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MEASURING ICE THICKNESS USING GROUND PENETRATING RADAR (GPR)

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GPR THEORY

Ground Penetrating Radar (GPR) is the general term applied to techniques which employ radio waves, typically in the 1 to 1000 MHz frequency range, to map structures and features below the surface. The concept is to detect the presence of features by sending a pulse of radio frequency energy into the subsurface and collecting the energy that reflects from an object or a boundary and travels back to the surface. Figure **1** shows how GPR detects the location and depth of a buried utility. The yellow waves of energy are transmitted from the GPR and the red waves reflect from the utility back to the surface. Utility locating is one of the many applications for GPR technology.

Figure 1 - *GPR systems use a transmitter to send a pulse of radio frequency energy into the subsurface and a receiver to collect the energy that reflects back from objects or boundaries. The time it takes the energy to travel to the object and back to the surface can be used to determine the depth of an object or the thickness of a layer.*

GPR is used for many applications including locating buried utilities, mine site evaluation, forensic investigations, archaeological digs and, as the main section of this document describes, monitoring the ice thickness of winter roads on frozen water bodies.

Motivation for Ice Profiling with GPR

Historically, ice profiling surveys involved drilling a number of ice cores spaced out along an ice road. The thickness of the ice at the core location was used to estimate the ice thickness between holes (Figure 2).

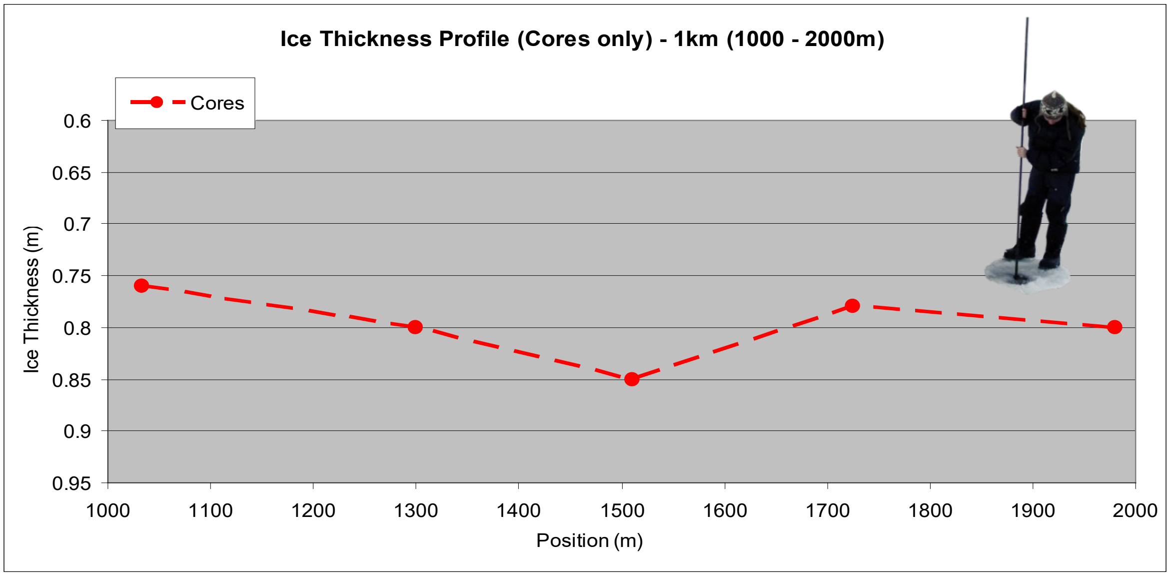

Figure 2 - *Before GPR was used for measuring ice thickness, the methodology was to drill cores at intervals and assume the ice thickness between cores was consistent.*

The reality is that ice thickness can vary significantly between core holes, and localized areas of thinner ice are not often detected using this method.

Ice profiling with GPR provides a more complete picture of the ice than coring because ice thickness measurements are collected more frequently, at sub-meter intervals. Figure 3 shows the ice thickness measured by GPR (blue line) compared to ice cores (red line). Clearly, many thin areas were missed due to the large intervals between the ice cores.

