A low frequency wideband depth sounder for sea ice

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Abstract— **Sea ice plays an important role in the Earth climate system. Techniques used in the past to determine sea ice thickness had fundamental limitations in terms of spatial and temporal coverage. We performed extensive simulations using published ice-core data from both polar regions, and our results suggested the use of a UHF radar system (300-1300 MHz) for sounding thin Antarctic sea ice and thin ice in the Arctic and a VHF radar system (50-250 MHz) for sounding thick Arctic sea ice. Based on the simulation results, we designed a prototype radar system that operates on both the frequency ranges. We have successfully used the system to collect data over sea ice at Barrow, Alaska. The experiments show that with our system, we can measure sea ice thickness with less than 20 cm uncertainty in thickness.**

Keywords-sea ice; thickness; remote sensing

I. INTRODUCTION

Sea ice plays an important role in global climate. The thickness distribution of sea ice is an important geophysical parameter that may be used as a proxy indicator for climate change. Recent studies with submarine sonar profiling have indicated significant thinning of Arctic ice during the last decade as compared to prior decades. Thus monitoring of sea ice thickness in both polar regions is important to determine its current state and its future response to climate change.

The most successful technique for determining sea ice thickness distribution is upward-looking sonar profiling from submarines. Although this technique gives accurate thickness data [1], it provides limited spatial and temporal coverage. A few airborne measurements were made using impulse radars operating at VHF mounted on a low- and slow-flying helicopter [2]. Both short pulse – referred to as Impulse – and Step-Frequency Continuous Wave (SF-CW) systems were used in these early experiments [3]. Most of these systems did not have sufficient range resolution to resolve the air-ice and ice-water interfaces for ice with a thickness of less than about 2 m and/or were not optimized for measuring sea ice thickness. The technologies required for implementing high-sensitivity, wideband coherent radars were not available during these experiments. Researchers using both electromagnetic sounding and radar techniques have also noted difficulties related to the nature of the varying ice properties, such as water intrusion into the bottom layer, masking the bottom echoes [2].

Using ice core data from both polar regions, we performed EM simulations and determined that a radar system operating in the frequency range of 50-250 MHz is needed to measure thick first-year or multiyear sea-ice thickness in the Arctic region, while a 300-1300 MHz frequency range is needed for measurements in the Antarctic region and thin sea ice in the Arctic. We designed and developed a radar system that operates over both frequency ranges, and performed field trials at Barrow, Alaska. Our initial results show that the radar system is capable of measuring sea-ice thickness accurately. In this paper, we present our approach to determine the optimal radar for sea ice thickness measurements, simulation results, and results from field trials at Barrow, Alaska.

II. BACKGROUND

Sea ice is a complex medium characterized by its crystal structure, air and brine content, and surface properties such as snow cover [4]. Sea ice is broadly divided into different classes based on its formation and development stage [5]: frazil ice, nilas, pancake ice, gray ice, first-year ice and old ice. Frazil ice, nilas, pancake ice and gray ice are usually less than 30 cm thick and can be seen during the early stages of sea-ice formation. First-year ice is usually 30 to 200 cm thick with salinities in the range 3-5 psu, and is further subdivided into thin (30-70 cm), medium (70-120 cm) and thick (>120 cm) categories. Sea ice is produced in the form of granular and columnar ice crystals separated by brine inclusions. The ice that survives the summer melt is referred to as *old ice* and is characterized by salinities of 1-2 psu and increased number and size of air bubbles. It is further subdivided into second-year and multi-year ice depending on whether the ice has survived one or more summers. Multiyear ice is commonly found in the Arctic region where it can reach several meters of thickness (a few tens of meters in pressure ridges) and last several decades.

III. APPROACH

We have approached the problem of finding the optimal radar for sea ice depth sounding by first constructing geophysical models of various sea ice types to characterize their physical composition and structure. We developed simple electromagnetic models using the permittivity profiles generated from the geophysical models. Then, we performed extensive simulations with these electromagnetic models to determine the optimal radar frequency for measuring thickness of sea ice.

A. *Sea ice characterization and modeling*

We represent the sea ice as multi-layered media, where each layer is characterized using its dielectric constant, density and average particle size. The interface between the last sea ice layer and sea water is modeled as a dendrite interface.

We used a dielectric mixture model proposed by Tinga et al [6] to compute the dielectric constant of sea ice from published salinity, temperature, and brine-and-air volume fraction data. The dielectric loss factor of sea ice is low in the frequency ranges from 1 to 100 MHz. At frequencies lower than 1 MHz, the ionic conductivity of brine increases the dielectric loss, and at frequencies higher than 100 MHz, the relaxation process of brine increases the dielectric loss. The real part of the dielectric constant of sea ice is in the range of approximately 3.0-4.0 for the frequency ranges of interest.

