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Remote Detection of Water Under Ice-covered Lakes on the North Slope of Alaska

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ABSTRACT. Results from using an impulse radar sounding system on the North Slope of Alaska to detect the existence of water under lake ice are presented. It was found that both lake ice thickness and depth of water under the ice could be determined when the radar antenna was either on the ice surface or airborne in a helicopter. The findings also revealed that the impulse radar sounding system could detect where lake ice was bottom-fast and where water existed under the ice cover.

INTRODUCTION

Lakes on the North Slope of Alaska are typically less than 2 m deep. As a result, by March or April most of them are solidly frozen to the bottom. By May, even lakes 2 m deep become solid ice. The few lakes deeper than 2 m in the Prudhoe Bay area are used extensively for a fresh water supply. However, because of drawdown during the winter, the water in these lakes is frequently depleted. A similar situation exists in the nearby rivers, where water is drawn from a few "deep" pools. Heavy pumping from these pools has in the past also depleted this water resource. Recently, use of this resource has been restricted by the State of Alaska, to maintain a water depth adequate to sustain the fish populations that over-winter in the deep pools.

During May 1976, the supply of water for consumption and housekeeping, as well as for fire-fighting, became very short in the area of Prudhoe Bay. The normal sources of water under the ice of the lakes and rivers were rapidly being exhausted. High demand, and therefore excessive pumping, was a cause as was the cold winter, which had increased the ice cover thickness and thereby reduced the quantity of water available. Many camps imposed restrictions on water use. New sources of water were also sought by the tedious drilling of holes through lake and river ice in hopes of locating a depression with a supply of potable water.

During this period, impulse radar was used near Prudhoe Bay to profile sea ice thickness (Kovacs, 1977, 1978). Because of the water shortage, it was decided to determine if airborne impulse radar could be used for locating water under lake ice. This report presents the findings of this study.

RADAR SYSTEM

The impulse radar system used produces a signal with a center frequency of approximately 100 MHz over a band from 50 to 150 MHz (at the -3db points). The equipment functions as an echo-sounding system which generates

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gaussian-shaped electromagnetic impulses of only a few nanoseconds duration. The electromagnetic energy is radiated from an antenna into the subsurface and is then reflected from one or more subsurfaces back to the antenna. The depth of penetration is dependent on the electrical characteristics of the subsurface, i.e. the dielectric constant or conductivity of the subsurface material. The impulse radar signal information collected in the field was stored on magnetic tape for later analysis and also displayed in real time on a graphic recorder, in a manner similar to a single-trace acoustic-profiling system used for the subbottom profiling of marine sediments. The primary quantity measured is the difference in travel time between various echoes. An example of an impulse signal received by the radar receiver and how multiple impulses are recorded for on-site field interpretation is shown in Figure 1. A more detailed description of the radar system has been given by Morey (1974).

For material whose dielectric constant (ϵ_r) is known, the velocity (V) of the transmitted electromagnetic signal can be calculated by:

