MULTI-YEAR EXPERIENCE OF REMOTE SENSING OF ICE THICKNESS ON THE ST. LAWRENCE RIVER

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ABSTRACT

Clarkson University has conducted winter ice condition and hydraulic surveys for the St. Lawrence Seaway Development Corporation since the winter of 1977-1978.

Thickness of the main ice sheet cover and frazil ice accumulations (hanging dams) were measured using an impulse type radar. The radar system was carried in a Canadian Coast Guard helicopter flying approximately 10 feet (3 meters) above the ice surface on a flight path from Wilson Hill Island, Massena, New York to Cardinal, Ontario, Canada, a distance of about 24 miles (38 km).

The field calibration, data reduction, and ice thickness profile plotting of the radar data are presented. Examples of the ice thickness and frazil ice accumulations obtained from the radar data are presented and compared to ground truth measurements.

INTRODUCTION AND BACKGROUND

The reach of the St. Lawrence River in the vicinity of Ogden Island, Waddington, New York has presented unique problems for river regulations since the construction of the Seaway and Power Project. The ice and river flow conditions in this reach are of particular interest because of their impact upon extending the navigation season and hydro-power generation. The accumulation of frazil ice on the underside of ice cover causes regions of locally high energy loss in the river flow which in turn produces a decrease in the water surface elevation that is detrimental to both shipping and power generation. The requirements for extending the navigation season may conflict with the requirements for power generation. For example, power generation requires the ice cover to be formed quickly to minimize the area of open super-cooled water in which frazil ice is generated, but extending the shipping season would require that the ice cover formation be delayed.

The St. Lawrence Seaway Development Corporation (SLSDC) has funded ice condition surveys since the winter of 1975-76 to collect field data on ice growth and decay, development of mathematical models to predict the growth and decay of the ice cover, and models to predict the generation and accumulation of frazil ice under the main ice surface. Clarkson University conducted the winter ice condition surveys starting with the winter of

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1977-78; two prior winter surveys were conducted by the U.S. Army Cold Region Research and Engineering Laboratory (CRREL), Hanover, New Hampshire (Dean - 1977).

This paper reviews the techniques used for remote sensing of the ice thickness using an impulse radar system, related field measurements for calibration, data reduction and plotting of the ice thickness profile since the winter of 1977-78. The contents of this paper are based on the reports listed in the references and individual reports are not cited in the text of the paper.

Figure 1 is a map of a reach of the St. Lawrence River between Cardinal, Ontario, Canada and Wilson Hill Island, New York a distance of 24 miles (38 km) where most of the winter ice condition surveys have been conducted. Dredging for ship navigation and the construction of a control structure, Iroquois Dam, eliminated the river rapids in this reach during construction of the Seaway.

The initial ice cover for this reach is usually created by reducing the flow at Moses-Saunders Dam when two or three days of very cold weather with clear night skies are predicted. These weather conditions allow an ice cover to be formed nearly up to Iroquois dam. The open water that remains is a source of frazil ice generation when weather conditions for supercooling of the water exist. The frazil ice is flushed under the ice sheet and accumulates at various places in this reach of the river; sometimes to depths of 20 feet (6 m) or more in river depth of 60 feet (18 m). Large accumulations of frazil ice have occurred off Sparrowhead Point, between Leishman Point and Ogden Island and in the shipping channel on the north side of Ogden Island. These accumulations of frazil ice are not the same from one winter to the next and these accumulations change position during the winter ice season. An understanding of the formation, accumulation and decay of the frazil ice and main sheet ice cover on the hydraulics of this reach of the river are of vital importance to extending the navigation season, power generation, protection of the water and the aquatic environment.

REMOTE SENSING EQUIPMENT

The remote sensing equipment used was a broad band impulse radar system manufactured by Geophysical Survey Systems Incorporated, Hudson, New Hampshire (GSSI). The early surveys were conducted using a SIR system model 7 but was updated for the winter survey of 1980-81 with a model 4800. Figure 2 is a simplified block diagram of the components of the radar system model 7 which has the same components as the model 4800 except that a microprocessor was added to the control unit for digital filtering of the radar data. The graphic display has been replaced with a faster one and the analog tap recorder will be replaced with a digital tape recorder this year. A solid state power converter replaced the original rotating type power converter which provided AC power for the analog tape recorder and DC power for the radar controller. The digital tape recorder will operate on DC power.

The field surveys, surface or airborne, required only the radar control unit, tape recorder, power converter and antenna. For the airborne surveys the 24v DC power available in the helicopter was directly connected to the power converter. The airboat engine batteries were connected to the power converter for surface surveys.

The control unit operates on a 50 kHz signal which triggers a fast impulse generator. The radiated pulse by the antenna has a center frequency of 250 MHz and a pulse width of 3 ns. The depth of penetration of the pulse into the ice, frazil and water depends on the distribution of frequencies in the pulse and the resolution (the distance between interfaces) depends on the pulse width. A short pulse width has good resolution but less penetration than a wider pulse which would have better penetration but poorer resolution of interfaces. Each pulse contains a wide spectrum of frequencies, the lower frequencies having a good penetration and the higher frequencies providing good resolution. A portion of the radiated electromagnetic pulse penetrates into the material being scanned, in this case air, ice sheet, frazil and water. Analogous to principles of reflection and refraction in optics, some of the electromagnetic pulse is reflected from the air-ice interface and some is refracted into the ice sheet as shown in Figure 3. At an ice-water or ice-frazil interface the portion of pulse refracted into the ice sheet is reflected back

