Instruments and Methods

An integrated lightweight ice-penetrating radar system

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ABSTRACT. We describe a portable low-frequency impulse radar system intended for ground-based surveys that employs off-the-shelf hardware integrated with custom-designed software. The hardware comprises a 1–200 MHz transmitter, digitizer, computer and GPS receiver, which together weigh ~1.5 kg. The entire system, including waterproof enclosures and batteries suited for >8 hours of continuous operation, weighs <10 kg plus the weight of the antenna housing. The system design is flexible, permitting hardware components such as the digitizer or navigation device to be exchanged. The software includes acquisition parameter control, real-time visual ice-depth rendering and data management capabilities using a hierarchical data format. The system described here has been successfully used to sound polythermal ice up to ~220 m thick in ski-based surveys in the Yukon, Canada, and temperate ice up to ~550 m thick in machine-based surveys in Iceland.

1. INTRODUCTION

Ice-penetrating radar is one of the most powerful and popular geophysical tools in glaciology (see Bogorodsky and others, 1985, for an introduction), with applications ranging from ice-depth sounding (Sverrisson and others, 1980) to mapping the internal stratigraphy of ice sheets (Nereson and others, 2000) to inferring englacial (Catania and others, 2008) and subglacial conditions (Jacobel and others, 2009). Airborne radars are used extensively for surveys covering large areas (Steinhage and others, 1999), but ground-based radars remain in demand for use in surveys of modest spatial extent or complex terrain. Here we describe the characteristics of a portable impulse radar system, constructed from lightweight, inexpensive commercial components, that is intended for ground-based surveys and is well suited to non-motorized travel. The novelty of this system is the integration of general hardware components (Fig. 1) with software, rather than innovations in the hardware itself (Matsuoka, 2004).

This system has been used to measure the thicknesses of two small polythermal glaciers in northwestern Canada (DePaoli and Flowers, 2009) and two ice-filled calderas in the temperate Vatnajökull ice cap, Iceland (personal communication from F. Pálsson, 2009). Below we describe the radar system hardware and its deployment, the data acquisition and management software and the system operation. While the applications to date have been limited to ice-depth sounding in alpine and sub-arctic environments, the system could be adapted to other purposes through the exchange of components and/or modification of the software.

2. HARDWARE

2.1. Transmitter and antennas

We use a monopulse radar transmitter based on the design of Narod and Clarke (1994) and fabricated by Icefield Instruments Inc. This proven transmitter is available off the shelf and provides sufficient power to survey ice depths of several hundred metres in both cold and temperate glaciers. The transmitter itself is small and weighs only 200 g (Table 1), making it ideally suited to surveys without vehicular support. The transmitter delivers 1100 V (±550 V) pulses into 50 Ω at a rate of 512 Hz across a resistively loaded dipole antenna (Shen and King, 1965; Wu and King, 1965). It has a rise time of <2 ns and can operate within a 1–200 MHz frequency range (Narod and Clarke, 1994), with the peak radiated frequency governed by the dipole arm length of the antenna. In the application described here, we use antennas of 4 m half-length (8 m each for transmitting and receiving), producing a centre frequency of 10.5 MHz. The receiving antenna was connected directly to the 1 MΩ impedance input of the digitizer. The antennas, constructed by Icefield Instruments Inc., have resistors of 30, 33, 39 and 47 Ω at distances of 0.5, 1.5, 2.5 and 3.5 m from the antenna centre. Lower-frequency systems to sound deeper ice could be constructed with longer antennas (e.g. Conway and others, 2009). For details on the transmitter and antennas we use, see Icefield Instruments (2005).

2.2. Digitizer, ‘netbook’ and GPS receiver

To integrate data acquisition, storage functions and visualization (Fig. 1), we combine off-the-shelf computing and digitizing hardware. We use a National Instruments NI-5133 digitizer, which serves as a digital oscilloscope platform with all interactive functions such as signal input, triggering and display settings shifted to a software environment. This universal serial bus (USB) device is lightweight (250 g) and does not require additional voltage supply, as it is powered through its USB cable. The NI-5133 digitizer has been used in at least one other glaciological radar study, which took place in 2008 and 2009 in Iceland (personal communication from K. Matsuoka, 2010).

