Some Airborne Applications of Subsurface Radar

STEVEN A. ARCONE

The results of several helicopter-borne short pulse radar surveys over frozen and thawed freshwater bodies are discussed. The examples given are geologically simple so that effects of the system could be separated from the complications of wave propagation in the ground. As expected, best performance was achieved using well.isolated and small high-frequency antennas at slow speeds and low altitudes over smooth interfaces defining low loss media. In addition the isolation of the airborne antenna from ground loading permits application of deconvolution filtering based on the known, constant radiated pulse waveform. The major obstacles to deeper earth penetration using high power, low frequency transmitters and antennas are high surface reflectivity and aircraft clutter. Current research is looking at methods to suppress these unwanted effects.

Short pulse radar was originally developed for ground surface applications. The first commercial systems introduced by the Geophysical Survey Systems, Inc. (GSSI) in the early 1970s were airborne over frozen lakes, rivers and seas (*1-5*) within a few years in attempts to measure ice thickness. Simple geologic situations that were easily interpretable were encountered in some of this work, but most of the applications outdistanced the systems used. The more difficult applications required signal processing for dealing with incoherent reflections from inhomogeneous media (e.g., brash ice) and high-power, low-frequency antennas for greater penetration into water or wet soils. These requirements have only begun to be addressed in the last few years.

This paper discusses several ice survey examples and other applications using a system identical in principle to those used in the references mentioned above, and one system that is radically different. The purpose is to introduce the reader to present and future possibilities of airborne short pulse radar. The examples illustrate both great successes and experimental failures. At present helicopter rental rates ($400-600/hour for a Bell Jet Ranger), it is hoped that distinct coherent reflections will appear as soon as the survey site is attained. As the helicopter moves along, it is thought that the time separation of the reflections will vary. All too often, however, within 60 seconds of takeoff, the oscilloscope display is cluttered with coherent events that either remain immobile in the scan or never change their relative position as range or altitude changes. Although exploration geophysicists are generally reluctant to report negative results, some examples of geophysical exploration "garbage" will be given here.

U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H. 03755.

EQUIPMENT: THE RADAR SYSTEM

In short pulse radar the fundamental idea is to connect some sort of discharge device to a very broadband antenna, radiate the resulting pulse, and receive a reflection whose time of propagation can be timed with suitable clocks in a control unit. Common methods of pulse generation are not much more sophisticated in principle than Hertzian spark gap generators, but pulse compression techniques using code modulation are now being developed. The standard commercially available short pulse radar system has been discussed in many articles (*6, 7*). Here the radar system will also be reviewed, but with an eye toward its airborne application.

Transmit and Receive Antenna Units

The antennas are usually resistively loaded dipoles, the design of which seeks to attenuate all oscillations of the current discharge. Such antennas sacrifice all the glamour of conventional radar antennas—high gain, narrow beamwidths, efficiency, excellent front-to-back ratio—in order to achieve this short pulse shape, two of which are shown in Figure 1. To the left in Figure 1 is shown a GSSI Model 101C resistively loaded dipole, vintage 1979. The right side of Figure 1 depicts A-cubed "pulse ekko" low frequency folded dipole, vintage 1985. The waveforms have been modified slightly by filters of a control unit. Range resolution is always at a premium; angular location is presumed to be directly beneath the antenna, lacking any directionality in the beam radiation pattern. Frequency spectra of commercial models are centered between 50 and 1000 MHz, with a few special application antennas as low as 10 MHz.

A short pulse radar antenna placed on the ground will experience ground loading; i.e., excitation of the ground will induce radiation that slows the flow of current on the antenna. This reaction lowers the frequency content of the pulse and alters its shape depending on ground electrical properties. The ground also causes a curious lobing to the radiation pattern, as energy is divided mainly between the critical angle $\theta_c = \sin^{-1} 1/n$ where, n is the ground index of refraction, and the broadside directions (*8*). An airborne antenna radiates a single broad lobe with minimal pulse width, and guarantees that the transmitted waveform will never vary; an important consideration for deconvolution (i.e., pulse compression) signal processing schemes such as Wiener filters. The major drawback of airborne antennas is the interference of radiation reflected from the aircraft, examples of which will be shown later.

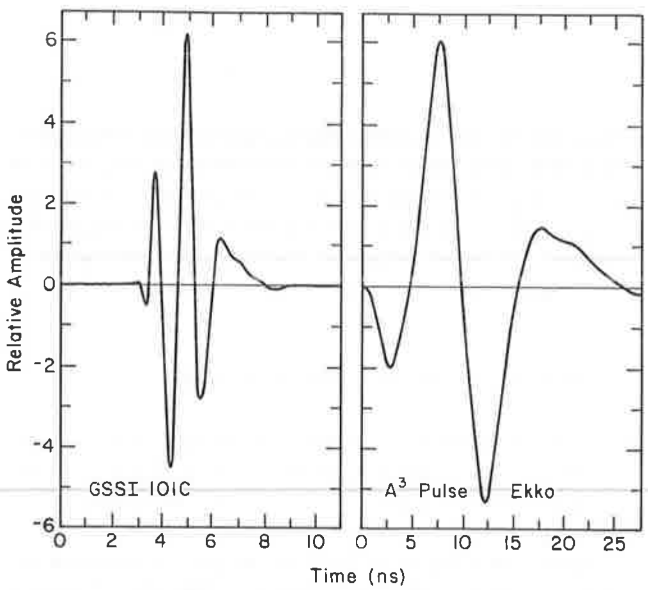

FIGURE 1 Waveform examples in short pulse radar.

