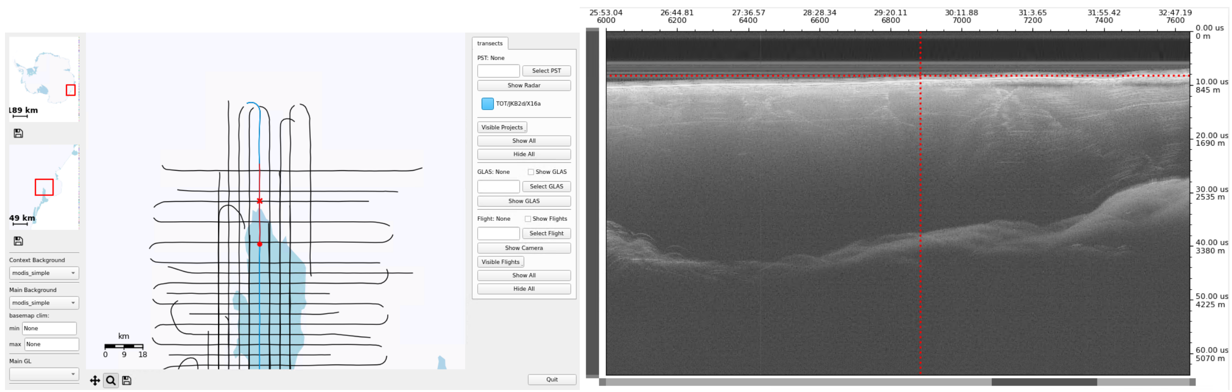

Figure 2: (left) Basemap showing locations of radar survey lines in the region. Clicking on a line opens a radar viewer in a new window. **(right)** Single radargram. The user selects the region of data that is displayed by clicking and dragging on the horizontal/vertical bars, and the result is also highlighted in red on the basemap. A cursor on the basemap follows the location of the displayed trace on the radargram.

3.2 System and process architecture

The proposed tool's workflow will be very similar to that described for Deva (Section 3.1.4), but it will be implemented as a QGIS plugin. QGIS (QGIS Development Team, 2021) is a free, open source desktop GIS application that is actively supported and developed by its user community. It runs on all major operating systems: Windows, OS X, and Linux.

We have chosen to use QGIS thanks to the success of the Quantarctica and QGreenland projects and their wide adoption by the polar community. We expect this choice to reduce barriers to adoption, as QGIS is already a familiar tool, and it allows us to leverage the professionally-curated and -styled QGIS layers provided by Quantarctica/QGreenland to achieve immediate interoperability with a broad range of other datasets.

While we did consider a web-based application, we ruled that idea out because: (1) it would not provide the easy integration with user-created datasets that QGIS features; (2) a full-resolution radargram viewer would only be usable with a high-bandwidth internet connection; (3) it would lead to a more complicated software implementation that is not as straightforward to extend to supporting analysis tasks like labeling horizons; and (4) it would require mirroring and hosting copies of all relevant data, which is an up-front expense and ongoing maintenance burden.

3.2.1 Scope

Datasets: We are focusing on airborne surveys in order to maximize supported line-kilometers within the available resources. However, we will support the ground-based data that is released as part of the OPoRa project. We will also provide documentation about how to convert existing data to a suitable format (if necessary) and how update the index to include it via a pull-request workflow. This will enable the community to contribute support for data that they care about.

Interpretation: The focus of this project is on low-overhead exploration of existing datasets, not on replacing or replicating the workflow that commercial tools can provide. As such, we do not propose to provide extensive analysis tools beyond the ability to cross reference features in the radargram with their location in map view.

We do think that a simple picking feature that enables labeling horizons and exporting the resulting georeferenced lines would complement this tool and enable it to support the full pipeline from discovery to analysis. The biggest obstacle to doing so is that the community has not converged on standards for labeling horizons: for example, CReSIS and UTIG have very different philosophies and approaches. When the Open Polar Radar project arrives at standards in this area, we look forward to discussing how to implement them in the tool as either a supplement or follow-on proposal.

3.2.2 Index Layer

A QGIS layer showing all known airborne ice penetrating radar transects will provide the main user interface for this plugin. These will be grouped in two levels: first, by country/institution, then by season/project. Lines will be color-coded based on data availability, and will have different functionality when clicked on:

- **light gray**: Radargram is not openly available – selecting one of these lines will yield a dialog window showing known metadata about the line, which will ideally include the country/institution and date.
- **dark gray**: Radargrams have been published, but either not in a format suitable for use with our tool or not yet integrated. In this case, the popup will also include a link to the data repository and a link to our tutorial on how to integrate new datasets into the plugin.
- **black**: Data is available and fully supported by this plugin. Clicking on this line pops up a menu with options to download the data and view the radargram.

This QGIS layer will include all metadata required for citing, downloading, and displaying the data.

3.2.3 Download

As a first step before viewing the data, we need to download it to the user's local filesystem. The plugin will support both single-line download via clicking on a transect in the map and batch download via area selection. In order to preserve the ability of the data centers to collect statistics on users, we will prompt our users to obtain their own login credentials where required and provide them to the plugin. We expect that this tool will dramatically increase the number of requested radargram downloads, which has the potential to affect the data hosting infrastructure. Before implementing batch download, we will reach out to the involved data centers regarding whether there will be issues in balancing user convenience with their resources.

3.2.4 Radar Viewer

The radargram will be displayed at full resolution, using a configurable color palette and dynamic range for optimal contrast, and with controls that allow the user to pan/zoom up to the full resolution of the underlying data. Meanwhile, in map view, the currently-displayed segment of the radargram will be highlighted on the survey line. In order to promote data traceability and encourage citation, the viewer will also display the DOI and the requested citations for the data release and associated research paper.

Surface and Bed Horizons will be displayed if they are included in the radargram data file, with an option to toggle them on/off. We believe that this is a useful check on the quality of published interpretations even without the ability to edit them.

The current trace will be optionally drawn on the radargram, showing the amplitudes vs. fast time, updating based on the mouse location. In map view, a cursor will show the geographic location corresponding to the displayed trace, enabling precise association between features on the map and in the radargram.

