Instruments and Methods

Sub-ice topography in Patriot Hills, West Antarctica: first results of a newly developed high-resolution FM-CW radar system

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ABSTRACT. We present a newly developed high-resolution frequency-modulated continuous-wave (FM-CW) radar system for sounding the sub-ice topography. The system, working in the frequency range from 200 to 400 MHz, was developed to measure thickness and internal layers in cold ice with a resolution better than 1 m. This system has the potential to measure accumulation rates, an important input for improved knowledge of the mass balance of polar ice sheets. First measurements for the test, calibration and optimization of the new ice sounder were made in December 2005 near the Ellsworth Mountains, specifically in Patriot Hills, West Antarctica, at 80°18′ S, 81°22′ W. The complete radar system was installed on a ski-mounted support frame, and towed by hand across the ice surface. The measurement results show the capability of this system to measure ice thickness up to 1000 m and to define internal layers within the ice body.

INTRODUCTION

Since the 1950s, radar systems have been an efficient tool for mapping the ice thickness of the polar ice sheets. Mainly focused on thickness measurements by means of pulse systems, previous studies (Nixdorf and others, 1999; Damm and others, 2001) with these systems suffered from low depth resolution not better than a few meters in cold ice. Former frequency-modulated continuous-wave (FM-CW) systems (Forster and others, 1991; Yankielun, 1992) suffered due to heavy and expensive equipment for the measurement set-up. Yankielun (1992) reported on a Ka-band FM-CW system for measuring ice thickness with a depth resolution of 5 cm in ice, and Forster and others (1991) reported on an X-band FM-CW radar for snow-stratification investigation showing reflections to depths of ~6 m. Faster digital waveform generators and increasing data acquisition capabilities led to the development of strongly improved FM-CW radar systems for the measurement of ice thickness as well as internal reflection horizons (Kanagaratnam and others, 2004).

Here we present the development of a lightweight and easy-to-handle FM-CW radar system with a bandwidth of 200 MHz for sounding polar ice caps. The objective of this system development was a depth resolution in ice better than 1 m, with the prospect of further increase in resolution. This should make the system well suited to accumulation rate measurements, a key piece of information for determining the mass balance of the polar ice caps (Steinhage and others, 2005).

The first test measurements were carried out at Patriot Hills, near the Ellsworth Mountains, West Antarctica, at 80°18′ S, 81°22′ W. Due to strong katabatic winds north of Patriot Hills, a large and flat blue-ice area exists, which can be used as a landing strip by large cargo aircraft to maintain logistical support of some summer camps in this region. In addition to other research groups, the Instituto Antártico

Chileno (INACH) operates a summer camp at Patriot Hills, which was used as base station for the Antarctic test campaign in December 2005. The increasing ice thickness, from 0 m at the foot of the mountains to about 600 m at a distance of ~2.5 km (Cassasa and others, 2004), and the homogeneous ice body makes this region well suited for test measurements carried out on a simple sledge with the support frame for the radar system. Several test profiles were taken to optimize the measurement capabilities of the FM-CW sounder. We present technical details of the radar system, including waveform generation, broadband antennas and data acquisition. Typical measurement results of our test profiles, showing ice thickness up to 600 m and internal layers of the ice body, are provided.

FM-CW RADAR SYSTEM

The principle of FM-CW radar operation is depicted in Figure 1, and a block diagram of the FM-CW system is shown in Figure 2. The transmitted signal is a repetitive linear modulated frequency sweep of bandwidth B and sweep time T. The received signal, reflected from the ice surface or internal ice layers, is delayed by the two-way travel time, τ, which is usually much shorter than the sweep time. After mixing the transmitted and received signals and low-pass filtering (LP) the mixer output (Fig. 2), the intermediate frequency $f_{IF} = \Delta f$ (Fig. 1) contains the distance information of the target.

