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Applying GPR in Assessing the Ice Bridges, Ice Roads and Ice Platforms

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Ice covers over rivers and lakes have been used for decades as temporary working platforms in areas where site access is difficult or expensive. Designers for these temporary ice structures have relied mainly on ice thickness measurements to determine the load capacity for both moving and stationary loads. Ground Penetrating Radar (GPR) has been used since the 1990s to provide a continuous profile of ice thickness for freshwater ice covers. GPR is effective because of the contrast in dielectric properties between that of water and ice. However, most users focus on the ice thickness measurements and overlook the additional information contained within the GPR signal or its additional applications.

EBA has carried out hundreds of kilometers of GPR surveys of floating ice for a variety of projects in Canada. Our current practice is to use the GPR data to determine the minimum ice thickness and quality of the ice cover. Given the modest effort required to rerun the surveys with a low frequency antenna, we often collect bathymetric data with the GPR. Depending on the antenna frequency and water depth, GPR is able to detect the interface between water and the underlying solid (sediment/or rock). When the ice profiling data are combined with the bathymetric data, we're better able to discern floating ice, ground-fast ice, and frozen-unfrozen soil boundaries in shallow water. Such data sets provide the ice engineer with a clearer understanding of the ice structure and its variability over the project site.

We are now exploring the use of the ice dielectric data collected during the GPR profiling. The dielectric properties of the ice cover are affected by its air content and unfrozen water content and these also influence the mechanical properties of the ice. Measuring ice dielectrics could reveal additional information about the properties of the ice that affects its ability to support loads. Load assessment of the temporary ice structure can then be undertaken with additional confidence in ice quality.

1. Introduction

Floating ice covers on lakes (ice roads) and on rivers (ice bridges) are used in northern regions where road access is limited and traditional road or bridge construction is expensive. Most of these ice roads are essential in bringing in supplies, equipment and fuel to isolated communities. Resource exploitation and development also rely on winter roads that maximize the use of ice covers to provide economical means for re-supply and access of remote sites. Winter conditions (freezing temperatures, winds and snow cover) are typically sufficient to establish and grow freshwater ice covers that reach a thickness and duration for use as transportation routes. Because building an all season road is very costly and can have an environmental impact on the sensitive tundra that would be hard to eliminate, using ice covers over water bodies is often the preferred method of transportation in the Canadian north.

Working and travelling over floating ice covers should be undertaken as a planned activity that recognizes and reasonably addresses the hazards associated with the bearing capacity of the ice cover (Alberta 2009). The consequences of ice breakthrough failure have been documented by the Canadian Red Cross (2006) who found there were 447 deaths associated with activities on ice between 1991 and 2000. Severe environmental damage to water bodies can also result given the types of cargos being transported. Alberta (2009) uses a hazard management approach to ice cover safety. Hazards are identified and assessed in terms of consequence and risk. If the hazard cannot be eliminated, then a variety of engineering, administrative and PPE controls are implemented to reduce the risk to acceptable levels.

The controls for reducing the risk of breakthrough failure are ice road design, ice monitoring, ice road maintenance and rules of the road. Alberta (2009) discusses the risk management approach which emphasizes the interdependence of the design, monitoring, maintenance and administrative controls. For most ice road projects, design of the ice roads is limited to determining the minimum ice thickness required to support the planned load. Alberta (2009) presents ice capacity charts which provide a range of ice thickness based on the level of risk and the extent of the risk management controls the user is prepared to implement. While maintenance and administrative controls have a role in reducing the risk of breakthrough, ice monitoring (ice thickness measurements and ice quality observations) is the critical component in determining if the ice meets design requirements.

Two methods have traditionally been employed to measure ice thickness. One is augering a hole and simply measuring the ice thickness directly. Ice auger measurements can adequately characterize the ice thickness over small areas as long as the operator follows an auger spacing plan and records the measurements systematically (Alberta 2009). However, this process becomes impractical and time consuming once you evaluate ice roads over kilometers in length or over areas with highly variable ice covers. Ground Penetrating Radar (GPR) has several ways to address the disadvantages of ice auger measurements.

EBA's experience with GPR ice profiling it that it is a rapid means to assess the ice thickness over long ice roads or over large ice pads with a variety of vehicles (snowmobiles, Hagglund low ground pressure, pickup trucks). GPR data is readily geo-referenced when using differentially corrected GPS. Data processing routines allow us to rapidly analyze kilometers of ice profiling data, provide statistics or provide figures showing ice thickness against vehicle chainage or UTM coordinates. GPR data can also be collected in grids to provide contours of ice thickness in areas where there's a need to locate thin ice conditions. Calibrations of GPR equipment are regularly conducted in the field.

