Instruments and Methods
A novel backpackable ice-penetrating radar system

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ABSTRACT. We have developed a novel ice-penetrating radar system that can be carried on a backpack. Including batteries for a 3 hour continuous measurement, the total weight is 13 kg. In addition, it operates reliably down to −25°C, has a low power consumption of 24 W, and is semi-waterproof. The system has a built-in-one controller with a high-brightness display for reading data quickly, a receiver with 12-bit digitizing, and a 1 kV pulse transmitter in which the pulse amplitude varies by <0.2%. Optical communications between components provides low-noise data acquisition and allows synchronizing of the pulse transmission with sampling. Measurements with the system revealed the 300 m deep bed topography of a temperate valley glacier in the late ablation season.

1. INTRODUCTION

Impulse (monopulse) radars at frequencies of 1–10 MHz have been widely used for ground-based glacier surveys since the 1970s (Watts and England, 1976; Macheret and others, 1993). Miniature transmitters (Watts and Wright, 1981; Narod and Clarke, 1994) and portable systems with digital recording (Jacobel and others, 1988) allow measurements on small glaciers and ice caps without vehicular support. Recently, impulse radar measurements of glaciers have been used not only to investigate bed topography but also to characterize bed conditions (Gades and others, 2000; Copland and Sharp, 2001). For such purposes, it is essential to make the system stable in transmitting-wave amplitude.

Here, we briefly describe our novel, backpackable, ice-penetrating radar system. This system uses a new transmitter architecture and is stable, rugged and easy to use. This system has been successfully tested on temperate and cold glaciers.

2. A BACKPACKABLE ICE-PENETRATING RADAR SYSTEM

The radar system comprises three modules: a controller, a transmitter and a receiver (Fig. 1a and b; Table 1). Including the batteries, which last for 3 hours of continuous measurement, the total weight of the system is 13 kg. Electromagnetic coupling between the modules and antennas is minimized by using fiber-optical cables that carry control commands, trigger signals and digitized radar data. The receiver and the transmitter are electrically sealed. Unlike the system of Wright and others (1990) with optical communication, our system does not send the analog waveform to a separate digitizer from the receiver; instead, it digitizes the waveform at the receiver. This helps increase the measurement accuracy of the waveform amplitudes.

Gathering one stacked dataset requires 30 s, when the stacking number of received waveforms is 256 (Table 2). In conjunction with a barometer (Vaisala PTB210) for leveling and a standard hand-held global positioning system receiver, we can profile the ice thickness, the bed elevation and the glacier surface. Based on barometer accuracy (0.2 hPa) and radar sampling intervals (Table 2), the elevation errors are within several meters.

2.1. Controller

The controller sets the measurement parameters, and displays and stores data. Parameters that may be changed include observation time-window widths, stacking numbers and trigger sources (Fig. 1a; Table 2). One can evaluate each waveform and the radargram on the display at various scales (Fig. 1c).

The stacked radar data together with time, latitude, longitude, and atmospheric pressure are stored in a compact

Table 1. Components of the new ice-penetrating radar system. Power consumption for the controller with display backlights turned off is given in parenthesis

Item	*Dimensions* (cm)	*Weight* (kg)	*Power consumption* (W)
Controller	23 × 37 × 10	4.2	13.8 (9.7)
Receiver	15 × 22 × 11	1.8	6.2
Transmitter	10 × 14 × 8	0.7	3.5

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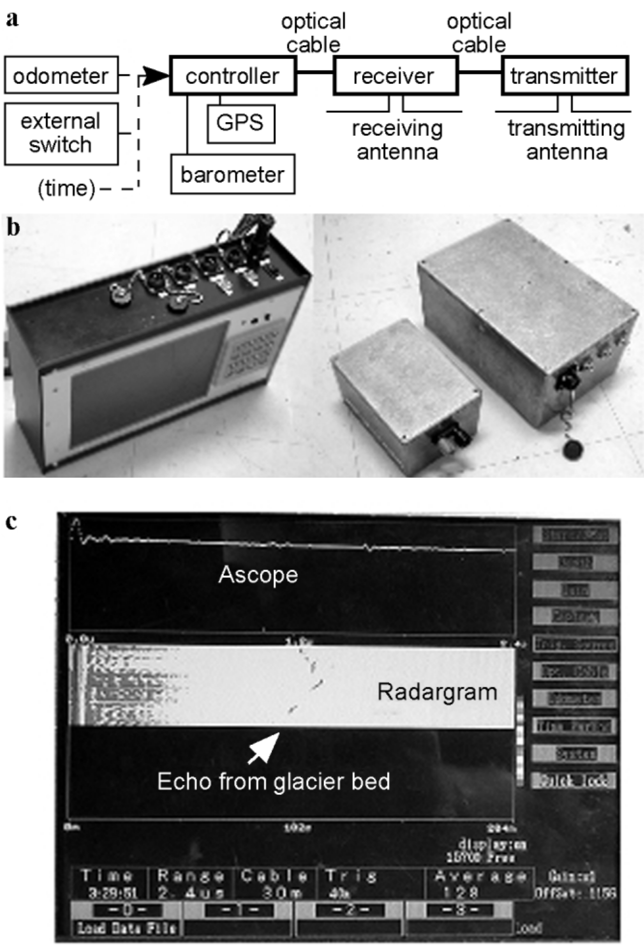