3.3 Project Plans and Management

3.3.1 Management

Personnel: PI Lindzey is also the only cyberinfrastructure professional funded by this award. Her role includes: (1) Coordinating with stakeholders regarding: data formats and interoperability issues, scope and feature requests, and dissemination plans; (2) Implementation of the cyberinfrastructure, including compiling required metadata and coding the plugin; (3) Mentoring undergraduate students; and (4) Outreach, both to potential users and the broader community. Relevant stakeholders have been identified in Section 3.5 and are participating as unpaid collaborators on an advisory committee.

Coordination Mechanisms: PI Lindzey will hold yearly virtual meetings, in which she will present project plans and accomplishments and solicit feedback from the advisory committee. The expected milestones for these meetings is: (2022) Project roadmap and planned functionality, (2023) Initial demonstration of functionality, (2024) ; (2025) Final status, metrics, and follow-on plans. She also plans to attend AGU in 2022 and SCAR-ISAES in 2023 to participate in project meetings for related projects and meet with collaborators in person. However, we expect that much of the coordination will be more informal, and will continue to arrange one-on-one videoconferences with members of the advisory committee as needed to address technical details or solicit user feedback.

3.3.2 Development Timeline

We are proposing a project that will be funded for three years, with the bulk of the development work happening in years one and two and year three focusing on support and outreach. Our implementation plan is based around the goal of getting the minimal compelling feature set out to a few collaborators as soon as possible, so that we can user feedback to drive further development decisions.

With this in mind, **Year 1** will involve: creating QGIS layer for Antarctica with the appropriate metadata; automating download of radargrams; and implementing the ability to visualize radargrams with a cursor linking the radar data and the map view. In the interest of obtaining user feedback as early as possible, the first iteration will only support OS X and Ubuntu, and will leave out a few features that we know will be popular. We will enlist 2-3 collaborators to start using the plugin at this stage.

Year 2 will focus on expanding coverage and adding features. This includes expanding coverage to include a QGIS layer for Greenland, adding Windows support, and integrating any major Antarctic datasets that weren't completed in Y1. In addition to implementing features based on user feedback, we intend to add: the ability to display surface and bed picks, where available; the option to view elevation-corrected data; and batch download. Our beta tester pool will expand to include all "end user" members of the advisory committee.

In **Year 3** our focus shifts to adoption and sustainability. At this point in the project, we expect to have a solid tool, and want to get it out into the community while we still have time in the period of performance to provide support and possibly implement requested features. A significant part of this will be developing solid documentation, aimed both at data consumers and for streamlining expected maintenance tasks. Outreach efforts will include an announcement to Cryolist, as well as providing a tutorial session at SCAR-OSC 2024.

3.4 Building on existing, recognized capabilities

EarthCube is a partnership between NSF's Office of Advanced Cyberinfrastructure and Geosciences Directive; it funded several of the projects that we will be building upon.

We have chosen to implement this tool as a QGIS plugin due to to the success of the Quantarctica and QGreenland projects and their wide adoption by the polar community. Using QGIS will allow us to achieve interoperability with a wide range of relevant datasets by leveraging work that Quantarctica/QGreenland have performed to collect and beautifully format them as QGIS layers. QGreenland is currently funded by EarthCube award #1928393.

Additionally, we plan to support data products created by the recently-funded Open Polar Radar (OPoRa) project (EarthCube #2126503, #2126468, #2127606). The OPoRa project is particularly exciting thanks to its aims to both standardize data formats and to re-release historic data in the same format. Those aims will help to reduce the complexity of our tool (by reducing how many data formats it must support) and magnify its impact (by increasing the number of line-km that can be included).

Finally, this tool will help researchers find and download existing published radargram data hosted at providers chosen by the original data collectors, and thus it leverages the capabilities provided by the NSF-funded NSIDC and USAP-DC.

3.5 Close collaborations among stakeholders

We have assembled an advisory committee composed of researchers working on complementary cyberinfrastructure and of end users for whom this tool would eliminate bottlenecks in their research.

All members will be invited to yearly virtual (and recorded) meetings that will demonstrate current project status and encourage discussion regardingcom prioritization of next steps. Additionally, they have all agreed to coordinate with PI Lindzey as described below and documented in the attached letters of collaboration.

3.5.1 Complementary Cyberinfrastructure

Several currently-funded projects will make the proposed tool more effective, easier to implement, and will increase the available data coverage.

First, we have chosen to use QGIS as the basemap for this tool based on the success and wide adoption of Quantarctica and QGreenland. A significant section of the community is already familiar with QGIS, which reduces the learning curve for this tool. More importantly, interoperability with Quantarctica/QGreenland means that researchers will be able to view radargrams in context with a broad selection of curated geological and glaciological data, facilitating interdisciplinary work. Long-term, we hope to see the metadata layer describing all radar lines be integrated into these datasets, to encourage discovery of this tool and so that users only need to download the corresponding plugin.

Kenichi Matsuoka (Quantarctica PI) and **Twila Moon** (QGreenland PI) have agreed to: (1) coordinate regarding a strategy to more tightly integrate this tool into Quantarctica/QGreenland, and (2) assist with dissemination and outreach to their respective communities.

Second, Open Polar Radar (OPoRa) is a collaborative project that seeks to standardize ice penetrating radar data processing pipelines and products among the major data collectors in the United States. In addition to setting standards for future data collection, they also intend to re-process existing data and make it available in the new format. This will both reduce the number of formats that this proposal needs to support and "rescue" old data that isn't currently openly available (increasing total data supported). The Open Polar Radar project kicked off in Fall 2021, and as such their data formats are not yet defined; we will develop against their standard as soon as it is announced.

Duncan Young (UTIG OPoRa PI) and **John Paden** (CReSIS OPoRa PI) have agreed to: (1) include PI Lindzey in data format discussions; (2) represent the expert user and data provider use cases regarding desired functionality; and (3) strategize on next steps and a pathway to sustainability for this tool at the end of the period of performance.