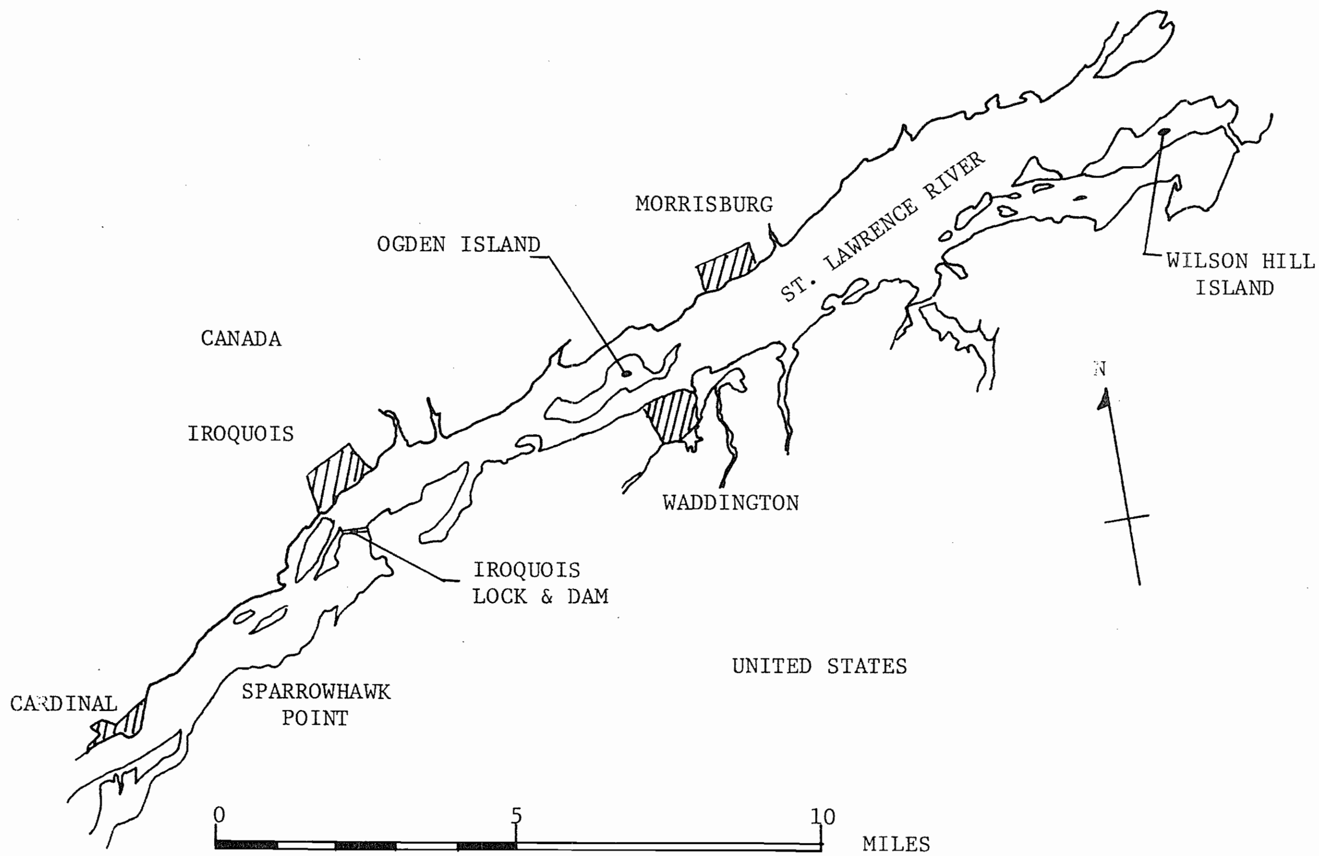

Figure 1. Project Area for Winter Ice Condition Surveys between Cardianl, Ontario and Wilson Hill Island, New York.

into the ice sheet and some is refracted through the ice-water or ice-frazil interface. The process continues until the energy of the pulse is dissipated. The portion of the pulse reflected from air-ice interface is detected by an antenna. Likewise a portion of the pulse that was refracted into the ice sheet and reflected from ice-water interface also penetrates back up through the ice-air interface and is detected by the antenna. The portions of the electromagnetic pulse that are reflected back from the various interfaces and detected by the antenna re recorded on the magnetic tape. Various filtering programs are used to remove background signals and reflections that made identification of the weak interface of frazil ice and water difficult to observe on the graphic display.

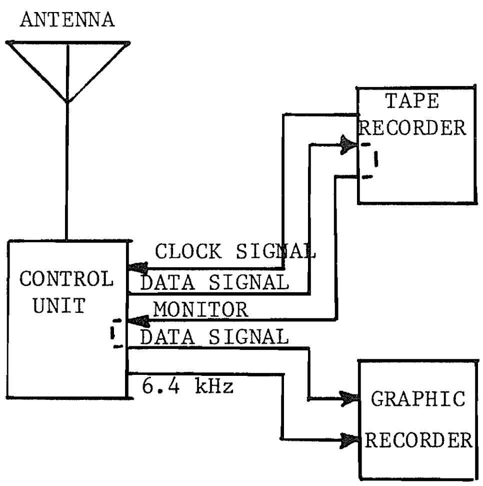

Figure 2. Schematic Block Diagram of Radar System.

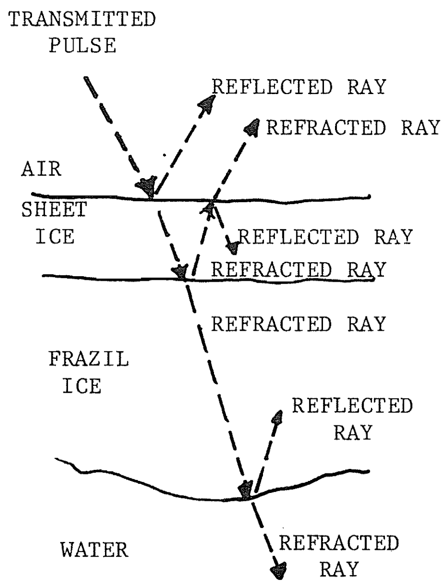

Figure 3. Schematic of Radar Pulse Reflections and Refractions at Material Interfaces.

