Abstracts for Presentations – Polar Radar Science and Technology Conference – April 4-6, 2022

Day 1 Monday 4/4

0820 - Presentations - 4 people for 10 minutes each - 40 minutes

1. **Bastien Ruols. Current science & logistics using radar: "Drone-based GPR system for alpine glacier surveying"**
   Ground-penetrating radar (GPR) surveys over glaciers are typically performed either directly on the surface (e.g., on foot, skis, or with snowmobiles), or by helicopter well above it. In the scope of 3D data acquisitions, both techniques have advantages but also drawbacks. While air-based surveys allow the coverage of large areas safely and efficiently, it comes at the expense of reduced resolution of glacier internal structures. On the other hand, ice-based acquisitions offer high-resolution opportunities, but are time-consuming, labour intensive, and dangerous as well. However, recent advances in the development of drone technologies open new data acquisition possibilities, and we have developed a drone-based GPR system that combines advantages of both methods. Our custom-built GPR instrument uses real-time sampling to record traces of length 2800ns, which corresponds to a depth of over 200m in glacier ice. Each trace is stacked over 5000 times and acquired using a sampling frequency of 320Mhz, the latter which is just enough to avoid aliasing with our single lightweight 70Mhz-center-frequency antenna. Traces are recorded at a rate of 14Hz, meaning that a drone speed of at least 4m/s can be considered while maintaining a sufficient high trace density for high-resolution studies. We performed initial tests on summer 2021 on two Swiss Alpine glaciers and recorded around 100-line kilometers of 3D GPR data, over 11 days of fieldwork. With further development, we are aiming to automatise as much as possible the 3D GPR data acquisitions. And coming back on a regular basis to record data on the exact same area, we might be able to move toward 4D GPR data to investigate temporal glacier variations such as dynamics and hydrology.
2. **Olaf Eisen. AWI's radar systems, current science, future science: "AWI's ultrawideband radar systems - access, technology & science"**
   AWI's ultrawideband (UWB) radar system was developed by CReSIS as MCORDS v5, a 24 element system, operating in the range 150-600 MHz at 4 kW maximum peak power. In addition, a microwave UWB system has been used for very high resolution surveys. We will present highlights of operational deployment obtained in Greenland and Antarctica over the last years, specifics of the system and processing as well as an outlook for future surveys. Moreover, we will inform how external users can apply for usage of the radar system.

3. **Sarina Kapai. Current commercial radar systems, research, and development: "SAR Focusing of Mobile ApRES Surveys"**
   The Autonomous Phase-Sensitive Radio Echo Sounder (ApRES) is a relatively inexpensive commercial ice-penetrating Frequency-Modulated Continuous-Wave (FMCW) radar that is widely utilized in the glaciological community to obtain estimates of ice-sheet basal melt, vertical strain, and compaction rates [1]. However, these instruments are designed for stationary deployments, which prevents glacier- and catchment-scale surveys [2]. To expand the range of available applications, we assess the feasibility of mobile ApRES surveys. Our investigation reveals that utilizing the ApRES in this manner introduces artifacts into the raw data. This paper characterizes the two types of artifacts (Doppler Blurring and grating lobes), investigates the conditions for when they occur, and attempts to correct them by modifying synthetic aperture radar (SAR) focusing algorithms for FMCW radars. We ultimately identify the main obstacle in focusing radargrams from mobile ApRES surveys to be grating lobes; future work that reduces the presence of this artifact could enable more widespread use of mobile ApRES surveys.

4. **Joe MacGregor. Current & future community radar systems: "Current & future community radar systems"**
   Ground-based radar sounding is essential for process studies of Earth's many temperate glaciers, but airborne systems are required for regional-scale mapping of glacier thickness. Radar sounding of the thickness of temperate glaciers is challenged by substantial volume scattering (englacial water), surface scattering (crevasses and debris) and high attenuation rates (warmer ice). Lower frequency radar sounders are often deployed to mitigate these effects, but the lack of a global synthesis of their success limits progress in system and survey design. Here we extend a recent global compilation of glacier thickness measurements (GlaThiDa) with the center frequency for radar-sounding surveys. From a maximum reported thickness of ~1500 m near 1 MHz, the maximum thickness sounded decreases by ~500 m per frequency decade. Between 25–100 MHz, newer airborne radar sounders generally outperform older, ground-based ones. Based on globally modeled glacier thicknesses, we conclude that a multi-element, ≤ 30-MHz airborne radar sounder could survey most temperate glaciers more efficiently.

