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INSTRUMENTS AND METHODS

A PORTABLE DIGITAL DATA-ACQUISITION SYSTEM FOR SURFACE-BASED ICE-RADAR STUDIES

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Abstract. We have built a radio-echo sounder which utilizes a low-frequency broad-band impulse transmitter and a microprocessor-based digital-recording system. The unit is mounted on skis and power is delivered by a small generator and batteries. The receiver uses a portable digital storage oscilloscope which passes data via a microprocessor unit to a cassette tape for off-line analysis on a personal computer. Though originally intended primarily for sounding temperate ice, the system has been tested in the Antarctic during the 1987–88 field season with good results. The radar performed well there and also in field tests and subsequent studies on South Cascade Glacier, Washington, and many interesting results were obtained. An oblique incidence profile, where transmitter–receiver separation varied, was used to study the dielectric permittivity of the ice and to locate internal layers at shallow depths. The sounder was also deployed in conjunction with hot-water drilling experiments attempting to create cavities at known locations within the ice. Wave forms from different transmitter–receiver orientations around the bore hole were combined in the off-line analysis to produce a more directional synthetic aperture emphasizing returns from the bore-hole region. Changes in the radar echoes from within the ice were *not* seen during these experiments, possibly because the drilling was not able to create regions with dimensions or orientations approximating those of naturally occurring cavities.

INTRODUCTION

Although radar systems of various design have been used in sounding ice for more than 20 years, it has only been recently that digital recording of the echo wave forms has been feasible. The principal difficulty has been the need for high-speed digitizers to achieve band widths on the order of 100 MHz to record accurately the wave forms, and secondly the speed needed to repeat the process rapidly while storing the data, as required in profiling applications. The advantages of digital recording over earlier analog methods occur both in the acquisition of data and in off-line processing. Digitally recorded wave forms can be "stacked" in time to reduce incoherent noise and thus enhance a signal. Signals from different points in space may also be combined to produce a synthetic aperture, thereby narrowing the radar beam width. In off-line processing, wave forms can be easily filtered, power spectra can be produced, and a host of post-processing techniques widely used in geophysical analysis can be applied. For example, methods of predictive deconvolution, which allow the removal of effects due to imperfect input wave forms, can be applied. Statistical techniques such as principal-moment analysis can be employed to enhance subtle echo differences such as one might expect over changing bed conditions (Jones, unpublished).

Because of the specialized requirements of these radar systems, a number of groups have developed receiving and recording equipment specifically for this purpose. We have instead chosen to adapt commercially available electronics to our needs and so have designed a system which could be fairly easily duplicated by others. The unit was built for under $10 000 and weighs under 32 kg. It is mounted on skis and is intended for stationary as well as small-scale profiling applications.

RADAR TRANSMITTER

With minor modifications, the radar transmitter is similar to the one described by Watts and Wright (1981), and Watts and England (1976). Two pulser units were built along with separate triggering circuits which allow "free-running" trigger rates to vary between 0.1 and 10 kHz. The transmitter may also be triggered by pulses from an odometer wheel, linked to the transmitter by a fiber-optic coupling which typically would be used when profiling. The system also operates in a "wake-up mode", where wave forms may be recorded at a fixed location at pre-set time intervals without an operator being present. A block-diagram overview of the system is shown in Figure 1.

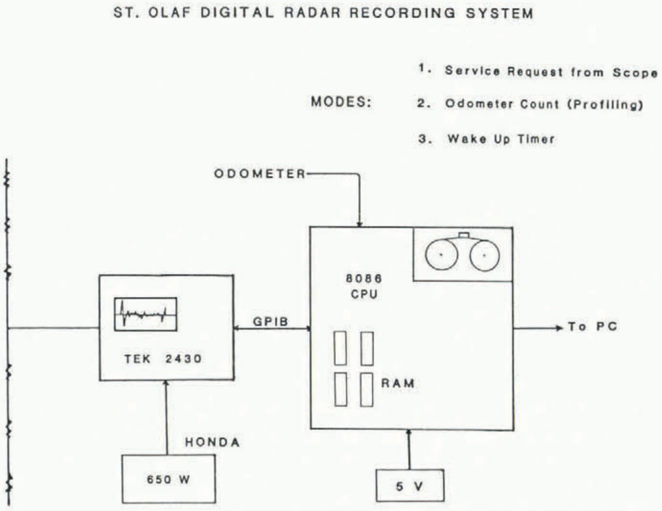

Fig. 1. Block diagram of the radar recording system.