Finally, the BEDMAP3 project is in the process of collecting every ice penetrating radar dataset of Antarctica and using it to create an updated bed elevation and ice thickness map. Previous versions of BEDMAP have only included a data mask; however, as part of the current effort, they are also planning to release the full underlying ice thickness data along with metadata including data owners and DOIs where available. The initial release will include this metadata for all of the post-2013 datasets, and they are making an effort to assemble it for the older data as well. This metadata will make it significantly easier for our proposed project to identify and track down additional data that should be supported by our plugin.

Alice Fremand (BEDMAP3 Data Manager) has agreed to: (1) coordinate regarding appropriate metadata to include in their releases; and (2) assist with identifying/tracking down data that should be included.

3.5.2 End Users

For the end user component of the advisory committee we have recruited an interdisciplinary set of polar researchers representing a variety of use cases where the proposed tool would remove bottlenecks:

Christine Dow (University Waterloo) is a glaciologist specializing in Antarctic subglacial hydrology modeling. These models rely on large-scale bed topography prducts such as BedMachine (Morlighem et al., 2020), which are subject to errors due to kriging and input bed topography, and it is currently prohibitively difficult to locate the original radargrams used in creating the bed topography datasets. The ability to access georeferenced radargrams would allow direct causal analysis of regions not converging well in the model, and would guide whether areas should be smoothed or model meshes refined to best replicate the basal drainage system. Furthermore, access to radargrams would allow analysis of hydrological features produced by the model such as subglacial lakes, large channels, and grounding line plumes to be checked against features visible in the radar data.

Jamin Greenbaum (Scripps) has spent 13 Antarctic field seasons collecting geophysical data, and his work uses IPR to constrain inverse models of sub-ice-shelf bathymetry derived from potential fields. He is currently building a research group with an active undergraduate component. With current tools, it can require an entire summer for a student to get up to speed with using these data; the ability to easily access and visualize georeferenced radargrams would expand the scope of feasible undergraduate projects.

Nicholas Holschuh (Amherst College) uses radar to study the flow history of the Antarctic Ice Sheet and is involved with the site selection for the Hercules Dome Ice Core drilling project. His research is primarily done using CReSIS data, in part due to the ease of access. However, his site selection and survey planning work requires the ability to discover and visualize data from all previous surveys collected at possible ice core sites. A centralized tool which makes metadata (and data, where available) accessible would improve the site selection workflow and improve scientific outcomes.

Lenneke Jong (AAD) is a modeller involved in the search for million year old ice. She needs the ability to visualize radargrams collected by multiple different systems with intersecting survey lines in order to track down model discrepancies and evaluate candidate sites based on layer and bed characteristics.

Joseph MacGregor (NASA) is a geophysicist studying controls on ice-sheet flow. At spatial scales $\geq\sim$ 1 km, most surface features are related to perturbed basal conditions, and the only large-scale way to observe the bed is with IPR. Reconciling surface observations with the processes controlling them requires the ability to visualize radargrams in direct spatial context with other rasterized geophysical datasets (e.g., surface DEMs, gravity and magnetic field). To be able to do so efficiently in QGIS would accelerate scientific discovery in this domain.

Felicity McCormack (Monash University) is an ice sheet modeler using geophysical data to study the physical processes driving ice sheet flow. She teaches an undergraduate course that includes introducing how radar data can be used to understand Antarctica's role in the climate system. A tool like we propose would lower the barrier to entry to these data, both enabling students to visualize the complex 3-dimensional nature of the Antarctic Ice Sheet and facilitating more ambitious course projects that link different data sources to study specific ice dynamic processes.

Theodore Scambos (CIRES) is a glaciologist who performs significant field work in the Antarctic. When scouting an area for a field site or station he needs to cross-reference features in a radargram with proposed locations and other datasets.

Martin Siegert (Imperial College London) is a glaciologist whose work focuses on improving the physical basis for ice sheet models. Visualizing and interrogating ice-penetrating radar data with multiple orientations offers the chance to measure anisotropy within the ice sheet, and from that to gain insights into ice fabric and rheology.

They have all agreed that they or an advised student will try a pre-release version of the proposed tool and provide feedback.

4 Measurable Outcomes

4.1 Deliverables

The underlying radargrams are already hosted at data centers chosen by their originators, as detailed in Section 2.2.

This project will generate two primary products:

1. QGIS layers for Greenland and Antarctica, containing all known radar lines
2. Source code for the QGIS plugin

In addition to releasing the data layers to the appropriate region-specific NSF-supported data center and the code via GitHub, we will work with Quantarctica and QGreenland to integrate with their distribution methods. Further details are given in the *Delivery Mechanism and Community Usage Metrics* supplementary document.

4.2 Sustained and sustainable impacts

4.2.1 Software Licensing

All software developed under this project will be hosted in a GitHub repository with a BSD license. We have chosen GitHub because it is currently the most popular online version control system, so it should be familiar to many of our users. The BSD license will be used because it is maximally permissive – we want to enable anybody to be able to build on this code, so long as it is properly attributed. We specifically do not want to deter potential users who are concerned by the viral nature of a GPL license.

4.2.2 Documentation

User documentation will be provided in a static site also hosted by GitHub under the project's organization. Attaching the documentation to a GitHub organization rather than to a university's web sites means that it would be simple to add maintainers or even hand off control of the project if required for long term sustainability.

The documentation to be produced will include tutorials for:

- How to set up the tool and use it to browse radargrams. This will be provided in both text and video format.
- How to update the data layer to add new data from already-supported sources. (e.g. updating after the next season of UTIG/CReSIS/BAS data is released.)
- How to convert data into a supported format and integrate it with the tool so other researchers can use it. (e.g. the PI of a small ground-based survey wants to make their data accessible.)
- How to import data in the field (e.g. during a survey, no internet connection available).
- How to create a compatible QGIS layer so that the radar viewer plugin can be used in non Greenland/Antarctic contexts. (e.g. surveys of Alaska or the Canadian Arctic.)

4.2.3 Potential for Sustainability

There are two main obstacles to long-term sustainability in a project like this.

