High-Resolution Monitoring of Internal Layers Over the Greenland Ice Sheet

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ABSTRACT

The global sea level rise has been attributed to the melting of mountain glaciers among other causes. The mass balance of the glacial ice plays an important role in the rise of the Earth's sea level. A key variable in assessing the mass balance of an ice sheet is accumulation rate, which is currently determined from ice cores and pits. Accumulation data are sparse, and there are large uncertainties in existing accumulation rate maps derived from sparely distributed ice cores and pits. The accumulation rate can be estimated more accurately if we are able to obtain a continuous profile of the dated layers in the ice sheet. In this paper we describe the development of a high-resolution radar system to map the layers in the ice sheet and present the results obtained at the North GReenland Ice core Project (NGRIP) ice camp with our prototype system.

INTRODUCTION

The global sea level has been rising at a rate of about 2mm a year over the last century. Scientists have attributed half of this rise to thermal expansion of the ocean and melting of mountain glaciers. To assess the contribution of the Greenland and Antarctic ice sheets to sea level rise we will need to determine the mass balance of these ice sheets. A key variable in assessing the mass balance of an ice sheet using this method is accumulation rate. Other required measurements are surface elevation, ice thickness, aerial extent, intensity of summer melt, wind-generated surface roughness, ice temperature, and absolute velocities.

Currently, accumulation rate is determined from ice cores and pits [1]. These data are sparse and there are large uncertainties in existing accumulation rate maps [2] derived from sparsely distributed ice cores and pits. A more efficient means of accurately estimating the accumulation rate would benefit the scientific community in their modeling of the ice sheets and mass balance estimation. An accurate estimate of the accumulation rate can be obtained by mapping a continuous profile of the dated layers in the ice sheet. The dated layers here refer to known volcanic and melt events. Volcanic events register a change in acidity when it is encountered in the ice core, whereas the melt events mark a change in the density. These changes can be measured remotely using a radar system. Radar echograms from ice-sounding radar systems show many internal reflections between the bedrock and the surface, and the source of these internal reflections has been identified as layering involving small permittivity changes due to changes in acidity (from large volcanic events) [3]. Although there are several radar systems now that can measure the thickness of the ice sheet, there have been no concerted efforts to develop systems that can sound shallow ice with high resolution in order to map internal layers to estimate accumulation. By mapping the internal layers, we will be able uniquely to identify known volcanic and melt events, and this information combined with published density and thickness data can be used to estimate the accumulation rate.

To determine the optimum radar parameters for this task we performed some simple simulations on ice sheet models. The electrical conductivity measurements of ice cores were used to model the electrical properties of the ice sheet. The finite-difference time-domain (FDTD) [4] technique was then used on the ice model to determine the optimum radar parameters by simulating the scattering response of the ice sheet due to radar sounding.

We then proceeded to design an ultra wideband Frequency-Modulated Continuous-Wave (FMCW) radar system [5] to map the internal layers in the ice. The radar system operates over the frequency range from 170 to 2000 MHz for imaging the top 200 to 300 m of ice with high resolution. We performed shallow radar sounding experiments at the North Greenland Icecore Project (NGRIP) site during August of 1999. We collected data over a 10-km traverse with the radar mounted on a tracked vehicle.

SYSTEM DESCRIPTION

Fig. 1 shows the Frequency-Modulated Continuous-Wave (FMCW) radar system that was developed for imaging the top 200-300 meters of ice with high resolution. The FM sweep is digitally generated and converted to an analog signal on a PCI card that is housed in the host computer. Although we developed the system to operate over the frequency range from DC to 2 GHz, we operated it from 170 MHz to 2 GHz because the antenna's cutoff frequency at the lower end is 170 MHz.

The DC- to 2-GHz sweep is generated by downconverting a 4- to 6-GHz chirp from the YIG oscillator using a 4-GHz phase-locked signal. The frequency of operation can be varied within this bandwidth via the computer. The variable gain amplifier at the output stage of the radar system enables us to set the output power to a constant level. The amplifier output is supplied to the transmit antenna through a coupler, an attenuator and a power amplifier, which increases the signal level to about 23 dBm. The coupler is used to derive a sample of the transmit signal to serve as a local oscillator. The attenuator minimizes multiple reflections between the amplifier input and the coupler output ports.

The receive antenna collects the reflected signal from the target. This signal is supplied to a mixer through an amplifier padded with attenuators both at the input and output ports. Attenuators are used because the wideband amplifier Voltage Standing Wave Ratio (VSWR) approaches values close to 2 at certain frequencies. In the mixer a beat frequency signal whose frequency is proportional to the range is obtained by mixing the received signal with a sample of the transmitter signal. The beat frequency signal is further amplified and low-pass filtered and digitized. The digitized signal is processed to extract amplitude and phase information as a function of range (depth).

EXPERIMENT AND RESULTS

We performed shallow radar-sounding experiments at the NGRIP site during August of 1999. We mounted the radar on a tracked vehicle and collected data over a 10-km transect.

Fig. 2 shows the radar echograms of internal layers observed at NGRIP. We can see that some of the layers correspond to peaks in the ECM (electrical conductivity measurement). The ECM plot begins from a depth of 10m as the density of the firn is too low in the top 10m to make accurate measurements. The peaks in the ECM correspond to volcanic events. These measurements were made by scientists from the Alfred Wegner Institute (Germany) and the Department of Glaciology at the University of Copenhagen (Denmark). The layer depths measured with our radar are within +/- 2 m of the volcanic layers obtained from the ice-core data.