The NI-5133 is equipped with two simultaneously sampled analog inputs with independently selected peak-to-peak ranges from ±0.04 to ±40 V with eight-bit resolution. It has a 50 MHz bandwidth (35 MHz for the lowest amplitude range, 50 MHz otherwise), and a sampling rate up to 100 MS s^{-1}. The system’s on-board memory size is 4 MB per channel, so the buffer can store 40 ms of data at

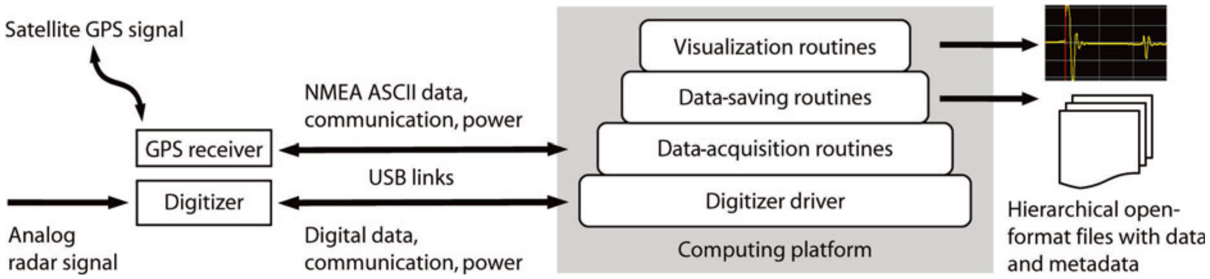


Fig. 1. Diagram of software-based radar system.

100 MS s^{-1} (assuming a wave speed in ice of 1.68×10^8 m s^{-1}, the two-way travel-time for a signal penetrating 3000 m of ice is ~35 μs). Taking into account the eight-bit vertical resolution and the root-mean-square (RMS) noise on the lowest voltage range, the lowest detectable signal is ~0.02 mV. At the time of writing, this system had been used to sound ice ~220 m thick in Yukon, Canada, with 10.5 MHz antennas, and ice ~550 m thick in Iceland with 5 MHz antennas (personal communication from F. Pálsson).

With a wave speed in ice of 1.68×10^8 m s^{-1} and a sampling rate of 100 MS s^{-1}, the distance between two consecutive samples in a trace (or waveform) corresponds to 1.68 m of ice. While this is one limitation on the vertical resolution, it is less than that introduced by the operating frequency of 10.5 MHz in this case. If we assume a maximum vertical resolution of $\lambda/4$, 10.5 MHz gives 16 m/4 = 4 m. Limitations on the vertical sampling interval arising from the digitizer sampling rate could be circumvented with more advanced digitizers, which support better resolution, higher sampling rates and/or implement, for example, equivalent-time sampling methods or random-interleaved methods. The rate at which the digitizer can deliver stacked data, combined with the travelling speed of the surveyor, will give an estimation of the spatial resolution of the system (discussed below). Finally, low-cost digitizers such as the NI-5133 (~US$1,500) are intended for indoor use and therefore must be protected when used in the field.

For computing hardware we use a small (8.9 in display, ~990 g), low-power 'netbook' computer with solid-state drives (SSDs). Netbooks are sold at a fraction of the cost (~US$500) of more specifically ruggedized computers in which the hard-drive assembly has been shockproofed. These netbook models tend to have small SSDs, a significant fraction of which is devoted to the operating system. We therefore use memory cards for data storage.

We use a simple, low-cost (~US$50) GPS receiver based on the SiRFstar III chip found in many hand-held GPS receivers. The unit is small, waterproof, reasonably rugged and USB-powered, so no additional battery or wiring cable is required. The driver for the device creates a virtual serial port, which causes the GPS receiver to appear as a serial device at the software level. The GPS streams standard US National Marine Electronics Association (NMEA) 0183 data including location, fix quality and number of satellites. We use these GPS data to identify the horizontal coordinates of the radar survey, not to map the ice surface elevation.

