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FIRST RESULTS FROM MAPPERR: THE MULTI-FREQUENCY ACTIVE PASSIVE POLAR EXPLORATION RADAR-RADIOMETER

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ABSTRACT

Here we show the initial design and results from MAPPERR: The Multi-frequency Active Passive Polar Exploration Radar-Radiometer. MAPPERR addresses fundamental limitations in traditional ice-penetrating radar sounders and microwave radiometers stemming from non-unique contributions of different glaciological conditions. By utilizing active radar channels at 2, 22, 330, and 1000 MHz MAPPERR is designed to disentangle basal roughness and basal material conditions, while also providing important constraints on englacial temperature via measurements of attenuation. Passive radiometer channels at 330 and 1000 MHz provide additional constraints on englacial temperature via measurements of thermal emission and attenuation. Here, the system design is described and initial field results from campaigns in Svalbard, Iceland, and Antarctica are presented.

Index Terms— Radar sounding, radiometry, glaciology

1. INTRODUCTION

The Multi-frequency Active Passive Polar Exploration Radar-Radiometer (MAPPERR) is a new ground-based microwave remote sensing system designed to measure basal and englacial conditions of Earth's ice sheets with higher precision and accuracy than ever before. Specifically, MAPPERR combines a chirped, coherent multi-frequency ice-penetrating radar based off [1] with a dual-frequency microwave radiometer based off [2]. These two instruments are combined into one system, enabling high fidelity measurements of basal roughness and material characteristics, as well as top-to-bottom measurements of ice sheet thermal state. Data from MAPPERR will provide important observational constraints on ice-sheet basal and englacial conditions to be incorporated into large-scale ice-sheet models and improve overall understanding of ice-sheet flow and evolution.

2. MAPPERR SYSTEM DESIGN

MAPPERR is a multi-frequency joint radar-radiometer system designed to disentangle the effects of basal roughness, basal material, and englacial temperature signatures. The backbone of MAPPERR is an Ettus X310 software-defined radio (SDR) with two UBX-160 daughterboards that operate with up to 160 MHz bandwidth between center frequencies 10 MHz and 6 GHz [3]. Front-end electronics are added to enhance performance of the system. MAPPERR is controlled using a custom codebase that runs coherent chirped radars on multiple SDRs within the Ettus family and provides basic ice-penetrating radar processing code. This code has been successfully deployed in multiple ice-penetrating radar applications and will be publicly released in the near future.

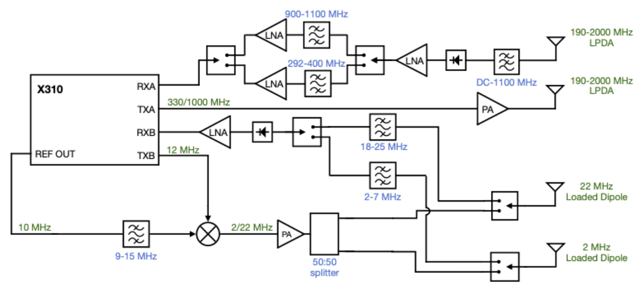


Fig. 1. Block diagram of the full MAPPERR system. An Ettus X310 SDR is controlled via a computer (not shown) to transmit and receive RF signals.

Figure 1 shows a block diagram of the overall MAPPERR system. Two transmit ports and two receive ports are used on the SDR. One transmit port is connected to a 200-2000 MHz log-periodic dipole antenna (LPDA) with an optional 100 W power amplifier in the transmit chain that is included depending on target properties and experimental design. This port is used to transmit chirps at center frequencies of 330 MHz and 1000 MHz. Typical bandwidths used are 10–50 MHz. The other transmit port is used to transmit 2 MHz and 22 MHz chirps.

The UBX-160 daughterboards have a lower limit of 10 MHz, so an external mixer is needed to generate chirps with a 2 MHz center frequency. The mixer receives a 12 MHz signal from the SDR transmit port and a 10 MHz signal exported from the SDRs internal clock. Mixing the 10 MHz and 12 MHz signals results in the desired 2 MHz and 22 MHz outputs. The 2 and 22 MHz chirps are amplified and the amplified output is fed into a power splitter that connects

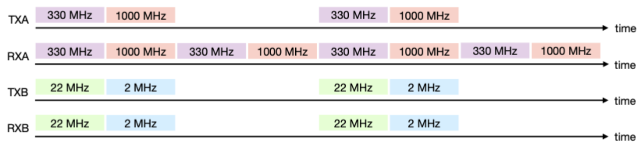


Fig. 2. Schematic depicting a typical combination of time-division multiplexed and simultaneous transmission and reception of RF signals at different center frequencies on different SDR channels.