The reflected electromagnetic pulses are recorded in real time on the magnetic tape and are a measure of the time taken by the reflected portion of the pulses to travel from one interface to the next. The distance between the interfaces can be calculated if the velocity of travel of the electromagnetic wave in the various layers of material is known. The velocity will depend primarily on the conductivity and the dielectric constant of the materials penetrated by the pulse. The depth can be computed from

$$D = \frac{Ct}{2\sqrt{\varepsilon_r}} = \frac{V_m t}{2}$$

where
- D = depth in feet
- C = velocity of light = 3×10^8 meters/sec $\approx$ 1 foot/nanosecond
- t = time of pulse travel in nanoseconds
- ε_r = relative dielectric constant of material
- $V_m = \frac{C}{\sqrt{\varepsilon_r}}$ = velocity of propagation in material

The velocity of the pulse in a given material depends on the dielectric constant. The reflection is caused by the change in the pulse velocity in the material on either side of an interface. The greater the change in the dielectric constant the greater the change in velocity and the stronger will be the reflection (Morey - 1974). Table 1 lists typical average values for round trip impulse rates for selected materials (Ulriksen - 1982).

Table 1. Average Round Trip Propagation Rates, Conductives and Dielectric Constants

Material	Impulse Rate ns/ft (ns/m)	Conductivity mholm	Dielectric Constants
Air	2 (6.6)	0	1
Fresh Water	18 (59.1)	10^{-4} to $3x10^{-12}$	81
Fresh Water Ice	4 (13.1)	10^{-4} to 10^{-2}	4
Frazil Ice	11 (36.1)	-	-
Snow, firm	2.4(7.9)	10^{-6} to 10^{-5}	1.4
Sea Water	18 (59)	4 to 5	81 to 88
Sea Water Ice	5 (16.4)	10^{-2} to 10^{-1}	4 to 8

Because most real materials contain water which has a very significant influence on the conductivity and the dielectric constant, ground truth data are used to determine the velocity and thus the distance between interfaces. The velocity of the pulse will change as the physical structure of the ice changes from initial freeze-up to break-up. Therefore ground truth data was necessary for each airborne survey.

The depth of scan can be varied up to 400 ns. A shallow scan was 20 to 40 ns and a deep scan was 80 to 160 ns. These times depend on the dielect constant and conductivity properties of the materials being penetrated by the electromagnetic pulse of the radar system and the depth of penetration desired.

Data processing, reduction and ice thickness profile plotting were done at Clarkson University. No real time data processing was done while conducting the remote sensing surveys in the field.

RADAR SURVEYS

Surface and airborne radar surveys were conducted, but the bulk of the surveys were airborne.

Surface Surveys: Surface surveys were conducted by towing the antenna on a wooden sled about 100 feet behind an airboat. The radar control unit and tape recorder were carried in the airboat connected to the antenna by an electrical cable. The antenna could be towed at 4 to 5 mph, but on rough ice or snow surfaces the sled with the antenna would flip over and sometimes damage the cable connection to the antenna. The very cold weather and added wind chill due to the propeller draft made for very uncomfortable working conditions.

Airborne Surveys: The airborne surveys were conducted using a Jet Ranger class of helicopter flown by Canadian Coast Guard pilots. Initially the antenna was slung by cables about 10 feet (3 m) below the helicopter, but this created problems for the pilot when making turning maneuvers. The antenna was next lashed to the cargo frame with 12 inches (0.3 m) of microwave absorbing materials between the antenna and the cargo frame of the helicopter to reduce reflections from the helicopter. The antenna was about 4 inches (0.1 m) above the skids of the helicopter as shown in Figure 4.

One survey flight usually consisted of a shallow and a deep radar scan between Cardinal, Ontario and Wilson Hill Island along approximately the center of the shipping channel, the south channel around Ogden Island, flights along holes for ground truth calibration data and along predetermined paths over hanging dams (large frazil ice accumulation) laid out by surveying crews that collected the ground truth data.

Figure 4. Antenna Mounted Beneath Helicopter.

The helicopter was flown about 10 feet (3 meters) above the ice surface into the wind, if possible, at an air speed of 30 to 40 mph (50 to 66 km/s). At this low altitude the pilot had to use the shadow of the helicopter on the ice surface to judge his altitude. Generally he held the altitude within a couple of feet (0.7 m). Adverse weather conditions, such as snow squalls, lack of shadow on the ice surface or high cross winds to the flight path would terminate the airborne surveys. The control unit, tape recorder and power converter along with the radar system operator occupied the rear seat of the helicopter as shown in Figure 5. An assistant seated next to the pilot placed electronic marks (blips) on the magnetic tape to record the flight path position related to ground control features, such as fixed shipping navigation aids or fixed structures on the shore of the river. These marks were necessary for the plotting of the ice thickness profile along the river.

Slow airborne flights with an airspeed of about 5 mph (8 km/s) were conducted for short distances in selected areas to collect calibration data and in areas of heavy accumulation of frazil ice (hanging dams).

About one half hour of preflight time was required to load the helicopter, three hours of engine time for the radar survey and one quarter hour to unload the helicopter. During a flight it took about 10 minutes to adjust the radar controls for a survey by the radar system operator using a tape recording spped of 15 inches per second (0.38 m/s), one of three channels available on the tape for recording lasted about 20 minutes. The helicopter would land while the tape was rewound for recording on the next channel. There are four channels on a tape, but one channel is reserved for a prerecorded timing signal for synchronizing recorded data. Recording the timing signal was done prior to the survey flights and took about one half hour per tape.

The airborne surveys were conducted at 51.2 scans per second. For an air speed of 40 mph (66 km/hr) one radar scan was obtained about every one foot (0.3 m) along the flight path.