2.3. Physical deployment

For initial testing and deployment, we configured the radar system for ski-based surveys (Fig. 2a). The receiving unit (Fig. 2b; 3 kg total) comprises the computer, digitizer and GPS mounted in a waterproof case suspended from the operator with a chest harness intended for a camera. Both the GPS and digitizer are connected by USB cables to the computer. A port is drilled into the waterproof case through which the receiving antenna is threaded and connected to the digitizer. An additional port accommodates a power cable to connect the computer to an auxiliary external battery, carried in the operator's backpack. The foam used to stabilize the contents of the case also insulates the internal computer battery, but in some cases may impede the cooling of the computer processor. We took the precaution of ensuring the computer fan was not obstructed by foam, especially at higher air temperatures or in direct sunlight. The transmitting unit (Fig. 2c) houses the transmitter itself and a battery. The transmitting antenna is connected through ports in the waterproof case, which was mounted with removable pins on skis. Both transmitting and receiving antennas are housed in 1 m sections of polyethylene plumbing tubing (PEX) connected with couplers that can

Table 1. Radar system component characteristics for ski-based implementation described here. Depending on environmental conditions and recharging capabilities, smaller batteries than those listed could be used to power the transmitter and computer. Total cost of all components listed is US$4,000

Component	Dimensions cm	Weight g	Comments
Transmitter (Icefield Instruments Inc.)	10 × 8 × 3	200	180 mA draw at 12 V (active)
TX/RX antennas (Icefield Instruments Inc.)	400 half-length	200 each	Resistively loaded dipole
Battery (Sonnenschein 12 V 10 Ah)	15.2 × 9.8 × 9.8	4000 each	One each to power TX/computer
Digitizer (NI-5133)	19 × 4 × 11	250	230 mA draw at 5 V (USB-powered)
GPS (Rikaline 6017)	6 × 5 × 2	95	~50 mA draw at 3–6 V (USB-powered)
Computer (ASUS EeePC 900)	22.5 × 16.5 × 3.5	990	Draw depends on, e.g., sampling rate
Pelican 1400 case (TX/RX)	34 × 29.5 × 15.2	1800 each	TX towed, RX suspended with chest harness

be assembled and dismantled without use of tools. This proved convenient for field assembly and transport: all 16 lengths of tubing plus connectors and tow ropes, along with the transmitting-unit skis, could be packed into a simple snowboard bag. The transmitting unit was towed using a 12–15 m long cord behind the receiving antenna. In practice, the transmitting unit can be towed by the operator or by another surveyor (for roped teams of two). In our deployments, the use of the full receiving antenna (as opposed to a half-length) necessitated that the team member ahead of the operator tow the leading length of the receiving antenna.

3. SOFTWARE

3.1. Data acquisition

We describe the acquisition software interface, followed by the general programming steps. The software application was developed within the graphical LabVIEW development environment. Screen-shots of the graphical user interface (GUI) for the hardware settings and real-time data display are shown in Figure 3. The digitizer settings are defined using the GUI, which gives access to control parameters such as Source Channel (Channel 0, 1 or both), Vertical Range, Offset, Coupling, Sampling Rate, Record Length and Trigger Type (e.g. positive, negative, level, hysteresis, analog/digital). These settings are analogous to oscilloscope hardware settings and are tailored to the signal being acquired. Additional settings (GUI not shown) relate to data saving and define constructs such as radar survey lines and sounding locations. A real-time visual ice-depth rendering (Fig. 3b) is used for quality control during the survey and shows the GPS-measured survey-line track (upper left panel), the current radar trace (upper right panel) and the radargram under construction (lower panel). In this display, the radargram is shown as a function of trace number (horizontal axis) and approximate depth (vertical axis), given a user-defined wave speed in ice. User-defined parameters and data streamed from the GPS receiver are displayed in the far-right panel of the GUI.

Programmatically, the software interfaces with both the digitizer and GPS receiver. Once the acquisition settings are committed to the digitizer hardware, the radar signal is captured based on trigger settings, sampled, and sent to the digitizer buffer at a rate controlled by an on-board internal clock. A pre-triggering scheme allows us to trigger on the rising limb of the airwave while still capturing several data points before the trigger point, resulting in a trace that includes the entire airwave. Each time a radar trace is collected, the GPS is also queried to return the NMEA 0183 GGA sentence (one of several sentences contained in the NMEA standard) with position and fix-quality indicators. Overall, the computer processor usage is kept to a minimum during all of the operations described above, at $\sim$10% for the dual-core computer. This leaves ample processing power for additional computing, if needed, and maintains a reasonably low power drain on the battery.