1. Data needs to be updated, whether because it has been moved or because new data has been created.
2. Code rot: even if nothing in the code changes and no new bugs are found, changes to the underlying software ecosystem mean that maintenance will be required over time. These are typically minor updates, but without upkeep, the software will not be able to be installed on new systems.

A key component to sustainability will be making the required maintenance as easy as possible once the plugin is feature-complete.

Data maintenance can be made less onerous both through streamlining the procedure and providing excellent documentation. The ideal case would be for all radar data providers to publish their data to a supported data center in a supported format, and create a pull request update the data layer with their metadata as a routine part of their processing. A slightly less ideal, but still manageable, scenario is for a maintainer to be notified of a data release, then run a script that updates the data layer and pushes it.

Code maintenance can be made less onerous by starting with high-quality well-documented code and being thoughtful about what features to add. While it is tempting to add every feature that every user could want, each new bit of functionality carries with it a maintenance and testing burden that can combine to make a project painful to update. Additionally, simply being open-source can help with maintenance – rather than simply receiving bug reports, some users are able to fix issues for themselves and push them back out to the community.

Another component is making sure that the project is not tightly tied to a single individual/institution. We plan to create a project-specific GitHub organization that will hose the code in order to make adding collaborators and/or transferring ownership straightforward.

4.3 Metrics

We propose to track three categories of metrics: (1) data availability – how many line-kilometers of radar data can be accessed through this tool; (2) downloads – how often our data layer is downloaded, and how often our tool is used to download other data; (3) community engagement – interactions with our advisory committee, an initial tutorial at SCAR-OSC, and community interactions via GitHub.

Further details, including collection mechanisms and yearly targets, are described in the *Delivery Mechanism and Community Usage Metrics* supplementary document.

5 Broader Impacts

5.1 Enhanced Research Infrastructure

The most direct impact of this proposed work is making it easier for the scientific community to access and use ice penetrating radar data.

5.1.1 Training

We propose to hold a tutorial session during the 2024 SCAR Open Science Conference, aimed at introducing non-expert radar users to these datasets and how to use our QGIS plugin to access and view them. The Quantarctica team has run similar tutorial successfully in the past, and found that they were successful for reaching participants from small or not-yet-well-established research groups.

5.1.2 User Stories

In proposing this tool, we have kept the needs of a few archetypal end users in mind.

The Early-Career Grad Student is reading widely while attempting to converge on a thesis topic, and is spending significant time becoming proficient with tools and datasets. They need the ability to easily explore existing radar data in comparison with the literature and other published datasets in order to quickly evaluate whether their candidate research hypothesis is supported by existing data and might be worthy of more in-depth investigation.

The Reviewer wants to check the interpretation of key features against the raw data, or wants to pull up neighboring radargrams that weren't included in the paper's analysis.

The Artist: A few years ago, PI Lindzey received an email from an artistic group working on an installation piece about climate change. They had found radar images on Lindzey's blog, and were looking for more images. I would have loved to be able to point them to this tool, and in developing it, we seek for it to be usable by an interested and motivated non-scientist. Their use case highlights the importance of clear documentation and straightforward installation.

The Modeler wants to check the interpretation of Level 2 (thickness/elevation profiles) or Level 3 (gridded) data before relying on them. They are not attempting to do full-scale QC of the provided data products, but instead want to investigate a critical area (e.g. a grounding zone) or a region where the data and model do not agree. This use case drives the need to support plotting interpreted Level 2 surface and bed horizons on top of the raw radargrams.

The survey planner is planning the next day's flight or traverse, often reacting to features observed earlier in the survey. This use case drives the need for users to import their own data into the plugin, in addition to downloading data from online sources.

The Interdisciplinary Researcher is looking for radargrams that illustrate a given feature, but does not have close ties to any of the groups collecting the data. For example, researchers looking at basal ice shelf channels as evidence supporting a subglacial water flow model (Le Brocq et al., 2013) or their impact on ice shelf stability (Alley et al., 2016) need to associate radargrams with features observed in satellite imagery. Our tool would provide them with an easy way to see where radargrams exists in relation to any georeferenced image loaded into QGIS, and enable easy download and inspection of potentially-relevant data. This use case highlights the need for data browsing and the utility of a low-overhead pipeline for analyzing single relevant radargrams.

5.2 Undergraduate Involvement

We plan to hire undergraduate students in Summer 2023 to assist with testing the plugin. Their research projects will be designed to require browsing through a significant volume of radargrams, in order to meet the dual objective of data quality control and experience with research. They will be encouraged to attend seminars, in person and/or virtually, in order to obtain a broader view of the field, and will be required to present their work at an end-of-summer poster session.

When recruiting students, we will look beyond those already engaged with polar science and reach out to organizations on campus that work with students who are underrepresented in STEM. These include: the STARS Scholars program, which helps students from a low-income, first-generation, or underserved background transition to college and be successful in an engineering or computer science degree; the Louis Stokes Alliance for Minority Participation; and a variety of student-run clubs.

5.3 Public Outreach

Climate Change//Curiosity Expo (previously "Polar Science Weekend") is an event held annually 2006-2020 that was a partnership between the University of Washington's Polar Science Center and the Pacific Science Center It features dozens of booths presenting hands-on activities aimed at engaging the public with research. While it has been on hiatus thanks to COVID, we are optimistic that it will resume by 2024.

PI Lindzey will take part in the "Science Communication Fellowship" program offered by the Pacific Science Center during Y2 of this project. This course prepares STEM professionals to explain their work in an engaging way, and assists with compelling activity/presentation design. We think that ice penetrating radar data is both immediately visually compelling and that the ability to "see" through kilometers of ice is just really cool, and look forward to sharing that. Our initial presentation idea is to design the exhibit around the question "How do we know how much ice is in Antarctica?", and we would plan to participate in the event during both Y2 and Y3.

SciPy is a conference focusing on Scientific Computing with Python, where most of the participants are software engineers rather than disciplinary researchers. We plan to present a talk to the geosciences track that would introduce ice penetrating radar and its use in polar science, then discuss our technical approach to making the data more explorable. We see this as a great opportunity for scientific outreach aimed at at a highly technical audience outside this discipline.