The center frequency of the transmitted impulse is determined by the length of the attached dipole antenna, and may be varied by simply changing the length of these wires (Watts and England, 1976). The broad-band characteristics of the wave form result from the impulse created by the transmitter and are a positive feature of the system design in that information about internal scattering sources is contained in the power spectrum of the returned energy (Jacobel and Raymond, 1984; Jacobel and Anderson, 1987). A negative feature of low-frequency impulse radars is the lack of directionality of the antennas. We devoted considerable time to this problem in an attempt to build antennas which would better direct energy into a well-defined region of the ice.

Although the electrical engineering literature abounds with studies of various antenna configurations, both theoretical and applied, very few deal with the radiation pattern of antennas which transmit a sharp impulse (see, for example, Franceschetti and Papas (1974), and references therein). We chose, as the most promising design, a conical spiral configuration (Harrison and Williams, 1965) with antenna wire coiled in a helix of constant pitch and oriented with the cone apex pointed into the ice. An identical antenna was made for the receiver. ' These had a cone height of 2 m and a diameter of 1 m at the opening, and were designed to be collapsible to a disc of the same diameter for transport. These were tested on South Cascade Glacier, Washington, with unsatisfactory results due to ringing as discussed below.

An inescapable fact of impulse transmission is "ringing" which occurs when the signal is reflected from the antenna ends. The dipole antennas we have used are resistively loaded to "taper" the signal strength so as to avoid reflections. This results in some sacrifice of transmitted power in exchange for a clean transmitted pulse which approximates one cycle of a sinusoid. The dipole elements are typically placed directly on the glacier surface in a straight line and oriented with transmitter and receiver antennas parallel to each other or along a line. This avoids inductance coupling between parts of the antennas, which we believe is the reason why the conical spiral antennas gave unsatisfactory results. Ringing in the transmitted wave form persisted for several microseconds, obscuring not only echoes from internal scatterers but also the reflection from the bedrock. Even with the antennas heavily damped by resistive tapering, ringing persisted. To be certain, the elements showed good directional sensitivity but their other characteristics made them unacceptable for sounding purposes.

We report these negative results on attempts to improve antenna design in some detail because of the lack of information in the engineering literature, and in the hope that they may be of some use to glaciologists. Our subsequent attempts to gain more directionality from the radar focused on post-processing techniques as described in the results section below.

RECEIVER AND DIGITAL-RECORDING SYSTEM

The radar receiver is a Tektronix 2430 portable digital storage oscilloscope. This instrument we feel represents the best optimization of a number of competing requirements, among them: band width, power consumption, cost, weight, and reliability. The oscilloscope utilizes a 100 megasample per second digitizer and will automatically switch into a sampling mode for sweep speeds requiring higher digitizing rates. The vertical amplifier has an analog band width of 150 MHz, more than adequate even for the highest frequencies present in the echo wave form. Each wave form is digitized into 1024 points, and stacking to eliminate noise is available in an averaging mode which can be varied from 2 to 256 wave forms.

The digital scope has a triggering feature which makes it ideal for radar application. Signals fed to the input are continuously digitized, whether a trigger is received or not. The scope is set to trigger in a particular bin (for example. bin 128 of 1024) when the voltage exceeds a selected threshold level. When this condition is fulfilled, the digitizer is latched and the wave form is displayed and stored in memory. Thus, information is present about the wave form which actually *preceded* the trigger. Gone are the problems, typical in analog scopes, of capturing the first arrival of the air wave and uncertainties about timing relative to it. The scope may simply be set to trigger on a stable part of the air wave, and the complete wave form, including time before the trigger, is recorded and saved (Fig. 2).