By means of a direct digital sythesizer (DDS), the signal generator provides a linear frequency sweep of bandwidth B and sweep time T. Both parameters can be set by means of the program of the microcontroller (μP), controlling the DDS. The ramp parameters of the frequency generator are calculated from the demands of the frequency sweep by means of respective formulas given in the data sheet of the
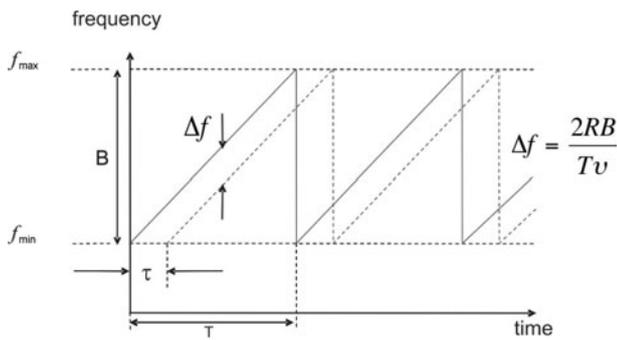
Fig. 1. Signal waveform of transmitted and received signal.

DDS (Analog Devices, http://www.analog.com/static/imported-files/data_sheets/AD9858.pdf). A part of the filtered and amplified output signal is used as local oscillator for the subsequent mixer. After mixing the transmitted and received signals and lowpass filtering the mixer output, the intermediate frequency (IF) contains the thickness information of the ice layers.

Analog to digital (A/D) conversion of the IF signal and a subsequent fast Fourier transform (FFT) yields the spectrum of the IF signal, including distinct difference frequencies, Δf (Fig. 2), which are directly proportional to different reflector distances. The distances of the reflection horizons are determined with the well-known propagation velocity of electromagnetic waves in cold ice ($v = 168 \times 10^6 \, \mathrm{m\,s^{-1}}$) (Bogorodsky and others, 1985). Data acquisition, storage of data and data visualization are carried out with a laptop, running a LabVIEW® program, also setting the parameters of the A/D conversion.

The components of the FM-CW radar system used are shown in Figure 3.

SYSTEM COMPONENTS

Signal generator

A block diagram of the signal generator is shown in Figure 4. The main signal source is a DDS, AD9858, which produces an analog waveform by generating a time-varying
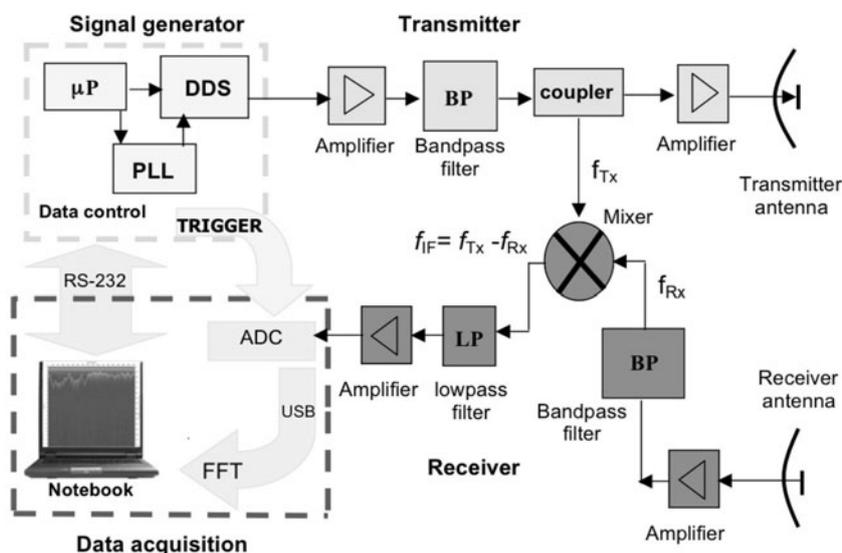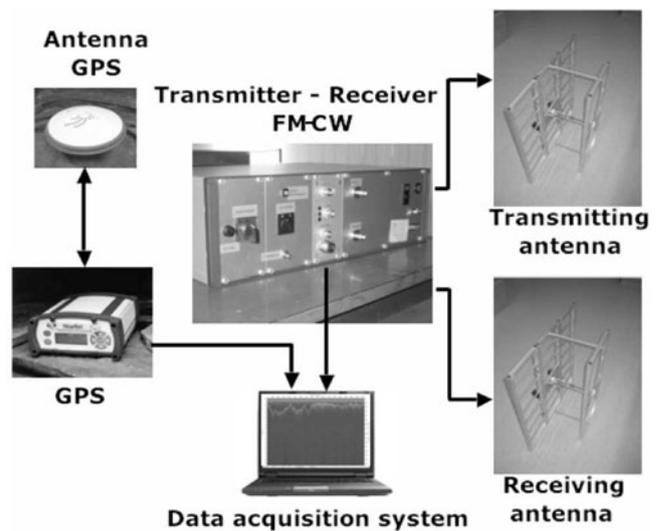