$$V = \frac{c}{\sqrt{\epsilon_r}} \tag{1}$$

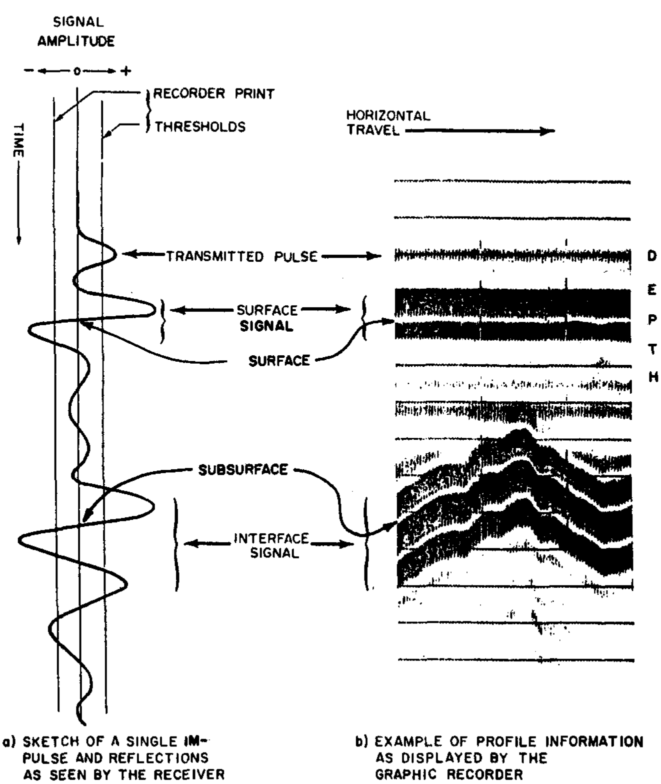

FIG. 1. An example of the radar impulse signal versus time and its equivalent real time graphic recorder display.

where c = velocity of electromagnetic signal in air (approximately 3 x 10^8 m/s). Representative dielectric constants at 100 MHz for fresh water and freshwater lake ice are 81 and 3.2 respectively.

Because the two-way travel time of the impulse radar signal from the ice surface to the ice bottom and back to the surface can be measured, it is therefore possible to determine the ice thickness from:

$$D = V\frac{t_d}{2} \quad (2)$$

where t_d = travel time from the surface to the subsurface interface and back.

FIELD STUDIES

There is no doubt that impulse radar can profile the thickness of freshwater ice. For example, this system was used as early as 1971 to measure sea ice and lake ice thickness (Bertram et al., 1972). More recently, the radar system was used to determine the thickness of river ice, frazil ice accumulations and the contour of the river bottom (Annan and Davis, 1977a, b; Dean, 1977) and the thickness of glacial ice and snow (Kovacs and Gow, 1975, 1977a, b; Kovacs, 1977).

An example of the impulse radar data displayed on a graphic recorder during sounding from the surface of lake ice is shown in Figures 2 and 3. The profiling was accomplished in 1974.

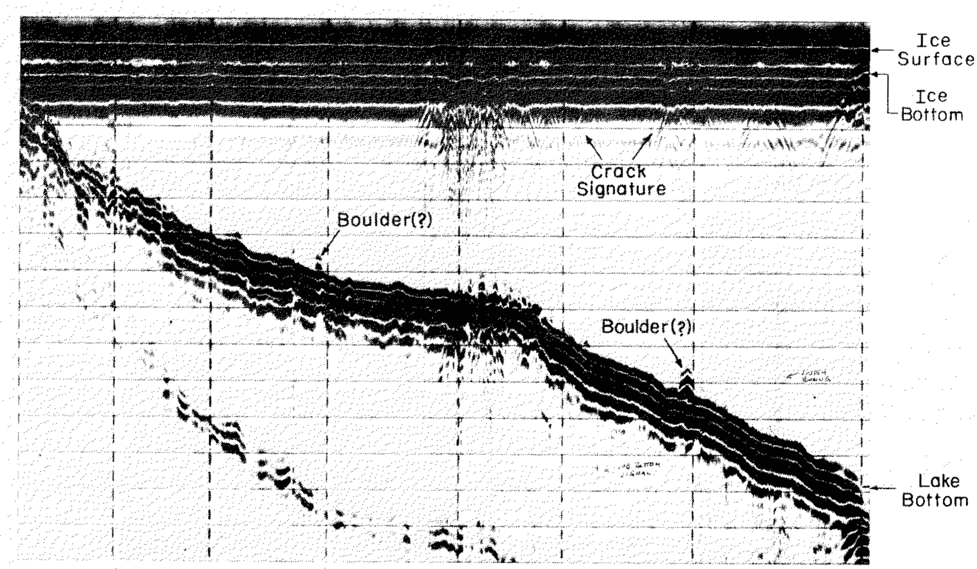

FIG. 2. Radar sounding data taken from the ice surface on Canaan Street Lake, Canaan, New Hampshire. The record shows interfaces and other detail typically obtained during impulse radar profiling on freshwater ice. The distance between vertical event marks is 20 m.