Power consumption of the scope is significant, however, and necessitated designing the system to be ski-mounted instead of movable in a back-pack. The oscilloscope requires up to 180 W, although during typical operation 120 W is more common. Nevertheless, this is more power than can be easily supplied by batteries and, as a result, we have employed a 650 W Honda generator for the power source. The scope and the generator each weigh about 16 kg. The latter provides remarkably clean and quiet power. Any electrical noise is eliminated by using the scope's averaging mode when acquiring wave forms.

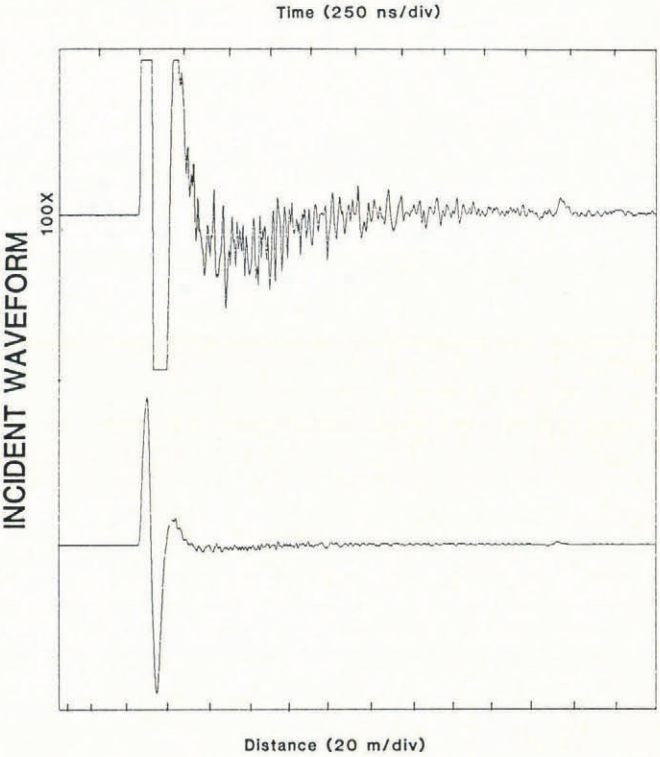

Fig. 2. Digitally recorded wave form on two amplitude scales. Note that parts of the wave form occurring prior to the trigger (on the rising edge of the first arrival or air wave) are recorded as well.

The 2430 communicates set-up and wave-form information over a standardized interface, the General Purpose Interface Bus (GPIB or IEEE-488) and may be linked to a number of microprocessor devices which can receive parallel information in this format. This is an advantage over more specialized time-base and digitizing systems, because it uses standard commercial technology, and because of the ease of compatibility with recording devices. For example, a personal computer with a GPIB interface plug-in board could be used to store the received wave forms. For our system, we have chosen to utilize a dedicated microprocessor, the Intel 8086, with data storage on digital micro-cassette tapes. This part of the system operates on 5 V and draws only 3 A of current. Originally selected because of low power and weight requirements, its function alternatively could be fulfilled by a personal computer because of the generator power now available for the oscilloscope. Although a PC has the advantage of more flexibility, disk writing and storage for data is not highly reliable in the field, and ultimately a tape system is still needed. The Intel 8086 microprocessor accomplishes the task of delivering digitized wave forms to tape effectively, rapidly, and reliably. Essentially, we have elected to use commercial technology for the more difficult job of wave-form acquisition (the Tektronix 2430 oscilloscope), and to handle the data transfer and storage with a dedicated microprocessor and in-house designed interfacing.

The Intel System Design Kit (SDK-86) uses a 8086 microprocessor which is supported by 4 K of RAM, 8 K of ROM, a key-pad/LED display interface, RS-232 serial communications, and standard 8255A I/O chips all supplied by the manufacturer on a single board. For the purpose of communicating with and collecting data from the Tektronix 2430 digital oscilloscope, we added a General Purpose Interface Bus and controller chips which allow two-way communication between the SDK-86 and the oscilloscope. Through machine-language programs stored in ROM, we are able to set up and interrogate the oscilloscope in three operating modes: manual, profiling, and wake-up. Virtually every function of the scope can be controlled remotely, which gives us the flexibility to take the system into different environments and perform a variety of tasks. All programs for acquiring data as well as tape utilities are permanently "burned" into ROM, and so are immediately available upon power-up.