Ground Truth Data

Field data was obtained by drilling holes through the ice sheet to measure its thickness at preselected sites for calibration of the radar data. Approximately 10 to 15 holes

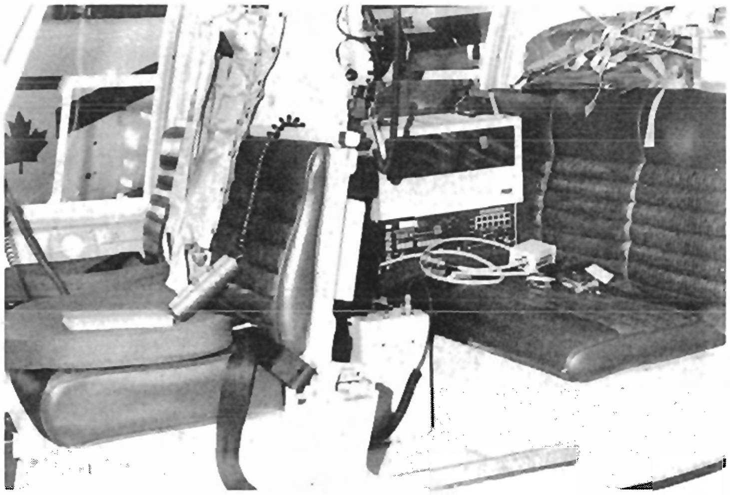

Figure 5. Radar Equipment in Rear Seat of Helicopter

were used for calibration of the radar data.

Crews working on the ice surface obtained field data on the ice sheet thickness, frazil ice thickness, depth to the bottom of the river using sonar, and water velocities. (The depth of river and water velocity were for other studies associated with the winter ice condition surveys.)

DATA PROCESSING

The remotely sensed data of the ice survey was recorded as a analog signal on magnetic recording tape. The tapes were returned to Clarkson for processing, graphic display and plotting. The processing of data was very time consuming because the tapes had to be played back for signal processing sixteen times slower, 15/16 inches per second, (0.02 m/s) than the recording speed to extract the maximum amount of information. If only the main ice thickness was required and not the depth of frazil ice, the data was processed at 3 3/4 inches per second (0.09 m/s) which reduced the time for processing from 6 hours to about 2 hours per channel of tape.

The microprocessor came with programs furnished by the manufacturer with selectable filtering characteristics for the removal of background signals to enhance the identification of the weak interfaces, such as the frazil ice and water, and was done at the slowest tape speed of 15/16 inches per second (0.02 m/s). New filter programs are currently available on EPROM chips from the equipment manufacturer to plug into the circuit boards of the microprocessor which improve the detection of weak interfaces.

The up and down motion of the helicopter adds to the difficulty of identifying the weak frazil ice and water interface. Removal of the helicopter motion by the modification of the program during data processing is currently being done. Each scan has 240 samples and the beginning of each scan is controleed by a clock signal. By identifying the samples in the scan associated with air-ice interface, a high energy signal reflection, program for plotting the scans on the graphic display can be modified to start printing with the energy level identified with the air-ice interface and thereby remove the vertical motion of the helicopter.

Graphic Display of the Radar Data

A microcomputer has two programs such as those furnished by the manufacturer of the radar system for the removal of background signals, reflections from the helicopter, and this enhances the rapidly changing data compared to slowly changing data with depth. These programs were stored on one kilobyte chips (EPROM). The first program had two different algorithms for background signal removal. One algorithm evaluated a running average using past and current values of the radar scans and could be run in real time. The second algorithm evaluated an ensemble average using present and future data and could not be run in real time. The ensemble average is determined during one pass of the data through the microcomputer and then subracting this average on the next pass of the data through the microcomputer. The second program required replacing the I/O board and chip for the first program with another I/O board and chip (EPROM) containing the second program. The program allowed the selection of various combinations of high and low band filters for the removal of constant or slowly varying background signals.

Figure 6 shows a portion of the unprocessed data from a shallow survey with the various interfaces and reflections noted for a survey of 2 March 1982. The blip at the top of the figure is for the landmark channel navigation aid #58. A series of vertical lines spaced at 1-inch intervals between landmarks were drawn on the graphic output. These vertical lines provided the horizontal distance along the direction of flight measured from Cardinal, Ontario, Canada. It was assumed the helicopter air speed was constant between the landmarks. This was not correct, but the error in the assumption had very little practical affect on the plotting accuracy of the sheet ice profile.