We accounted for the volume scattering effects due to brine inclusions and air pockets by using effective medium approximation to compute the attenuation loss caused by volume scattering [7].

The real part of the dielectric constant of sea ice is around 3.0-4.0, while that of seawater is about 80. In the ideal case with a planar interface, this dielectric contrast will result in a large reflection from the ice-water interface. However, most sea ice has a groove-shaped dendrite interface. The interface is called the SKeletal layer (SK). The length of the skeletal layer is usually about 1-5 cm and the width of the dendrites is about 0.8 to 1 mm [4]. The significance of this layer in the context of remote sensing is the reduction in the reflected energy from the ice-water interface, since it presents a smooth impedance transformation from the low sea-ice dielectric constant to the high sea-water dielectric constant. This impedance match is significant at the higher microwave frequencies where the wavelength is comparable to the length of the skeletal (dendrite) layer. We modeled the impedance matching effect using an exponential variation for the dielectric constant along this interface, as given below:

$$\varepsilon(x) = \varepsilon_1^{\left(1-\frac{x}{d}\right)} \varepsilon_2^{\frac{x}{d}} \qquad (1)$$

where $\varepsilon_1, \varepsilon_2$ are the dielectric constants of sea ice and seawater respectively, *x* is the distance from the start of the dendrite interface and *d* is the length of the dendrite interface.

B. *Radar operating frequency*

Based on model simulations, the best frequencies of operation would be in the range 10-500 MHz. A radar system operating in this range will be optimum for multi-year ice, but will lack sufficient range resolution to resolve the bottom echo over first-year ice.

To sound thin first-year ice, we require a radar system with fine range resolution. We can operate the radar system at microwave frequencies (> 2 GHz) to attain this objective, but the disadvantage of using microwave frequencies is the very high return loss due to the impedance matching effect of the skeletal layer at the ice/water interface. Based on the results of numerous simulations, we decided to use the frequency range of 300 – 1300 MHz for sounding first-year ice. This radar system has sufficient range resolution (15 cm) and operates at frequencies where the impedance match effect of the skeletal layer is minimal. The dielectric loss at these frequencies is large, but the decrease in return loss more than compensates for the dielectric loss.

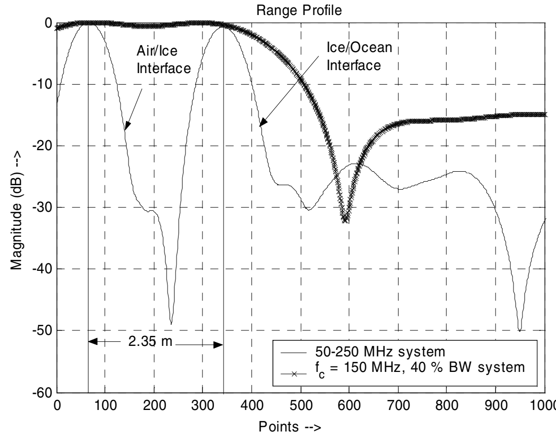

Figure 1. Range profile for a 50-250 MHz radar system and a 150 MHz system with 40% bandwidth over a 2.35 m ice sheet.

Figure 2 illustrates the requirement for sufficient bandwidth to sound thin ice. We used a 50-250 MHz (133% BW) system and a 120-180 MHz (40% BW) system to simulate the response from a 2.35 m ice sheet, using data from [8]. The bandwidth of the 120-180 MHz system is insufficient to provide range resolution required to identify the bottom echo. Impulse radars usually have about 40% bandwidth, and hence they are not suitable for sea-ice depth sounders. This experiment also illustrates the main reason for the failure of previous attempts by researchers using impulse radars for sea-ice depth sounders.

Figure 3 illustrates the impedance matching effect of the skeletal layer. We used a 1000-2000 MHz (microwave) system to simulate the response from a 0.75 m first-year ice sheet, using data from [8]. The 1-2 GHz radar system has sufficient range resolution to sound a 0.75 m first-year ice sheet, but the effect of impedance matching increases the return loss. The return power from the ice/water interface for this system is about 35 dB less than the air ice interface. Unless we have an ideal system with minimum losses and ringing, it is not possible to identify the bottom echo.

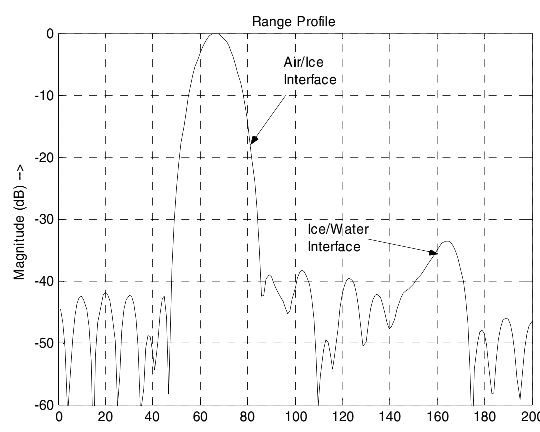

Figure 2. Range profile for a 1-2 GHz radar system over a 0.75 m first-year ice sheet.