The transmitter and most of the receiver electronics are placed at the antenna terminals to reduce noise, and both antennas and electronics are often placed in one package that is shielded to reduce back radiation (Figure 2). Semiconductor discharges are used to generate Gaussian-shaped pulses, peak amplitudes of which are now available at over 1000 volts. The signals received are immediately amplified and then sampled to convert the frequency content into the audio range for tape recording and data display on conventional graphic devices. Real-time digitization is not yet possible, since the frequency bandwidth of the smaller antenna units extends into the low GHz range. The sampled returns are reconstructed into scans extending over time windows ranging generally from about 50 to 2000 ns. The pulse repetition frequency (PRF) of all commercial units is about 50 kHz, so that approximately 6700 pulses go into the construction of 1 scan at a scan rate of about 8/sec: a rather large waste of energy.

Control Unit

A control unit contains the hardware to set the scan rate, time windows, overall gain and the all-important TRG

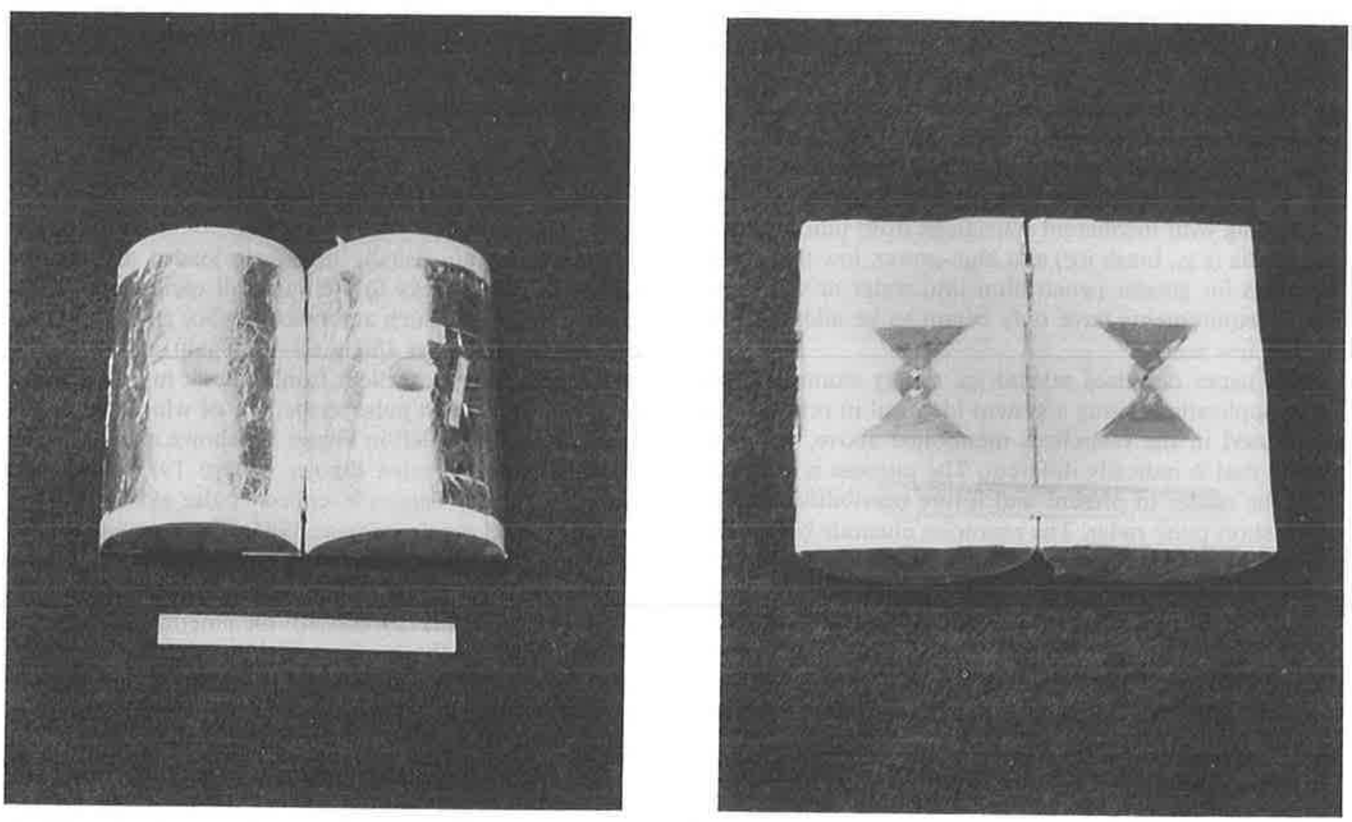

FIGURE 2 Single unit packaging of shielded transmit and receive antennas.

(time range gain) function. This function allows the gain to be varied over the scan to enable suppression of the strong early returns and amplification of the weaker later returns. A small oscilloscope for viewing the scans and a cassette tape recorder are available, along with a variety of high and low pass filter settings to exclude most ambient noise. Some units may include digital circuitry to allow the audio signals to be stacked continuously—an excellent technique for enhancing the signal to noise ratio in the presence of incoherent noise. Unfortunately, the antennas must be kept motionless while this operation is performed. Therefore, the function is of no use in an airborne survey where the aircraft altitude constantly varies, even by tens of centimeters over a 1- or 2-second time span.

