Airborne Measurement of Snow Thickness Over Sea Ice

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Abstract— Snow cover on sea ice plays an important role in the climate of the polar regions. Snow on the sea ice reduces the heat exchange between the ocean and the atmosphere by its high albedo (reflectivity) and low thermal conductivity. The lower the albedo, the less solar energy is reflected back into the atmosphere. This energy is absorbed into the ocean. The warmer water will melt more sea ice, and eventually the warmer atmosphere above the warmer water will melt more of the sea ice in the polar regions. Better data on the extent and thickness of snow cover are therefore needed to understand the condition and future behavior of sea ice.

Up until recently, the only practical means of observing snow cover over sea ice was by satellite remote sensing. The Advanced Microwave Scanning Radiometer (AMSR-E) onboard NASA's Aqua satellite does precisely this. To validate the measurements made by AMSR-E, the University of Kansas developed an ultra-wideband frequency-modulated continuous-wave (FM-CW) airborne radar to measure snow thickness over sea ice. This system was flown over the Arctic sea ice in March 2006 to measure the snow thickness. This paper will present the preliminary results from this experiment.

INTRODUCTION

Scientists have various theories for why sea ice is thinning. Some of these theories suggest that greenhouse gases or thermal expansion of ocean water could be the causes of the melting. The major question that scientists are trying to answer is whether polar sea ice is melting faster than new ice is being added. Sea ice is continuously melting, and in winter snow accumulates and adds on to the ice sheets.

This has an impact on animals, the earth, and humans as well. Snow is crucial for the survival of mammals in the Artic and Antarctic regions. For example, polar bears use the snow on top of the sea ice to make dens for their young. Polar bears create a snow drift around their bodies to keep a layer of warmth. If there is an insufficient amount of snow the polar bears can not build dens. Polar bears are left in the open sea or on the land of the Artic regions because of the sea ice retreating.

Snow depth on sea ice is important to polar climate change and global environment also. Changes in snow depth contribute to the heat being transferred to the atmosphere. If the atmospheric temperature increases, so will the earth's climate temperature. This increase in global temperature causes the rising in sea level and precipitation. These changes lead to an increase in the degree and intensity of heat waves, droughts, floods, hurricanes, and tornados. Other effects are glacier retreat, species extinction, low or high agriculture yields, and increase of range of disease vectors. Snow thickness over sea ice represents a climate change on a larger scale.

The earth's reflectivity (albedo) of radiation is an important climate factor. There are only two surfaces on earth that have high albedos -- ice and snow. Sea ice has a higher albedo than the surrounding ocean. If less solar radiation is absorbed by the ocean and is reflected back into the atmosphere, this could lead to a temperature drop and sea ice would expand. With sea ice the atmosphere can cool by up to 30°C (Ruddimann 2001) due to the lack of heat exchange and the increased albedo radiation budget. Without sea ice cover, high-latitude oceans transfer large amounts of heat to the atmosphere, especially in winter. This dramatic difference in air temperature is just one factor making sea ice an important control on global climate. With global warming, greenhouse gases are being trapped in the earth's atmosphere, causing surface air, and subsurface ocean temperatures to rise. Rising temperatures could have a negative effect at the edges of both landmasses, causing rates of melting to increase. Although the oceans have an enormous heat storage capacity, if global atmospheric temperatures rise, the oceans will absorb heat and expand.

Sea ice play a major role in the world's climate because of the amount of water that sea ice puts in or pulls out of the ocean and atmosphere. Sea ice affects the ocean in various ways. One way is the salt /fresh water budget. Sea ice is formed by saline sea water, but in ice formation the salt molecules are rejected (brine rejection) back into the ocean. This leads to an area of high salinity water due to brine rejection, which sinks once the density is higher than the surrounding water. Polyna is another way sea ice can be formed. Polyna is when ice is blown offshore, cold air forms new sea-ice near shore, which is also blown away. Deep water is formed when there are cold air temperatures and when the salinity of the surface waters is rather high. Combining cold air temperatures with a saline surface makes the water denser and causes it to sink to the bottom. Sea ice holds large amount of fresh water, so when it melts, salt is carried to the ocean surface layer. The density of this water causes it to sink and this helps form North Atlantic Deep water.