The digitized wave-form data are sent over the GPIB on command and stored in RAM until the entire wave form has been collected. Typical transfer times are 0.3 to 0.4 s depending on the command issued. In profiling applications, position information is obtained with an odometer wheel and shaft-encoder arrangement and wave forms may be acquired at intervals selected in a set-up menu. From RAM, the wave form is written to tape via a Braemar CM 600 Mini-Dek digital cassette recorder. The CM 600 operates at 300 baud which is significantly slower than the GPIB. Thus, writing a single wave form to tape takes approximately 3 s and the total collection/write time is therefore approximately 3.5 s.

This factor limits the speed of operation in profiling. For example, in dense sample profiling, with one wave form recorded each meter, surface speed is limited to approximately 0.25 m/s. Speeds of up to 6 m/s are possible for less dense profiling, and we found this to work quite acceptably, for example, when the system was towed behind a snowmobile. A second limiting factor is the tape density and length which allow only 70 wave forms per tape side. These two constraints dictate the scale of operations for which the system will be most effective: profiling at moderate speeds and densities over distances on the order of several kilometers, or dense profiling done more slowly over a more limited distance.

To retrieve the records from tape for processing and analysis, tapes are read off-line by a cassette deck and transferred to a personal computer over the RS-232 line. In our field trials, this has been accomplished at a base camp within hours of acquiring the data. Much of the data manipulation and wave-form processing can be done on the PC so that, for example, stacked A-scope or Z-scope displays can be produced in the field. In this way, decisions can be made immediately which may influence the subsequent work.

PERFORMANCE TESTS AND RESULTS

The system was tested and deployed in several experiments on South Cascade Glacier, Washington, in the summer of 1986, and on Ice Stream B in West Antarctica during the 1987–88 field season. Figures 3 and 4 show the results of a profile 120 m in length made on Ice Stream B employing antennas with a center frequency of approximately 2 MHz. The nearly flat bed at 800 m depth in this part of the ice stream is clearly seen in Figure 3. Wave amplitudes in this and subsequent figures have been multiplied by the scaling function shown at the left of the figure which corrects for attenuation losses and also has the effect of suppressing (and distorting) the air–wave arrival. Figure 4 is an expanded view of the upper 100 m of the same profile and shows more clearly changes in the pattern of near-surface crevasses which are typical of this part of the ice stream. In this application, the system was housed in an insulated shipping box mounted to a frame on the skis, and pulled by snowmobile. Typical air temperatures ranged from −20° to −25°C and presented no problems for the electronics.

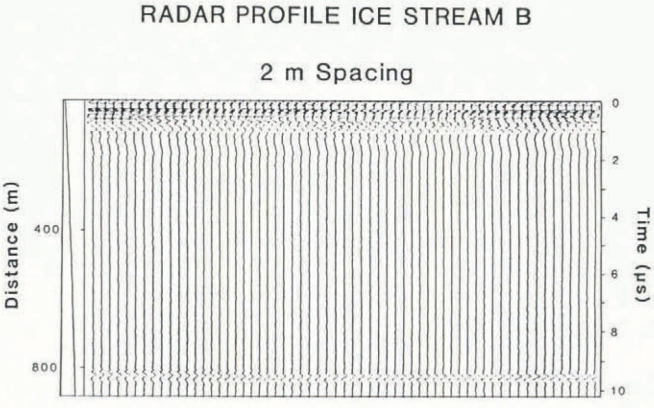

Fig. 3. Profile recorded with 2 MHz antennas on Ice Stream B, West Antarctica, showing smooth bottom returns at 800 m depth.

