An Airborne Radar System for High-Resolution Mapping of Internal Layers

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***Abstract*-Accumulation rate is a key variable in assessing the mass balance of polar ice sheets. An improved knowledge of the mass balance of polar ice sheets is needed to determine their role in current and future sea level rise. Existing accumulation maps, derived from sparsely distributed ice cores and pits, contain accumulation rate errors as large as 20% in certain areas. Remote sensing methods to complement and supplement in situ measurements are required to generate improved accumulation maps. For this reason we have been investigating the use of high-resolution radars for mapping of near-surface internal layers and generating continuous profiles of the dated layers in the ice sheet (isochrones). We successfully mapped isochrones within ± 2 m of those in an ice core up to a depth of 280 m at the North GReenland Ice core Project (NGRIP) ice camp during the 1998 and 1999 field seasons using a 170-2,000 MHz Frequency Modulated Continuous Wave (FM-CW) radar. We described the system and reported results of our experiments in previous IGARSS meetings [1,2]. Recently we performed detailed analysis of the data collected from these experiments and determined the frequency response of reflections from the internal layers. The results showed the optimum frequency range for monitoring near-surface layers is between 500 and 1000 MHz. Based on these results we are developing a 600-900 MHz coherent airborne radar for high-resolution mapping of the internal layers in the Greenland ice sheet. We designed this system to operate in different modes: simple pulse, chirped pulse, step-frequency, and FM-CW. We have also developed a digital data acquisition system to collect and process data. We designed this system such that it can operate in an undersampling mode to digitize the received signal directly without down conversion. In this paper we will present results of recent data analysis and detailed design of the airborne radar. We hope to present at the conference the preliminary results from airborne radar data to be collected over the Greenland ice sheet during May 2001.**

I. INTRODUCTION

The Greenland and Antarctic ice sheets play an important role in global climate change studies. The sea level has been rising at a rate of about 2 mm per year over the last century and about half of this rise has been attributed to the melting of these ice sheets, but with a large uncertainity. An improved knowledge of the mass balance of these ice sheets will help us determine more precisely their role in the sea level rise. A key variable in assessing the mass balance of an ice sheet flux method is the accumulation rate. Now accumulation rates are determined from ice cores and pits [3]. These data are sparse and the uncertainties are in the order of 20% in existing accumulation rate maps [4]. To provide improved spatial and temporal coverage, the development of remote sensing methods for estimating the accumulation rate are thus required. An accurate estimate of the accumulation rate can be obtained by mapping a continuous profile of dated—with cores--volcanic layer and melt layers in the ice sheet. Volcanic events register as a change in conductivity, whereas the melt events as a change in the density. These can be measured remotely using a radar system.

To test this concept we designed an ultra-wideband Frequency-Modulated-Continuous-Wave (FM-CW) radar to operate over the frequency range from 170 to 2000 MHz for imaging the top 300 m of ice with high vertical resolution on the order of 0.5 m. We successfully mapped isochrones to within ± 2 m of those in an ice core up to a depth of 280 m at the North Greenland Ice core Project (NGRIP) ice camp during the 1998 and 1999 field seasons [5].

Frequency analyses of the layer reflections reveal that the reflections are strongest at the 500-1000 MHz frequency range (Fig. 1). Based on this result and taking into consideration the frequencies used for communication in the P-3 aircraft, we developed a 600-900 MHz coherent airborne radar for high-resolution mapping of the internal layers in the Greenland ice sheet. We have designed this system to operate in the simple-pulse, chirped-pulse, step-frequency, and FM-CW modes. A 2 gigasample per second (GSPS) data acquisition system has been developed to digitize the received signal directly without down conversion.

II. SYSTEM DESCRIPTION

Fig. 2 shows the radar system that we have designed. The signal source is the STEL-9949 programmable digital chirp synthesizer (DCS). It can be operated with a maximum clock frequency of 1 GHz to generate a chirp signal between 1 MHz and 400 MHz. Also it can be programmed to generate a single carrier frequency in this range. The DCS has a TTL level trigger input that is used to start the chirp and control its duration. The trigger input is used to set the pulse width when the radar is operated in pulse mode. The 600 to 900 MHz chirp is generated by upconverting a 100 to 400 MHz chirp from the DCS using a 500 MHz phase-locked signal. The 500 MHz signal is obtained by dividing the 1 GHz phase-locked oscillator (PLO) clock by 2. A sample of the 1 GHz signal is used as the input clock for the timing system. This ensures that all the signals are synchronized. The chirp signal is then amplified and propagated through a limiter that sets the output power to a constant level. The switch on the transmit side is used in the pulse mode to turn off the transmitter after the pulse is transmitted, while the switch on the receive side is turned on when receiving returns from the ice sheet. This prevents the receiver from saturating due to leakage from the transmitter. However, in chirp mode the switches must be left on due to the longer duration of the pulse. The leakage signal can be removed using a digital filter during post-processing. The signal is finally amplified to 25 W by a 40-dB gain amplifier and is passed through a bandpass filter and coupled to a TEM horn antenna. The bandpass filter is used to suppress any spurious and harmonic signals.