Thermohaline circulation is controlled by temperature and salinity. Thermohaline transfers warm and salty water to the north, where water is cooled and sinks to the bottom of the ocean. The density of the Millennial oscillations (a thousand fluctuations) can be produced from changes in the northward flow of warm, salty surface water along the conveyor belt. Stronger conveyor flow releases heat that melts ice and lowers the salinity of the polar regions, eventually slowing or stopping the formation of deep water. Sea ice changes the course of the thermohaline circulation, and is crucial to the prediction of the amount of heat and water the earth loses to the atmosphere.

In the polar regions, the ocean's heat is relative to the sunlight that is absorbed. A minor fluctuation in heat can lead to a significant portion of sea ice melt in the polar regions. With the sea ice extent decreasing, the effects of global warming accelerate. This increases the temperature of the earth and reduces sea ice extent even further. Arctic sea ice has been decreasing in both thickness and surface cover with a total loss of volume of about 40% in the past three decades. In the Arctic, approximately 50% of sea ice survives three to seven years without melting

Statistics show that 37% of the world's population lives in coastal regions. If the sea ice melted, there would be a potential threat for coastal cities and towns because of worldwide sea levels being raised.

Global warming can cause precipitation, which has the capability to either thicken or thin the sea ice. This increase in precipitation can be caused by the ocean being exposed to shortwave radiation, warmer air with increased moisture, or increased ocean water evaporation. In the polar regions, precipitation usually falls in the form of snow, covering the ice with a layer of reflectivity and insulation against the ocean heat. With global warming, Greenland and Antarctica should experience greater snowfall.

A decrease in snow cover contributes to the acceleration of the climate change because snow cover has a role in the thermodynamic evolution of sea ice. It accounts for approximately 10% of the total snow and ice volume of sea ice. Snow can insulate a growing sea ice cover, causing a reduction in maximum thickness of sea ice; this is because, while the top of the ice is insulated from the sunlight, the bottom is in contact with the warmer ocean water. Snow depth is extremely difficult to observe, as is the amount of snow on the sea ice. Snow depth has usually only been measured manually (with meter sticks) or by ship.

BACKGROUND

A. *FMCW Concepts or Fundamentals*

Frequency modulated continuous wave radar (FMCW) is an effective and inexpensive way to obtain a high resolution with low power. FMCW uses a linear frequency modulated high frequency (chirp) signal . The FMCW signals are continuously being transmitted and received. The FMCW uses an oscillator as the source for the transmitter. FMCW transmits a chirp signal which hits a target, and an echo signal is received from that target by an antenna. The echo signal and the transmitted signal are put into the mixer, yielding a difference frequency or beat frequency.

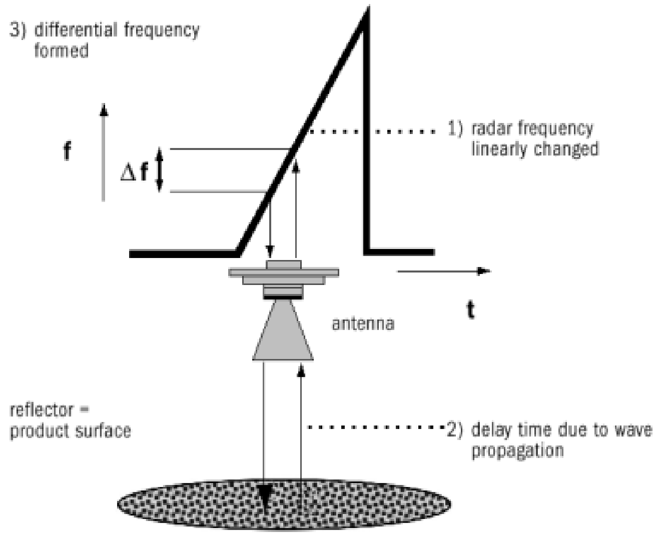


Figure 1

Sweep velocity is showed by:

$F = df/dt \cdot T$ [1.1]

T is time sweep delay, t is the time travel (ms), df is difference of the frequency, dt is the difference of time travel, f is the frequency. The reflector difference is equal to the frequency.