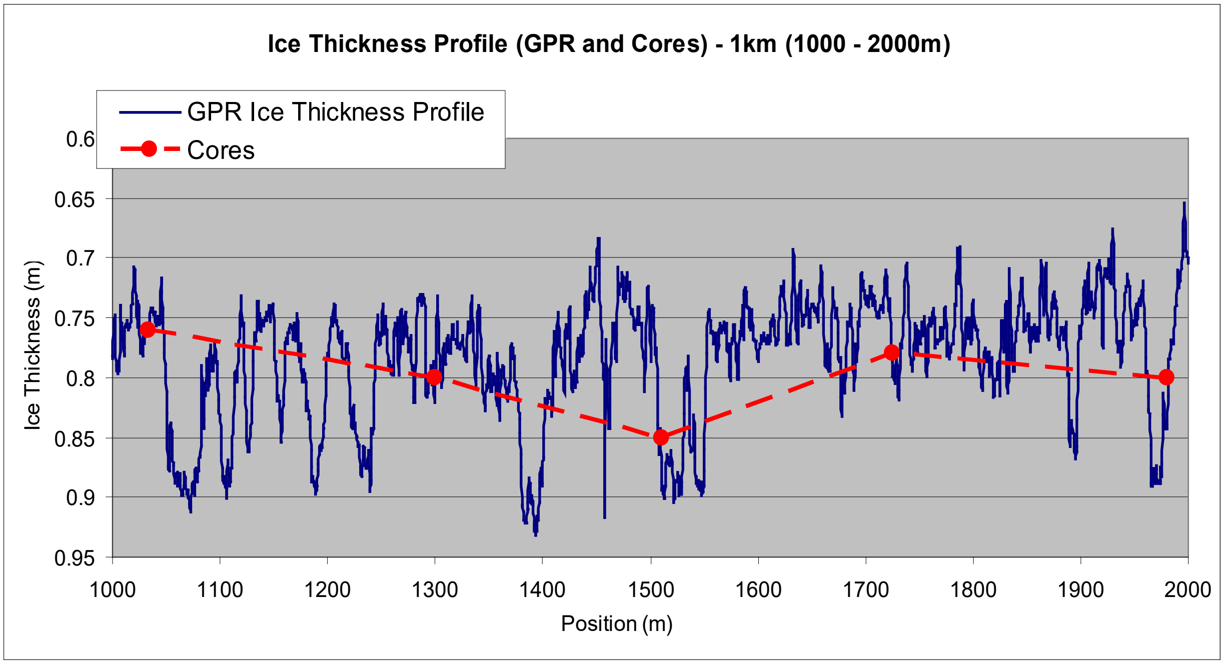

Figure 3 - *Ice thickness measurements with ice cores (red line) and GPR (blue line). The finer sampling interval of GPR compared to the ice cores is very effective for measuring the rapid changes of ice thickness.*

Ice Profiling with GPR

For ice profiling applications, GPR data is typically collected with a system that includes a towed sled containing a GPR sensor and a display unit in the cab of the tow vehicle (Figure 4). The GPR equipment continuously collects ice thickness measurements and the system operator monitors that data collection in real-time as the equipment is towed along the ice road.