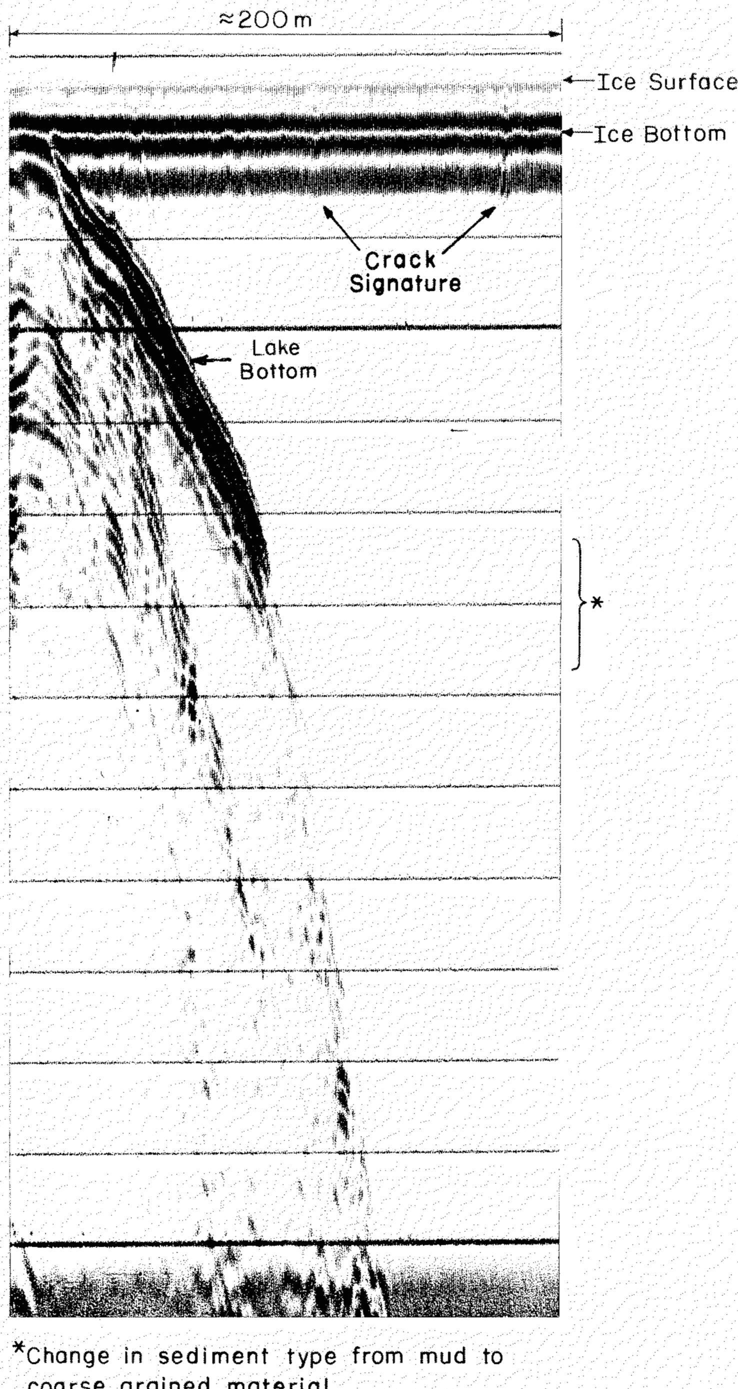

FIG. 3. Radar sounding data taken during a profile run with an elevated antenna on Post Pond, Lyme, New Hampshire.

Figure 2 was obtained by pulling the radar antenna across the ice surface of Canaan Street Lake, Canaan, N.H. Figure 3 was obtained by moving an elevated antenna across the surface of Post Pond in Lyme, N.H. The time between horizontal scan lines in Figures 2 and 3 is 15 ns. Therefore, from equations 1 and 2, the distance between scan lines within the water column is 0.25 m. The top and bottom of the ice can be seen in the record. The thickness of the ice in Figure 2 was 0.64 m. The record also shows the lake bottom relief and what may be several of the many large boulders known to rest on the bottom of the lake. The thickness of the ice in Figure 3 was 0.74 m.