When the transmitted signal and the echo signal are mixed they find out the target range. Difference and sum frequency are created from the mixing.

This is shown by:

$fT + fR$ and $fT - fR$
[1.2]

Once being passed through a filter, the sum frequency is removed. The term that is left is now the beat frequency. This is shown by:

$F_b = fT - fR$ [1.3]

The time frequency of the chirp signal (transmitted signal) is shown by:

$F_t(t) = f_0 + \alpha \cdot T$ [1.4]

The received frequency of the chirp is:

$fR(t) = f_0 + \alpha \cdot (T - \tau)$ [1.5]

F_0 is start of the time sweep, f_1 is the end of the time sweep, α is the rate of change frequency. The difference between f_0 & f_1 is the bandwidth.

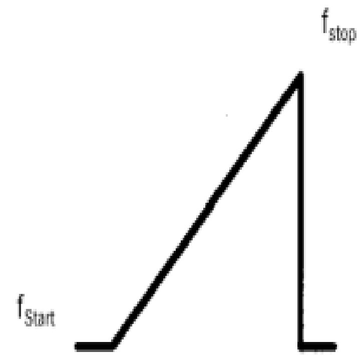
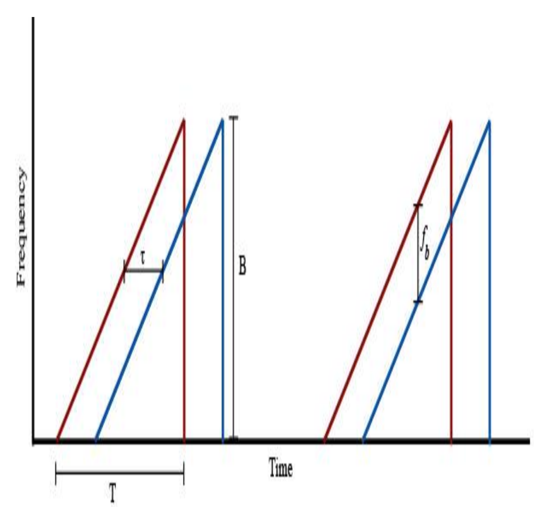


Figure 2

The rate of a change frequency is shown by:

$A = B/T$ [1.5]



Figure

In the Figure 3 (red) is the local oscillator signal, the received signal is (blue) and f_b is the beat frequency, T is the chirp time, B is the bandwidth, R is the target range, c is the speed of light, τ is the time delay between the transmitter and the target. This beat frequency is directly proportional to the distance to the reflecting interface.

The equation for diagram 1.1, the rate of change of a frequency is showed by:

$$f_b = \frac{B\tau}{T} \qquad [1.6]$$

The time delay is related to the target range by:

$$R = \frac{c\tau}{2} \qquad [1.7]$$

By combining equations [1.1] and [1.7], you can get the beat frequency, which is related to the target range:

$$f = \frac{B}{T} \bullet \frac{2R}{C} = f_b = \frac{2RB}{cT} \qquad [1.8]$$

In this project, the Fast Fourier Transform (FFT) will be use to find the frequency spectrum and the distance can be calculated from equation [1.8].

B. System Description

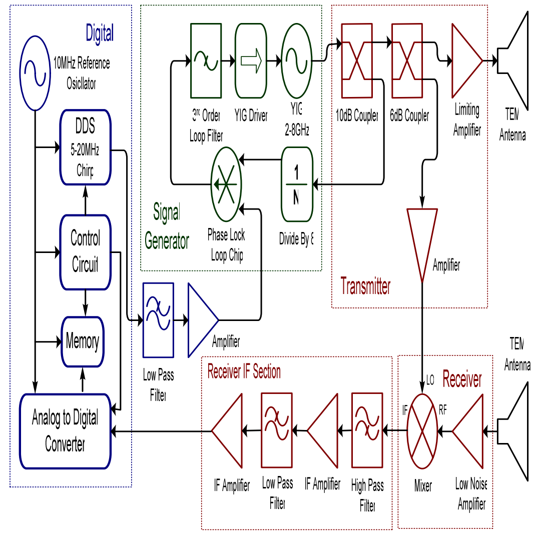


Figure 4. System diagram.