To improve the signal-to-noise ratio, we perform software-based stacking. A prescribed number of traces or records (e.g. 256) are sequentially acquired, and each record is transferred individually to computer memory before the next record is acquired in the digitizer internal buffer. In order to minimize the computer memory required, only the sum of the transferred records is stored. When the desired number of records has been obtained, the sum of the records is divided by their number to obtain the average waveform, which is then written to disk. The rate of stacked data delivery and surveyor travelling speed give a measure of the spatial resolution of the system. For example, with a transmitter repetition rate of 512 Hz, a digitizer sampling rate of 100 MS s^{-1}, the netbook's 1.6 GHz Intel Atom 270 processor, a record length of $\sim$1000 data points and 256 stacked waveforms, each stack is produced in $\sim$1.5–2 s. This

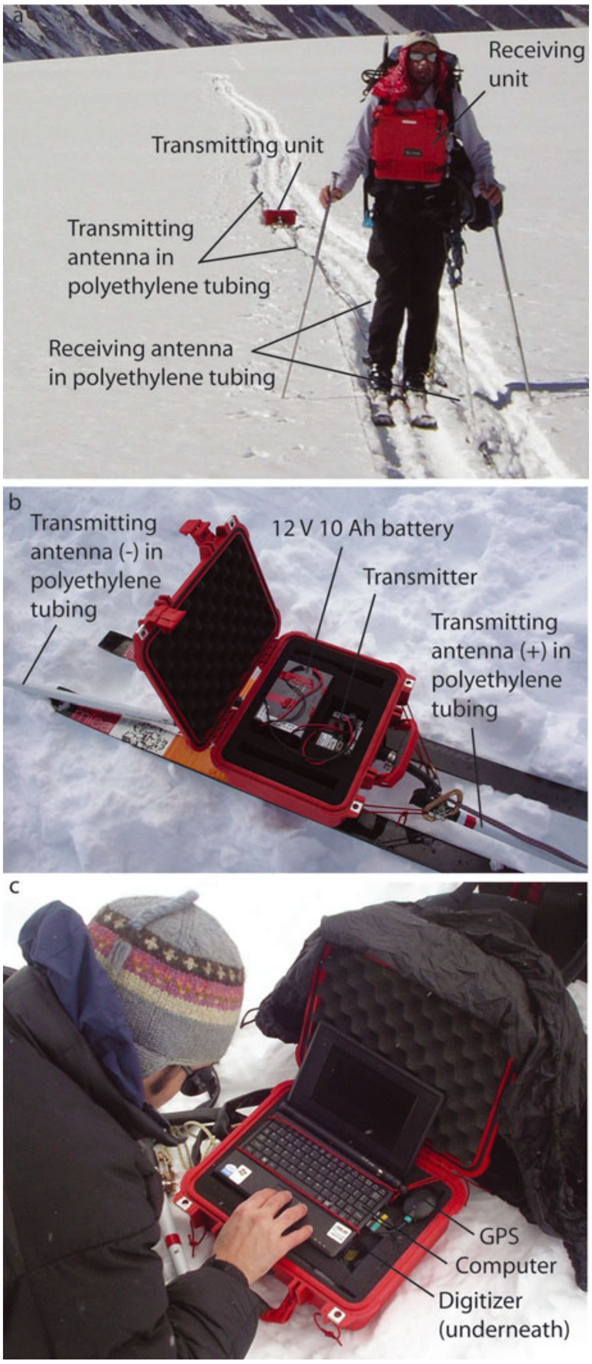
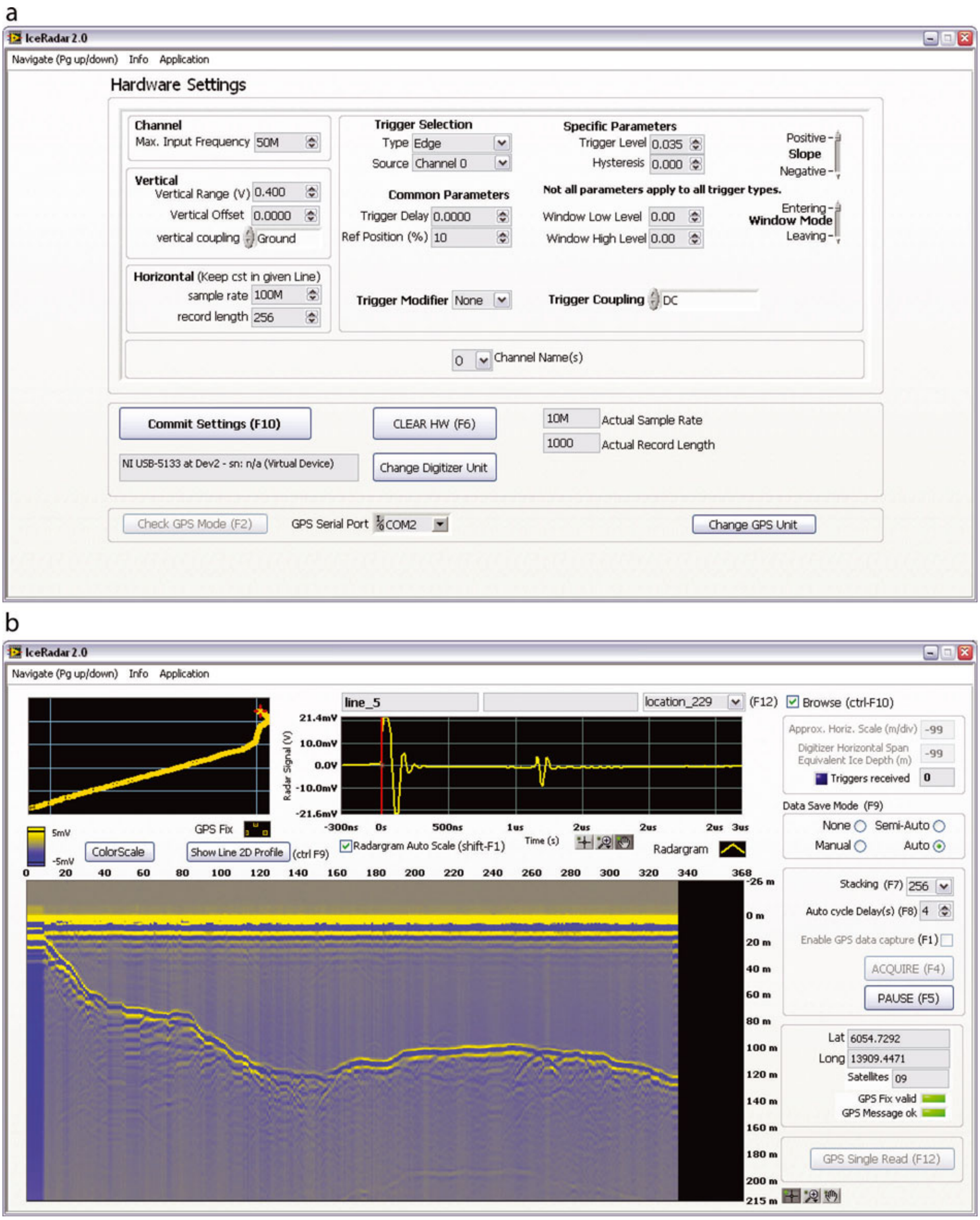