The signal is received with a TEM horn antenna and it is amplified before being split to two channels. The first channel is used to digitize the strong near-surface signals while the second channel is used to amplify the weaker returns from within the ice. The second channel has a 50-dB gain amplifier to amplify weaker signals before digitization. This scheme effectively increases the dynamic range of the receiver.

The data acquisition system consists of four modules: A/D converter card, averaging card, multiplexer (MUX) card, and computer interface card. The configuration of these modules is in Fig. 3. The A/D converter card contains the gigasample A/D integrated circuit (IC) that is the heart of the entire system. Since the output signals of the converter are too fast for current memory/processing technologies, the A/D converter card also performs de-multiplexing to widen the data path and slow the clock rates. The averaging card performs coherent integration of data using four digital signal processors (DSPs) and also multiplexes the data into their original order after processing. Finally, data from the averaging card pass through a multiplexer card that switches access from the four acquisition channels to a single digital input/output (DIO) card on the host computer. In Fig. 3 it can be seen that the system actually consists of four separate A/D channels. Using independent analog inputs, the system can be operated with four independent channels at 1 GSPS each. By placing a power divider at the inputs of channels 1-2 and 3-4 as shown in the figure and providing 180° clock timing to the converters a 2-channel, 2 GSPS (interleaved) system is realized.

III. SIMULATION

We performed a simple simulation of the FM-CW radar reflection signals from the ice sheet based on the density and conductivity data obtained from the NGRIP ice core. Density data were available to a depth of 300 m but conductivity data were only available from a depth of 140 m to 300 m. Fig. 4 shows the result of the simulation. This result was normalized with respect to the transmitted signal. The reflections due to density changes are about –60 dB for the first 120 m. As we go deeper into the ice sheet the density changes reduce, resulting in fewer reflections from density changes. From a depth of 140 m onward we can observe a number of reflections corresponding to peaks in the conductivity data. The normalized reflection from the reflections due to conductivity ranged from –110 dB to –90 dB. The total absorption loss from 140 m to 300 m was about 10 dB. The next step in the simulation is to study the effects of losses due to surface and volume scattering. We are also studying the possibility of deconvolving the effects of these losses [6].

IV. SUMMARY

The accumulation rate is an important parameter required for mass balance computation of the polar ice sheets. The current accumulation rate maps have errors in the order of 20%. The development of remote sensing methods for accurately estimating the accumulation rate is required. In this work we described the design of an airborne radar system to map the internal layers in the Greenland Ice Sheet. The radar was designed to operate in the simple-pulse, chirped-pulse, step-frequency, and FM-CW modes. A 2 GSPS per second data acquisition system has been developed to digitize the received signal directly without down conversion. A simple simulation was performed to study the response of FM-CW signal to density and conductivity changes in the ice. The radar is scheduled to be flown on NASA P-3 aircraft during May-June 2001. We hope to present preliminary results from these flight at the conference.

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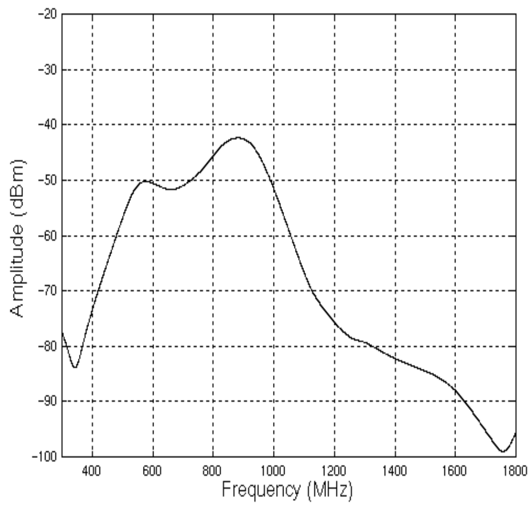

Fig. 1. Frequency response of reflection from layer located at about 148 m at NGRIP.