SUMMARY

The accumulation rate is an important parameter required for mass balance computation of ice sheets. Previous accumulation rates were computed from the density of ice cores and accumulation maps were drawn based on these sparse results. Some parts of this map have been shown to have about 20% errors. Although there is a significant effort to update accumulation maps with additional cores and pits, remote-sensing techniques are needed to extrapolate and improve these maps.

In this work we designed a radar system to map the internal layers in the Greenland Ice Sheet remotely. We developed a prototype ultra wideband FMCW radar system that operates from 170-2,000 MHz based on some simple FDTD simulations of the volcanic layer characteristics in the ice. We tested this system during the 1999 NGRIP field season and the results show that they are within +/- 2m of the measured depths of the volcanic layers.

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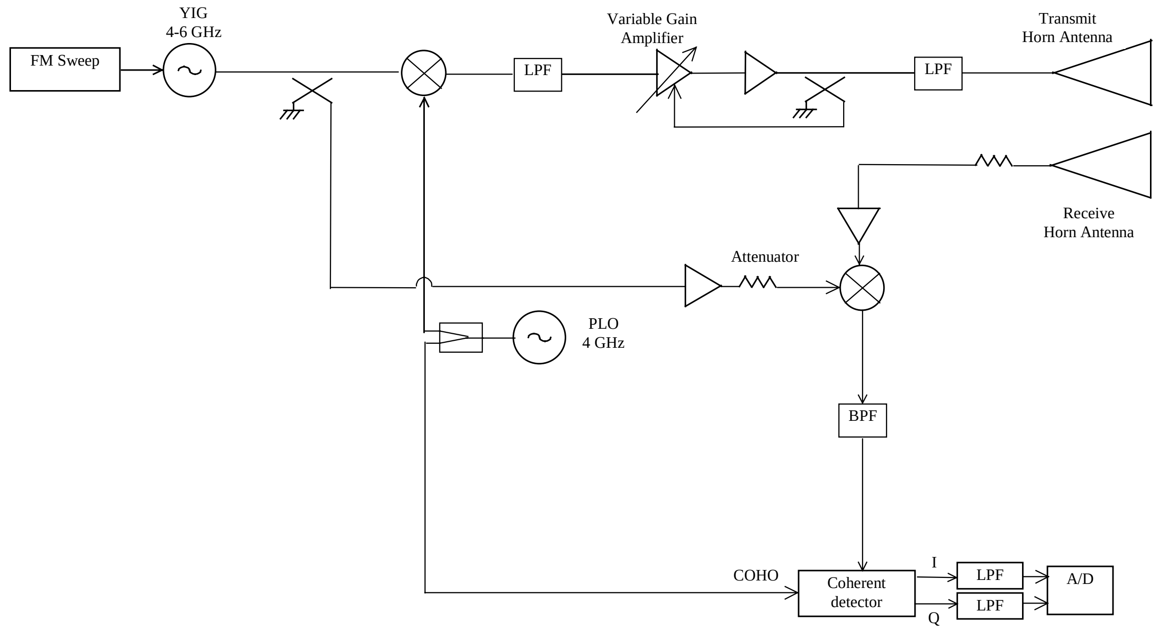

Figure 1. Block diagram of the prototype wideband FMCW radar system for mapping internal layers.

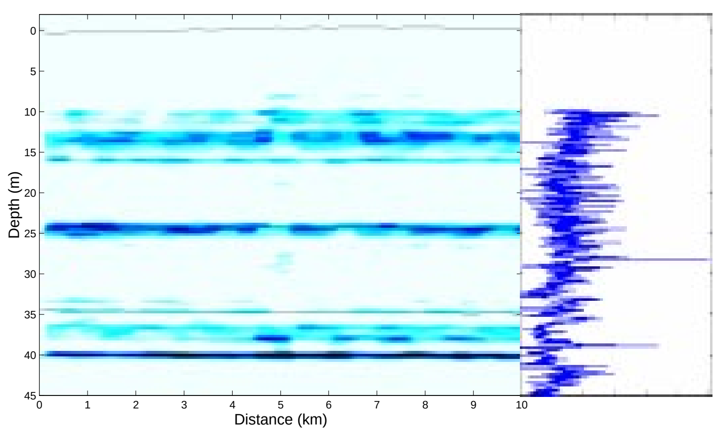

Figure 2(a). Radar echogram of internal layers observed along a 10-km transect at NGRIP in 1999 (0-45m depth).

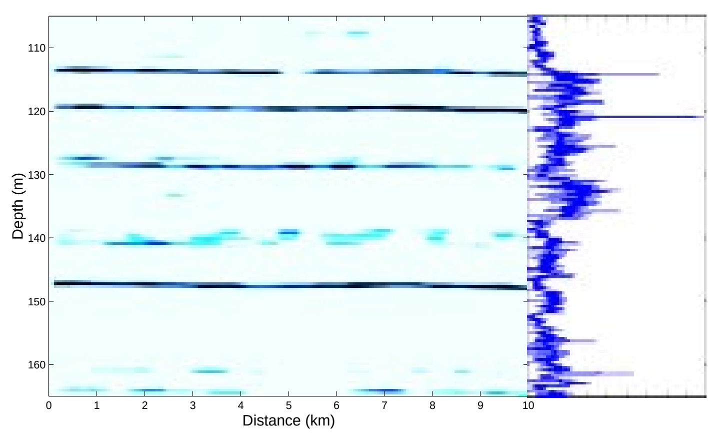

Figure 2(b). Radar echogram of internal layers observed along a 10-km transect at NGRIP in 1999 (105-165m depth).