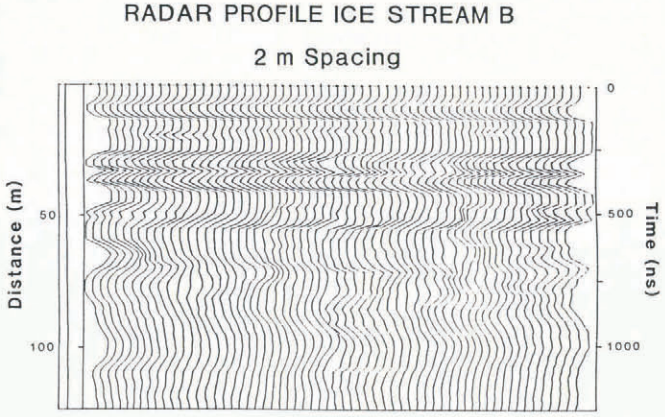

Fig. 4. Expanded view of the upper 100 m of the profile in Figure 3 showing variations in the pattern of near-surface crevasses typical of this part of the ice stream.

The radar and recording system were also deployed in a number of tests and experiments on South Cascade Glacier. A coarse profile was made near the equilibrium line (P-1) with 10 m spacing using the manual mode with wave forms recorded by individual commands (Fig. 5). Antennas were oriented perpendicular to the profile line in a time-intensive operation involving many moves and set-ups. The success of this trial (and also its tediousness) encouraged us to develop an automated profiling mode with antennas oriented along the profile line and recording triggered by an odometer wheel, so that the operator could simply move along the surface without stops and antenna set-ups. This work was completed in the summer of 1987 and the automated profiling capability was tested on Ice Stream B as described above.

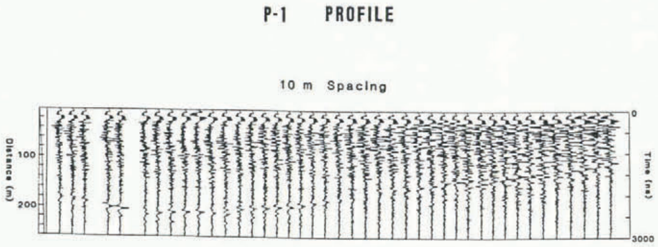

Fig. 5. Cross-sectional profile of South Cascade Glacier, Washington, in the region of the equilibrium line (P-1). Wave forms were recorded in the manual mode at a spacing of 10 m.

Because many times questions have arisen about the effects of wires and metal in the near-field of the radar antennas, we performed a number of simple tests to see the influence of these kinds of objects. The radar system is mounted on wood skis with an aluminum frame of approximately 1 m dimensions which itself produced no changes in the wave form. Similarly, other metal objects up to several meters in size located in the near field produced no effects on the wave form. Wires and steel tapes which were comparable in length to the antennas (10 m) or longer caused ringing in the system, particularly when oriented parallel to the antennas. However, this was only true when they were in the near field of the antennas: between the transmitter and receiver or within a wavelength or so of one or the other. Thus, this radar system is not highly sensitive to interference from metal objects in the area.

In two of the experiments on South Cascade Glacier we co-ordinated with A.G. Fountain of the U.S. Geological Survey, Project Office Glaciology, who was conducting hydraulic studies of englacial water flow with a hot-water drill. The goal of these collaborative experiments was to effect hydraulic changes at known locations within the ice which would be detectable with the radar and thus provide a "ground truth" for the remote sensing. In an effort to gain more directionality from the antennas in the region of the bore hole, we typically made recordings with transmitter and receiver located in turn at intervals around a circle with the bore hole at the center. In our data processing, these wave forms were easily combined, producing a "synthetic aperture" which enhances reflectors common to all views, and reducing those which are not. For example, the strength of the bedrock echo is enhanced relative to the noise, and so presumably are echoes from internal targets beneath the drill site.