A basic rule of ground surveying is to go as slowly as human patience will permit, as this affords the best-quality data. The same holds true in the air; 5 mph or less is best. Data have been successfully recorded at speeds between 5 and 20 mph at 8 scans/second. Higher scan rates are necessary at greater speeds. Table 1 shows the approximate ground area of sensitivity for one scan as a function of speed for the GSSI model 101C antenna (center frequency—900 MHz) operating at 8 scans/sec at an altitude of 3 m. The calculations are based on a measured transmit-receive 3 dB beamwidth of 70 degrees (*9*) in both principal radiation planes. These beamwidths should hold for other antenna units of similar design (e.g., model 3102 at 500 MHz), the dimensions of which scale according to the center frequency of operation.

The necessary time range window is determined by the expected time of return for the deepest reflection (or "event") sought. The free space velocity of electromagnetic waves is 30 cm/ns, so that every meter of altitude adds 6.2 ns to the needed time window. Propagation velocities beneath the earth's surface are much slower, varying from about 17 cm/ns in dry sand to about 3 cm/ns in icy water. Care must be taken that the frequency range of the pulse does not lie in the dispersive and absorptive region for the particular material of interest, or else the distorted pulses that return may hardly be recognizable, much less visible.

Signal Processing and Graphic Displays

The signal processing functions mentioned above, audio conversion, filtering, time range amplification, and stacking are all available in modern, commercially available subsurface radars. Missing are matched filters or deconvolution schemes designed to recognize the reflected wavelets of interest and suppress all other events. Such filtering schemes have been developed by individual organizations (e.g., United States Geological Survey in Denver, Colorado, and U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire), but not for commercial use. At present, data storage, handling, and processing are the major priorities in subsurface radar development.

TABLE 1 AREA OF SENSITIVITY AS A FUNCTION OF ALTITUDE

Altitude (m)	Area (m^2)
3.0	16
4.5	35
6.0	60
7.5	90
9.0	130

NOTE: Approximate ground area of sensitivity as a function of altitude based on the 3 dB beamwidth of the pulse center frequency. Values are good to ±10 percent for scan rates between 8 and 50 sec^{-1} and flight speeds up to 7.5 m sec^{-1}.

The most common method of data display is electric current burning on chemically treated paper. Figure 3 shows a hypothetical radar scan and equivalent graphic display, an ideal model if the radar events were to remain unchanged over a short distance. Darkness is proportional to signal amplitude and the horizontal bands represent the consecutive positive and negative oscillations of the pulse waveform. The chart paper rolls out as fast as the data were recorded on magnetic tape, which means that it takes as long to display data as it does to do a survey. As stacking is impossible in an airborne survey, it is virtually the raw data that are displayed on the graphic. The advantage of this display is that the banding formed by the density of the consecutive scans allows the eye to follow the continuity of various events within a profile with ease. The disadvantage is that individual waveforms cannot be readily examined as in a seismic section, but must be retrieved. Retrieval is not easy unless the waveforms have been digitally recorded and stored (there is one manufacturer who now offers this service).

Aircraft Mounting

The primary consideration for mounting a short pulse radar antenna to an aircraft is minimizing reflections from

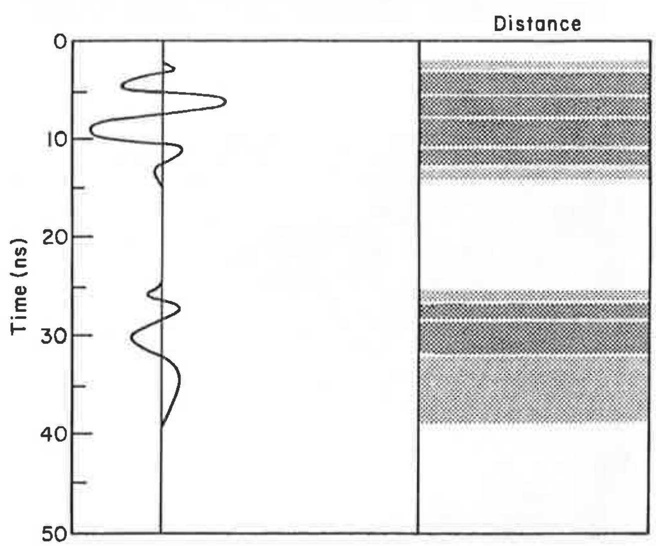

FIGURE 3 Hypothetical radar scan and equivalent graphic display.

the aircraft. This requires either a shielded construction or a remote mounting. Many antenna units now available are metallically backed to confine radiation to one hemisphere. Nevertheless, energy will radiate from the sides of the unit and even leak around the back of the shielding: a front-to-back ratio of about 20 dB is common. Larger antenna units operating below 150 MHz are generally not shielded owing to the added weight of the metallic backing.

Figure 4 shows two experimental mountings for which data will be shown later. Figure 4a shows a GSSI model 3102 "500 MHz" antenna fixed to the skids of a Bell Jet Ranger 206B. The antenna unit weighs about 3 kg and is set about 1 m from the nearest skid. Figure 4b shows a low frequency unit of unshielded antennas slung beneath a helicopter. In both cases, the antennas must be far enough from the nearest reflector (ground or aircraft) to allow the direct transmission to the receiver to clear before any events of interest are received.