Fig. 3. Components of the FM-CW radar system.

signal in digital form and then performing a digital to analog conversion (Analog Devices, http://www.analog.com/static/imported-files/data_sheets/AD9858.pdf). By this technique the DDS of the signal generator directly generates an output signal with a stepwise increase of its output frequency, thus producing a quasi-linear stepwise frequency sweep. The time-step is $\Delta t = 7.8125 \, \mathrm{ns}$, and the frequency step is $\Delta f = 7.8125 \, \mathrm{Hz}$, which leads to an almost continuous but highly linear frequency sweep from $f_{min} = 200 \, \mathrm{MHz}$ to $f_{max} = 400 \, \mathrm{MHz}$. For the DDS, the phase-locked loop (PLL Best, 2007) provides a stable reference frequency, $f_{ref} = 1024 \, \mathrm{MHz}$ with a fixed phase relation to a crystal oscillator.

From this reference clock (SYSCLK) the DDS generates all ramp parameters for the frequency-modulated output signal. With a 1024 MHz reference clock, the smallest time-step (eight clock cycles) can be calculated to 7.8125 ns, and the widths of frequency steps are determined from T and B. The frequency step, Δf, and the length of each step, Δt, are controlled by different tuning words
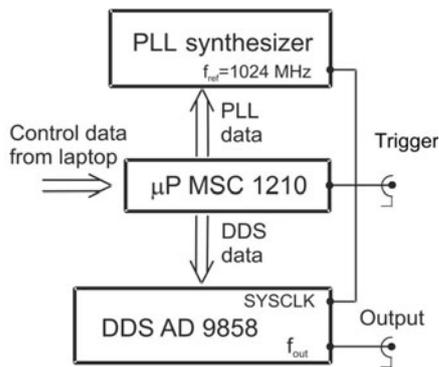

Fig. 2. Block diagram of the FM-CW system.

Fig. 4. Block diagram of the frequency generator.

Fig. 6. Simulated and measured return loss of the FM-CW antenna.

(Analog Devices, http://www.analog.com/static/imported-files/data_sheets/AD9858.pdf) to be calculated by the μP and written into the registers of the DDS.

The DDS increases its output frequency step by step from the starting frequency, $f_s = 200$ MHz. After sweep time, T, also controlled by the μP, the frequency of the DDS is reset to f_s, thus starting the next sweep. The output power of the DDS is 3 ± 1 dB m across the frequency range used. Typical ramp parameters of the signal generator, used for our radar system, are summarized in Table 1.

Together with the bandwidth B and propagation velocity v of the radar signal in cold ice, a theoretical depth resolution can be calculated by means of the definition of radar resolution, $\Delta r = v/2B = 0.42$ m, a promising value for the investigation of internal ice layers.