The system contains a signal generator, transmitter, receiver, filters, couplers, and amplifiers. The signal generator has a 2-8 GHz oscillator, a divider, a phase lock loop (PLL), and a low frequency direct digital which generates a linearly chirped transmitter signal. The signal is split into two parts with the first directional (10 dB) coupler. The signal from the coupler is then sent to the external prescalar circuit, next the signal is divided by 8 with and passed to the input of the PLL. This signal is divided again by the PLL chip to generate a 100-400 kHz signal, which is supplied to the PLL's phase detector input port. The DDS creates a reference chirp signal over the frequency range from 5 to 20 MHz.

The chirp signal is divided and sent through a low pass filter and amplifier; after that it is sent to the phase detector. The phase detector creates an error signal that is filtered, amplified and used by the YIG to create a linear chirp. The linear chirp is over a frequency range from 2 to 8 GHz. Measurements of the delay line help determine the linearity of the sweep. The linearity of the sweep is confirmed by the signal sinc response. The signal from the first directional coupler is passed through another directional (6 dB) coupler and an amplifier, and sent to the transmit antenna. Two antennas are used for transmitting and receiving the signals. The receive antenna gathers the signals reflected and scattered by snow and passes these signals to a low-noise amplifier with 10-dB gain and high reverse isolation of 40 dB or more.

The main purpose of the amplifier is to minimize radiation of the local oscillator signal through the receive antenna. The amplifier sends the signal to the RF input of a mixer. A copy of the transmitter signal, taken from the second directional (6 dB) coupler, is mixed with the received signals to create beat-frequency signals proportional to the target range.

The signals are passed through to a high-pass filter that prevents saturation of the IF amplifier. The signals from the IF amplifier are passed to a low-pass filter and then to the Analog to Digital Converter (ADC) for digitization and storage. The digital sector contains circuits for generating timing signals and digitization. It also includes an A/D converter and circuits for sampling and digitizing received signals. Table 1 shows the specifications of the radar system.

TABLE 1. FM-CW RADAR SPECIFICATIONS.

Description	Characteristic	Unit
Radar type	FM-CW	
Sweep frequency	2-8	GHz
Free space range resolution	2.5	Cm
Sweep time	10	Ms
Transmit power	13	dBm
PRF	25	Hz
A/D dynamic range	12-bit, 72	dB
Sampling rate	50	MHz
Antenna	TEM Horn	

Airborne snow radar experiment description

The University of Kansas tested their radar system on board the NASA P-3 aircraft during the NASA Arctic 2006 Field Campaign over the Alaskan coastal region. The objective of this field campaign was to acquire a comprehensive data set that will enable validation of a snow thickness retrieval algorithm from NASA's AQUA AMSR-E passive microwave sensor measurements. The experiments were conducted out of Fairbanks, Alaska, from March 18 to March 29, 2006. We installed our snow thickness radar along with a laser altimeter, radar altimeter and a precise GPS navigation system on board the P-3 aircraft. The installation of the systems is depicted in Figure 4. SRA indicates the snow radar rack and antennas. The nadir-looking TEM horn antennas were installed in the belly of the aircraft. The radar system and computer were installed in a rack right above the antennas. A low-loss microwave cable was used to connect the transmitter and receiver to the antennas. The aircraft flew about 500 ft above the surface of the ice at a speed of about 100 ms^{-1}. We conducted a total of six missions out of Fairbanks. Each mission took about 8 hours.

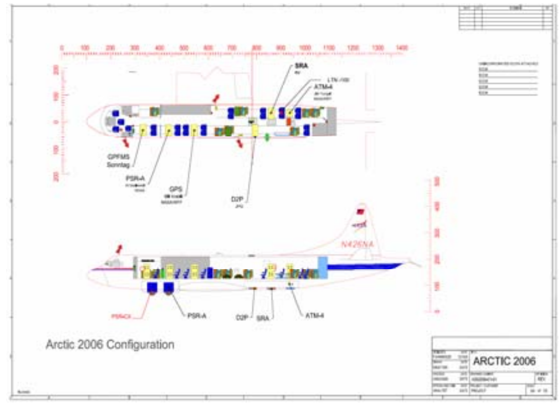


Figure 5. Snow radar system and antenna installation on the NASA P-3.