IV. RADAR SYSTEM

We designed a prototype radar system operating in the Frequency-Modulated Continuous Wave (FM-CW) mode to generate both the desired frequencies. Figure 3 shows the block diagram of our prototype radar system.

We designed the radar system such that it can be operated over the frequency range of 50-250 MHz or 300-1300 MHz. The unique features of the radar are: an extremely linear chirp generated using a YIG oscillator in a phase-locked loop driven by a Direct Digital Synthesizer (DDS), a Gaussian-response high-pass filter to suppress leakage signals between the antennas, and antennas with minimum ringing and low return loss. These features have significantly improved the system performance and sensitivity.

V. FIELD MEASUREMENTS

We mounted the prototype system on a sled that was custom built at the University of Kansas, and collected data over sea ice located off Barrow, Alaska during May 1-4, 03 in conjunction with in-situ and EM induction thickness measurements. Figures 4 and 5 show the 50-250 MHz radar response as a function of depth at two locations. The first peak at about 3.2 m is the surface return, and the peaks at 7.5 m (figure 4) and 4.8 m (figure 5) are the returns from the ice-water interface. We converted the electrical range into thickness by dividing the measured range by the ice index of refraction. The physical thickness measured at a nearby locations match closely with the measured data.

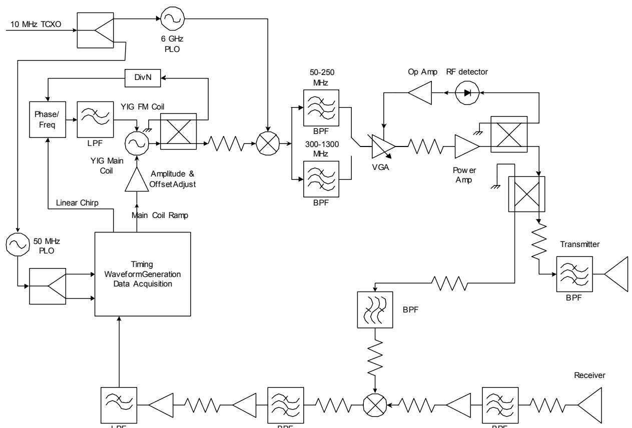

Figure 3. Block diagram of the proposed radar depth sounder.

VI. CONCLUSIONS AND FUTURE WORK

There is a strong scientific need to determine and monitor the sea-ice thickness distribution over the Arctic and Antarctic regions. Techniques that have been used in the past had key limitations in terms of the spatial and temporal coverage possible. In this paper, we have presented an ultra-wideband radar system operating in the FM-CW mode to determine sea-ice thickness in the Arctic and Antarctic. We have successfully tested our prototype radar system at Barrow, Alaska. Future work in this direction will be the development of model-based signal processing and de-convolution techniques to accurately extract the thickness information from the collected data.

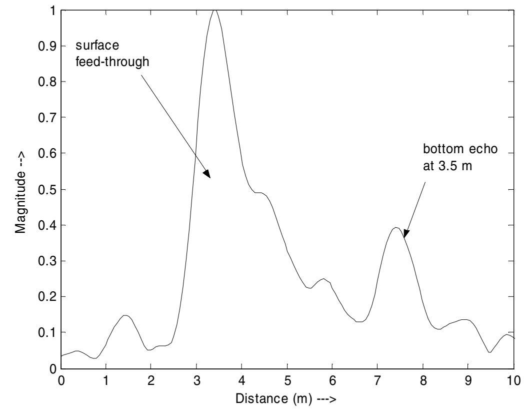

Figure 4. Radar return as a function of depth

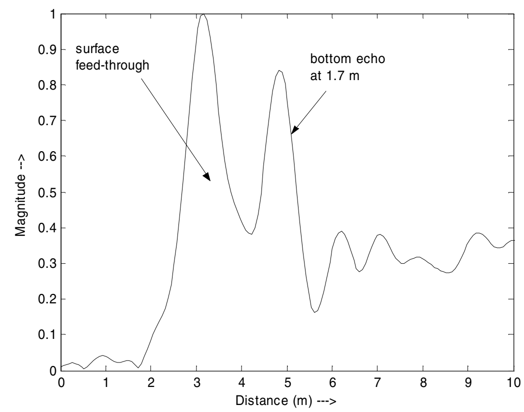

Figure 5. Radar return as a function of depth

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