EXAMPLE SURVEYS

Sheet Ice: Lakes

There is hardly a geophysical exploration system that does not base its data interpretation upon the theoretical interaction of the energy involved (e.g., seismic or radar waves, d.c. currents) with a model of smoothly layered earth. Such an ideal model is often realized in cold regions where layers of water, ice, and thawed and frozen soils are common, as well as the usual sedimentary layering found everywhere. Most ideal is a frozen lake where motionless water allows even freezing. Somewhat less ideal is a river, where the energy of flowing water produces frazil and brash ice formations which distort the homogeneity and smooth interfaces of the ice sheet.

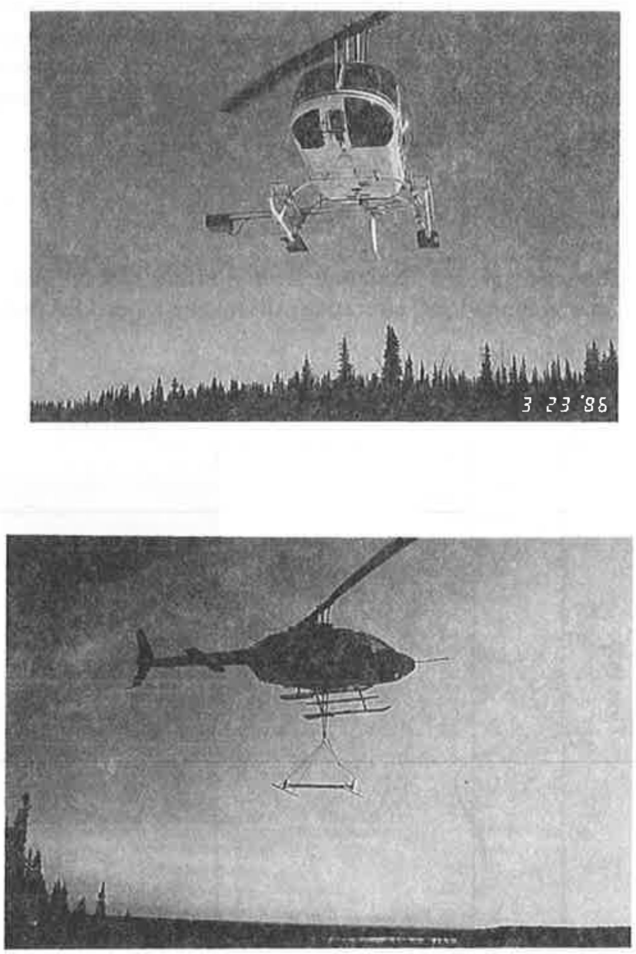

FIGURE 4 Short pulse radar antennas on a Bell Jet Ranger 206.

Figure 5 is a helicopter survey performed in late March 1986 of a lake in interior Alaska, whose ice was just over 1 m thick. The vertical ice thickness scale shown in the figure applies only within the first two reflections. The decibel values given in parentheses refer to the round trip propagation loss for the water and ice multiple events at the points indicated. Portions of some events depicted in this figure may not be visible because the figure has been made light enough to view the signal zero crossings (thin white lines) in the stronger events.

The transmitted pulse was centered near 500 MHz. Helicopter speed was about 18 m/sec, or 40 mph (generally air speed is much less), and the total record is about 4300 m long. The large changes in the vertical position of the reflections are due to wind-aided changes in altitude. The figure demonstrates many aspects of an airborne survey of a simple two-layer medium: direct coupling, helicopter reflections, ice surface and bottom reflections and a faint multiple reflection that occurred between water and the helicopter. Two of the events are labeled with attenuation figures given in decibels (dB). These figures represent the amount of propagation loss calculated to have been suffered by the particular event labeled at the altitude indicated at the arrowhead. These losses are due to geometric spreading of the beam and transmission and reflection losses at the ice-air and ice-water interfaces. All of the ice reflections are coherent: i.e., the banding indicates retention of the transmitted waveform. At 18 m/s airspeed, 10 m altitude, 8 scans/s and a beamwidth of 70 degrees, the antenna has sensed over 170 m^2 of ice while compiling 1 scan. Generally, earth layering over such a large area will not be so uniform as to allow radar returns at 500 MHz to retain this degree of coherency, as is now seen.

Sheet Ice: River

Figure 6 depicts a very low altitude survey of a section of the frozen Yukon River that contained a stretch (approximately 200 m) of open water, with a hanging dam of frazil ice. The transmitted pulse was centered near 900 MHz. Altitude was kept at about 1.5 m and air speed was very slow at about 1.8 m/sec (4 mph). The time scale is only about 25 percent of that of Figure 5, so that the small vertical variations seen most clearly in the surface reflections represent altitude changes of only tens of cm. At the right of the figure are temporally coherent reflections from a smooth cover of sheet ice. The reflections seen beneath open water reflections are multiple bounces between the helicopter and water. Attenuation at 900 MHz in fresh-