The record in Figure 3 is important as it illustrates that the radar reflection signal strength is greater at the ice/water interface, as indicated by the darker print contrast, that at the air/ice interface. This is because the electromagnetic signal power reflection coefficient is lower at the air/ice interface than at the ice/water interface since there is a larger difference in the dielectric constant between ice and water than between air and ice. The power reflection coefficient at the air/ice interface ($R_{a\text{-}i}$) can be determined by:

$$R_{a\text{-}i} = \left[\frac{\sqrt{\epsilon_2} - \sqrt{\epsilon_1}}{\sqrt{\epsilon_2} + \sqrt{\epsilon_1}}\right]^2 \tag{3}$$

where ϵ_1 = dielectric constant of air and ϵ_2 = dielectric constant of ice surface. Since ϵ_1 is the dielectric constant of air and is equal to 1 and ϵ_2 is the dielectric constant of the ice surface, taken to be 3.2, then $R_{a\text{-}i}$ is 0.08. Similarly, the power reflection coefficient at the ice/water interface ($R_{i\text{-}w}$) can be determined by:

$$R_{i\text{-}w} = \left[\frac{\sqrt{\epsilon_3} - \sqrt{\epsilon_2}}{\sqrt{\epsilon_3} + \sqrt{\epsilon_2}}\right]^2 \tag{4}$$

where ϵ_3 = dielectric constant of water.

Assuming 3.2 for ϵ_2 and 81 for ϵ_3, then $R_{i\text{-}w}$ is 0.45. The power transmission coefficient (T) at the ice surface is:

$$T = \left[1 - \sqrt{R_{a\text{-}i}}\right]^2 = 0.50 \tag{5}$$

The signal power returning to the antenna from the ice bottom is determined by the total power reflection coefficient (R_T) from:

$$R_T = \left[T \cdot \sqrt{R_{i\text{-}w}} \cdot T\right]^2 = 0.11 \tag{6}$$

Therefore, the signal power reflected from the ice bottom is at least 50% greater than that reflected from the ice surface. Ice surface roughness or a snow cover will modify these values, making the return from the ice bottom proportionally larger.

A similar contrast should exist where freshwater ice is in contact with the lake bottom. This will be true if the bottom sediment is frozen where ϵ_r is approximately 4-8 or saturated silt or clay where ϵ_r is on the order of 8-12. Therefore, the strength of the reflected signal from the bottom of lake ice should be an indicator of whether the ice is in contact with water or soil.

ALASKA FIELD STUDY

During the spring of 1976, Atlantic-Richfield Co. (ARCO) was one of the very few companies in the Prudhoe Bay area that did not experience a water shortage, because in 1974 ARCO increased the depth of Webster Lake (Fig. 4) to create a storage reservoir with a capacity of 6 million barrels (9.5×10^5 m^3) of water (Fig. 5). It was estimated that with a 2-m-thick ice cover, the lake would yield approximately 4 million barrels (1.5×10^4 m^3) of water. When full, the lake was approximately 5.5 m deep. A typical cross section of the lake is given in Figure 6. This cross section was taken on 7 June 1975 at the position given in Figure 5 and shows that the lake has relatively steep sides and a flat bottom.

On 6 April 1976, the water depth near the pump house intake was 4.54 m and the ice thickness 2.01 m.

A short profile run was made with the impulse radar antenna on the ice surface to ensure that the system was operating properly. Both the ice and lake bottom were detected as shown in Figure 7. The dark signal band below that of the ice bottom is due to double reflection of the impulse within the lake ice. The numerous horizontal bands on the record are system noise.

FIG. 4. The Atlantic Richfield Co. camp and runway complex is shown in the lower left and Webster Lake at center right. The ice cover shows the outline of Webster Lake before its boundary was changed during dredging and before the pumphouse was installed as shown in Figure 5.

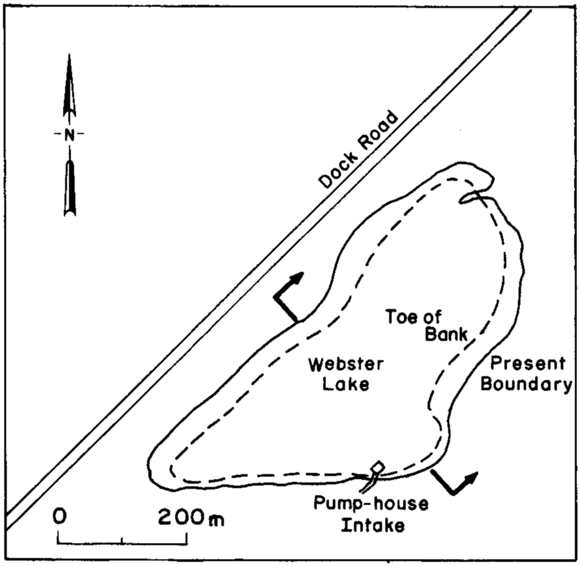

FIG. 5. Present outline of Webster Lake and location of cross section shown in Figure 6.