References Cited

AGAP-GAMBIT, 2021: Antarctica's Gamburtsev Province Project (AGAP) + Gamburtsev Aerogeophysical Mapping of Bedrock & Ice Targets (GAMBIT). Lamont-Doherty Earth Observatory, URL `https://doi.org/10.1594/IEDA/306568`.

Alley, K. E., T. A. Scambos, M. R. Siegfried, and H. A. Fricker, 2016: Impacts of warm water on Antarctic ice shelf stability through basal channel formation. *Nature Geoscience*, **9 (4)**, 290–293.

Arnold, E., C. Leuschen, F. Rodriguez-Morales, J. Li, J. Paden, R. Hale, and S. Keshmiri, 2020: CReSIS airborne radars and platforms for ice and snow sounding. *Annals of Glaciology*, **61 (81)**, 58–67.

Bell, R. E., F. Ferraccioli, T. T. Creyts, D. Braaten, H. Corr, I. Das, D. Damaske, N. Frearson, T. Jordan, K. Rose, et al., 2011: Widespread persistent thickening of the East Antarctic Ice Sheet by freezing from the base. *Science*, **331 (6024)**, 1592–1595.

Blankenship, D., J. Roberts, J. Greenbaum, D. Young, T. Van Ommen, E. Le Meur, and L. Beem, 2018: EAGLE/ICECAP II RADARGRAMS, Ver. 1. Australian Antarctic Data Centre, doi:10.26179/5bcff4afc287d.

Blankenship, D. D., S. D. Kempf, D. A. Young, T. G. Richter, D. M. Schroeder, J. S. Greenbaum, T. van Ommen, R. C. Warner, J. L. Roberts, N. W. Young, E. Lemeur, M. J. Siegert, and J. W. Holt, 2017a: IceBridge HiCARS 1 L1B Time-Tagged Echo Strength Profiles, Version 1. NASA National Snow and Ice Data Center Distributed Active Archive Center, doi:10.5067/W2KXX0MYNJ9G.

Blankenship, D. D., S. D. Kempf, D. A. Young, T. G. Richter, D. M. Schroeder, G. Ng, J. S. Greenbaum, T. van Ommen, R. C. Warner, J. L. Roberts, N. W. Young, E. Lemeur, and M. J. Siegert, 2017b: IceBridge HiCARS 2 L1B Time-Tagged Echo Strength Profiles, Version 1. NASA National Snow and Ice Data Center Distributed Active Archive Center, doi:10.5067/0I7PFBVQOGO5.

Cantini, F. and A. Ivanov, 2016: MARSIS/SHARAD viewer plug-in for QGIS. GitHub, `https://github.com/eSpaceEPFL/marsissharadviewer`.

Carter, S. P., D. D. Blankenship, M. E. Peters, D. A. Young, J. W. Holt, and D. L. Morse, 2007: Radar-based subglacial lake classification in Antarctica. *Geochemistry, Geophysics, Geosystems*, **8 (3)**.

Chu, W., R. Culberg, A. M. Hilger, T. M. Jordan, D. Schroeder, H. Seroussi, D. A. Young, and D. G. Vaughan, 2021: U.S. Antarctic Program (USAP) Data Center, doi:10.15784/601436.

Corr, H., F. Ferraccioli, T. Jordan, and C. Robinson, 2021: Processed airborne radio-echo sounding data from the AGAP survey covering Antarctica's Gamburtsev Province, East Antarctica (2007/2009) (Version 1.0) [Data set]. NERC EDS UK Polar Data Centre, doi:10.5285/A1ABF071-85FC-4118-AD37-7F186B72C847.

CReSIS, 2021: CReSIS Radar Depth Sounder Data. Lawrence, Kansas, USA. Digital Media, URL `http://data.cresis.ku.edu/`.

Cui, X., H. Jeofry, J. S. Greenbaum, J. Guo, L. Li, L. E. Lindzey, F. A. Habbal, W. Wei, D. A. Young, N. Ross, et al., 2020: Bed topography of Princess Elizabeth Land in East Antarctica. *Earth System Science Data*, **12 (4)**, 2765–2774.

Ferraccioli, F., H. Corr, T. Jordan, R. Forsberg, K. Matsuoka, A. Diez, A. Olesen, M. Ghidella, A. Zakrajsek, C. Robinson, and O. King, 2021a: Processed airborne radio-echo sounding data from the ICEGRAV survey covering the Recovery Catchment and interior Dronning Maud Land, East Antarctica (2012/2013) (Version 1.0) [Data set]. NERC EDS UK Polar Data Centre, doi: 10.5285/C6324118-94A2-4E03-8715-B24B82322A57.

Ferraccioli, F., H. Corr, T. Jordan, C. Robinson, E. Armadillo, E. Bozzo, and G. Caneva, 2021b: Processed airborne radio-echo sounding data from the WISE-ISODYN survey across the Wilkes Subglacial Basin, East Antarctica (2005/2006) (Version 1.0) [Data set]. NERC EDS UK Polar Data Centre, doi:10.5285/70ADAB3D-3632-400D-9AA1-DDF2D62A11B3.

Fretwell, P., H. D. Pritchard, D. G. Vaughan, J. L. Bamber, N. E. Barrand, R. Bell, C. Bianchi, R. Bingham, D. D. Blankenship, G. Casassa, et al., 2013: Bedmap2: improved ice bed, surface and thickness datasets for Antarctica. *The Cryosphere*, **7 (1)**, 375–393.

Greenbaum, J., D. Blankenship, D. Young, T. Richter, J. Roberts, A. Aitken, B. Legresy, D. Schroeder, R. Warner, T. Van Ommen, et al., 2015: Ocean access to a cavity beneath Totten Glacier in East Antarctica. *Nature Geoscience*, **8 (4)**, 294–298.