GPR can also be used to collect bathymetry. Bathymetry, or lakebed topography, can affect the carrying capacity of the ice in three ways. Firstly, where the lake bottom is shallow, the ice can freeze to the ground (grounded ice or ground-fast ice) and is therefore not considered part of the floating ice sheet. Although the carrying capacity of grounded ice exceeds the capacity of the floating ice cover, it can develop stress points at the transition zones between the two. Secondly, shallow areas or shoals can lead to erosion of the ice from underneath and prevent the ice from building at that location. Thirdly, lakebed morphology can confine hydrodynamic wave energy that can cause damage to the ice sheets or blowouts (uplifting of the ice sheet.)

We have found that ice profiling data can be combined with the bathymetric data to discern floating ice, ground-fast ice, and frozen-unfrozen soil boundaries in shallow water. These provide the ice engineer with a clearer understanding of the ice structure and its variability over the project site. Under these conditions the ice engineer is confident that the ice profiling measurements have adequately characterized an ice road or ice pad. We provide examples of ice profiling and bathymetry data collected from various project sites in Canada that identify conditions that helped the ice engineer to interpret site conditions. The potential for using ice dielectrics obtained from GPR data are also discussed.

2. GPR Ice and Bathymetric Profiling

2.1 Theory

Ground Penetrating Radar (GPR) transmits an electromagnetic (EM) pulse of extremely short duration from a transmitter antenna, which is partially reflected from multiple subsurface objects. The reflections are detected at the receiver antenna, which accurately records the pulse travel time. A series of these soundings, taken at regular intervals along a line, builds up a cross-sectional profile of the reflections beneath the line.

As the EM pulse propagates downward through the ground, it encounters and passes through materials having specific electrical properties. The two important properties for GPR surveys are the electrical conductivity and dielectric permittivity. The first property, the electrical conductivity of the material, controls the attenuation rate, of the EM pulse, or how quickly the energy of the EM pulse is absorbed by the material it is passing through. This property governs how far the GPR signal will penetrate the material. The dielectric permittivity is a measure of the charge capacity of various materials (whose ratio to that of free space is called the material's 'dielectric constant') and it controls the velocity of the EM pulse through the material.

Velocity is related to the dielectric constant through this generalized (and simplified) depth equation:

$$d = \frac{c}{\sqrt{\varepsilon_r}}\frac{t}{2} = \frac{v_m t}{2} \qquad [1]$$

where t is the two-way travel time of the propagation medium, v_m is the velocity of the radar pulse in the material, ε_r is the dielectric constant (or relative permittivity) of the material, and c is the velocity of the electromagnetic wave in a vacuum.

At interfaces having different dielectric constants, a dielectric contrast exists and a reflection of some of the EM pulse’s energy will occur. The magnitude of the energy reflected is proportional to the contrast in permittivity. Water has a very large dielectric constant of approximately 81, whereas the dielectric constant of ice can range between 3 and 5. Therefore, a large reflection is always encountered at the water-ice interface. An abrupt change in dielectric constant will be more detectable than a gradual change. This makes GPR the ideal tool for ice thickness profiling. If the thickness of the ice is known (for example, through auger calibration) the velocity and thus the dielectric constant can be back calculated.

Table 1 shows typical electrical properties of various materials.

Table 1. Electrical Properties of Materials
(after Sharma, 1997; Davis and Annan, 1989, Stevens et. Al. 2009)

Material Type	**Dielectric Constant**	**Velocity (m/ns)**	**Conductivity (mS/m)**	**Attenuation (dB/m)**
Fresh Water	80	0.033	0.5-2	0.1
Salt Water	80	0.033	5 x 10^3-3 x 10^4	1000
Ice	3-5	0.13-0.17	0.01-1	0.01-1
Snow	1.6-2.1	0.21 to 0.24		
Frozen sediment	7.5	0.11		
Unfrozen sediment	11	0.09		
Wet Sand	10-30	0.05-0.09	0.2-10	0.03-0.3
Sand	3-5	0.13-0.17	0.01-1	0.01
Silts	5-30	0.05-0.13	0.5-100	1-100
Clay	5-40	0.05-0.13	5-1000	1-300
Granite	4-6	0.12-0.15	0.001-3	0.01-1

Galley et. al. 2009 conducted a field program with GPR using 250 MHz and 1 GHz antennas to measure snow, river ice and sea ice thickness in Churchill Estuary. Snow, river ice and sea-ice velocities and dielectric constants obtained from the GPR measurements compared well with the laboratory measurements made on field samples. GPR measurements of river ice thickness were within 3.6% of measured ice thickness. GPR measurements of snow-covered sea ice using both 250 MHz and 1 GHz antennas were within 8.3% of the measured thickness.