Fig. 2. Hardware deployment. (a) Configuration for ski surveys. (b) Transmitter. Impulse transmitter and battery are carried in a Pelican case mounted on skis. Transmitting antenna is threaded through ports drilled into the case and housed in 1 m sections of plumbing tube. (c) Receiver. Digitizer and PC are housed in a Pelican case worn with a chest harness by the operator. Digitizer and GPS are connected to the PC by USB. Receiving antenna is connected by BNC to the digitizer through a port drilled into the case.



a

Hardware Settings

Channel
Max. Input Frequency 50M

Vertical
Vertical Range (V) 0.400
Vertical Offset 0.0000
vertical coupling Ground

Horizontal (Keep cst in given Line)
sample rate 100M
record length 256

Trigger Selection
Type Edge
Source Channel 0

Common Parameters
Trigger Delay 0.0000
Ref Position (%) 10

Specific Parameters
Trigger Level 0.035
Hysteresis 0.000

Positive – **Slope** – Negative

Not all parameters apply to all trigger types.

Window Low Level 0.00
Window High Level 0.00

Entering – **Window Mode** – Leaving

Trigger Modifier None
Trigger Coupling DC

0 Channel Name(s)

NI USB-5133 at Dev2 - sn: n/a (Virtual Device)

10M Actual Sample Rate
1000 Actual Record Length

GPS Serial Port COM2

b

line_5
location_229 (F12)
☑ Browse (ctrl-F10)

Approx. Horiz. Scale (m/div) -99
Digitizer Horizontal Span Equivalent Ice Depth (m) -99
Triggers received 0

Data Save Mode (F9)
None ○ Semi-Auto ○
Manual ○ Auto ●

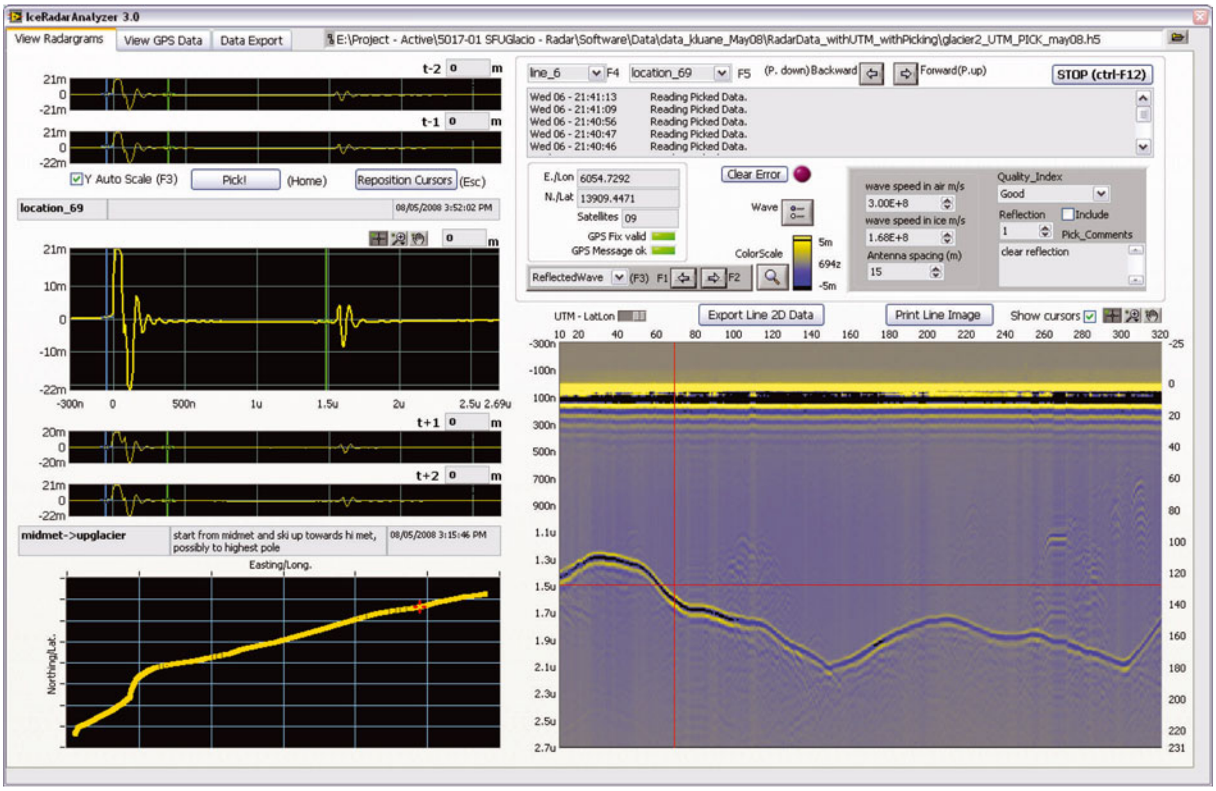
GPS Fix
☑ Radargram Auto Scale (shift-F1)

Stacking (F7) 256
Auto cycle Delay(s) (F8) 4
Enable GPS data capture (F1) ☐

Lat 6054.7292
Long 13909.4471
Satellites 09
GPS Fix valid
GPS Message ok

Fig. 3. Screen shots of graphical user interface for data acquisition. (a) Hardware settings. (b) Real-time data display. Note that some settings in (b) are only displayed during acquisition. Due to limited space, axis labels are omitted from the GPS plot, which is merely intended to alert the user to GPS malfunction. Data in (b) are from an unnamed valley glacier in the Yukon. Transmitting and receiving antennas were 4 m (half-length) and separated by 15 m in this survey.