Holt, J. W., D. D. Blankenship, D. L. Morse, D. A. Young, M. E. Peters, S. D. Kempf, T. G. Richter, D. G. Vaughan, and H. F. J. Corr, 2006: New boundary conditions for the West Antarctic Ice Sheet: Subglacial topography of the Thwaites and Smith glacier catchments. *Geophysical Research Letters*, **33 (9)**, doi:https://doi.org/10.1029/2005GL025561.

Kjær, K. H., N. K. Larsen, T. Binder, A. A. Bjørk, O. Eisen, M. A. Fahnestock, S. Funder, A. A. Garde, H. Haack, V. Helm, et al., 2018: A large impact crater beneath Hiawatha Glacier in northwest Greenland. *Science advances*, **4 (11)**, eaar8173.

Le Brocq, A. M., N. Ross, J. A. Griggs, R. G. Bingham, H. F. Corr, F. Ferraccioli, A. Jenkins, T. A. Jordan, A. J. Payne, D. M. Rippin, et al., 2013: Evidence from ice shelves for channelized meltwater flow beneath the Antarctic Ice Sheet. *Nature Geoscience*, **6 (11)**, 945–948.

Lee, W. S., J. I. Lee, L. E. Lindzey, L. H. Beem, D. A. Young, E. Quartini, D. D. Blankenship, C.-K. Lee, J. Lee, and S. D. Kempf, 2020: Radar observations of an active subglacial lake system in the David Glacier catchment, Antarctica. Zenodo, URL `https://doi.org/10.5281/zenodo.3874655`, doi:10.5281/zenodo.3874655.

Lindzey, L. E., L. H. Beem, D. A. Young, E. Quartini, D. D. Blankenship, C.-K. Lee, W. S. Lee, J. I. Lee, and J. Lee, 2020: Aerogeophysical characterization of an active subglacial lake system in the David Glacier catchment, Antarctica. *The Cryosphere*, **14 (7)**, 2217–2233.

Lough, A. C., D. A. Wiens, C. G. Barcheck, S. Anandakrishnan, R. C. Aster, D. D. Blankenship, A. D. Huerta, A. Nyblade, D. A. Young, and T. J. Wilson, 2013: Seismic detection of an active subglacial magmatic complex in Marie Byrd Land, Antarctica. *Nature Geoscience*, **6 (12)**, 1031–1035.

Matsuoka, K., A. Skoglund, G. Roth, J. de Pomereu, H. Griffiths, R. Headland, B. Herried, K. Katsumata, A. Le Brocq, K. Licht, , F. Morgan, P. D. Neff, C. Ritz, M. Scheinert, T. Tamura, A. Van de Putte, m. van den Broeke, A. von Deschwanden, C. Deschamps-Berger, B. Van Liefferinge, S. Tronstad, and Y. MelvÃ¦r, 2021: Quantarctica, an integrated mapping environment for Antarctica, the Southern Ocean, and sub-Antarctic islands. *Environmental Modelling & Software*, **140**, 105 015.

Moon, T., M. Fisher, L. Harden, and T. Stafford, 2021: QGreenland. URL `https://qgreenland.org`, doi:https://doi.org/10.5281/zenodo.4558266.

Morlighem, M., E. Rignot, T. Binder, D. Blankenship, R. Drews, G. Eagles, O. Eisen, F. Ferraccioli, R. Forsberg, P. Fretwell, et al., 2020: Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the Antarctic ice sheet. *Nature Geoscience*, **13 (2)**, 132–137.

Nicholls, K., H. Corr, C. Robinson, and T. Jordan, 2021: Processed airborne radio-echo sounding data from the FISS 2015 survey covering the Foundation Ice Stream, Bungenstock Ice Rise, and the Filchner Ice Shelf system, West Antarctica (2015/2016) (Version 1.0) [Data set]. NERC EDS UK Polar Data Centre, doi:10.5285/3507901f-d03e-45a6-8d9b-59cf98a03e1d.

Parrenin, F., M. G. Cavitte, D. D. Blankenship, J. Chappellaz, H. Fischer, O. Gagliardini, V. Masson-Delmotte, O. Passalacqua, C. Ritz, J. Roberts, et al., 2017: Is there 1.5-million-year-old ice near Dome C, Antarctica? *The Cryosphere*, **11 (6)**, 2427–2437.

Peters, M. E., D. D. Blankenship, S. P. Carter, S. D. Kempf, D. A. Young, and J. W. Holt, 2007: Along-track focusing of airborne radar sounding data from West Antarctica for improving basal reflection analysis and layer detection. *IEEE Transactions on Geoscience and Remote Sensing*, **45 (9)**, 2725–2736.

Popov, S., 2020: Fifty-five years of russian radio-echo sounding investigations in antarctica. *Annals of Glaciology*, **61 (81)**, 14–24.

Purdon, K., 2014: OpenPolarServer (OPS)-An Open Source Spatial Data Infrastructure for the Cryosphere Community.

QGIS Development Team, 2021: *QGIS Geographic Information System*. QGIS Association, URL `https://www.qgis.org`.

Roberts, J., B. K. Galton-Fenzi, F. S. Paolo, C. Donnelly, D. E. Gwyther, L. Padman, D. Young, R. Warner, J. Greenbaum, H. A. Fricker, et al., 2018: Ocean forced variability of Totten Glacier mass loss. *Geological Society, London, Special Publications*, **461 (1)**, 175–186.

Schroeder, D. M., J. A. Dowdeswell, M. J. Siegert, R. G. Bingham, W. Chu, E. J. MacKie, M. R. Siegfried, K. I. Vega, J. R. Emmons, and K. Winstein, 2019: Multidecadal observations of the Antarctic ice sheet from restored analog radar records. *Proceedings of the National Academy of Sciences*, **116 (38)**, 18 867–18 873.

Studinger, M., R. E. Bell, G. D. Karner, A. A. Tikku, J. W. Holt, D. L. Morse, T. G. Richter, S. D. Kempf, M. E. Peters, D. D. Blankenship, R. E. Sweeney, and V. L. Rystrom, 2003: Ice cover, landscape setting, and geological framework of Lake Vostok, East Antarctica. *Earth and Planetary Science Letters*, **205 (3)**, 195–210, doi:https://doi.org/10.1016/S0012-821X(02)01041-5, URL `https://www.sciencedirect.com/science/article/pii/S0012821X02010415`.