2.2 Conventional GPR Ice and Bathymetric Profiling System

The conventional ice profiling system consists of a bi-static (separate transmitter and receiver antennas) GPR system, with a 500 MHz antenna for ice and a GPS system for positioning. The data is stored digitally on a laptop and can either be interpreted in real-time while collecting or processed afterwards. The real-time interpretation mode usually allows the user to input a velocity so that a thickness scale can be shown on the screen. The operator will then use this display to visually assess the ice condition and identify and mark in the field suspect areas. This mode is typically used by ice road construction personnel and technicians pioneering the ice road routes. If post-processing is required, specific velocities can be applied to various portions within the data set and QA analysis software can be run. However, it's our experience that most users find this impractical due to the large quantities of data collected and their inability to efficiently process the data for supervisor review.

Historically EBA has used a digitally modified GSSI SIR-8 GPR system, with a 500 MHz antenna and a Trimble Ag132 / CDGPS real time differential GPS system for positioning (Figure 1). Equivalent hardware such as MALA's Ramac system or Sensors and Software's Ice Noggin are also used for ice profiling. Data collection profiling speeds are typically around 15 km/h to achieve a horizontal resolution of one trace every 20 cm. EBA imports the raw data into a custom analysis routines running in a data analysis package (Matlab, The Mathworks). Data processing parameters are applied to the raw data files using digital filters and gain functions to try to remove as much background noise as possible. For most ice data little processing is needed to see the ice-water reflector. Positioning corrections are applied to remove any offset distance between the GPS antenna location and the GPR antenna. Final plots are generated to display the ice data profiles and corresponding GPS coordinates in UTM coordinates, using the NAD 83 datum or another applicable datum. These processing steps are carried out in a semi-automated procedure to speed processing time requirements. We have developed this process to document and archive all of the collected data in a manner that can be reported to stakeholders within a turn-around time of 1-2 days.

Figure 1. Ice Road Radar Truck
with SIR 8 GPR and 500 MHz antenna

Bathymetric profiling uses a similar system with a 100 MHz antenna to give depth information for a target zone of up to 6 m (Figure 2). Lower frequencies, such as 50 or 80 MHz, can also be employed to profile portions of the lake deeper than 6 m. Due to the optimization of the system for bathymetry, the ice thickness is not obtained using lower frequency antennas. Instead EBA profiles the ice and bathymetry in separate runs and use our own software to join the bathymetry and ice data based on GPS information to combine the results in a two-layer thickness interpretation.

Figure 2. Snowmobile with SIR 8 GPR
and 120 MHz antenna

Stevens et. al. (2009) found they were able to GPR to map subsurface conditions within the near-shore zone of Middle Channel of the Mackenzie Delta. Using multi-frequency GPR (50, 100 and 250 MHz antennas) their study was able to resolve floating ice versus bottom (ground) fast-ice, river bathymetry, sedimentary structures, and the interface between frozen and unfrozen sediment to depths of 5 to 8 m. Besides relying on interpretation of reflection patterns due to dielectric contrasts, they also analyzed reflection amplitude values to distinguish the groundfast ice from the floating ice and to resolve frozen/unfrozen interfaces from sedimentary structures. Depth estimates were augmented by a multi-layer velocity model to account for changes in dielectric changes.

3. GPR Ice and Bathymetry Results from Ice Bridge, Ice Road and Ice Platform

Since 2001 EBA has conducted quality assurance ice profiling and engineering services for a number of mining, oil and gas, and transportation clients in Alberta, Ontario, NWT and Saskatchewan. Projects range in scale from ice bridges a few hundred metres long to extensive winter road system incorporating lake ice crossings up to 70 km long. Projects also include stationary loads, such as bulk sampling rigs, using ice platforms to drill targets located under lake ice. Quality assurance ice profiling is an independent assessment of the ice thickness and ice conditions that our ice engineers use to verify the bearing capacity of these ice bridges, ice roads, and ice pads. GPR bathymetry survey has also been conducted to investigate ice road re-alignments to avoid problem areas. Four example case studies are presented.