time depends primarily on the stacking (as our current stacking method requires as many calls to the digitizer as there are waveforms in a stack) and is compatible with ski-based surveys, where travelling speeds are slow (say <1 m s^{-1}). For a travelling speed of 1 m s^{-1}, all 256 stacked waveforms would be acquired within a 1.5–2 m horizontal distance. For machine-based surveys and higher travelling speeds, the waveforms in a given stack would be collected over a correspondingly longer horizontal distance. Increased spatial resolution could, of course, be achieved by decreasing the survey speed. A judicious choice of record length, depending on the ice depth, and stack size, depending on required signal-to-noise ratios, will help to optimize resolution for a given system. Stacking increases the signal-to-noise ratio and therefore, in principle, allows deeper sounding; however, this assumes that the signal plus noise is



IceRadarAnalyzer 3.0

E:\Project - Active\5017-01 SFUGlacio - Radar\Software\Data\data_kluane_May08\RadarData_withUTM_withPicking\glacier2_UTM_PICK_may08.h5

line_6 F4 location_69 F5

Wed 06 - 21:41:13 Reading Picked Data.
Wed 06 - 21:41:09 Reading Picked Data.
Wed 06 - 21:40:56 Reading Picked Data.
Wed 06 - 21:40:47 Reading Picked Data.
Wed 06 - 21:40:46 Reading Picked Data.

E./Lon 6054.7292
N./Lat 13909.4471
Satellites 09

wave speed in air m/s 3.00E+8
wave speed in ice m/s 1.68E+8
Antenna spacing (m) 15

Quality_Index Good
Reflection 1 ☐ Include
Pick_Comments clear reflection

☑ Y Auto Scale (F3)

location_69 08/05/2008 3:52:02 PM

midmet->upglacier | start from midmet and ski up towards hi met, possibly to highest pole | 08/05/2008 3:15:46 PM

☑ Show cursors

Fig. 4. Screen shot of graphical user interface for manual picking. Data from an unnamed valley glacier in the Yukon.

detectable at the lowest-resolution threshold of the digitizer's analog-to-digital converter. An additional consideration with this stacking method is the GPS acquisition rate of NMEA sentences. Specifications for the device we use indicate an update rate of 1 s; we have not encountered problems with the update rate, provided static mode is switched off.

If the time to perform this software-based stacking is considered too long, as could be the case for surveys carried out at substantial vehicle speeds, an alternative hardware-based stacking approach called 'multi-triggering' could be used with appropriate digitizer models. For devices supporting this feature, all records in a given stack are stored successively in the digitizer internal buffer and then transferred to computer memory in a single call for further processing. Such an approach increases the overall stacking speed but would require functionality beyond that currently implemented in the NI-5133.

3.2. Data management

To facilitate viewing and post-processing of recorded data, we choose a data management strategy that lends itself to defining and linking heterogeneous data types (e.g. radar traces, GPS output and metadata such as sounding locations and user comments). For instance, a single radar trace is expressed as an array of numbers (voltages) at nanosecond intervals, while a GPS location and metadata are represented by ASCII strings. For a typical survey entailing soundings at many locations, one sounding location can be interpreted as the parent of an individual radar trace, with which a set of GPS coordinates is associated. Several locations might in turn be grouped into a parent object called a line or transect. A line contains the series of locations along a meaningful path in the survey. Conceptualizing the data in a tree-like structure makes their retrieval more intuitive and efficient. With this structure, all 'datasets' within any 'group' become addressable and can be directly retrieved from a file. We save the data using Hierarchical Data Format 5 (HDF5), an open format with software libraries available for general use. This format allows analysis to be carried out with many different software packages and programming languages. HDF5 was initially developed by the US National Center for Supercomputing Applications (NCSA) and is maintained by the HDF Group at the University of Illinois.