Antennas

For the FM-CW radar system a broadband two-reflector antenna was developed, fed by a slotted quasi-coaxial line between both reflectors (Fig. 5). This antenna is a redesign of a similar antenna for the frequency range 100–200 MHz used for subsurface soil investigations (Eisenburger and others, 2008). The optimization of return loss and bandwidth was done by CST MICROWAVE STUDIO®. The simulated and measured return loss of this antenna is shown in Figure 6 for comparison.
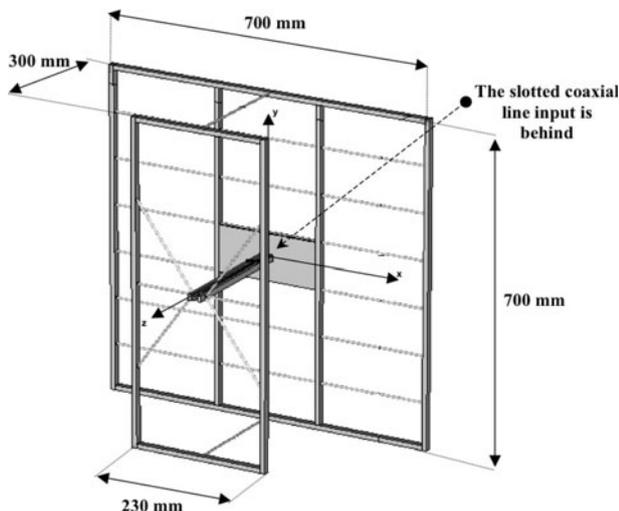
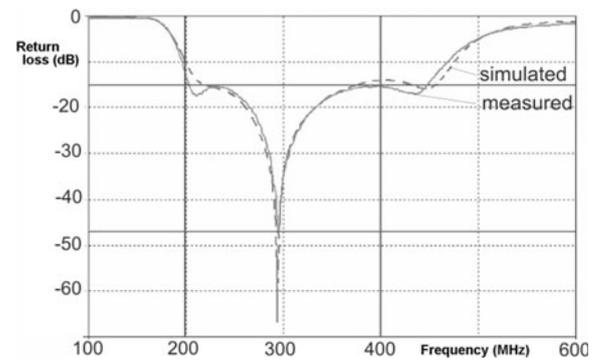

Fig. 5. Dimensions of the FM-CW antenna.

From 230 to 370 MHz the simulated return loss (RL) is better than 15 dB, resulting in a relative bandwidth of ~45%. The simulated gain in the band 200–400 MHz is between 8 dB at the lower end and 9 dB at the upper end of the frequency band used. There is very good agreement between simulated and measured return loss of the antenna. From the measured RL curve the relative bandwidth of the antenna at an RL level of 15 dB is calculated to 55%.

HF components

Other system components of the FM-CW system (e.g. amplifiers, bandpass filters, mixer and couplers) are commercially available components. The output power of the system is 1 W in the frequency band used. The power supply of the radar system and GPS is a 12 V, 7.5 A h battery, sufficient for ~4 hours operating time, much longer than the operating time of the laptop used.

Data acquisition system

Sampling of the IF signal is carried out by means of a 16-bit A/D converter with a maximum sampling rate of 500 kHz. From the laptop, complete control of converter parameters and data processing is provided by the LabVIEW® program. An FFT of the time signal is performed in real time, thus giving the raw data of the measured depth profile on screen. For further data processing, the sampled time signals and the raw depth profiles are stored on the hard disk. By means of a time stamp, taken from the GPS-controlled system time of the laptop, in the trace header of each set of depth profile data, the exact position of the measurements can be determined in later post-processing of the data.