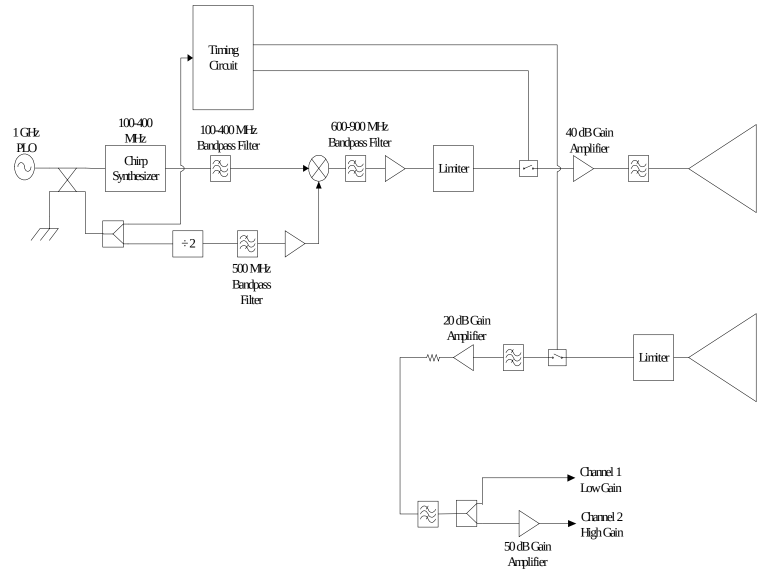

Fig. 2. Block diagram of the prototype wideband FMCW radar system for airborne mapping of internal layers.

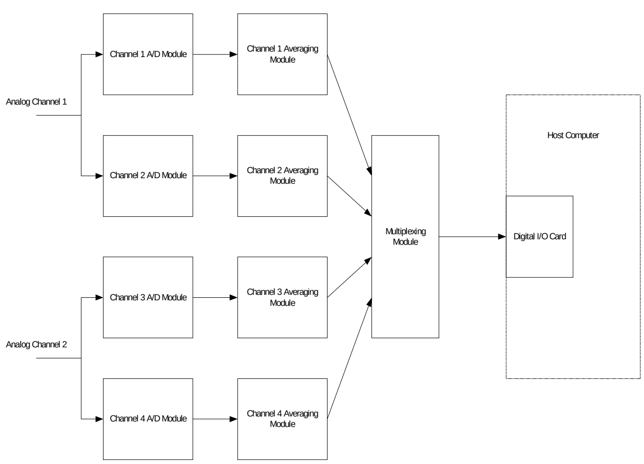

Fig. 3. Overview of the Data Acquisition System.

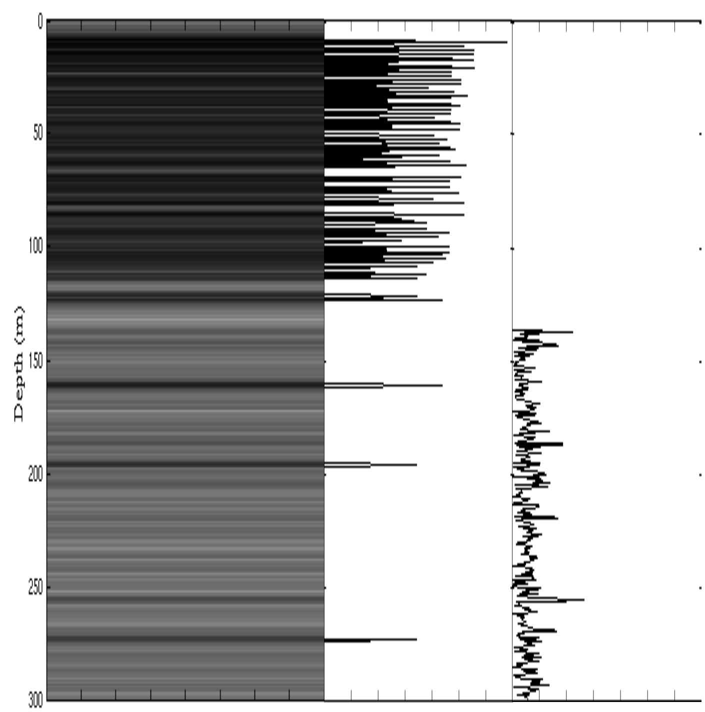

Fig. 4. FM-CW radar simulation results of reflection from ice sheet due to changes in density and conductivity. The section in the middle is the reflection coefficient due to changes in density and the section on the right is the reflection coefficient due to changes in conductivity.