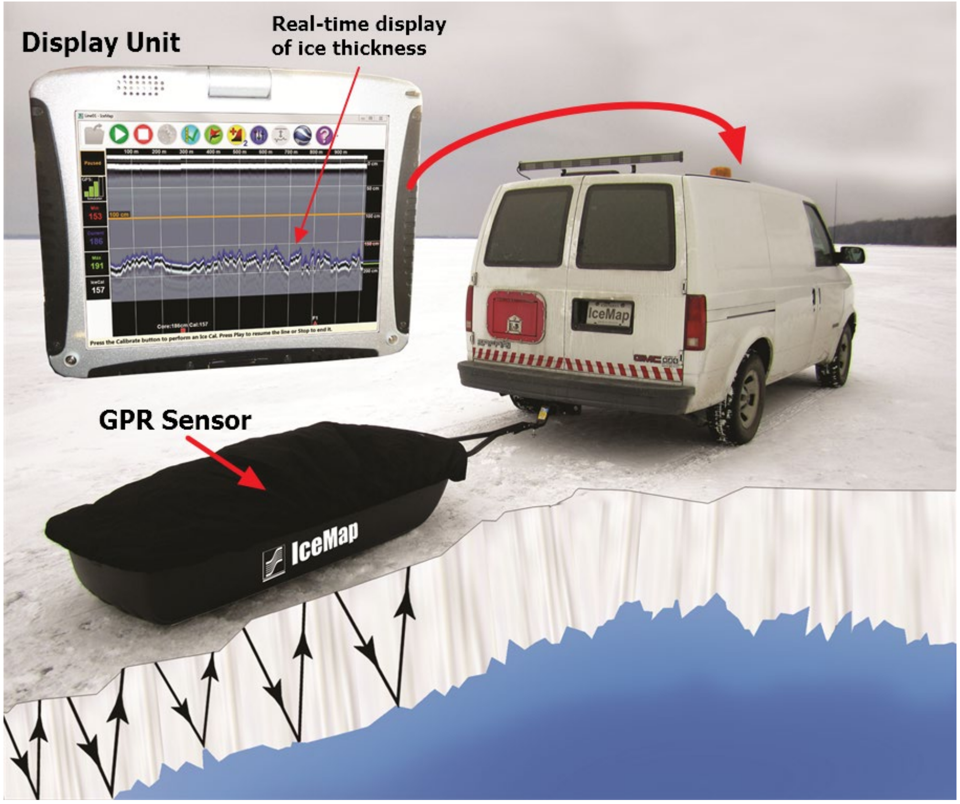

Figure 4 - *The GPR sensor is typically deployed in a non-metallic toboggan with the data sent wirelessly or by cable to the display unit in the cab of the towing vehicle. The operator can monitor the ice thickness measurements in real-time.*

Ice profiling with GPR improves overall safety by providing more ice thickness measurements and improves survey efficiency through a reduction of the number of manually collected ice cores.

Figure **5** shows an example of a GPR cross-section across ice.

