L-Band Radar Sounder for Measuing Ice Basal Conditions and Ice-Shelf Melt Rate

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***Abstract*—A new L-band radar system is proposed to measure ice thickness, basal conditions and ice-shelves bottom melt rates. The concept for ice measurements with an L-band radar is based on the recent success in sounding shallow low-loss ice (< 1 km) and measuring ice-self melt rates with a 600-900 MHz low-power radar, referred to as accumulation radar [1]. A surface-based radar operating over 1.2-1.4 GHz with a peak transmit power of 2 kW is proposed to sound and image more than 4 km thick ice. The higher frequency at 1.3 GHz will provide the sensitivity required to detect basal water film as thin as 0.5 mm as compared to radars operating now at frequencies less than 600 MHz. These radars need a minimum film thickness of 4 mm or more for reliable detection. The proposed L-band radar will also measure the bottom melt rate of ice shelves. The current plan is to deploy the proposed radar for field test in Antarctica during the 2018-2019 field season.**

Keywords—Radar, ice, L-band, sounder

I. Introduction

Over the past century, global mean sea level has increased by 20 cm ± 2 cm as a result of the ocean thermal expansion and ice loss from glaciers [2]. With the continued population growth in the coastal areas and increased occurrence of extreme weather events, it is critical to have a reliable projection of future sea level rise so that policy-makers can identify and implement strategies to minimize future flood risks. Greenland Ice Sheet (GIS) and Antarctica Ice Sheet (AIS) are the two largest potential contributors to sea level rise. Measurements over the past decade have shown that the GIS has experienced an accelerated rate of mass loss [3-4] that is faster than current models predicted [5]. Such discrepancy can largely be attributed to the lack of knowledge on the basal boundary conditions of ice sheets [6]. While airborne radar soundings of ice sheets since the early 1990s have provided ice basal topography data to improve ice-sheet modelling, the basal stress is still poorly constrained. The presence of a thin-film of subglacial meltwater could result in significant difference in the stress resisting ice flow [7-8]. At present, there is no remote sensing technique for retrieving the spatial distribution of subglacial water layer with millimeter scale thickness.

Ice shelves also play a major role to the stability of ice sheets, as their hydrostatic force generally acts as an anchor to grounded ice. Research suggests that glacier flows could accelerate drastically as an ice shelf rapidly collapses or retreats [9-10]. Being able to accurately monitor ice shelves bottom melt rate is, therefore, critical for predicting the evolution of ice sheets [11]. Such measurements have recently been demonstrated using an airborne UHF radar [1]. And similar measurements shall be made over the West AIS (WAIS) where the world's largest ice-shelves reside, and the ice is mostly grounded to 2-km below the sea-level. In contrast to the WAIS, most of the East AIS (EAIS) is situated above the sea-level and is less vulnerable to ocean warming. Nevertheless, simulations with more recent ice-sheet models have shown that parts of the EAIS could also undergo a substantial retreat. The models successfully reproduced the EAIS's contribution to global sea level rise in the past warm climates [12-13]. While these simulations were performed using the most recent Antarctica bed map – BEDMAP2 [14], the uncertainty in bed elevation over the EAIS remains relatively large. Figure 1 shows a comparison between the bed topography data retrieved from BEDMAP2 and radio echo sounding (RES) data collected by a Very High Frequency (VHF) radar operating at 195 MHz near the Wilkes Basin as part of the NASA Operation IceBridge (OIB) mission [15]. A large discrepancy can be seen between the two datasets and BEDMAP2 missed a lot of fast-changing features of the bed topography modulating the ice flow. Fine-resolution bed topography data are necessary to constraint and improve the accuracy of ice models to predict the future of ice sheets.

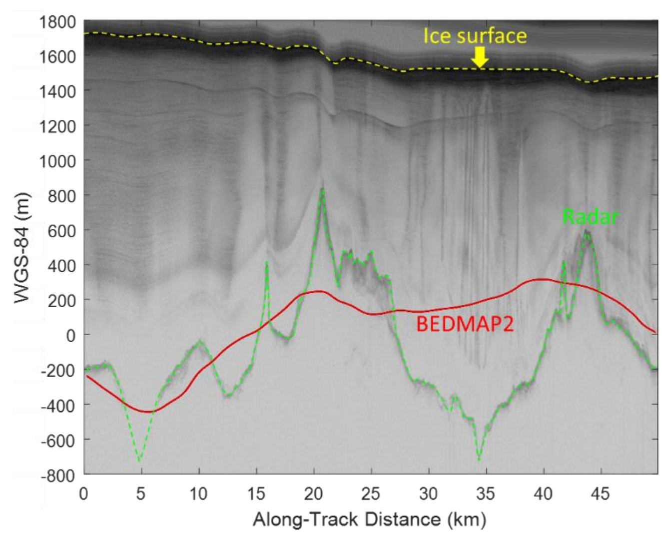

Figure 1: Comparison between bed topography data retrieved from BEDMAP2 [14] and RES data generated from a VHF radar [15], over the Wilkes Basin.