Fig. 1. The new ice-penetrating radar system. (a) Block diagram. A 30 m long fiber-optical cable is used to connect the receiver and the transmitter for profile measurements, but it can be replaced with a 100 m cable for common-midpoint measurements. The three modules each have their own external battery (not shown). The power-supply cable is <1 m. A sequence of measurements can be done manually, or by being automatically triggered by distance or time. (b) The controller (left) has a high-brightness color display and a keypad. The current status of the system is displayed by two lights above the keypad. The transmitter (center) and the receiver (right) are also shown. (c) Upper- and lower-half plots of the controller display respectively show one waveform (A-scope) and a radargram with up to 150 waveforms. Observation parameters are listed at the bottom and at the right.

flash card. The controller can also be used to display the stored data.

2.2. Receiver

The receiver controls the timing of the pulse transmission and the sampling of received waveforms. For the sampling, setting the origin of the two-way travel time accounts for delays in the circuit and the optical cable. Digitizing is done sequentially; a received waveform with 1024 data points reconfigures with repeating 1024 sampling of waveforms at a two-way travel time. This architecture results in less power consumption than faster digitizing methods.

A received waveform is digitized into 12 bits (4096 steps) with the least significant bit corresponding to 0.5 mV. Most portable oscilloscopes (e.g. Tektronix THS700 series, Fluke 190 series) can only attain 2–5 mV and digitize into 8 bits (256 steps). To increase signal-to-noise ratio, the user can increase the number of waves that are averaged for a given location (Table 2).

Table 2. System specification

Center frequency[1]	5 MHz
Pulse amplitude[1]	990 V
Repetition rate of the transmission	1 kHz
Observation time-window width[2]	2.4 μs, 4.8 μs, 7.2 μs
Received waveform sampling interval[3]	2.34 ns, 4.69 ns, 6.96 ns
Stacking number (selectable)	0, 2^n ($n = 1, 2, \ldots, 8$)

[1] See section 2.3 for more details.

[2] Selectable. 2.4 μs corresponds to about 200 m of ice thickness.

[3] The number of sampling points is always 1024, regardless of the observation time-window width.

2.3. Transmitter

The transmitter generates a 1 kV peak-to-peak pulse that maintains phase coherence with the receiver sampling timing. In general, transmitters use high-speed switching to sequentially charge and discharge a capacitor. A bipolar transistor has been frequently used for the switch (Watts and Wright, 1981). However, the breakdown voltage of the switch generally varies from one to the next; there can be large variations in the resulting transmitting pulse amplitudes. Furthermore, to achieve large pulse amplitudes with low-voltage transistors, multiple stacking of the transistors is used (Narod and Clarke, 1994), which increases the number of components.

To achieve more stable pulse amplitudes with fewer components, we use a high-speed field effect transistor (FET; Hitachi, 2SK2225, 1500 V proof) as the switch. This architecture requires power consumption (Table 1) comparable to the transmitter with transistor switches by Narod and Clarke (1994). Basic design of a similar circuit with fast Fourier transform can be found in Weertman (1993). The resultant waveform has a peak-to-peak amplitude of 990 V

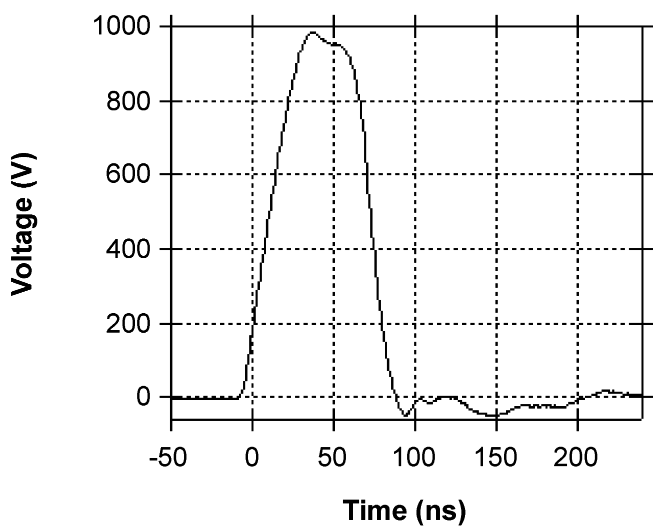

Fig. 2. Waveform of the transmitter output averaged over 16 pulses (no antenna loads, observation bandwidth of 100 MHz). The rise time is 28 ns and the decay time is 20 ns. Power spectrum of this waveform drops >10 dB at frequencies >11 MHz.