Next the radar system was installed in a helicopter and a profile flight made across Webster Lake. The flight was made down the long axis of the lake at about 15 knots. The altitude during the flight varied from approximately 18 to 25 m. The graphic record obtained during the flight is shown in Figure 8. The apparent variation in ice surface elevation is due to changes in aircraft elevation. Not only were the top and bottom surfaces of the lake ice detected but the lake bottom was too. The record also shows a double ice bottom reflection, indicative of the high reflection coefficient existing at the ice/water interface. The weak signal from the water/soil interface is not only due to the difference between the water/soil dielectric constants which affects the interface reflection coefficient but also to a reduction of signal strength associated with attenuation losses within the water column and to beam spreading losses.

Following this flight over Webster Lake, a profile flight was made over Big Lake along the flight path shown in Figure 9. The graphic record of the radar data collected during the flight is shown in Figure 10. At positions a, b, c and

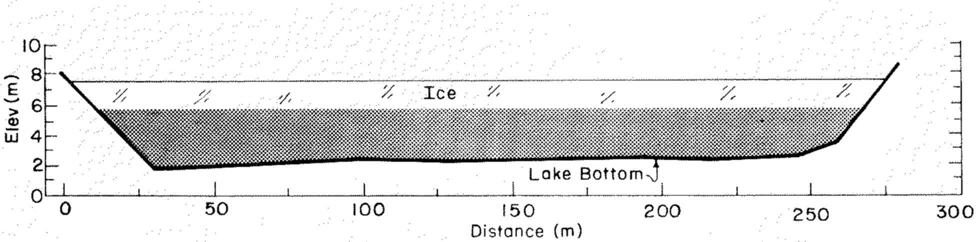

FIG. 6. Typical cross section of Webster Lake. Elevation is referenced to sea level.

d, the intensity of the reflection at the bottom of the ice is highest, as indicated by the darkness of the graphic trace. These high reflection "bright spot" areas indicate that water existed under the ice at these locations but that the remainder of the ice along the profile was probably in contact with the lake bottom. This was confirmed by drill hole measurements in the area of b in Figure 10 which revealed an ice thickness of 2.04 m and a water depth of approximately 4 cm at one site and 2.02 m of ice and 2 cm of water at another site. A drill hole measurement at a site south of position a in Figure 10 revealed an ice thickness of 1.63 m. Here the ice was in contact with the lake bottom.

The radar data in Figure 10 were analyzed to remove variations due to aircraft motion; the resulting cross section, shown in Figure 11, indicates that