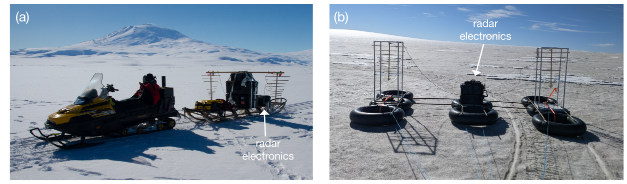


Fig. 3. MAPPERR deployed on (a) a wooden sled utilizing a wooden crossbar and (b) a custom RF-transparent inner tube sled.

to the 2 MHz or 22 MHz antenna through one of two transmit/receive switches. Depending on the platform, experiment, and field constraints, the system can be configured either with the power splitter located in between the mixer and power amplifier (requiring two power amplifiers, one for each channel) or after the power amplifier (requiring one power amplifier total). On all channels, after an echo is received, it is filtered, then passes through a limiter and at least one low-noise amplifier before being digitized by the SDR.

The SDR is connected to a laptop via Ethernet cable and data is saved directly to the laptop. MAPPERR is powered by an external 12 V battery, which is connected to a custom power distribution PCB, designed in house. This power distribution board uses several DC-DC converters to convert the 12 V input to all other voltages needed for operation of the system. Early field tests of the system relied on an DC-AC inverter and benchtop power supply for their power requirements. The more recent power distribution board is much more efficient than the inverter setup, however it currently does not support direct charging of the laptop.

We designed MAPPERR to operate using a combination of simultaneous and time-division multiplexed transmission and reception. An example of such a scheme is shown in Fig. 2. If a power combiner instead of an SP2T switch is used in place of the SP2T switch before the limiter on the RXB line, it is then possible to simultaneously transmit and receive 2 MHz and 22 MHz chirps. However, with just a SP2T switch there, these chirps must also be time multiplexed, as depicted in Fig. 2. We cease all transmissions, even of the lower frequencies, during the passive measurements in an effort to minimize radio-frequency interference (RFI).

Both the active and passive channels with center frequencies above 200 MHz make use of commercially available log-periodic dipole antennas. These antennas cover 190-2000 MHz with average gain of 6.7 dBi [4]. The 2 and 22 MHz channels rely on in-house resistively loaded dipoles. Resistive loading is determined following the Wu-King method [5]. The length of the antennas is adjusted based on empirical observations of the return loss made in the field using a vector network analyzer at the time of deployment. These measurements are affected by surface conditions, in particular wetness of the surface snow. As such, an antenna adjusted to resonate at a particular center frequency while laying on dry snow, may resonate at a slightly different frequency when laying on wet snow. It is therefore necessary to tune the center frequency in each new deployment location.

2.1. Transmit/Receive Switches

The design in Fig. 1 relies on transmit/receive (T/R) switches to connect the low frequency dipoles to either the transmit or to the receive port of the SDR. These switches must be able to handle transmit powers of up to 250 W and should have a switching time that is short enough for at least the basal reflection to be observable. The switches currently being used in MAPPERR have switching times on the order of 5 us, allowing sounding of ice thicknesses greater than approximately 450 m. In future versions, switching times closer to 1 us would allow sounding of ice as shallow as 100 m. As a result, the thin and temperate field sites presented in this paper include data from only the 330 MHz channel, which does not rely on a T/R switch.

While using a T/R switch limits the minimum thickness of ice that can be measured with MAPPERR, it is advantageous because it reduces the physical area required for deployment. Without a T/R switch, two antennas would be required for each of the two low frequency channels. Adding an additional 75 m of antenna for the 2 MHz channel and an additional 7 m of antenna for the 22 MHz channel makes managing the system cumbersome in the field. Since the primary goal of MAPPERR is to observe basal conditions in areas of relatively thick ice on Earth's ice sheets, we are willing to trade the inability to image very shallow ice for relative ease in deployment.