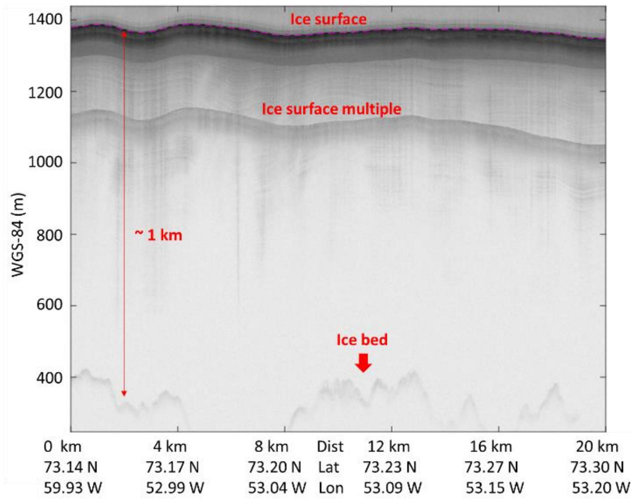

Figure 2: RES data collected using a UHF radar operating at 600-900 MHz in NW Greenland in 2017 [15].

In this paper, we describe an L-band (1.2-1.4 GHz) radar ice sounder concept to perform three critical measurements needed for ice-sheet models: i) unambiguous determination of basal boundary conditions; ii) measurements of bottom melt rate of ice shelves; and iii) sounding and imaging of ice bed.

II. Proposed Radar Concept

The concept of radar ice sounding at L-band is based on our success in sounding 1-km thick ice near the coast in northwest Greenland (73°N) using a UHF radar operating at 750 MHz with a bandwidth of 300 MHz and 1 W peak transmit power [1]. An example radar echogram collected with the radar is shown in Figure 2 [15]. The radar data only show ice thickness up to about 1 km as the radar was originally developed for mapping near-surface accumulation layers to depth of ~250 m. Since the ice loss does not vary significantly from 750 MHz to 1.3 GHz [16], our hypothesis is that an L-band radar designed with proper system parameters can sound close to 4-5 km thick low-loss ice in Antarctica. To demonstrate the feasibility, the signal-to-noise ratio (SNR) of the ice bed return is computed for both planar (rms height deviations less than 1 cm) and rough bed interfaces, and the results are shown in Table 1. In the link budget, we assumed a 3.5-km thick ice with a background acidity of 2 µM, and a one-way ice loss of 20 dB/km at -15°C at L-band [16]. We also assumed that the surface-based radar operates with a pulse repetition frequency of 12.5 kHz. The link budget analysis shows that an L-band radar with a peak transmit power of 2 kW and an antenna with 25 dBi gain would be able to sound 3.5-km thick ice with a reasonable SNR. Such radar is realizable with today's microwave technology.

The same UHF radar reported in [1] has also been shown to be able to measure ice shelf bottom melt rate. Using carefully calibrated UHF radar data collected at the Petermann glacier, it has been shown that conventional hydrostatic equilibrium method over-estimated mass loss within 10 km of the grounding line [1]. Since ice shelves are relatively thin (under 1 km), the proposed L-band radar will have sufficient penetration and vertical resolution to track the basal melt rate of ice shelves.

Table 1: Estimated radar link budget.

	Planar bed		Rough bed	
Frequency	1300	MHz	1300	MHz
Pulse length	20	us	20	us
Bandwidth	200	MHz	200	MHz
Transmit Power	63	dBm	63	dBm
Antenna Gain (2-way)	50	dBi	50	dBi
Wavelength	-12.7	dB	-12.7	dB
Air-ice power transmission coefficient (2-way)	-0.7	dB	-0.7	dB
Ice loss (20 dB/km; 1-way)	140	dB	140	dB
Ice-rock reflection coefficient	-7.5	dB		
Ice-rock interface scattering			-15.0	dB
Illuminated area			63.0	dB
Pulse compression gain	36	dB	36	dB
Integration gain	55	dB	55	dB
Spreading loss term 1	22.0	dB	33.0	dB
Spreading loss term 2	71.9	dB	143.8	dB
Noise Power	-91.2	dBm	-91.2	dBm
SNR	**40.4**	**dB**	**13**	**dB**

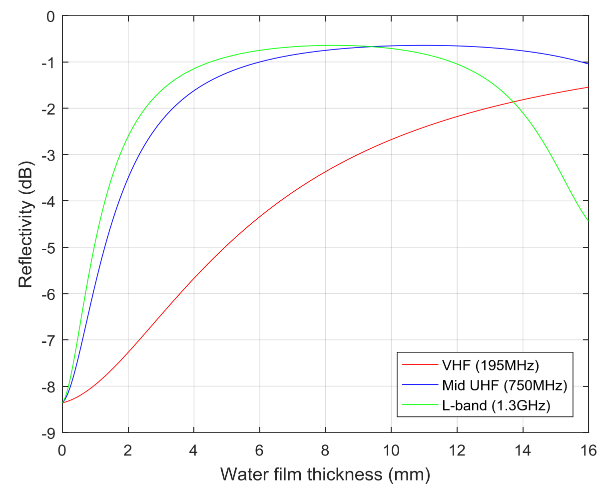

Figure 3: Reflectivity as a function of water film thickness and frequency.