3.1 *Example 1: Ice Bridge, Northern Alberta*

This northern Alberta ice bridge is usually built up by man-made flooding and has several areas of grounded ice, where the ice is frozen to the river bed (Finlay et al. 2008). EBA has conducted quality assurance ice profiling at this recurring ice bridge since 2005. After collecting the ice profiling data with the 500 MHz antenna, we switch over to the 120 MHz antenna to collect the river bathymetry and determine the river bed topography as it changes from year to year. The combined results are shown in Figure 3 which has three panels: the upper panel shows GPS positioning and auger locations on a UTM grid (background image is used when available); the middle panel shows the interpreted ice and water depth profiles where cyan is the ice-water interface, red is grounded-ice, and dark blue is the river bottom; and the lower panel shows the processed 500 MHz ice radar profile.

Although the interpreted data in panel 2 is adequate for assessing ice conditions for most ice crossings, there’s additional information contained within panel 3 that can be quite valuable. For example, the second reflector is frequently misinterpreted as an ice/water reflector where groundfast ice is present. In this case it is a reflection at the transition from frozen to unfrozen soil. This reflector will increase in depth through the winter season as the frost continues to penetrate throughout the winter. Also noticeable is the ice to frozen ground reflection, which is much fainter than the frozen to unfrozen ground reflection due to the reduced dielectric contrast. GPR can readily diagnose where water or unfrozen saturated soils are present below the ice based on the strength of the GPR reflection at that interface.

The ice environment can be inferred from the character of the ice/water reflection. At the margins of the main channel the ice is irregular in thickness when compared to the ice over the main channel. Statistics describing the thickness variations over distance can be used to identify the formation history of an ice sheet and this has a bearing on the long term stability of the ice at the end of the winter road season. Smooth ice indicates that the ice has frozen in place without much movement. Irregular ice indicates a more dynamic environment and generally represents locations where stress may be present and is frequently where ice will deteriorate first at the end of the season.

The transition zone from ground-fast ice to floating ice cover should also be monitored for the development of hinge cracks. Stresses can develop at these transition zones and as the water levels fluctuates with river flow or by moving load hydrodynamic waves. The GPR data can help assess these and track their location throughout the season.

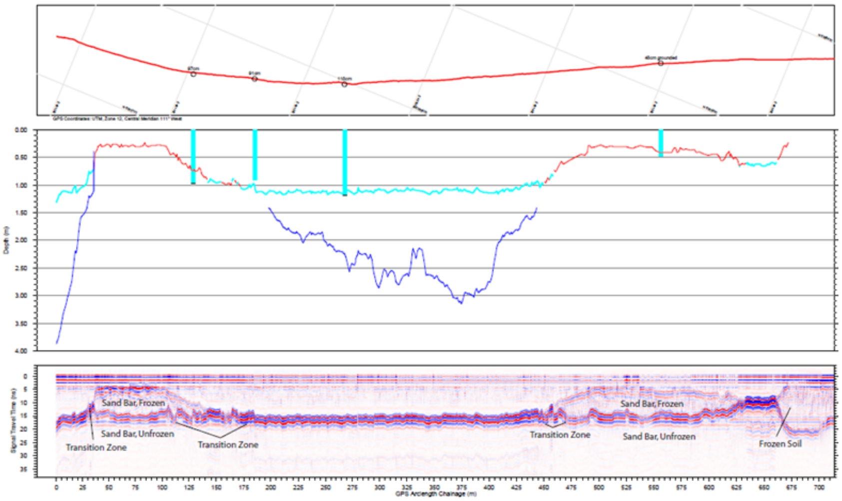

Figure 3. GPR ice and bathymetry profile of an ice bridge in northern Alberta.

3.2 *Example 2: Ice Platform on a River for Bridge Rehabilition*

A contractor retained EBA to perform ice quality assurance services (QA) and load recommendations for the 200 m long ice platform built on the river to facilitate bridge pier rehabilitation. The measured ice thickness and bathymetry data are displayed as a contour plots in map view in Figure 4 and Figure 5, respectively. The background image of the air photo was sourced from Google Maps and the approximate locations of the bridge piers have been outlined on the figure along with the track paths of the GPR surveys.

The ice generally trends to be thicker on the upstream side of the bridge and there are regions of thin ice near the piers. It should be noted that EBA personnel observed that the ice near the piers was raised above the elevation of the surrounding ice. One explanation for this occurrence may be that the ice formed earlier around the piers than it did in the open water. With a drop in water level either as the season progressed or as the remainder of the crossing froze, the ice that formed around the piers remained at a higher elevation than the surrounding ice. Due to the higher elevation of the natural ice around the piers, it is difficult to build up the ice thicknesses of these areas via flooding. Regions of thinner ice that have reduced bearing loads have been denoted by red dashed lines in Figure 4. Generally, these regions extend laterally between 10 to 15 meters from the center of each pair of piers.