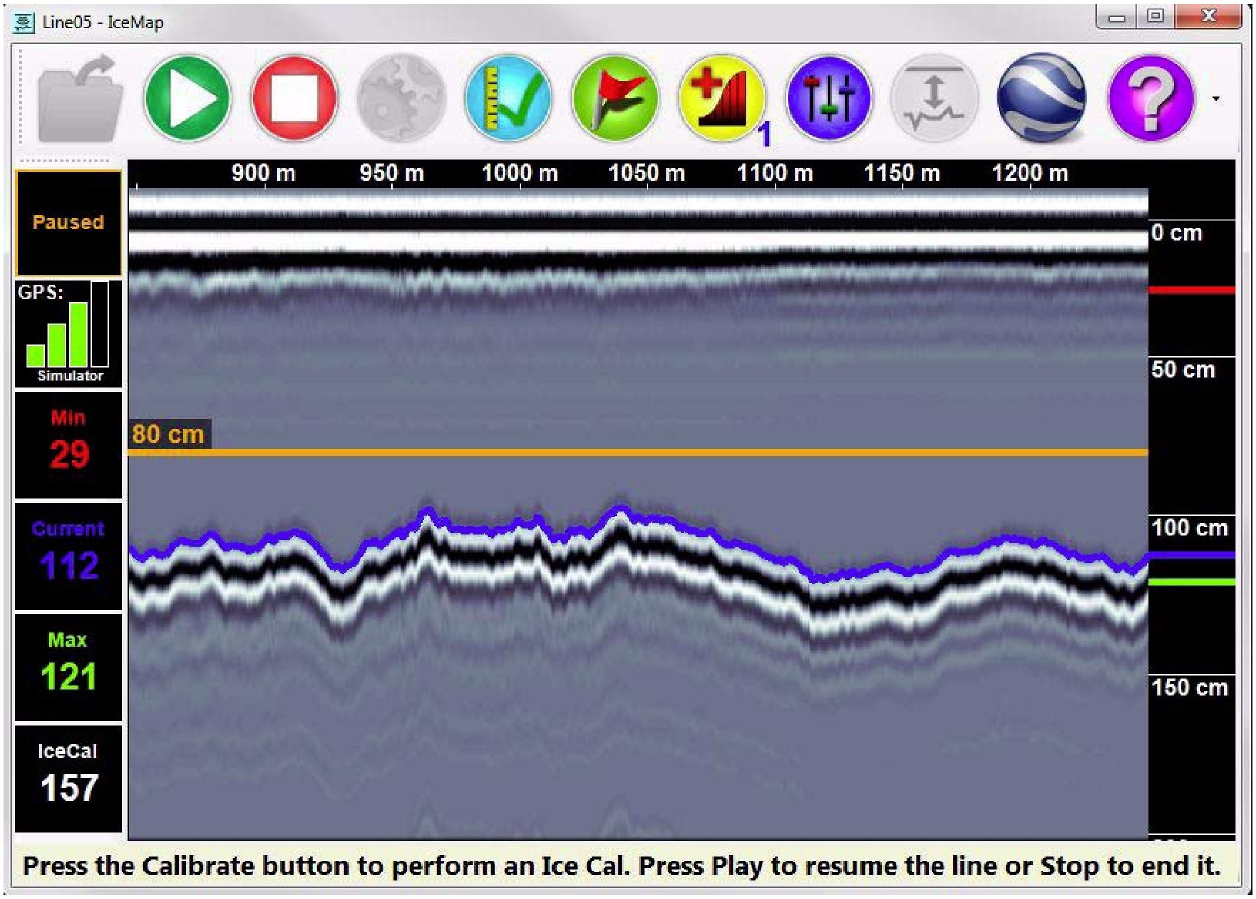

Figure 5 - *Typical GPR cross-section with ice over water. During data collection, the image scrolls from right to left. The GPR reflection from the bottom of the ice is displayed as 3 strong bands – white, black and white. The actual bottom of ice correlates to the top of the first white band. The GPR system automatically "picks" the bottom of ice and plots it as a blue line. The thickness of the ice at the current measurement point is on the right edge and the thickness (in cm or inches) is displayed under "Current" on the left.*

BEST PRACTICES FOR USING GPR ON ICE ROADS

When winter roads and bridges across rivers and lakes are used to transport people and goods, safety is critical; the ice must be thick enough everywhere to support the weight of vehicles and heavy loads. Frequent monitoring is important to ensure the proper load rating for that section of the winter road. Most northern jurisdictions use formulas, like Gold's formula, that relate the ice thickness to the maximum gross vehicle weight allowed on the road. Ground Penetrating Radar (GPR) is used to provide a continuous measurement of ice thickness over the entire length of the winter road.

Pre-Survey Considerations

1. Established and review a work plan before any surveying is carried out.
2. Confirm that the GPR system and laptop PC are in good working order.
3. Ensure that the toboggan or towing platform housing the GPR sensor does not have metal runners or other metal objects underneath or close to the GPR sensor that could interfere with the GPR ice measurements. The GPR sensor should be placed on the bottom of the toboggan to ensure good coupling with the ice surface.
4. If an odometer wheel is used to measure distance and trigger the GPR system to collect data at equal intervals, check that the odometer calibration is accurate by moving the system over a known distance and compare the results to the odometer distance measured by the system. If necessary, calibrate the odometer, following the GPR manufacturer's procedure.

Field Operations

1. When on site, ensure that the crews are at the correct location and that all data are correctly positioned so areas of thin or otherwise problem ice can be accurately re-located. Positioning methods include GPS, vehicle odometer measurements or flags, trees or other markers on the surface at known positions along the winter road.
2. Power up the GPR system. If using the wireless version, ensure the laptop PC wirelessly connects to the GPR sensor.
3. In the GPR system settings, set measurement depth value to 1.5 to 2 times the estimated ice thickness. This may require a short test line with a large depth setting (3 meters) to measure the ice thickness and then adjust the depth value.
4. In the GPR system settings, set a data measurement interval; for lake ice, set the interval to 0.5 meters. For rivers ice set the interval to 0.25 meters. A shorter sampling interval is required because of the highly variable ice thicknesses caused by river ice formation and changing river currents.

   The data sampling interval is measured one of two ways:

   - Collecting the data continuously and selecting the desired driving speed (this is most common)
   - Using an odometer wheel to trigger the GPR system to collect data

In both cases, the GPR systems can collect data at speeds from 1 to 80 km/hr but the driving speed used needs to be determined based on the ice conditions and local regulations; in most situations a speed of 30 km/hr or less is recommended.

When collecting data at a set driving speed without an odometer, maintaining the recommended driving speed or slower ensures that data are collected at the sampling interval or finer, providing a margin of safety. Exceeding the set driving speed by greater than 10% is not advised as it results in data sampling intervals greater than the recommended values.

5. Space survey lines approximately 5 meters (15 feet) apart. For example, a narrow, single lane road requires a single survey line; a 2 lane road requires 2 lines, one in each direction in the center of the driving lane. Wider roads will require more survey lines to sufficiently cover the driving area.
6. Since the GPR system is battery powered, data may be lost if the system experiences a power outage. Check the battery voltage between survey lines and replace/recharge the battery if required. Avoid collecting survey lines longer than 30 minutes to reduce the chance of significant data loss due to power problems.
7. During data collection, press the red "Flag" button (see Figure 5) to insert a mark in the data to indicate significant features or events, such as mile markers, turning around or other surface features. Make sure to log all flags in the field notes, so you or someone else analyzing the data later will know what the flags mean.
8. Try not to collect data where the snow drifts are very high or in areas of wet slush. These will all impact data quality.