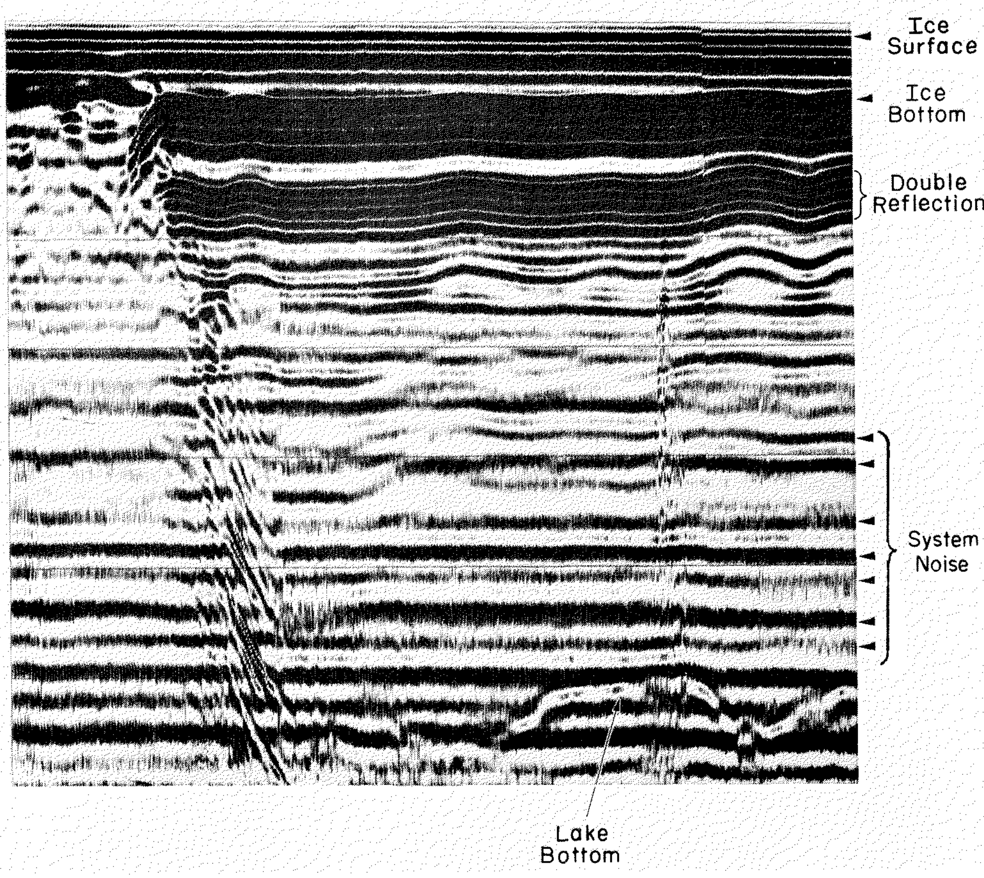

FIG. 7. Impulse radar data taken from the ice surface of Webster Lake. The sounding was made from the west side of the lake outward for about 75 m near the position of the cross section shown in Figure 6. The apparent increase in ice thickness at the shoreline is the result of the broad beam signal radiated by the antenna. The forward propagating portion of the radiated signal is first reflected from the lake shore ice interface before the antenna is over the interface. As the antenna moves closer to the interface the time of flight of the reflected signal decreases and this is displayed as a rising subsurface interface on the graphic record.

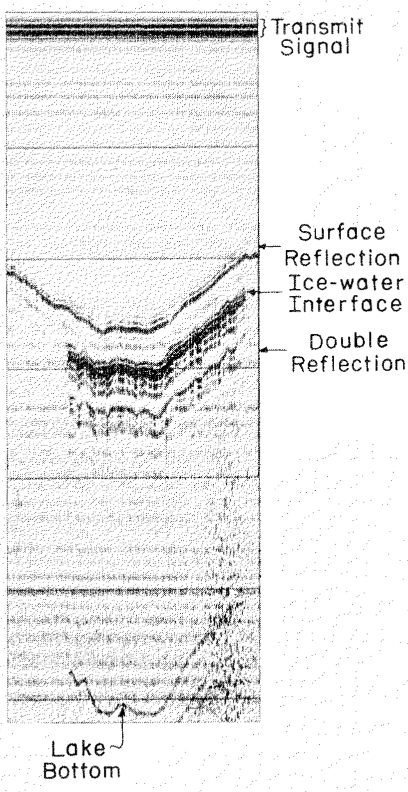

FIG. 8. Impulse radar record obtained during a helicopter sounding flight down the long axis of Webster Lake.