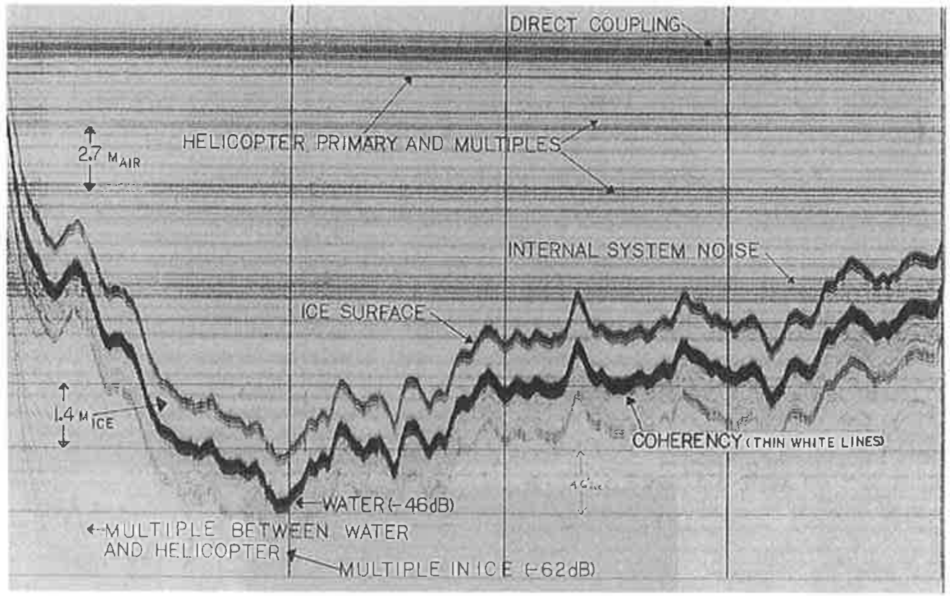

FIGURE 5 Antenna Model 3102 profile of ice thickness over Birch Lake, Alaska.

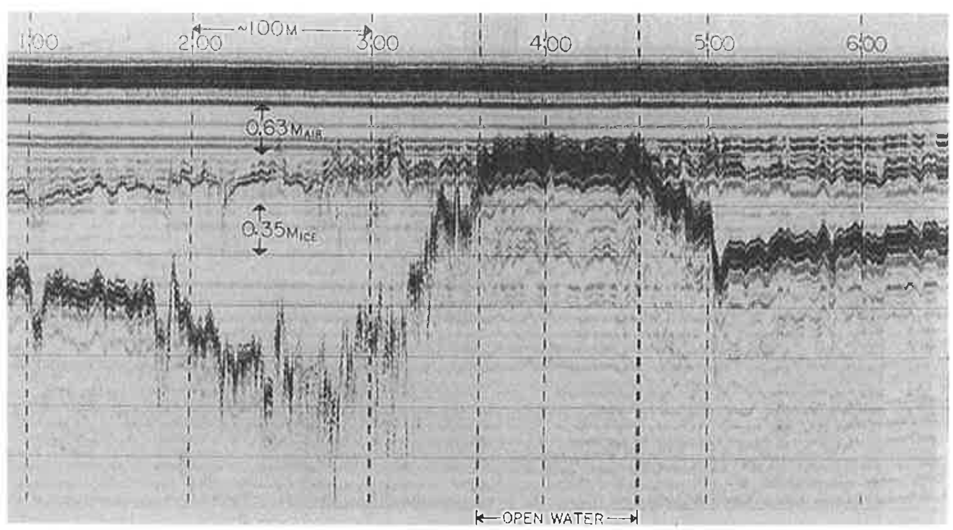

FIGURE 6 Very low altitude (<2 m) model 101c (900 MHz) antenna survey of section of Yukon River.

water at 0°C is over 70 dB/m so there is no chance that this is a subsurface event. Of greatest interest is the large lobe of frazil ice that formed under the sheet ice downstream (to the left) of the open water. The lobe ranges up to 1.7 m thick, which met the criterion for pier fortifications on the Yukon bridge (up to 3 m of ice was detected in a sun-shielded cove farther upstream). Note that the frazil ice reflections consist of coherent and incoherent signals. These returns cry out for some squaring and smoothing to establish a more traceable boundary.

Figure 7 is a survey conducted over the same transition from ice to water seen in Figure 6. The survey was done with the 500 MHz model 3102 antenna at 6 m/sec flight speed and a slightly higher altitude. The detail shown in Figure 6 is degraded in Figure 7, especially over the frazil ice formation. The lower figure shows an expanded section of the data was digitized and deconvolved using a Wiener filter based on a pulse waveform received over the open water. The noise suppression and the time domain pulse compression can be seen, which will enable the thickness of the ice to be measured more easily.

An ability to measure the thickness of thin ice is of interest to the Coast Guard or to municipal agencies responsible for regulating winter activities such as ice fishing, skating festivals, motorcycle races, etc. The minimum resolvable thickness from the raw data of the antenna used in Figure 6 (GSSI model 101C) is about 20 cm, and about 10 cm with deconvolution. Antennas with a broader