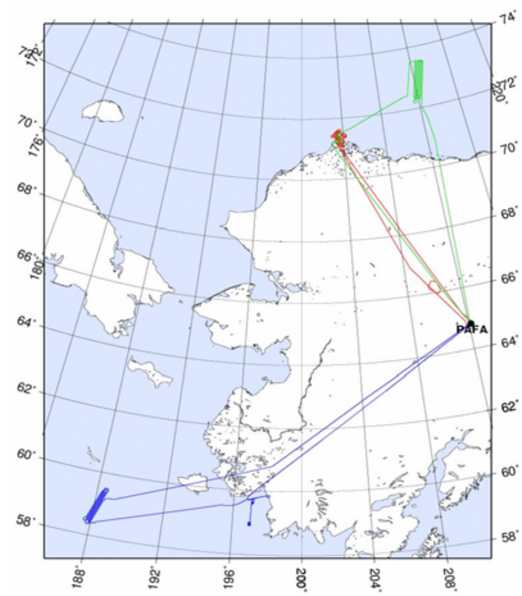


Figure 6 shows the flight lines of our measurements.

RESULTS

We completed the first order of digital signal processing and the FFT of the signal was taken. Figure 6 shows the preliminary results of this.

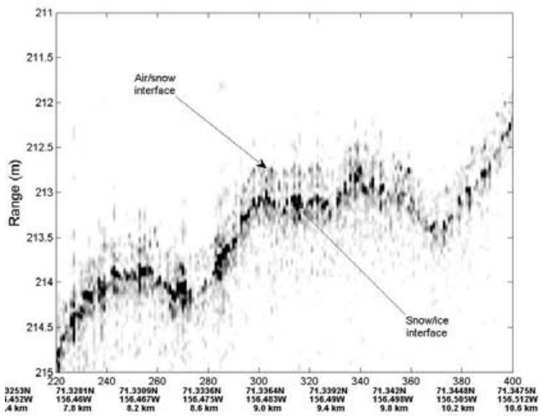


Figure 7: The air over snow interface and the snow over ice interface

The figure above shows that the radar is clearly capable of resolving the air/snow interface and the snow ice interface. We can determine the thickness of the snow by taking the difference of the two interfaces.

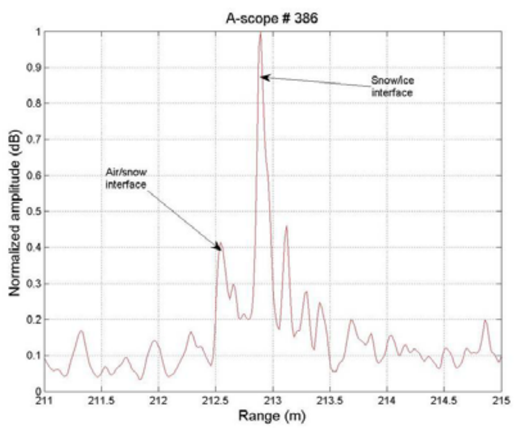


Figure 8: The amplitude and magnitude of scope 386

Figure 8 shows scope 386; this sample number is located in Figure 7 between 380-400. In scope 386, the return from the air-snow interface appears at approximately 212.5 m, and the return from the snow-ice interface is at approximately 212.8 m. The thickness of the snow at this spot is 3 centimeters.

CONCLUSIONS

The University of Kansas developed an ultra-wideband radar that has a frequency range from 2 to 8 GHz. This system was used to collect airborne measurements for determining the thickness of snow over sea ice in Alaska. The results from these experiments show that we can measure snow thickness with 3 cm resolution with this radar. The airborne radar helps to validate the Advanced Microwave Scanning Radiometer (AMSR) retrievals.