Studinger, M. S. and R. Bell, 2020: SOAR-Lake Vostok Survey airborne radar data. U.S. Antarctic Program (USAP) Data Center, doi:https://doi.org/10.1594/IEDA/306568.

Tabacco, I., C. Bianchi, J. Baskaradas, L. Cafarella, U. Sciacca, A. Zirizzotti, E. Zuccheretti, et al., 2008: Italian res investigation in antarctica: the new radar system. *Terra Antartica Reports*.

Tinto, K., L. Padman, C. Siddoway, S. Springer, H. Fricker, I. Das, F. C. Tontini, D. Porter, N. Frearson, S. Howard, et al., 2019: Ross Ice Shelf response to climate driven by the tectonic imprint on seafloor bathymetry. *Nature Geoscience*, **12 (6)**, 441–449.

Vaughan, D. G., H. F. Corr, F. Ferraccioli, N. Frearson, A. O'Hare, D. Mach, J. W. Holt, D. D. Blankenship, D. L. Morse, and D. A. Young, 2006: New boundary conditions for the West Antarctic ice sheet: Subglacial topography beneath Pine Island Glacier. *Geophysical Research Letters*, **33 (9)**.

Winter, K., J. Woodward, N. Ross, S. A. Dunning, R. G. Bingham, H. F. Corr, and M. J. Siegert, 2015: Airborne radar evidence for tributary flow switching in Institute Ice Stream, West Antarctica: Implications for ice sheet configuration and dynamics. *Journal of Geophysical Research: Earth Surface*, **120 (9)**, 1611–1625.

Wolovick, M. J., R. E. Bell, T. T. Creyts, and N. Frearson, 2013: Identification and control of subglacial water networks under Dome A, Antarctica. *Journal of Geophysical Research: Earth Surface*, **118 (1)**, 140–154.

Wrona, T., M. J. Wolovick, F. Ferraccioli, H. Corr, T. Jordan, and M. J. Siegert, 2018: Position and variability of complex structures in the central East Antarctic Ice Sheet. *Geological Society, London, Special Publications*, **461 (1)**, 113–129.

Young, D., J. L. Roberts, D. D. B. W. S. Lee, T. V. Ommen, C. Ritz, M. G. Cavitte, and M. Frezzotti, 2021: ICECAP radargrams in support of the international old ice search at Dome C - 2016, Ver. 1. Australian Antarctic Data Centre, doi:10.26179/5wkf-7361.

Young, D. A., J. L. Roberts, C. Ritz, M. Frezzotti, E. Quartini, M. G. Cavitte, C. R. Tozer, D. Steinhage, S. Urbini, H. F. Corr, et al., 2017: High-resolution boundary conditions of an old ice target near Dome C, Antarctica. *The Cryosphere*, **11 (4)**, 1897–1911.

Young, D. A., A. P. Wright, J. L. Roberts, R. C. Warner, N. W. Young, J. S. Greenbaum, D. M. Schroeder, J. W. Holt, D. E. Sugden, D. D. Blankenship, et al., 2011: A dynamic early East Antarctic Ice Sheet suggested by ice-covered fjord landscapes. *Nature*, **474 (7349)**, 72–75.

Data Management

This is primarily a software project, and does not involve collecting any primary data. Instead, we are helping users to locate existing data that is already available at a number of U.S. and international data centers.

As such, the one type of data that we will be generating an index of available ice penetrating radar survey lines associated with the information required to access their data. We have not yet settled on the exact format for that index, but we expect it will be in a human-readable file format in order to enable non-programmers to easily add pointers to their data to the compilation.

The QGIS layers for Antarctica and Greenland will be programmatically generated from the index and the resulting downloaded data. These layers in turn are what the plugin will interact with in order to download and display the radargrams.

Both the raw text file describing available survey lines and the generated QGIS layers will be available at the appropriate data center as required by the Office of Polar Programs: the NSF Arctic Data Center for Greenland, and the U.S. Antarctic Program Data Center for Antarctica.

All code, including the code for generating the QGIS layers from the index, will be publicly available on GitHub under a BSD license.

Delivery Mechanism and Community Usage Metrics

Deliverables

The underlying radargrams are already hosted at data centers chosen by their originators, as detailed in Section 2.2.

This project will generate two primary products:

1. QGIS layers for Greenland and Antarctica, containing coordinates and metadata for all known radar lines
2. Source code for the QGIS plugin

The QGIS data layers will be uploaded to the appropriate region-specific NSF-supported data center: USAP-DC for Antarctica and the Arctic Data Center for Greenland. Both data centers provide publicly-visible counters that track the number of downloads.

Additionally, we will work with Quantarctica and QGreenland to integrate as tightly as possible with their datasets, including following their compatibility guidelines for QGIS layer creation. Quantarctica has releases every few years; we will not have a product ready for inclusion in v4. Instead, we will seek to be linked on their website as an "Add-On Dataset". QGreenland is planning to keep their core data package small, and to develop a QGIS plugin that facilitates finding and downloading compatible datasets. Once both projects are ready, we will seek to be added to the list of suggested datasets.

All source code generated as part of this project will be released on Github under the permissive BSD license. We will also upload it to the QGIS plugin repository, which makes it possible for users to install it from within QGIS rather than having to be comfortable with git.

Metrics

Data Availability

While line-kilometers of data is the logical way to measure data availability, it is somewhat out of our control because it depends on what the different data providers choose to release, so we have chosen not to set targets around that number. However, we will calculate and display on our website the running total of supported line-kilometers compared to those used in the creation of BEDMAP3 as a way of making data availability more visible to the community.

Instead, we will set targets based the number of data providers whose formats and data repositories are supported.

Year 1 focuses on developing a proof-of-concept implementation that is ready to be used by our beta testers. As such, we will start with three of the largest available online datasets: CReSIS (e.g. CReSIS (2021)), BAS (e.g. (Ferraccioli et al., 2021b)), and ICECAP (e.g. Blankenship et al. (2017b)).