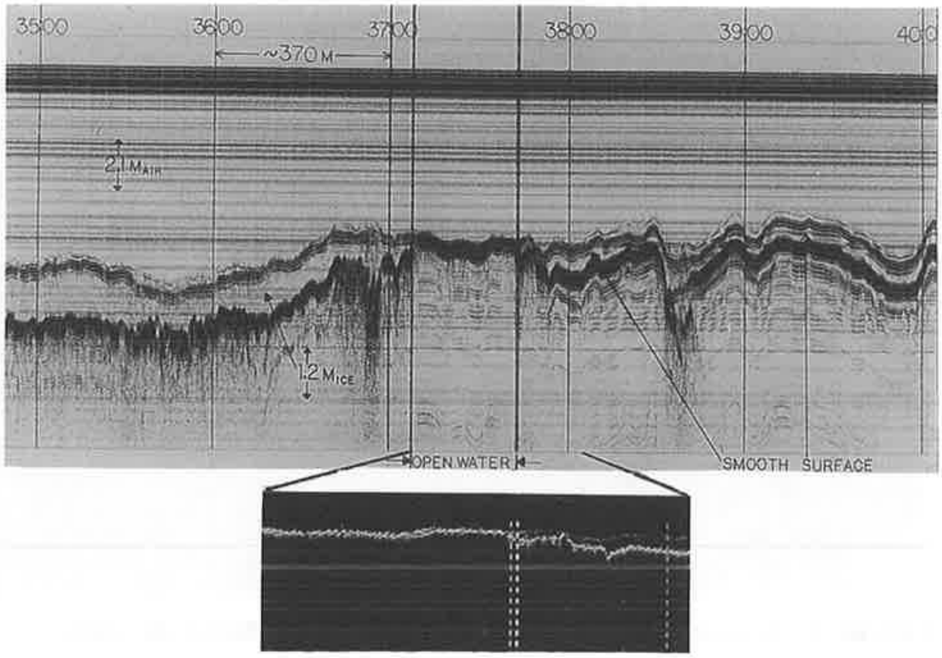

FIGURE 7 Same survey as Figure 6 except at higher altitude and flight speed.

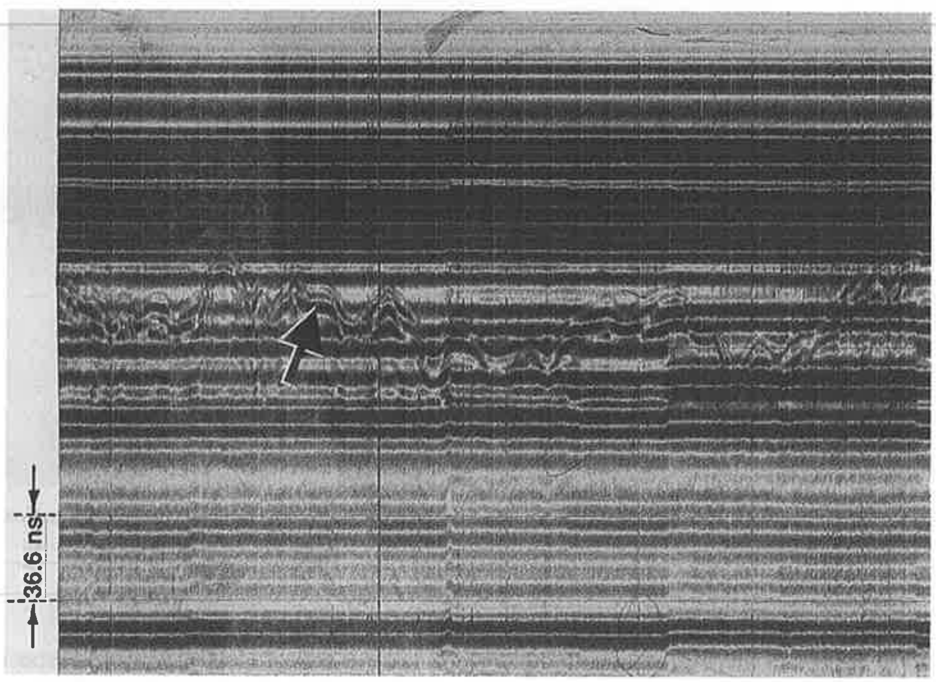

FIGURE 8 Frozen river survey using a GSSI Model 3112 antenna hard mounted between helicopter skids.

bandwidth at the same center frequency, that will reduce these thicknesses to about 10 and 5 cm respectively, will soon be available.

As promised earlier, an example of radar "garbage" is given in Figure 8, which is a profile of a shallow portion of an ice-covered river using a GSSI model 3112 antenna whose pulse was centered near 100 MHz. The antenna was shielded with electromagnetic absorbing material and was hard-mounted between the skids under a Bell Jet Ranger 206B body. The purpose of this survey was to profile the river bottom, hence the use of a lower frequency which gives far less attenuation per meter (see Figure 9, discussed below) than does 500 MHz. In the figure, the ice surface (indicated by an arrow) response is barely visible among the coherent noise of resonances between helicopter and antenna. Consequently, metallically shielded antennas slung beneath a helicopter have received experimental attention and will be discussed next.

Fresh Warm Water

Penetration of water by remote sensing techniques is required for applications such as dredging bathymetry surveys, and for inspection of bridge pier foundations which may have been improperly emplaced, damaged or which may have caused scouring. This is best done by sonar at the water surface, as its resolution is excellent both vertically and laterally. Radiowaves are also effective in freshwater and may be substituted where turbidity (which can block sound propagation) is high. The prohibitive attenuation rate cited above for cold water at 900 MHz vastly decreases as temperature rises and frequency decreases. Radiowaves are the only possibility for use in rapid, airborne surveys of freshwater bodies, because sound waves cannot penetrate the air-water interface. However, the reflectivity at the air-water interface is still a formidable obstacle to penetration as seen below.

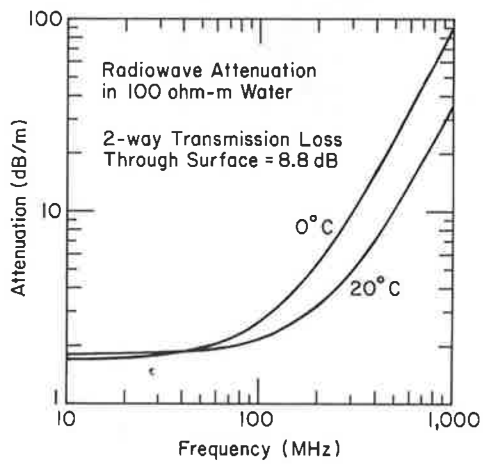

FIGURE 9 Attenuation rate of radiowaves in freshwater.