Day 2 Tuesday 4/5
0820 - Presentations - 4 people for 10 minutes each - 40 minutes

1. **John Bradford. Current science & logistics using radar: "Detailed mapping of the internal structure of Arctic pingos using ground-penetrating radar"**
   The Pingo SubTerranean Aquifer Reconnaissance and Reconstruction (Pingo STARR) project is a detailed geophysical study of Arctic pingos in order to better understand the evolution of hydrologic conditions that lead to pingo formation and degradation over time. The goal is to use information gained from the Pingo STARR project to inform studies of analogous features on extraterrestrial systems such as Mars and Ceres. Here we report preliminary ground-penetrating radar results from the first field season. In April 2021, our team surveyed four pingos near Prudhoe Bay, Alaska. The pingos ranged in height from 6 m to 19 m. At all four pingos we acquired data with a state-of-the-art multi-channel radar system with both multiple frequencies and multiple offsets. Qualitative interpretation reveals significant variation between the four pingos. In the largest pingo, a well-defined, massive ice core is easily identified in the radargram. The core of the three smaller pingos is either stratified or shows a chaotic reflectivity pattern. A deep (>20m), strong reflection is present at three of the four pingos, which may be a talik that serves as a groundwater source for pingo formation. Future work will include detailed imaging of the permittivity structure using reflection tomography to place constraints on the material contained in the pingo core and in the underlying formation. The study highlights both the capabilities and limitations of current multi-channel radar systems operating in Arctic conditions. We further discuss the possibilities and limitations of answering planetary science questions using terrestrial analogs and ground-based radar systems.

2. **Riley Culberg. Future science questions & logistics requiring radar: "Improving Geophysical Constraints on Firn Aquifer Total Water Storage by Combining Radar and In Situ Measurements"**
   Perennial firn aquifers play an important role in modulating surface mass balance and ice dynamics in Southeast Greenland by temporarily buffering meltwater runoff and smoothing water input to the subglacial system. Ice-penetrating radar has been used to map the spatial extent of these aquifers and, in some locations, infer their thickness. However, quantitative estimates of aquifer properties from radar observations typically require extensive a priori knowledge of the local firn structure and water properties. We develop a Markov Chain Monte Carlo joint inversion of radar reflectivity and attenuation to simultaneously estimate firn structure and aquifer properties and their associated uncertainty. We then use this model to explore the combination of radar and in situ measurements that would place the best possible constraints on the total aquifer storage capacity. Our results suggest that together, precise measurements of radar attenuation and aquifer water conductivity are sufficient to infer total water storage. Therefore, future field surveys of firn aquifer systems might prioritize water conductivity measurements and use low-frequency or high-power radar systems capable of resolving features beneath the aquifer body, rather than focusing on firn core density measurements or resolving the water table.

3. **Laurent Mingo. Current commercial radar systems, research, and development: "IceRadar: a tool for radio-echo sounding of glaciers"**
   In this presentation we describe the evolution of the ice-penetrating radar (IPR) system "IceRadar" and its use for glaciology work following its first implementation in 2008/09 and evolution to present. The radar system is positioned as a bridge between standard commercial systems and more re-configurable research tools so to be suitable for both scientific and industrial applications. Beside the roving IPR system mostly used for ground-based radio-echo sounding surveys, examples of implementation variants are described. For example, the UAV-IPR, as well as several automated stationary versions (sIPR) of the radar that operated in the Artic and Saint-Elias mountains in recent years and as late as 2021. The system's open data format will be quickly presented, together with relevant resources and tools. New developments for an helicopter-based system is also introduced with preliminary data obtained in summer 2021.

4. **Marie Cavitte. Radar data software, analysis, and interpretation needs: "The difficulty of having only access to open source software"**

Day 3 Wednesday 4/6

0820 - Presentations - 4 people for 10 minutes each - 40 minutes

1. **Rodrigo Rangel. Current science & logistics using radar: "Northern lake ice property analysis using ground penetrating radar"**
   The measurement of lake ice physical properties and thickness is valuable for understanding ice growth processes and estimating trapped gas and water content. Northern lakes are a globally significant source of atmospheric methane (CH_4), but there are large uncertainties in quantifying lake CH_4 emissions that limit the accuracy of climate change projections. Previous research has estimated lake ice properties using visual assessment of gas trapped in lake ice, and remote sensing. However, there remains a need for a quantitative method to estimate lake ice properties that bridges scales between ground (< 1 m2) and satellite remote sensing (> 100 m2) measurements. Here we suggest that this gap can be filled using ground penetrating radar (GPR) to acquire data non-invasively and estimate lake ice radar velocity and thickness. GPR measurements were conducted on 12 lakes in Alaska, including ten on the North Slope and two near Fairbanks. Our results suggest that lake ice thicker than the long-term seasonal average is associated with faster radar velocity, i.e., higher gas content. We found a weak correlation between radar velocity and synthetic aperture radar (SAR) T11 backscatter, and this discrepancy may be explained in part by the difference in measurement footprint between GPR (< 1 m2) and SAR (~156 m2). This study contributes to an improved understanding of lake ice properties and thickness that could be used to refine SAR measurements. Furthermore, a better estimation of lake ice properties is essential to project the impacts of climate warming.