Bathymetry contours are displayed in Figure 5. The bathymetry data does not indicate any regions where the ice may be or become unexpectedly grounded. The data indicates that the water is deepest at the center of the river, between the second and third set of piers. It should be noted that this area is expected to experience the highest volume of water flow and thus the greatest rate of ice erosion due to the flow of water beneath the ice.

3.3 *Example 3: Route Selection Using GPR Ice and Bathymetric Data*

Ice Crossing Approach to a Portage

Bathymetric data was collected for the purposes of exploring an alternate route for the road to exit onto the northern bank of the lake, as the current route has had problems with uniform ice cover due to shoals. Eight parallel profiles were collected at a line separation of approximately

25 m for a distance of approximately 450 m to the east of the peninsula at the north end of the lake. The road currently exits on the west side. A 50 MHz Ramac ground penetrating radar antenna was used with a NovAtel Smart-V1 realtime differential GPS unit to collect the data. Collection speeds averaged roughly 10 km/h at 3 traces per second, resulting in an average horizontal resolution of 1 trace per metre. Figure 7 illustrates the data in the form of a contour map superimposed on a geo-referenced air photo of the portage.

The shallow areas shown on the contour map clearly align with visible shallow areas in the high-resolution air photo, and are associated with nearby islands. Between these islands, there is a north-south oriented gap approximately 35 m in width where water depths fall between 6 and 8 m. The alignment of the ice crossing was changed to the new alignment to avoid the issues with the old alignment.

3.*4 Example 4: Ice Crossing Alignment Near Islands and Shoals*

The second dataset was collected on ice road detour lane on a large lake in NWT. This data was also collected for the purpose of exploring alternate routes for the main alignment of the ice road. The same equipment was used to collect the data as on previous lake, however, due to the size of the area being surveyed and survey rates due to the extreme cold, horizontal spacing was increased from 25 m to 50 m. This allowed the coverage of the area within the allotted time while maintaining adequate data density. Horizontal resolution along individual profiles remained the same at approximately 1 trace per metre.

Ice contour data along the road alignment collected earlier was overlain onto the bathymetric contour as shown in Figure 7. It is clear from the ice data that the thin areas correlate with the shallow areas in the bathymetric data. A large area north of the express lane is comprised mainly of shallow water less than 1 m deep, and some exposed land that protrudes above the lake surface. The water depth around this area is generally deeper than 4 m, although a shoal with water depths of less than 2 m extends off the southwest. From the southern portion of the shallow and above-surface area, a second shallow zone extends southward, including a chain of small islands 100 m or less in diameter. Extensive thin ice areas occur where the ice road crosses this shallow area.

The current location of the main route suffers from zones of thin ice and slow ice growth. This is clearly associated with shallow water depth and the constructed channel, leading to possible currents/water washing issues under the ice. These issues can be attributed to either natural causes or hydrostatic water movements generated by vehicle traffic. The contractor has since then chosen to relocate the main route to areas with shallower water depths and then ground the ice to bottom to minimize these problems.

4. Recent Developments

EBA has adapted its ROAD RADAR™ GPR technology for ice and bathymetry measurements which has two separate and synchronized radar systems integrated with linear and DGPS based geo-referencing systems (Mesher et. al. 2008). It uses a high resolution multi-channel surface coupled antenna array radar system that determines both the signal travel time and the ice dielectric at every measurement point for each detected ice sheet layer. This makes the system self-calibrating for ice thickness and eliminates the need for auger hole calibration. The ice radar system operates at 1.1 GHz and uses a single transmit antenna and three receiver antennas positioned at precise locations as shown in Figure 8. Samples are acquired at a programmed distance (typically every 100 mm at 80 km/h) and can resolve ice layers as thin as 10 mm to a nominal maximum depth of 2 m depending on the ice properties.

Figure 9 shows a sample data set from a single channel collected at 20 mm sampling resolution. During field trials the ice dielectric measurements were found to vary by more than 15% between blue ice and white ice. Intermediate structural layers are resolved within the ice sheet along with some structural defects (cracks and internal voids) also visible within the ice. Post-processing of the data is necessary to identify structural features within the ice. However, we're working on real-time analysis of ice thickness measurements to provide the operator the ability to identify thin areas during data collection.

Additional investigations are looking at relationships between ice dielectric properties and the composition (air bubbles) and mechanical properties (borehole jack strength).