Figure 9 plots the attenuation rate of 100 MHz radiowaves in fresh water at two temperatures and a conductivity of 0.01 S/m (or 100 ohm-m resistivity; polluted rivers in industrial areas have values closer to 50 ohm-m). Both dielectric dispersion and conductivity contribute to the attenuation rate at this frequency, with dielectric dispersion dominating at cold temperatures. At 100 MHz the attenuation falls to a near-minimal 2 dB/m for warm water. An additional loss of 8.8 dB must be added to any theoretical determination of attenuation to account for losses upon two-way transmission through the air-water interface. Additional losses will occur upon reflection from the bottom. The wavelength in warm water at this frequency is only about 33 cm, so that good resolution of bottom features is possible.

Figure 10 demonstrates the capabilities of surface radar in a fluvial environment. The survey profiled scour holes by the piers of the Buckley Bridge in Hartford, Connecticut; numbered vertical demarcations indicate the positions of the piers. The detail, even of the subsurface sedimentation, nearly rivals the quality of sonar profiles. Unfortunately, this profile was made with a partially submerged, high power antenna towed beside a small boat. The sob-

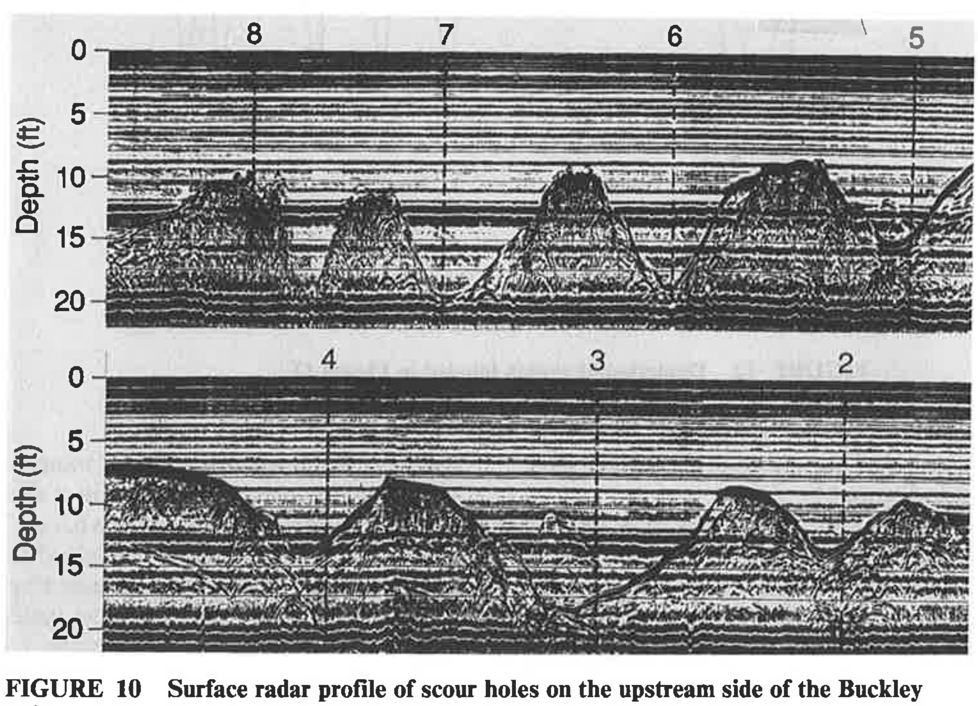

FIGURE 10 Surface radar profile of scour holes on the upstream side of the Buckley Bridge.

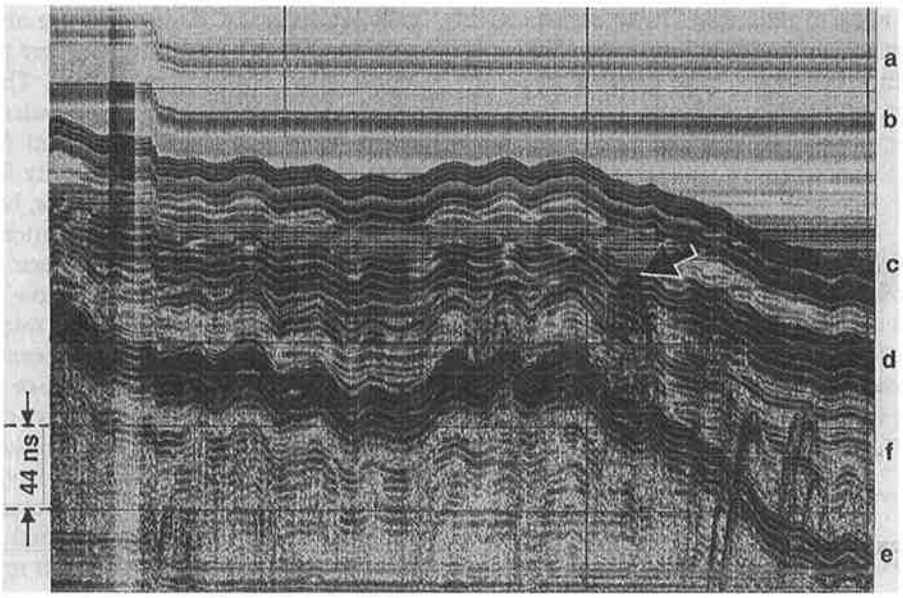

FIGURE 11 Helicopter survey of a shallow reservoir using antennas in a cargo net.