2.2. Physical Set Up

MAPPERR is built to be deployed as a ground-based system towed on a sled behind a snowmobile or other snow machine. All of the electronics, including the laptop used for command and data storage, are housed in a single enclosed plastic case. Power is provided by an external 12V battery. A GPS antenna is mounted and connected to the SDR's GPS port to enable real-time logging of positioning data. If a non-metallic sled is available, the LPDAs may be mounted using a wooden crossbar, as in Fig. 3(a), with the case housing electronics also mounted on the sled. A custom inner tube-based sled

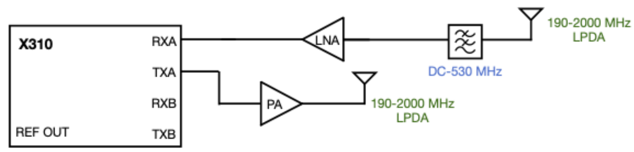
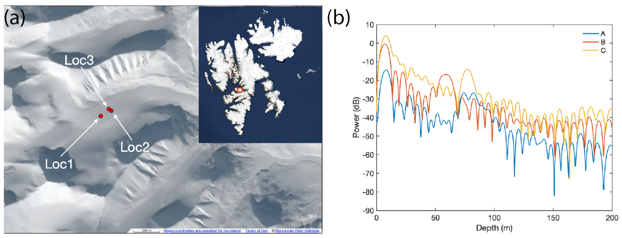
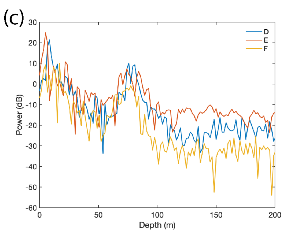


Fig. 4. Block diagram for the portion of the system used for collecting field data presented in this paper.





(d)

	Location	Center Frequency (MHz)	Chirp Length (us)	Chirp Bandwidth (MHz)
A	1	300	10	20
B	2	300	10	20
C	3	300	10	20
D	1	300	10	50
E	1	500	10	50
F	1	1000	10	50

Fig. 5. (a) Map showing location of Tellbreen within Svalbard (top right) and locations of specific measurements. (b) Pulse compressed depth profiles shown at three locations on Tellbreen, upsampled 10x. (c) Pulse compressed depth profiles at a single location measured with three different center frequencies. (d) Chirp parameters for the measurements in (b) and (c).

design has also been used successfully in cases where no non-metallic sleds are available, or if the surface roughness makes the crossbar impractical. The inner tube sled is shown in Fig. 3(b). It is made up of rubber inner tubes, plywood, bamboo, and lashing, making it completely RF transparent. Testing with metallic sleds has shown a detrimental increase in coupling between the transmit and receive LPDAs, so this method is not advised.

3. INITIAL RESULTS

Initial field campaigns using the MAPPERR system took place throughout 2022 on Tellbreen in Svalbard, on Vatnajökull Ice Cap in Iceland, and on McMurdo Ice Shelf in Antarctica. The radar measurements presented in this paper were made using a subset of the overall system, as depicted in Fig. 4. The LNA and lowpass filter in Fig. 4 were not present for the Svalbard campaign. Field testing of the 2 MHz and 22 MHz channels, as well as the passive channels, is ongoing.

Figure 5(a) shows the locations of stationary ice thickness measurements collected on Tellbreen in March 2022. One

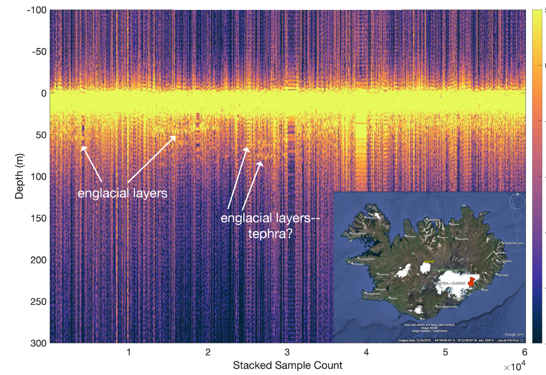


Fig. 6. Radargram collected on Skálafellsjökull in Iceland (inset shows location). The chirp has a center frequency of 300 MHz, 40 us duration, and 20 MHz bandwidth. The PRF is 100 Hz and average snowmobile velocity is 1 m/s. The total profile is just under 1.5 km.

dimensional range profiles of the pulse compressed chirp at each location are shown in Fig. 5(b). Ice thicknesses range from 60 to 85 m, which is consistent with prior measurements in this area [6]. Ice thickness measurements at multiple frequencies are shown in Fig. 5(c). Parameters for the chirps used in collecting these measurements are specified in Fig. 5(d). Figure 5(b) shows the visual difference between upsampled data as compared to non-upsampled data in Fig. 5(c). All data is originally collected at the Nyquist rate.