5. Conclusions

Through a number of examples presented here we've shown that GPR technology can not only measure continuous ice thickness but also provide information about groundfast ice conditions, frozen/unfrozen interfaces and river or lake bathymetry. Such data enables the ice engineer to better understand the ice conditions and analyze the bearing capacity for moving or stationary loads. Field data are readily obtained through available GPR systems along with selection of appropriate antennas. Interpretation of the data, however, should be conducted by professional geophysicists experienced with GPR profiling of ice and bathymetry and the underlying physics.

Other examples from the literature and from in-house projects indicate that GPR can be used to obtain the dielectric properties of ice and other materials encountered in the field. Through the use of multi-channel ice radar equipment such as the EBA Road Radar technology, ice dielectrics can be measured in the field without the need for calibration and can resolve features within the ice not currently discernable in conventional systems. Research is ongoing into whether variations in ice dielectrics can be correlated in a meaningful fashion with ice strength.

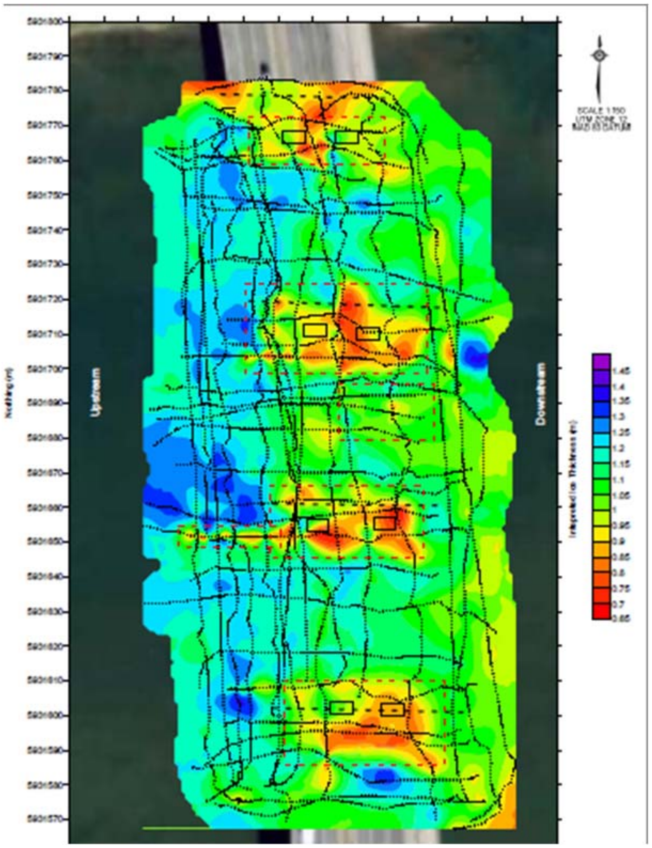

Figure 4. GPR ice thickness contours for an ice platform built for bridge rehabilation.

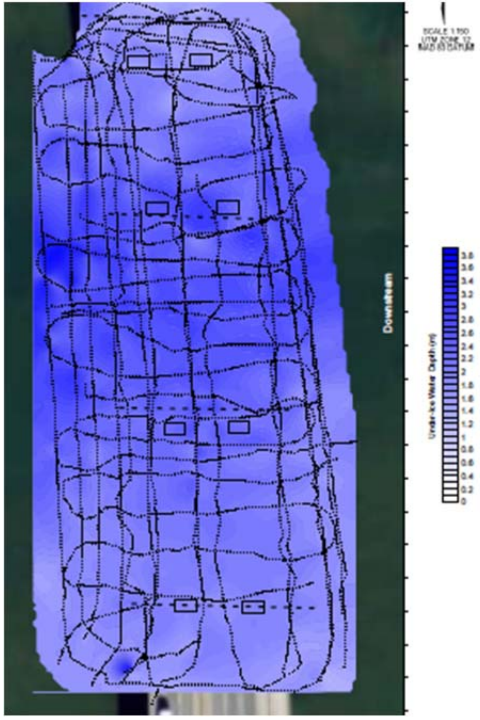

Figure 5. GPR bathymetry contours for an ice platform built for bridge rehabilitation.