2. **Anna Broome. Current & future community radar systems: "Development and Initial Field Testing of a Multi-Frequency Ice-Penetrating Radar"**
   Traditional ice-penetrating radar systems have a single center frequency and relatively narrow bandwidth. Inferring glaciological conditions from their data requires large-scale spatial averaging or along-track relative comparisons to overcome the ambiguities contained in each echo reception. To enable more accurate and precise interpretation of ice-penetrating radar data on a pulse-by-pulse basis, we are developing a multi-frequency radar system with three channels, whose center frequencies are separated by two orders of magnitude. Using a multi-frequency radar allows us to exploit the frequency dependent scattering from the basal interface and separate its effect on the echo power from the frequency independent basal material reflectivity. To further remove ambiguities in the system, we combine the radar echo power measurements with brightness temperature measurements from a multi-frequency microwave radiometer. Integrating the radar and radiometer measurements in this manner improves sensitivity to englacial temperature across the full depth of the ice column.

   Here we present the design and implementation of our multi-frequency radar system using an Ettus X310 software-defined radio (SDR). Implementing our system on an SDR provides us reconfigurability typically not available in fixed-hardware radar systems. This reconfigurability allows us to tailor our system design (center frequencies, bandwidth, radiometric resolution, etc.) to a specific glaciological setting. We also discuss results from initial laboratory and field testing of our system, including a recent deployment on ice in Svalbard, Norway.

3. **Thomas Teisberg. Current & future community radar systems: "Development of a fixed-wing UAV-borne frequency-modulated ice-penetrating radar system"**
   Ice-penetrating radar instruments carried by crewed aircraft are the primary tool available for measuring the englacial and subglacial properties of Earth's ice sheets at large scales. Conventional approaches to these surveys are expensive and logistically complicated, primarily due to their reliance on crewed aircraft and the associated requirements. We are developing a small-scale fixed-wing UAV system for collecting ice-penetrating radar data without the logistical complexities or expense of crewed aircraft. Our platform will be capable of carrying out automated surveying, including executing adaptive survey plans.

   With the availability of transportable UAVs capable of carrying multi-kilogram payloads on missions of more than 100 kilometers, UAVs have quickly become appealing platforms to replace crewed aircraft. The logistical complexity of flights in Antarctica makes ice-penetrating radar an especially appealing target to replace with an uncrewed solution. Additionally, the vast scale of the Antarctic Ice Sheet necessitates some degree of adaptive sampling to focus efforts on the collection of the most important data. Many such adaptive sampling approaches would benefit from a fully autonomous and uncrewed data collection platform that can be more easily programmed and be subject to fewer safety restrictions.

   We present preliminary flight testing data and future plans for our UAV-borne ice-penetrating radar system.

4. **William Harcourt. Current & future community radar systems: "Millimetre-wave radar at 94 GHz: A new tool for cryosphere research"**
   High spatial and temporal resolution measurements of cryospheric terrain is critical for enabling effective monitoring of the dynamic cryosphere. Here, I will demonstrate the new capabilities of a real-aperture,

mechanically scanning, millimetre-wave radar at 94 GHz for mapping glacier surfaces and snow-covered terrain. Millimetre-wave radar operates at a higher frequency compared to most conventional terrain mapping radar systems and hence achieves high angular resolution measurements through most weather conditions. Despite these advantages, the millimetre-wave region of the electromagnetic spectrum has seldom been used for terrain mapping and there are virtually no radar systems operating at these frequencies available for cryosphere research. I will therefore present new results that showcase the potential for using these higher frequency radar bands for cryosphere research. Firstly, the radar backscatter characteristics of glacier ice at 94 GHz will be presented using measurements collected at Rhônegletscher in Switzerland. Secondly, the results of monitoring changes in radar backscatter over snow to map active hazards such as avalanches will be presented. Finally, I will showcase results from Svalbard where millimetre-wave radar was used to analyse glacier calving activity using a time series of 3D ice front change. Overall, these results are a benchmark for using millimetre-wave radar for cryosphere research. The radar system used throughout the project was built and developed at the University of St Andrews (Scotland) and I hope this contribution can initiate a discussion about further developing millimetre-wave radar systems for Polar research.