These new datasets will be the key to estimate the future behavior of the WAIS under different climate settings.

The proposed L-band radar will also offer an enhanced sensitivity to detect and measure basal water film as compared to VHF radars. Figure 3 shows the sensitivity to water film thickness at L-band, mid-UHF and VHF. Both L-band and mid-UHF is significantly more sensitive to water film with thicknesses ranging from 0.1 mm to 5 mm. Ice flow changes from deformation to streaming when a water film thickness exceeds about 0.4 mm [17]. We need a minimum of 3 dB change in reflectivity for detection of a thin water film. With VHF radars, the film thickness must exceed more than 5 mm for reliable detection. An L-band radar can detect water film as thin as 0.5-1 mm from reflectivity change.

III. Proposed System Design

Figure 4 shows the proposed radar block diagram. The radar will consist of four sub-sections: digital section, transmitter, receiver and antenna. The direct digital synthesizer (DDS) in the digital section generates two phase-synchronized 1.2-1.4 GHz chirps at 2.5 GSPS with 8-bit voltage resolution. The chirp will

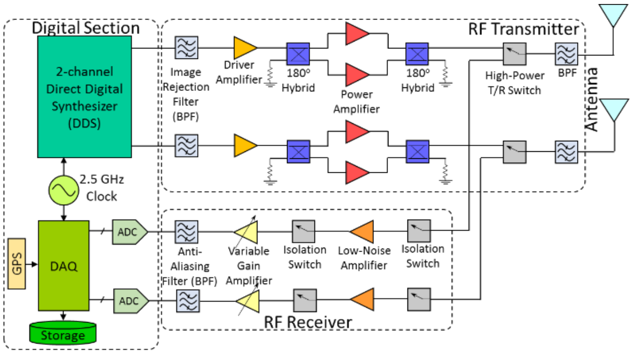

Figure 4: High-level radar system block diagram.

provide a vertical resolution of 42 cm in ice to enable tracking of the ice-shelf melt rate and internal layer imaging. For each transmit channel, the chirp will then be filtered and amplified before feeding into the transmit antenna. The backscattered signals from each antenna channel will be fed into a receive chain for filtering and amplification before digitization. The digitizer in the data acquisition (DAQ) unit will run at 2.5 GSPS and directly sample the radio-frequency chirp. The internal field programmable gate array (FPGA) will support on-board digital signal processing.

In terms of the radar antenna design, the link budget shows that a minimum of 25 dBi antenna gain is necessary to sound a 3.5-km ice. This translates to an antenna array with an aperture size of 1.2×1.2 m^2, which is manageable either on a surface-based platform. Figure 5(a) shows a proposed design of the antenna array implemented using 20×20 slotted microstrip patch elements. The antenna can be fabricated using printed circuit board and is only 20 mm thick. The simulated active voltage standing wave ratio (VSWR), antenna radiation pattern and gain are shown in Figures 5(b)-(d). The antenna array can be divided into two subarray panels and interface with the two-channel DDS to generate sum and difference beams and allow surface clutter suppression with incoherent processing.

IV. Conclusions and Future Work

While the NASA OIB mission has been providing valuable RES data over the past decades, the mission will end in 2020 with launch of the ICESat-2 and large data gaps still exist over the vast region of the AIS. We proposed to develop a new L-band radar system to measure ice thickness, basal conditions and ice-shelves bottom melt rates. The concept for ice measurements with an L-band radar is based on the recent success in sounding shallow low-loss ice (< 1 km) and measuring ice-self melt rates with a UHF low-power radar. The major advantage to scale the radar's operating frequency to L-band is the potential to perform these measurements from space (from a SmallSat) or a high-altitude long-range aircraft (such as a Gulfstream V aircraft) with a large antenna aperture as discussed in [18-19]. Our plan is to deploy the proposed radar for field test in Antarctica during the 2018-2019 field season.

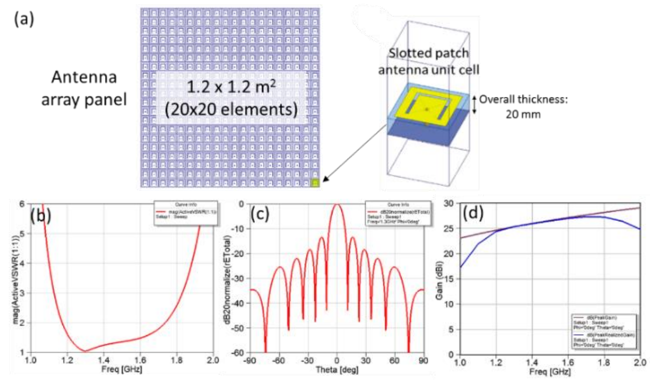

Figure 5: (a) Proposed patch antenna array; Simulated (b) VSWR, (c) radiation pattern, and (d) gain.

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