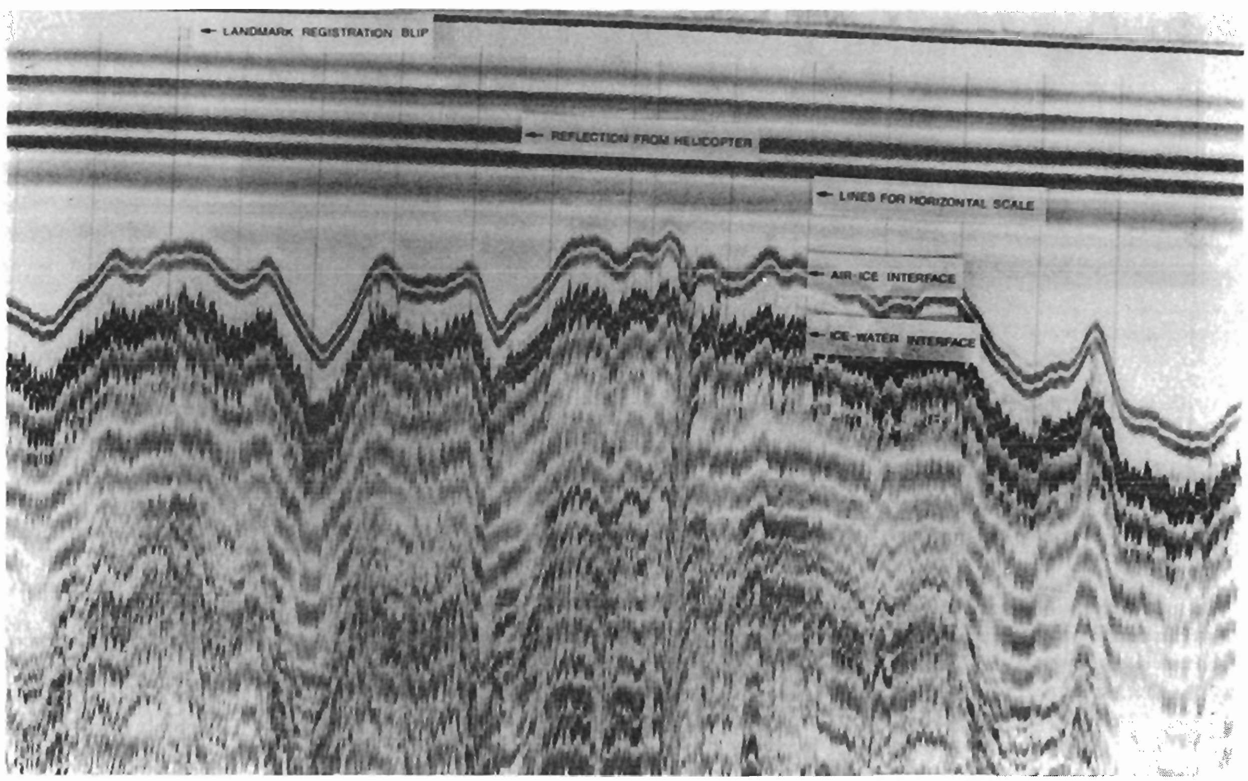

Figure 6. Unprocessed Graphic Display of Radar Data

Figure 7 shows the transition from unprocessed to processed data (left to right) using the first program with the running average algorithm. A time delay due to the time required to compute the average for number of scans specified by the bandwidth selected the time delay causes a small vertical shift downward of the processed data. Notice that the constant background signal due to reflections from the helicopter has been removed. The portion of the graphical display is from a survey made on 2/5/81.

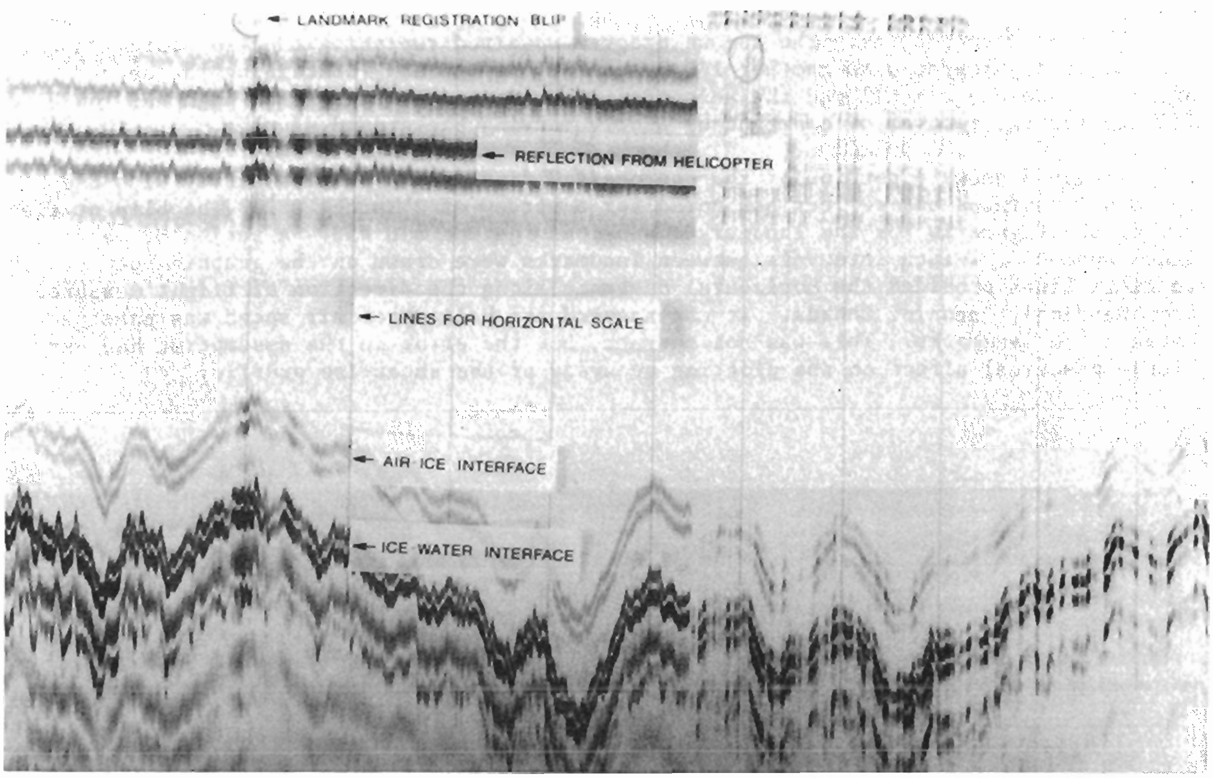

Figure 7. Transition from Unprocessed to Processed Data

CALIBRATION OF RADAR DATA

The distance between interfaces on the graphics display is the time required for the radar pulse to make a round trip between the interfaces. A 10 ns calibration signal is recorded at the beginning of each survey for the range, the depth of signal penetration in ns preselected by the radar operator. The 10 ns calibration on the graphic display was a series of bands, the distance between each band equalled 10 ns. By scaling the distance between air-ice and ice-water interface, the round trip travel time for the ice sheet thickness was determined. The measured ice sheet thickness from ground truth data divided into the signal travel time gave the rate of propagation of the impulse signal. An average for all the ground truth data on the day of airborne survey was applied to the entire length of the survey. Table 2 shows a typical computation for the rate of propagation on the signal pulse on 2/12/81. Table 3 shows the rate of propagation for each airborne survey for two winters.