Towed surveys were tested for the first time during field campaigns in Iceland in June and August 2022. Figure 6 shows the results from a towed survey collected on Skálafellsjökull, an outlet glacier on the southeastern side of the Vatnajökull Ice Cap. In Fig. 6, several subsurface layers are visible at depths of approximately 40–70 m. Some of these layers may be related to a near-surface hydrological system, while others are likely tephra layers deposited during eruptions of the nearby volcanoes [7]. No basal reflection is obvious in the 330 MHz data due to the high attenuation and scattering from englacial water in the temperate ice cap. The lower frequency channels at 2 MHz and 22 MHz may be less susceptible to this attenuation and scattering, but have not yet been deployed successfully in suitably thick portions of the Vatnajökull Ice Cap.

Figure 7 shows a profile collected on the McMurdo Ice Shelf in November 2022. For the first approximately 3.5 km of the profile, a brine layer is the primary reflector. This brine layer has also been extensively imaged on the McMurdo Ice Shelf using an impulsive ground-penetrating radar system in [8]. After about 3.5 km, returns from the brine layer are decreased and a strong reflection from the bottom of the ice shelf becomes visible. Depths are computed using a dielectric constant of 3.17 for ice, which is generally appropriate for deep ice radar sounding. Given the limited thickness of the ice

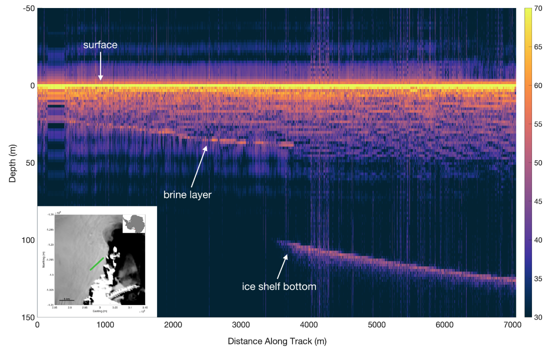


Fig. 7. Radargram collected on McMurdo Ice Shelf (location shown in inset) with center frequency of 330 MHz, chirp length of 20 us, and bandwidth of 50 MHz. Every 10 pulses are coherently summed. Average velocity of the snowmobile is 3.4 m/s.

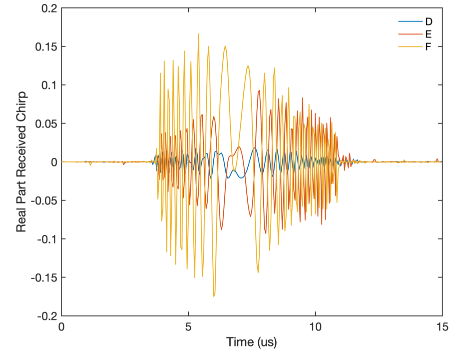


Fig. 8. Raw direct path chirps collected using the same parameters during testing in Svalbard, showing undesirable amplitude variations. Specific chirp parameters listed in Fig. 5(d).

shelf, a lower dielectric constant may produce more accurate depths in this area.

4. ONGOING WORK

In addition to their success, initial field tests of MAPPERR have also illuminated aspects of the system requiring further study, testing, and fine-tuning.

4.1. Gain Stability and Calibration

Understanding, measuring, and correcting for variations and fluctuations in gain level is essential to develop a system with precise radiometric resolution, which modeling has shown is important for disentangling basal conditions with a multi-frequency radar system [1]. Figure 8 shows the real part of the direct path of three received chirps collected with the same chirp parameters. The amplitude of these chirps is up to an order of magnitude different. Initial inspection of data suggests that gain variations occur primarily between recordings.

4.2. Low Frequency Active Channel Testing

Upcoming field tests on thicker, non-temperate portions of ice sheets will allow similar evaluation the lower frequency channels along with evaluation of the cross-frequency analysis of MAPPERR data, one of the key use cases for which this system was developed.

4.3. Passive Channel Testing

Some passive (radiometer) measurements were collected during the Iceland field campaigns. These measurements suffered from moderate RFI and post-processing to filter out that RFI and investigate initial brightness temperatures is ongoing.

5. CONCLUSION

Within 9 months of initial field deployment, MAPPERR has demonstrated successful soundings of subsurface layers and the ice-bed interface. The active channels on MAPPERR are chirped and coherent, and the data can be focused using traditional radar sounding focusing techniques and more sophisticated techniques, including analysis of the coherence and specularity content of reflected signals. Importantly, MAPPERR is designed to operate from a single snowmobile and sled, making it easily deployable by small field teams interested in conducting ground-based surveys. Further validation in upcoming field tests will help MAPPERR accomplish its goals of separating the effects of basal roughness, basal material, and englacial temperature.

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