3.3. Data processing

A second application was developed that benefits from the HDF5 data format, in which the raw data can be manually picked and ice depth computed assuming a simple survey geometry. In this application, the bed reflector is assumed to be horizontal and located vertically beneath the survey centre point. By specifying the wave speed in air and ice, as well as the separation of transmitter and receiver, ice depth can be estimated from the travel-time difference between the direct and reflected arrivals. This simple calculation assumes a constant wave speed within the glacier and hence should be applied with caution in the accumulation area, as the wave speed in snow and firn is greater than that in ice.

The GUI for this application (Fig. 4) displays location-specific radar traces (upper and middle left), the full-line radargram (lower right), the GPS-measured survey line trajectory (lower left) and GPS fix information. Intersecting cursors on the radargram define the location of the current trace (vertical) and the position of the cursor (horizontal) that is used to pick the desired reflected arrival(s) (blue cursor on the radar trace). Once a pick is made, its position is displayed on the radar traces with a dashed line (not shown) in order to facilitate tracking of individual waveforms between neighbouring traces. The information resulting from picking is added to the original HDF5 file in such a way that it is linked to existing data/metadata associated with the radar trace. An export utility returns the full set of HDF5 data in ASCII, including computed ice depth, GPS coordinates, GPS fix quality, and a user estimate of pick quality. Raw radargrams can also be exported to ASCII for processing with other applications.

4. SYSTEM OPERATION

We tested this radar system in 2008 and 2009 on two small valley glaciers in the Whistler–Blackcomb ski area in southwestern British Columbia, Canada. Radar surveys were then carried out on two unnamed polythermal glaciers in the Saint Elias Mountains of southwest Yukon in April/May of 2008 and 2009. Physically managing the transmitting unit and antennae was occasionally a challenging aspect of conducting these surveys, particularly in steep terrain (where the transmitting unit is prone to flipping over) or in soft, heavy snow (which can build up in front of the unit). A small sledge may perform better than skis for the transmitting unit.

Operation of the computer/digitizer system typically only required the operator to name the survey data file and lines (as desired) and to define the sampling rate. This allowed the operator to have hands free during travel. With the receiver box lid and PC open, the operator could follow the construction of the radargram, inspect the GPS input and otherwise monitor system performance. Alternatively, the lid can be closed and the system run unmonitored, as is often necessary in machine-based surveys. In this case, it is especially important to ensure the operating system settings prevent hibernation, standby or virus scans during a survey. Although the netbook we use is not outdoor grade, its screen is more visible in outdoor conditions than some older outdoor-grade screens. Even so, it was helpful to shade the screen in bright conditions. To our knowledge, inexpensive netbooks are not available with outdoor-grade screens. In its current configuration, the radar system could be operated by a single person if safety were not a consideration. Several hundred radargrams and MB of data were collected in 2008–09 in the Yukon without failure or data loss.

5. SUMMARY AND RECOMMENDATIONS

We have presented an ice-penetrating radar system that demonstrates how off-the-shelf hardware components can be integrated with software to provide a portable, flexible radar system at a reasonable cost. Several ski-based surveys in the Yukon and machine-based surveys in Iceland with this system have demonstrated the operation and robustness of the current implementation. The system described would work interchangeably with other NI digitizers with minor software changes, and is currently being modified to support a PicoScope 4224 digitizer. Future improvements are being considered that would increase the manoeuvrability of the system in the field. Use of a hand-held device to control the receiving unit would free the operator from the somewhat cumbersome chest-harness rig, while future software development will target two-device communication to support this improvement. Software modification could make the system adaptable to glaciological applications other than bed sounding.

ACKNOWLEDGEMENTS

G. Flowers is grateful to the Natural Sciences and Engineering Research Council of Canada (NSERC), the Canada Foundation for Innovation, the Canada Research Chairs Program and Simon Fraser University for funding. L. Mingo acknowledges O. Lessard Fontaine for developing the GPS communication routines. We acknowledge Whistler–Blackcomb for facilitating the radar system testing and thank A. Jarosch for assistance in the field. We are also grateful to J. Sommerville for his advice on implementing HDF5 in our application, and to F. Pálsson for feedback on system performance in Iceland. Discussions with G.K.C. Clarke and ideas based on his original radar software were helpful in developing this application. F. Pálsson, H. Björnsson and G.K.C. Clarke kindly reviewed the original draft of the manuscript, and R. Jacobel and H. Conway provided insightful reviews of the submitted manuscript.

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MS received 27 January 2010 and accepted in revised form 29 May 2010