Ice Thickness Profile Plotting

Using the pulse propagation rate, the ice sheet thickness was computed for approxi-

Table 2 Measured and Computed Ice Thickness on 2/12/81

(1) Station Number	(2) Measured Ice Thickness (in.)	(3) Distance Between Reflections (in.)	(4) Time Between Reflections (ns)	(5) Round Trip Propagation Rate (ns/ft)	Scan: Shallow Output Calibration 3.34 (ns/in)
1	15	1.12	3.74	2.99	
2	13	1.10	3.67	3.39	
3	20.5	1.75	5.85	3.42	$\bar{x}$: 3.13(ns/ft)
4	21	1.96	6.55	3.74	s: 0.372
5	28	2.22	7.41	3.18	
6	19	1.32	4.41	2.78	
7	29	2.32	7.75	3.21	
8	21	1.82	6.08	3.47	
9	22.5	1.47	4.91	2.62	
10	25	1.66	5.54	2.66	
11	20	1.47	4.91	2.95	
12	20	1.76	5.88	3.53	
13	17	1.14	3.81	2.69	

Column (#)
(1) South channel Ogden Island Reach, South to North
(2) Ground Measurement by Atlantic Testing Laboratory
(3) Measured on Radar Output
(4) Computed from column (3) with Output Calibration. (Output Cal. x (3)) = (4)
(5) Computed from column (2) and (4), $\left((4) \div \frac{(2)}{12(\text{in/ft})} \right) = (5)$

Table 3. Average Round Trip Propagation Rate for Sheet Ice

Date	Rate ns/ft (ns/m)	Date	Rate ns/ft (ns/m)
1/15/81	4.05 (13.3)	1/21/82	3.68 (12.1)
1/22/81	-	1/29/82	3.21 (10.5)
1/29/81	3.79 (12.4)	2/2/82	3.45 (11.3)
2/5/81	3.68 (12.1)	2/16/82	3.61 (11.8)
2/12/81	3.13 (10.3)	2/24/82	3.49 (11.4)
2/19/81	4.29 (14.1)	3/2/82	3.52 (11.5)
		3/16/82	3.47 (11.4)
		3/23/82	3.62 (11.9)

mately equal spaced intervals along the flight path of the survey. The data consisted of paired values, the distance from Cardinal and the ice thickness. These data were entered as separate files for each survey in a computer and the profile plotted as shown in Figure 8. The dashed line is the ice surface and the solid line is the bottom of the ice. The very jagged line for the bottom of the ice is due to the plotting of over 300 points along the horizontal axis which represents about 24 miles (38 km). The sequence of ice thickness profiles shows the growth and decay of the main ice sheet during the winter of 1982. The ice thickness grows very rapidly at the beginning and changes only slightly during the most of the ice season and decays very quickly at the end of the ice season. It should be noted that the profiles are for a very cold winter. There was one winter without an ice cover in this reach of the river and other winters in which the ice cover lasted only until the end of February.

Hanging Ice Dams

An important activity of the winter ice condition surveys was the collection of data on the location, thickness and distribution of large frazil ice accumulations, called haning ice dams. The location and profile of hanging dams by remote sensing with an impulse radar system was one of the major objectives of the winter ice surveys for SLSDC.