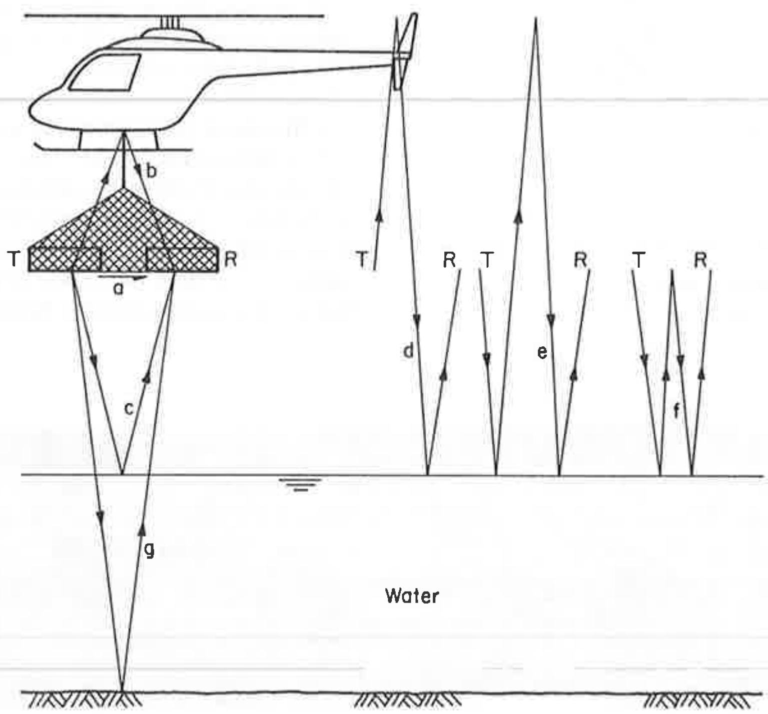

FIGURE 12 Depiction of events labeled in Figure 11.

ering reality of the status of our airborne subsurface river surveying is shown in Figure 11.

Figure 11 is a helicopter survey of part of a shallow reservoir near Hopkinton, New Hampshire, ranging up to 2.5 m depth and 0.0067 S/m conductivity. The reservoir is a flooded valley containing a now submerged concrete road. The antennas used were shielded, resistively loaded dipoles mounted in separate housings (transmit T and receive R in the figure) operating at a center frequency near 250 MHz and using a peak transmitter power of 0.8 kW. The antennas were carried in a sling 4 m below the helicopter and survey altitude was 6.8 m. The major events are labeled by letter and are explained in the depiction of Figure 12. The results are dominated by events c, d, and e, the latter two of which involve helicopter reflections, despite the shielding of the antennas. Event f is believed to be a multiple reflection between the antennas and the water. There is no perceivable bottom reflection which should occur 140–150 ns beneath the start of event c or about where event e is (event e was followed to the end of the reservoir at depths < 1 m but still remained at – 140 ns delay). However, at least the first hyperbolic reflection at the right of the record is due to the concrete roadway at 0.7 m depth while the other hyperbolas are at 1.5 to 1.8 m depth. Therefore, a very weak bottom reflection coefficient may have contributed to the lack of a bottom profile in this example.

SUMMARY AND RECOMMENDATIONS

Airborne short pulse radar is most successful in the following conditions:

(1) The ground surface is smooth and of low reflectivity; ice sheets and flat dry soils or bedrock exposures are ideal;
(2) Air speed and altitude are low; and
(3) The antennas are shielded.

Areas for further improvement include the following:

(1) Incorporation of a satellite-based positioning system for accurate reconstruction of flight lines.

(2) Fast digitization and storage of the analog data. A helicopter speed of 2 m/sec and a digitization rate of 25 ks/sec would produce 12.5 MB/km. Some units are now commercially available.

(3) Deconvolution software programs built into the system for rapid signal processing. The advantage of deconvolution was seen in Figure 7. Another approach is to use a pulse code modulation scheme that performs pulse compression by the cross-correlation of a transmitted pulse code with a stored, complementary code (*9*).

(4) Incorporation of video graphics display. The present paper chart method takes as long to display as does conducting the survey, and much information regarding the waveforms is lost.

(5) Development of more effective, low frequency, shielded antennas. Frequencies below 50 MHz are advantageous where penetration is as important as resolution, but antenna size and weight increase with decreasing frequency. Almost any size is manageable in a sling, but shielding causes a large increase in weight, especially for separate transmit and receive antennas needed for high-power work. A reasonable weight limit for a 4-seat helicopter would be 50 kg.

Alternatives to shielding are filtering, cross-polarization and circular polarization. Filtering out reverberations is common practice in seismic sub (water) bottom surveys where echoes between a water surface and bottom are clearly defined. In our case, however, there are many waveforms in the helicopter reflections and each would need its own filter design. Cross-polarization involves receiving at a polarization orthogonal to that transmitted. This eliminates reflections from flat surfaces, as only rough surfaces or volume inhomogeneities can cause polarization rotation. Consequently, radar echoes from flat river bottoms also would not be received. The most promising alternative is circular polarization. Water surface echoes will reverse the rotational sense of a circularly polarized wave, but the water bottom should not. Therefore, if an alternative receive mode is used to monitor the antenna height above the water surface, circular polarization may be used to monitor water depth. Broadband logarithmic spiral antennas excited by pulsed waveforms are currently receiving experimental attention.

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