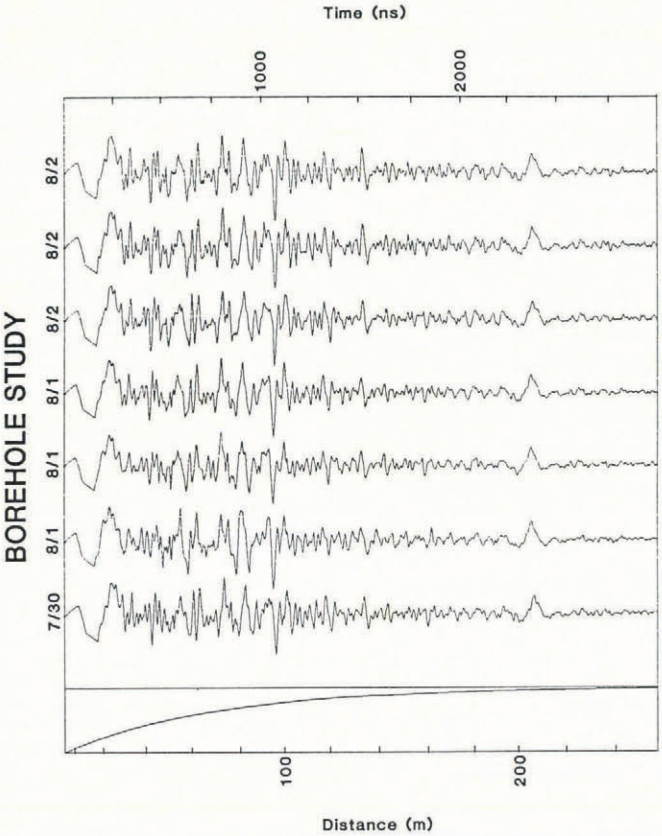

Fig. 6. Synthetic aperature wave forms made by combining data from pairs of transmitter–receiver locations taken in turn around a bore-hole location. Changes in time are not *evident as the hole was created, enlarged, and salt added.*

Figure 6 shows wave forms recorded at a drill site over a 4 d time period in an experiment designed to look for changes occurring as a result of hot-water drilling. Each wave form is actually the sum of four records made around the hole as described above. The wave form marked 7/30 was recorded at the site prior to drilling. On 7/31, a bore hole was drilled which reached the bed at a depth of 200 m (personal communication from A. Fountain). The figure indicates a bedrock echo at 200.0 ± 0.5 m (assuming a dielectric constant of 3.27), in good agreement with the drilling results. The bore hole did not connect at the bed during the time period covered by the figure, and water levels in the hole remained roughly constant at approximately 30 m below the surface.

The next wave form marked 8/1 was recorded on the day following drilling and shows little obvious change from the one made 2 d before. The subsequent two wave forms recorded on 8/1 were made after the hot-water drill had been lowered into the bore hole in an attempt to create an enlarged cavity which might be seen by the radar. Again, little change is evident in the radar record. To design a "blind" experiment, the depth of the drill was concealed from the radar operators but was subsequently revealed to have been 100 m. The radar record can neither confirm nor deny this fact. Because the hot-water drill loses its effectiveness due to convection as the size of the hole increases, the dimensions of the cavity created are neither large nor well known. Estimates by A. Fountain are that they are likely to be less than 1 m for the 30 min period that warm water was released at this level.

The fifth wave form was recorded on 8/2 and again shows little change. Next, salt was injected into the bore hole at the surface in an attempt to alter the dielectric properties of the water in it. The final two wave forms were recorded 2 and 4 h following this salt-injection experiment. Though salt has undoubtedly diffused throughout a significant part of the bore hole, the radar-echo wave form has not been affected in any obvious way. This is perhaps not surprising since the water-filled hole itself caused no appreciable change, and most of the dielectric contrast with ice is due to the water itself.