Ice Calibrations

Ice Calibrations, or IceCals, are a critical part of surveying. They are used to determine an accurate depth by determining the GPR signal velocity through the ice. Essentially the process is:

a) Collect some data over the ice
b) Slow down and stop the vehicle
c) Pause the data collection
d) Go outside, slide the sled over and auger a hole under where the GPR sensor in the sled was located before the sled was moved.
e) Measure the depth of the ice at that point. If there is snow cover, don't include that in the thickness measurement, just measure the ice itself.
f) Return to the laptop PC and input the measured ice thickness into the ice calibration software.

You have now done an ice calibration (IceCal) and the software will adjust the ice thickness scale accordingly.

IceCals are a function of snow cover, air & water entrainment, location (bays, inlets, rivers) and even the time of the season. As a result, they could vary on a single body of water.

Ice calibrations should be performed whenever the ice or surface conditions change:

2. Every new body of water

3. When changing from a bay to open lake
4. When there is a significant change in snow cover
5. When there is a dramatic change (> 20%) in the observed ice thickness

It's important to collect a few IceCals to see how much the value is changing. If the values are consistent, then they can be spaced farther apart. Remember that, for safety, the concern is always thin ice. Always take an IceCal where the ice is thinnest for maximum accuracy. If the IceCal values are changing, apply the lowest IceCal value. This results in the thinnest calculated ice thickness, providing a greater margin of safety.

Surveying Sea Ice

Surveying sea ice presents special challenges; sea ice absorbs GPR signals significantly more than fresh water ice. Depending on the amount of brine trapped in the ice, the amount of absorption may be so high that it may not be possible to detect the bottom of the ice and measure the ice thickness with GPR.

Sea ice can also be anisotropic, which means that GPR signals travel through the ice better when the antennas of the GPR system are oriented in a certain direction. When surveying sea ice, it is a best practice to survey the ice twice; once in the normal orientation and once after rotating the GPR system 90 degrees. Another option is to collect the survey lines simultaneously with two GPR systems oriented 90 degrees to one another.

Because of the lower response amplitude, the software may not pick the ice thickness correctly. Consult the user's manual for details on defining the correct zone, forcing it to "re-pick" the ice thickness boundary.

Data Storage and Archiving

It is important to archive the data properly, especially if there is a need to return to a point where the ice is thinnest.

Procedures

1. Copy, rename, and then save data folders and files using the established procedure. This typically involves including a date and/or location in the file structure.
2. Copy, archive, and back-up the data on a separate storage medium so that data are not lost or compromised in the event of the laptop PC failing.

Reporting

Data Reporting requires the melding of the multiple information sets (GPR data, ice bottom picks, IceCals and GPS) into a final presentation, in the proper context, so that decisions can be made. Typically, ice thickness information is made available in formats for communication to other parties.

Procedures

Capturing ice thickness information involves:

1. Displaying the ice thickness cross-section(s) in the GPR manufacturer's analysis software.
2. If automated software tools are used to determine the ice bottom, all data should be manually reviewed by qualified personnel and, if necessary, edited to ensure accuracy. Editing may involve "re-picking" the boundary in certain areas, such as grounded ice, slush pockets and snow drifts, to name a few.
3. Displaying the location of IceCals to calculate the most accurate ice thicknesses.
4. Output of the ice thickness information into standard output files. Typical output files include:

- Spreadsheet files (.csv) files that list position (GPS, odometer or marker) and ice thickness
- Google Earth (.kmz) files that plot color-contoured ice thickness values on Google Earth images

Summary Report

The culmination of collecting data is often the Summary Report. Since ice thickness data files can be very large, representing ice thickness measurements from thousands or even hundreds of thousands of locations, this summary report provides ice thickness statistics are beneficial for quickly assessing the survey, including the locations of thin ice sections.

When properly completed, the Summary Report will include:

- Date
- Operator(s)
- Total survey length
- Minimum thickness
- Maximum thickness
- ice calibration locations and results
- Locations of thinnest ice
- Locations of any exceptional data

User's Guide

For complete details and operation, please consult the IceMap User's Guide. This can be obtained by contacting the manufacturer listed below.

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For further information, please contact Sensors & Software:

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