Field measurements

First measurements for the test, calibration and optimization of the new ice sounder were made at Patriot Hills (Fig. 7). Test measurements were taken from the base camp Antonio Hunneus, operated by INACH, across the blue-ice field towards the mountains, thus providing a test profile with decreasing ice depth. For comparison of the test measurements,

Table 1. Typical ramp parameters

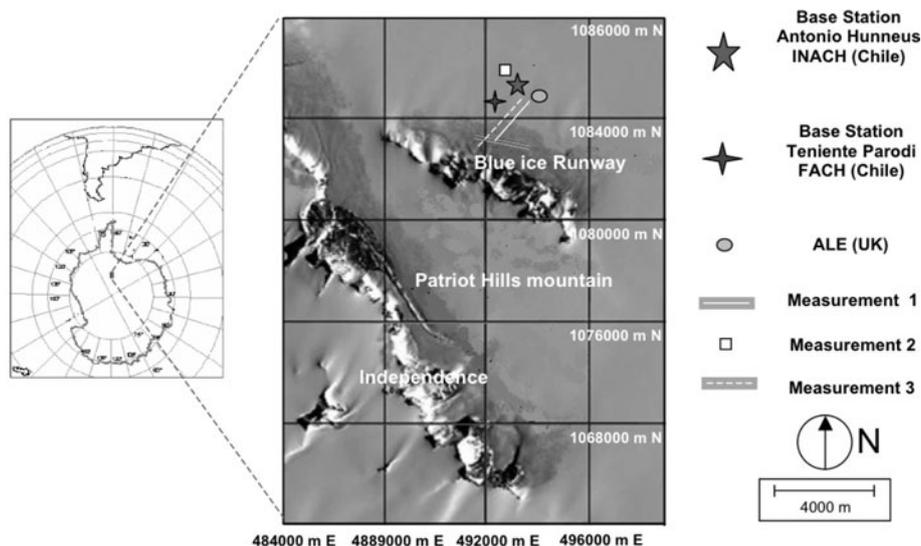|	
Bandwidth, B	200 MHz
Sweep time, T	200 ms
Time-step, Δt	7.8125 ns
Frequency step, Δf	7.8125 Hz

Fig. 7. Geographic location of Patriot Hills.

detailed information about the ice depth was available from former measurements (Casassa and others, 1998).

The complete radar system was installed on a ski-mounted support frame, pulled by hand across the ice surface (Fig. 8). A well-isolated aluminum box contained the transmitter and receiver of the radar system, data acquisition and GPS receiver. The inside temperature of the box was kept well above 0°C only by the rejected heat of the laptop inside the box. Both antennas were mounted at a height of ~2.5 m at a crossbar of the support frame. The total weight of the mounted system was ~30 kg. With this set-up, several depth profiles of a total length of ~15 km were measured.

Typical results are shown in Figure 9. For these measurements the bandwidth used was 200 MHz and the sweep time was chosen to be 800 ms, resulting in ~75 traces min^{-1}, which is sufficient for a low ground velocity.

The maximum measured thickness is about 600 m, with still promising signal strength of the reflected signals. The depth scale in both figures is relative to the antenna position and is calculated from the propagation velocity of the radar signal, which is well known for cold ice ($v = 168 \times 10^6 \, \mathrm{m \, s^{-1}}$).
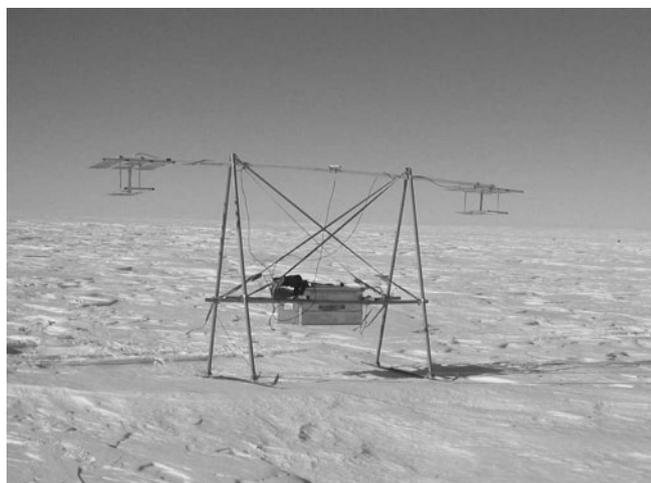
Post-processing and verification of the field data are conducted using the commercially available REFLEXW® software.