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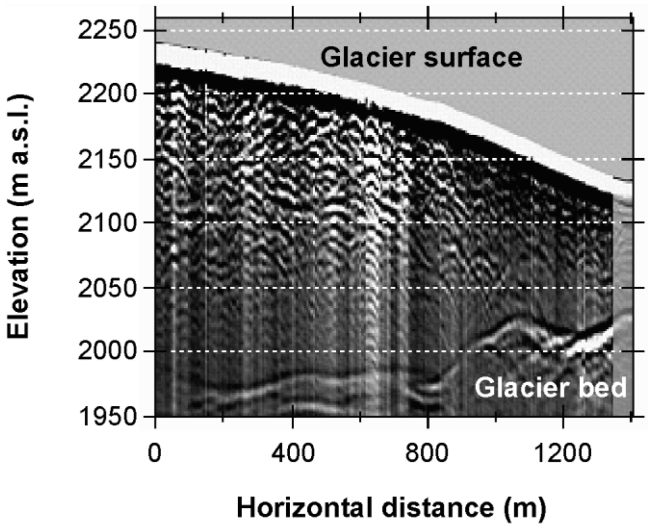

Fig. 3. Radargram taken on Athabasca Glacier using the new radar system. The two-way travel time is converted to a depth using a radio-wave speed of 169 m μs^{-1} in ice. The glacier surface elevation is obtained by barometric leveling. Amplitudes of the received waveform in the top 30 m of the glacier surface are saturated on a gray scale and shown as thick white and black lines.

(Fig. 2), and the amplitude variance between waveforms is ±2 V. For a constant antenna impedance, this stability gives a transmitting power variance of 0.4%. The transmitter is optimized for a radar frequency of 5 MHz.

2.4. Precautions for deployment under harsh conditions

We tested all components and the final product to −25˚C in a cold room. The silicon-rubber-covered electrical cables and optical cables (Oki Co., FC series) are flexible to −25˚C, and nickel metal-hydride batteries that consist of 11 cells (modified from HP30A, Paco Co., Tokyo) enable continuous measurements for 3 hours. Overall, all components are semi-waterproof and rugged.

Special attention was paid to ensure the system was reliable yet easy to use. The system does not require another oscilloscope and computer as all the needed features are built into the controller. This makes it lighter and easy to use. It also has a large keypad and a high-brightness display (Toshiba, LTM10C209H a-Si TFT, 640 × 480 pixels).

3. FIELD TRIALS

This system has been field-tested. In 2001, we did spot measurements with a prototype of this system and found reliable capability of the new transmitter architecture (Matsuoka and others, 2003). Then, in September 2002, we did profiling measurements on Athabasca Glacier, a temperate glacier in Alberta, Canada. As shown by the extensive surface water flow and many moulins, this glacier had significant liquid water that can impede radio-wave penetration. We focus on these latter measurements.

For the measurements, we used a route for the Snocoach bus that travels directly on the glacier between the lateral moraine and the central area of the glacier. The route is maintained daily and hence kept smooth. Resistively loaded half-wavelength dipole antennas at the center frequency of 5 MHz (Watts and England, 1976) were laid on the ice surface collinearly, and the data were collected by two people. Continuous profiles of the bed and glacier surface are shown in Figure 3. The relatively light columns at the right side of the image near 1400 m are likely due to electrical noise from the bus engine that was close to the radar system at that point. The light region near 650 m is probably related to the large amount of surface water (supraglacial water flow) that was observed at this location. Heterogeneous echoes from within the ice indicate that a significant amount of the radio-wave intensity was scattered. Nevertheless, the system revealed a continuous bed topography that ranges from 100 to 300 m below the ice surface.

Two other field trials were done in July 2003 at King Col, Mount Logan , Canada (4135 m a.s.l.), and in September 2003 at a small ice cap in the Tien Shan, China. Compared to the previous field-testing site, the trail at King Col had lower air temperature (−10 to −20˚C) and lower air pressure (610 hPa). Despite these harsh conditions, the system operated reliably. Therefore, the system can be used in a wide range of environments.

4. CONCLUDING REMARKS

We have developed a novel ice-penetrating radar system that can be carried on a backpack. The system has a stable 1 kV transmitter, a 12-bit-digitizing receiver and a controller with display for easy view of the data. To minimize electromagnetic coupling with antennas, the system uses optical communications between these components. These features help ensure that the device can operate reliably even under harsh conditions. Furthermore, a new architecture in the transmitter provides stable pulse amplitudes that allow the user to evaluate radar echo waveforms quantitatively. Therefore, this backpackable system should provide useful data in various locations where other radar equipment is difficult to use.

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