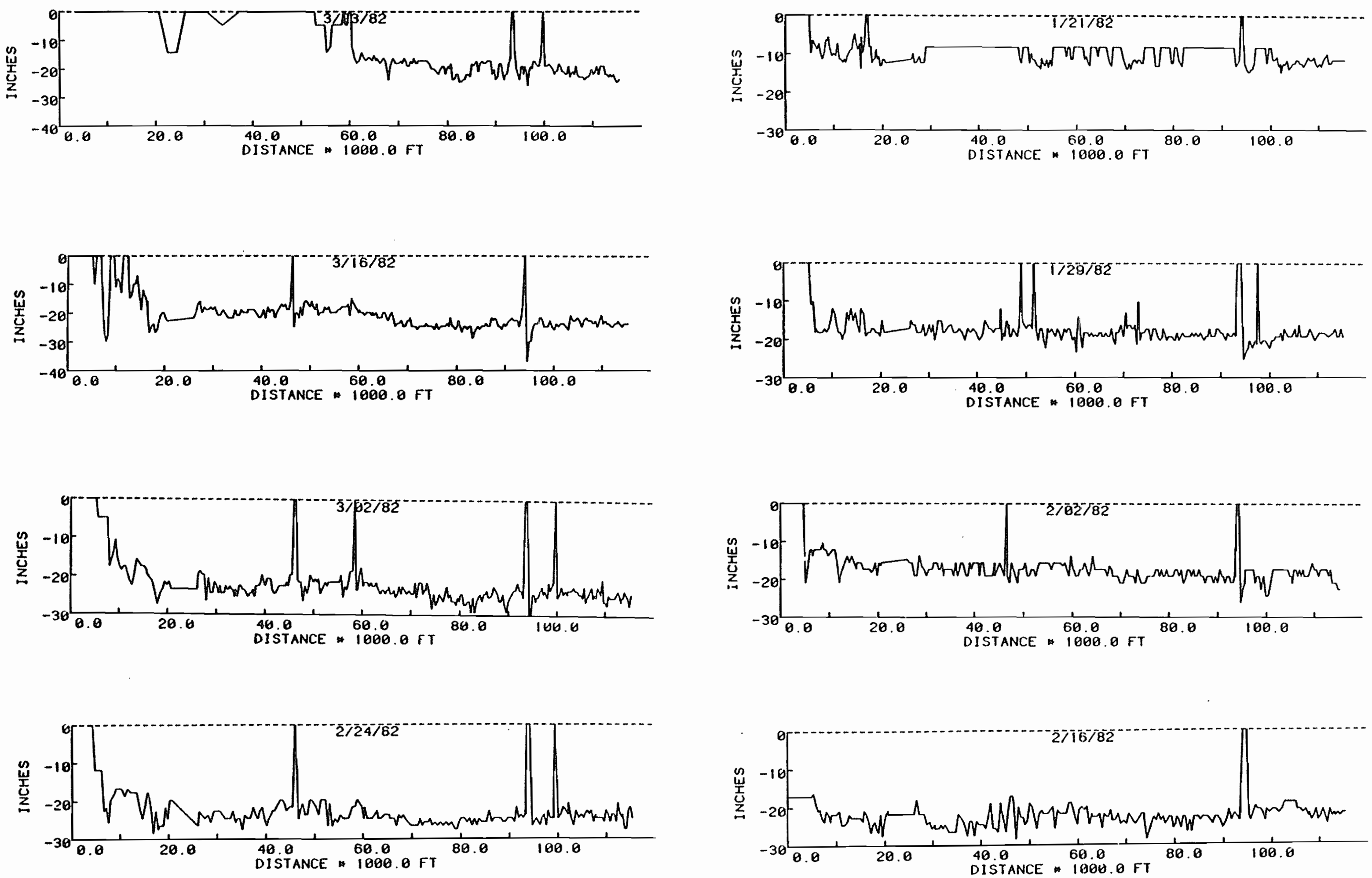

Figure 8. Plot of Ice Sheet Thickness Profile for Winter of 1981-82

Frazil has the consistency of slush, in fact the term snow slush or slush ice is used by some people instead of the term frazil. It is a very sticky material and adheres strongly, for example to trash racks in power intake structures. The frazil is a mixture of ice particles and water, the composition can vary from 30 to 60% or more of water. Usually the frazil is denser or compacted more near the bottom of the sheet ice and less dense near the frazil-ice water interface. The variation in water content results in a larger variation of the dielectric constant and conductivity in frazil ice than for the more homogeneous sheet ice. The rate of propagation of the impulse signal averages about 11 ns/foot (36 ns/m). Because frazil contains relatively large percentages of water, the interface between frazil and water does not produce a strong reflection. The weak reflecting interface is difficult to visually detect on the graphic display of the radar data even when using the programs for background signal removal. The vertical motion of the helicopter compounds the difficulty of identification.

Figure 9 shows the weak interfaces of a hanging dam for data processed with the second program that allows the selection of various high and low band filters for removal of constant or slowly varying background signals. In the graphical display the sloping frazil ice-water interfaces of the hanging ice dam can be seen. Figure 10 shows a complete profile of the hanging dam after considerable decay of its thickness has occurred. Figures 9 and 10 are from surveys in February and March of 1982, respectively.

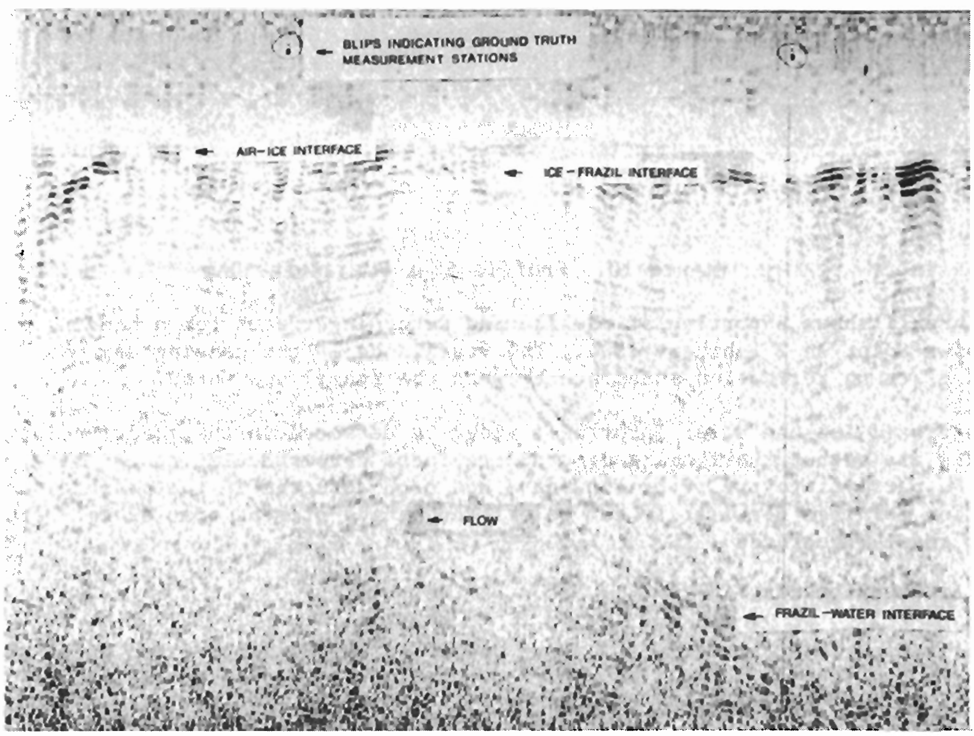

Figure 9. Frazil Ice and Water Interface of a Hanging Dam

Field measured thickness of the hanging dam used for calibration resulted in the computed rate of propagation of the impulse signal ranging from 6 to 10 ns/foot (19 to 33 ns/m). The smaller values were near the leading edge facing the river current and the largest value at the bottom surface near the middle of hanging dam.