The length of the measured profile in Figure 9a is ~3.5 km. At the beginning of the depth profile (starting point at the base camp, ice thickness 550 m) almost to the foot of the mountains (distance 2700 m, ice thickness ~50 m) and halfway back, the bedrock is seen.
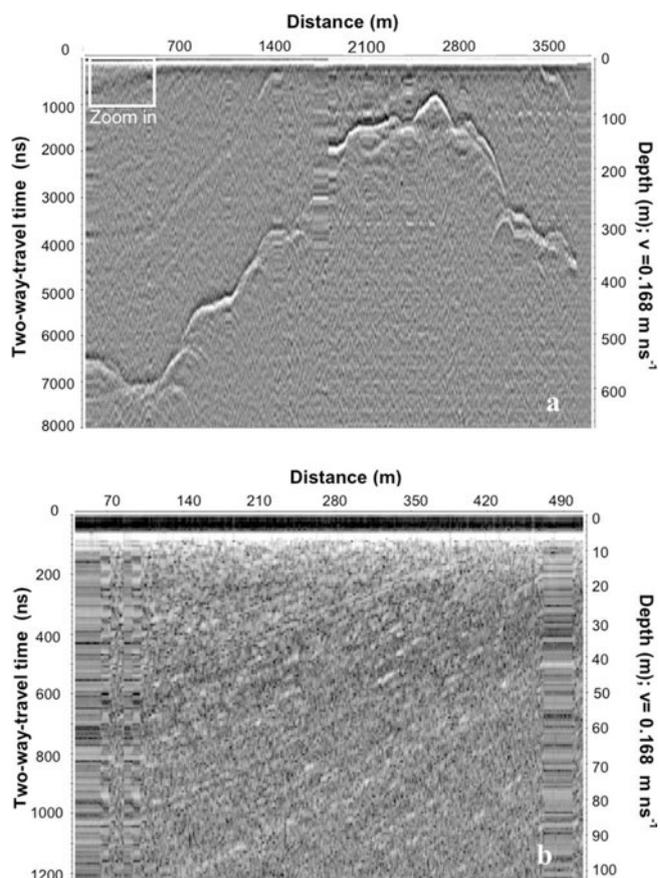

Fig. 9. Measured depth profile. (a) Depth profile from the camp to the mountains. (b) Zoom of the upper left corner.

Fig. 8. Radar system on the ice at Patriot Hills.

These results agree with the ice-thickness data given by Casassa and others (1998). The reported data show a very similar depth profile across the blue-ice field towards the mountains, with a maximum ice thickness of 351 m at the center of the blue-ice field.

Figure 9b shows a zoomed cut-out of Figure 9a from the beginning of the profile. Continuous layers in the upper 100 m of the ice body clearly demonstrate a depth resolution of the radar system of ∼1 m. The onset of the reflections is seen at 60 ns, resulting from the distance between antennas and ice as well as from the additional cable length between radar system and antennas. Any interference due to the frame was not recognized in the measurement results.

CONCLUSIONS

We have presented an FM-CW radar system for investigation of polar ice sheets. In contrast to former pulse radar systems, the depth resolution of this system in cold ice is ∼1 m or better. The relative bandwidth of the antennas used is about 50% at a return loss level of 15 dB. A software-controlled DDS is used to generate the quasi-linear frequency sweep of the system. Sweep bandwidth and sweep time are easily changed by means of the software. A 16-bit A/D converter with 500 kHz sampling rate is used together with a LabVIEW® program running on a laptop for data acquisition, visualization and storage of the measured data. The measurement results show the capabilities of the system. The bedrock at 600 m depth is clearly seen, and internal layers in the upper 100 m of the ice sheet can be resolved with a resolution of ∼1 m. Further development of the system will lead to an airborne ice-sounder system, which will be flown with 'Polar 5', the research aircraft of the Alfred Wegener Institute for Polar and Marine Research in Bremerhaven, Germany.

ACKNOWLEDGEMENTS

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