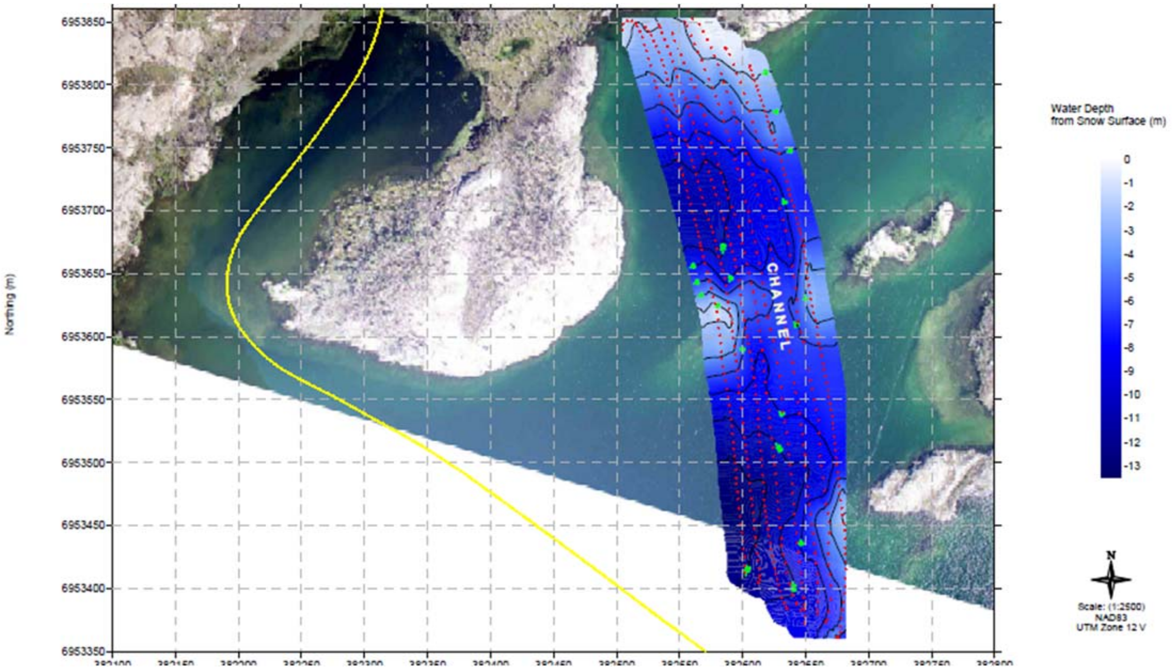

Figure 6. GPR bathymetry contours for considering an alternate route for an ice road.