Year 2 aims to expand access/coverage. We will add support for the remaining Antarctic datasets identified in Section 2.2 and at least two additional Greenland datasets.

Year 3 will focus on documentation and outreach. In support of that, we will work with data creators to add support for at least two smaller datasets to the tool and document the process.

Download Metrics

Collecting usage metrics is more challenging for an installed application than a web service. Given our architecture, there are two logical places to do this: counting downloads of the QGIS layers, and tracking which datasets users are requesting to download.

Our data centers track total downloads by default. During Y1 and Y2, we expect that downloads will closely track the number of scientists that we have reached out to and are directly corresponding with. We aim to have at least 100 additional downloads of both the Antarctic and Greenland layers during Y3, representing community adoption outside of our direct outreach. This count is publicly viewable on the USAP-DC and Arctic Data Center download pages.

The real measure of success is whether researchers continue using the tool. To enable tracking this, we will add anonymized reporting of which data is a user requests. In the interests of transparency and privacy, we will make this reporting opt-in, with a prompt at the first download request. Therefore, we expect it to be an underestimate of actual usage. Our target is for a quarter of users to download an additional radargram at least 3 months after downloading their first.

Community Usage and Engagement

We plan a staged roll-out to get early feedback from the community and ensure that most researchers' first encounter is either with a polished product or during a limited-enough release that one-on-one support is possible. The budget includes sufficient development time in years 2 and 3 to react to feedback and prioritize additional feature requests.

All project management related to the plugin's code will be performed using GitHub's issue tracker, which provides transparency into decisions around feature requests, documents of how issues were resolved, and is another metric for engagement.

Year 1 we will develop the core functionality and share it with 2-3 enthusiastic external collaborators. We aim for at least 2 feature requests from each, as a measure of their engagement. Additionally, during summer 2023 we will have a team of 3 undergraduate researchers complete projects that involve heavy use of the plugin. This will serve as a quality-control check on the imported data, a stress test on the interface and documentation, and will test usage on all of the supported operating systems (OS X, Windows, Ubuntu).

Year 2 will expand usage to the rest of our Advisory Committee. All of them have committed to try using it in their research and provide feedback; we aim for at least one request or bug report from each.

The beginning of **Year 3** will see the release of this tool to the broader community, including an announcement to Cryolist and a workshop at SCAR. We are targeting at least 15 attendees to the first in-person workshop and 10 issues of any type (suggesting features, reporting missing data, asking for help) reported on GitHub.

Towards the end of Y3, we will send out a short user survey to Cryolist. Quantarctica reports an abysmally low response rate for its surveys, so we only target 5 responses, but we think it is important to provide an additional avenue that invites feedback from users who may not be comfortable with the GitHub issue tracker workflow.

We will also submit a "Brief Communication" describing this tool to The Cryosphere, but would not to expect to start seeing academic citations before the period of performance ends.

CI Professional Mentoring and/or Professional Development Plan

PI Lindzey is also the only CI professional who will be supported by this project. As this is her first competitively-submitted proposal as PI or co-I, the entire project is in many ways an exercise in professional development.

In the process of preparing the proposal, she has sought out and found mentoring from more senior collaborators; a supportive supervisor and department head; and APL's excellent administrative staff. She expects that she will continue to seek out advice from senior colleagues throughout the project, particularly with regards to defining a presentation and publication strategy.

PI Lindzey will be responsible for writing the resulting publication, as well as for preparing and delivering the planned conference talks and tutorial. Presenting at the SciPy conference in particular will also serve as professional development along the CI axis, as it is an opportunity to learn about techniques and tools used by other software engineers who support scientific research.

Given the international nature of the datasets involved, preparing this proposal has already involved conversations with colleagues from at least six other countries. Collaborators on this project include both specialists in data/computing and a range of disciplines within the geosciences.

Facilities, Equipment, and Other Resources

The Applied Physics Laboratory at the University of Washington (APL-UW) is a university laboratory that was established by the US Navy in 1943. APL-UW has since broadened its research program beyond the traditional Naval focus to include a range of fundamental and applied research projects. APL-UW has a world-class workforce comprised of scientists and engineers with diverse back- grounds. Many of the personnel hold University of Washington joint faculty appointments, teach courses, and advise students.

Located on the campus of the University of Washington, APL-UW is a self-contained, fully-equipped research facility. The laboratory occupies three buildings and operates several vessels. On shore, APL-UW is equipped with an extensive machine shop, CAD/CAM facilities, a library, publication facilities.

This proposal does not require significant infrastructure or equipment. The primary activity is software development, and the budget includes both computers and hard drives for local data storage. Our planned participation in the Pacific Science Center's Climate Change Curiosity Expo will require putting together an engaging exhibit, for which we will leverage APL's 3D printing and graphics capabilities.

We plan to recruit interns for one of the summers, and for this we will benefit from APL-UW's close ties with the university.

Project Personnel and Partner Organizations

1. Laura Lindzey; University of Washington Applied Physics Laboratory; PI
2. Kenichi Matsuoka; Norwegian Polar Institute; Unpaid Collaborator
3. Twila Moon; National Snow and Ice Data Center; Unpaid Collaborator
4. Duncan Young; University of Texas Institute for Geophysics; Unpaid Collaborator
5. John Paden; University of Kansas; Unpaid Collaborator
6. Alice Fremand; British Antarctic Survey; Unpaid Collaborator
7. Christine Dow; University of Waterloo; Unpaid Collaborator
8. Jamin Greenbaum; Scripps Institute of Oceanography, UC San Diego; Unpaid Collaborator
9. Nick Holschuh; Amherst College; Unpaid Collaborator
10. Lenneke Jong; Australian Antarctic Division; Unpaid Collaborator
11. Joseph MacGregor; NASA Goddard; Unpaid Collaborator
12. Felicity McCormack; Monash University; Unpaid Collaborator
13. Theodore Scambos; Cooperative Institute for Research in Environmental Sciences at the University of Colorado Boulder; Unpaid Collaborator
14. Martin Siegert; Imperial College London; Unpaid Collaborator