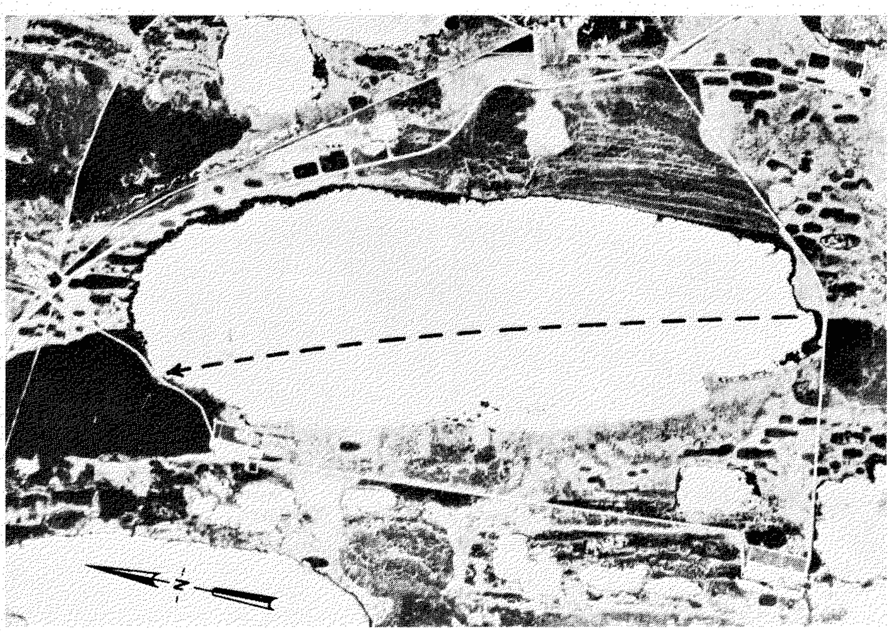

FIG. 9. Big Lake and the flight path taken during impulse radar sounding. The British Petroleum camp complex can be seen across the road on the east side of the lake.

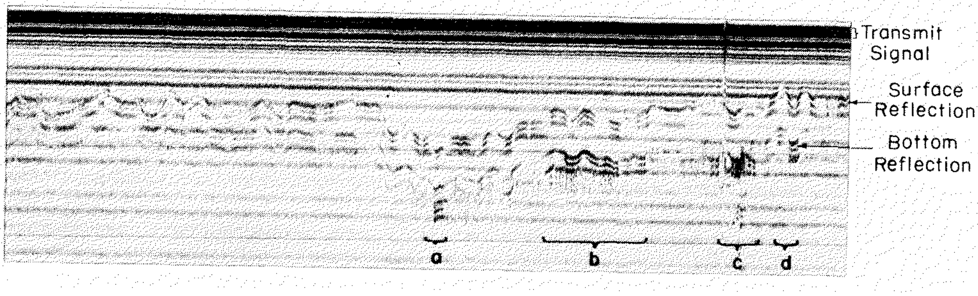

FIG. 10. Impulse radar record obtained along the helicopter sounding flight path shown in Figure 9 on Big Lake. The "bright spots," dark areas on the record, indicate potential sites where water still exists under the ice.

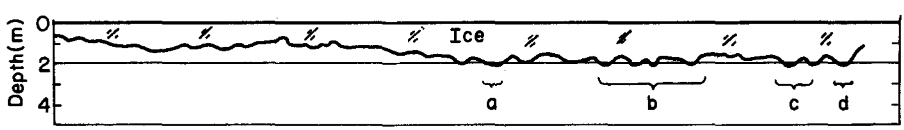

FIG. 11. Ice thickness cross section constructed by removing aircraft variation from the data in Figure 10 and calculating ice thickness from equations 1 and 2. Note that where the ice was > 2 m in thickness (maximum winter growth), the bottom reflection was also the strongest, indicating that free water existed under the ice cover at these locations.

the south end of the lake has thinner ice than the north end, in agreement with the drill hole measurements. Pools of water could probably be found in the areas of a, b, c and d where the ice is thickest and the radar signal from the ice bottom is the strongest indicating an ice/water interface.

SUMMARY

This study shows that impulse radar is capable of profiling lake ice thickness from the ice surface and from the air, and also the bottom of a lake with a 2-m ice cover floating on 4.5 m of water. It has also been determined that because of the significant difference between the radar signal reflection coefficient at an ice/water interface and that at an ice/soil interface, it is possible to determine where lake ice is bottom-fast and where free water exists under the ice, and that this may be accomplished remotely from the air. An airborne impulse radar system can therefore be used to determine rapidly potential sites of water under ice-covered lakes and rivers in late winter. This technique is especially important on the North Slope of Alaska where, historically, potable water becomes scarce during the winter.

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