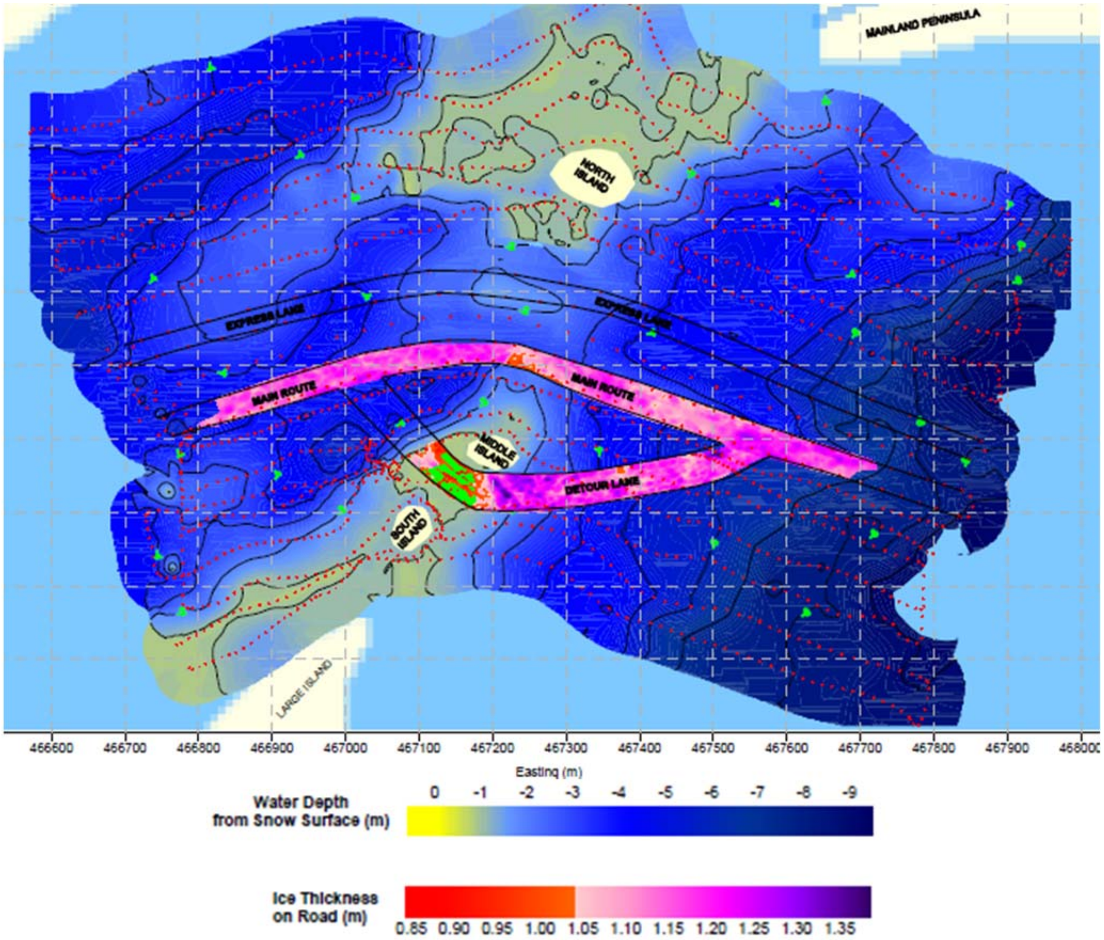

Figure 7. GPR ice thickness and bathymetric contours for evaluating a route between islands

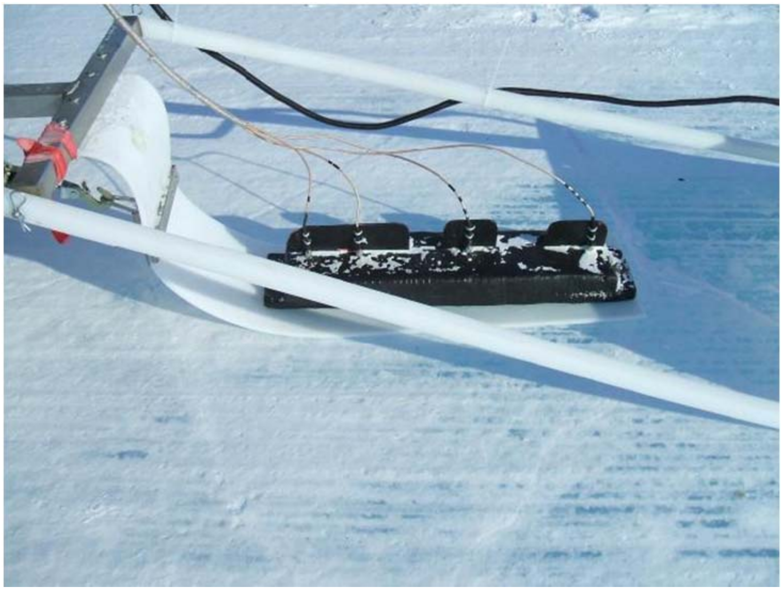

Figure 8. Ice Road Radar multi-channel ice antenna

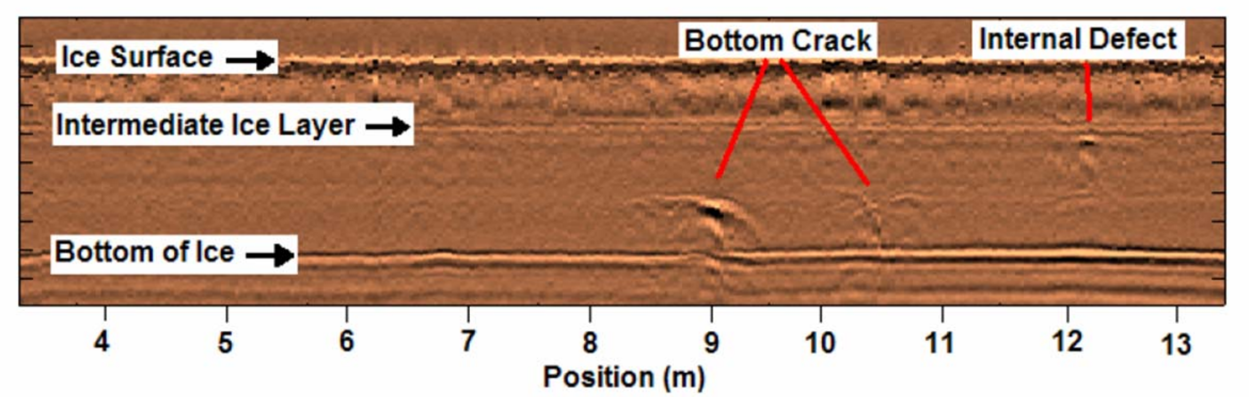

Figure 9. Sample of raw data from Ice Road Radar array

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