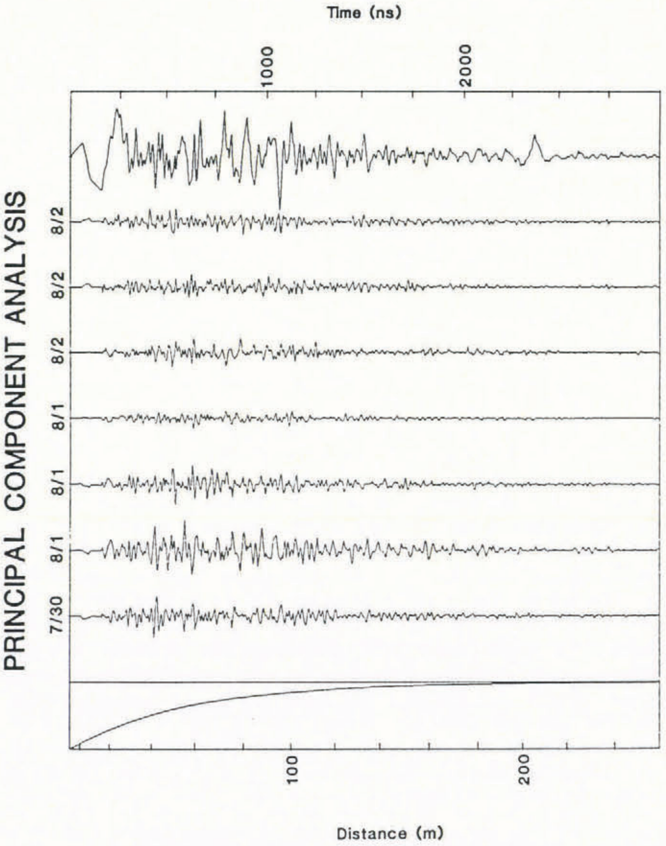

Fig. 7. Principal-component analysis of the wave forms in Figure 6. The wave form at the right is the principal component common to all wave forms in Figure 6. It has been removed from the seven wave forms as shown to emphasize differences among them.

In an effort to enhance the possible differences in these signals, the seven wave forms were processed in a principal-component analysis. In effect, this technique mathematically "rotates" the time-series data via a coordinate transform to a new vector space where most of the power is along one or two principal components. These components are the signal which is most common to all the data, and may be removed so as to emphasize the inherent differences. The data are then transformed back to the original form, minus the common signal. Figure 7 shows the results of a principal-component analysis of the data in Figure 6. As expected, one component (shown at the right) had nearly 90% of the power and was removed to emphasize the differences in the seven signals shown in the remaining part of this figure. Unfortunately, not much power remains; the signals were indeed very similar. The remaining wave-form amplitudes are near the noise level, and significant causally produced changes are not found.

Though this negative result is in some ways disappointing, it nevertheless reveals useful information. The most straightforward interpretation is that it is difficult for radar, with a wavelength on the order of 20 m in ice, to "see" structures which are significantly smaller than this.

Though the bore hole is 200 m long, the radar sees this nearly "end on" where the dimension is less than 1% of a wavelength. Evidently, naturally occurring cavities, at least occasionally, present a larger cross-section to the radar, either because of alignment or size. Because the impulse contains some power at shorter wavelengths, meter-sized cavities do produce scattering and return some of the higher-frequency components (Jacobel and Raymond, 1984).

In another experiment, an oblique-incidence profile, where transmitter–receiver distance is systematically increased, was used to calculate the depth of internal layers as well as giving information about the dielectric properties of the medium (Jezek and others, 1978). Such a profile is particularly useful for identifying shallow layers which are not otherwise observed in typical profiling configurations with a close transmitter–receiver separation because the echo is often obscured by the air-wave arrival.

Figure 8 shows wave forms from an oblique-incidence profile acquired on South Cascade Glacier near the equilibrium line where the transmitter–receiver separation was varied in nine steps from 20 to 100 m. In this figure, no scaling function is used. Thus, at the closest separations, the direct arrival of the air wave saturates the receiver and is cut off in the display but, as the separation is increased, the inverse-square losses increase substantially, and the air wave is diminished to the point that it is barely seen at 100 m. The bedrock echo is not particularly well resolved in this location for close transmitter–receiver separations, but can be clearly seen at about 180 m depth as the reflections become more oblique.

Most notable in the figure, however, are two echoes which emerge from "beneath" the air wave and which are most noticeable at separations greater than 50 m. The second of these has the largest amplitude and can be seen quite clearly at a separation of 60 m and beyond when the air-wave amplitude has decreased significantly. The first is seen most clearly between 60 and 90 m, thereafter decreasing in amplitude and becoming indistinguishable from the second. In both cases, these waves have a larger amplitude than the air wave, because the latter is diminished at greater distances by the increasing inverse-square-law losses, whereas the former are produced by reflection of a larger amount of energy entering the ice.