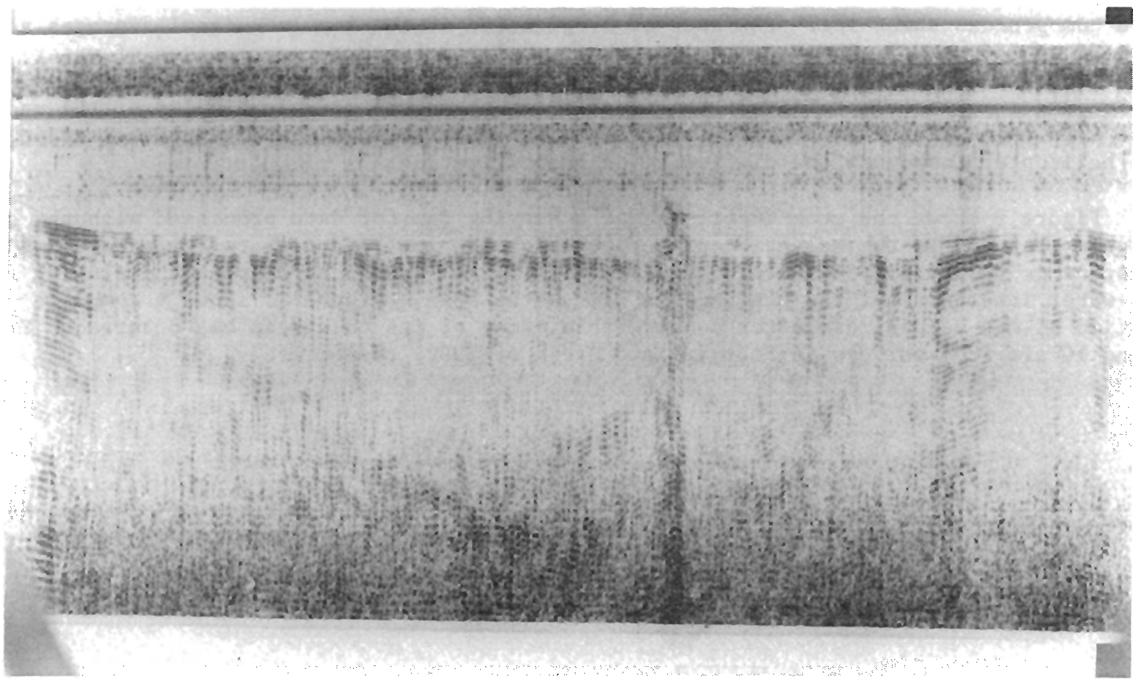

Figure 10. Profile of a Frazil Ice Dam

Figure 11 shows a portion of the ice and water interfaces for a hanging dam off Sparrowhawk Point on 2 February 1984. The frazil ice in the hanging dam was dense and thus provided a strong reflection interface between the frazil and water.

The frazil ice and water interfaces visually detected in the graphic display of the radar data are either the leading or trailing faces perpendicular to the river current. Interfaces parallel to the river flow have not been detected in the graphic displays. No explanation for this peculiarity can be offered at the present time except better filtering may show these interfaces.

COST OF AIRBORNE SURVEYS

The impulse radar system costs about $40,000. The helicopter and pilot cost about $500 per hour of engine time. The radar operator and assistant in helicopter cost $20 and $50 per hour. The ground truth data collection costs $50 per hour for a crew of two and the airboat costs $50 per hour. The data processing costs $50 per hour. For a survey that requires three hours of helicopter engine time, three hours for ground truth data collection and 24 man hours for processing and plotting the data, the cost would be about $3060 per three hour survey, or $1020 per hour exclusive of the investment for the equipment. The radar equipment can be leased or rented to reduce initial capitol investment.

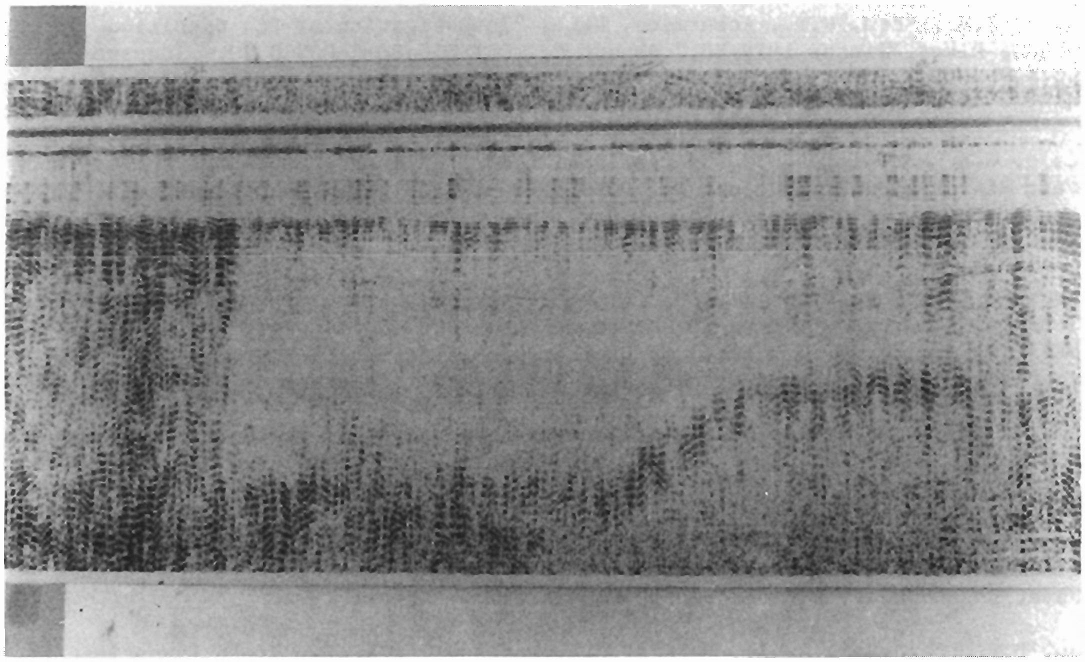

Figure 11. Portion of a Dense Frazil Ice Dam.

CONCLUSIONS

The impulse radar is an effective technology for obtaining a continuous profile of the sheet ice thickness from airborne surveys using a helicopter flying at 30 mph (48 km/hr). Long reaches of the river are limited only by flying conditions and pilot fatigue due to flying 10 feet (3 m) above the ice surface. Ground truth data collection can be done in 3 hours, assuming this data is valid for entire survey.

Processing data takes 6 to 12 times longer than the flying time, depending on speed at which the data is processed.

The plotting of the ice profile by computer is rapid once the ice thickness data from the graphic display has been computed. Ground truth measurements are necessary for calibration of each radar survey due to the changes in the dielectric constant and conductivity of the ice during the winter, particularly as the ice break-up time is approached.

Airborne radar surveys for detection of frazil ice accumulation appears to require slow flight speeds of 2 to 5 mph (3 to 8 km/m). Up to the present time only the up or down stream faces of the hanging dams have been detected in the processed data and not the faces parallel to the flow of the river.

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