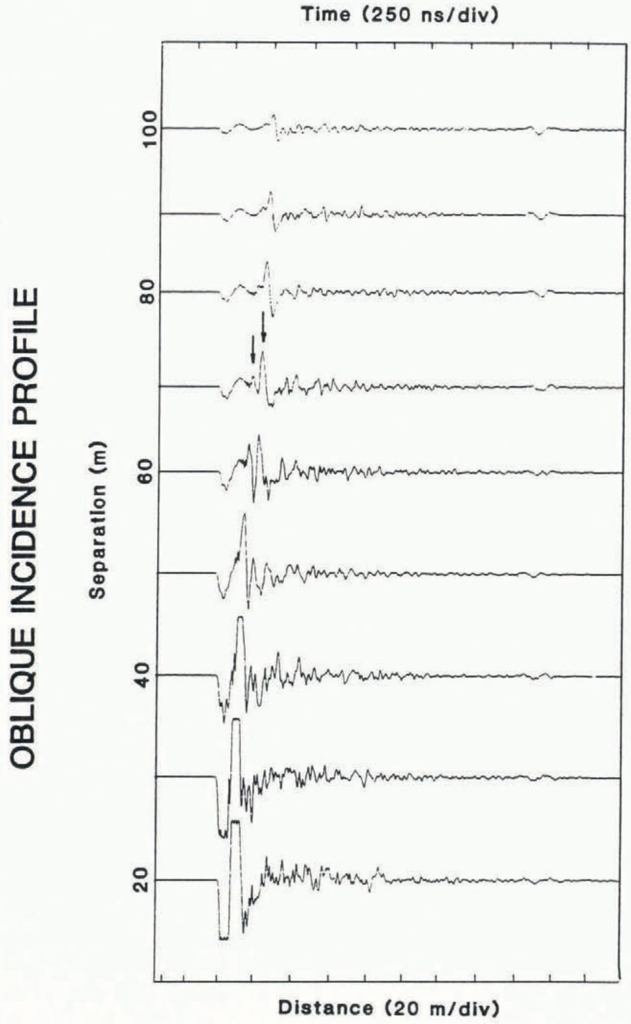

Fig. 8. Results of an oblique-incidence profile showing the direct arrival (air wave) decreasing in amplitude as separation is increased. Also present are two echoes (arrows) from internal layers seen most clearly at separations beyond 60 m.

The increase in arrival time of the echoes with respect to the air wave, as separation increases, arises because of the increasing distance along the oblique path. This time difference can be plotted as a function of transmitter–receiver separation to yield the velocity of propagation (or equivalently, the dielectric permittivity) and the depth to the layer. The data for both echoes were fitted to a straight line whose slope yielded an average value for the dielectric permittivity of 3.27 ± 0.15 for the first echo, and 3.26 ± 0.09 for the second. The corresponding depths were 0 ± 3 m and 13 ± 2 m, respectively.

The values of these dielectric permittivities are well within the expected range for ice and wet firn and, together with their small uncertainties, give confidence to the interpretation of waves reflected from a layer or layers. The depth corresponding to the first echo is consistent with zero, or the surface. Rather than an actual echo, this arrival probably represents a "direct" wave propagating in the wet snow above the firn (Bogorodsky and others, 1985). The snow depth in this part of the glacier at the time of the survey was approximately 1–2 m and the interface with the firn could provide enough dielectric contrast to produce a wave-guide effect.

The second echo is very likely a reflection from the firn water table, although the depth of 13 ± 2 m is somewhat below the expected firn/ice transition at approximately 10 m (personal communication from A. Fountain). Water content (water volume/void volume) within the firn at this time of year is typically about 0.7 and thus the firn holds a water table above the ice which might be expected to give rise to a reflection.

CONCLUSIONS

The radar system described is a multi-purpose tool now ready to be deployed in a variety of field settings. The data-acquisition and recording system has been adapted for cold-weather operation, and has been tested in the Antarctic. We anticipate that the system will be most effective in applications where digital recording and processing can yield information not otherwise available from analog recording, and where size and logistical constraints dictate the need for a small, portable surface-based system.

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