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Ground Penetrating Radar for Helicopter Snow and Ice Surveys

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Abstract

Lalumiere, L. 2006. Ground Penetrating Radar for Helicopter Snow and Ice Surveys. Can. Tech. Rep. Hydrogr. Ocean Sci. 248: iv + 44 p.

The report reviews available Ground Penetrating Radars (GPRs) that could be incorporated into existing hard-mounted helicopter surveying platforms to measure snow depths and freshwater ice thicknesses. Past GPR-based snow and ice thickness sensors are compared with new single and multi-attenna GPRs and recommendations are made for GPR hardware procurement for both the BO-105 and Bell 206L helicopters.

Résumé

Lalumiere, L. 2006. Ground Penetrating Radar for Helicopter Snow and Ice Surveys. Can. Tech. Rep. Hydrogr. Ocean Sci. 248: iv + 44 p.

Dans ce rapport on examine les géoradars qui pourraient être intégrés aux plates-formes héliportées de levés pour existantes la mesure de l'épaisseur de la neige et de la glace d'eau douce. Les géoradars capteurs d'épaisseurs de neige et de glace utilisés par le passé sont comparés aux nouveaux géoradars à antenne unique ou à multiples antennes et des recommandations d'acquisition de matériel pour géoradars destinés aux hélicoptères BO-105 et Bell 206L sont présentées.

1 Introduction

The purpose of this report is to provide information for the development of a helicopter hard-mounted Ground Penetrating Radar (GPR) system to measure snow and ice thickness.

Recent changes have been made in helicopter flight operations with the new helicopter hard-mounted EM-induction ice thickness sensor (Ice Pic). Flying height will now be in the 3 to 5 m range compared with the 20 to 50 m height range that was used with the *Ice Probe* system. Also, there are now two mounting configurations. For use with the BO-105 helicopter, the GPR antennas must fit inside a 25-cm pod. For use with a Bell 206 helicopter the GPR antennas must fit in a 27-cm tube.

In addition to snow depths, the system shall measure ice thickness in areas where a fresh water plume is under the ice. The fresh water plumes distort the measurement from an *Ice Pic* EM induction system.

A review of past GPR-based snow and ice thickness sensors is made and plots over snow and ice from past systems are made to demonstrate system performance. A qualitative look is made at how snow and ice thickness performance is controlled by operational constraints and GPR system parameters.

The performance obtained using seismic-based processing techniques are discussed and the performance between the previous snow thickness sensor is compared with a new single antenna and a multi-antenna GPR snow and ice thickness sensor.

A novel airborne multiple GPR antenna configuration is proposed to provide more reliable ice and snow thickness measurements.

Recommendations are made for GPR hardware procurement, which would be based on available funding for equipment and field trials.

2 Airborne Snow and Ice Thickness Sensors Background

A system developed at the Centre for Cold Oceans Resource Engineering (C-CORE), Memorial University of Newfoundland in the late 1970's was optimized for sea ice thickness measurement (Butt and Gamberg, 1979). This system was hard-mounted to a helicopter and it operated from 15 to 50 m above the ice. During a 1987 field trial, this system demonstrated the limitations that GPR technology of that era had, such as trouble with conductive first year sea ice and fractured multi-year ice (Rossiter and Lalumiere, 1988).

During the same 1987 field trial, a demonstration of helicopter-borne electromagnetic (EM) induction / laser technology was performed. Mounted in a towed bird flying at 10 to 20 m, this system used EM induction technology to give height over the electrically conductive seawater. It used a laser altimeter to provide the height to the top surface of the ice (or top of a snow layer over the ice). This technology provides ice thickness measurements independent of the sea ice type.

Several real-time EM induction ice thickness sensors have since been developed. Originally developed as a helicopter towed-bird system (Aerodat, 1995), recent EM induction technology improvements has enabled the building of a helicopter hard-mounted system which flies at an altitude of 1 to 6 m (Prinsenberg et al., 2002).

As the EM induction system measures the thickness of the combined snow and ice layer, GPR systems have been added to measure the snow layer so that the snow and ice layer thickness can be reported individually.

In the early version, the GPR system was mounted inside the towed bird (Prinsenberg et al. 1993). A later version had the GPR antennas packed in a hard-mounted pod attached to the helicopter's skid gear (Lalumiere, 2000). Both these approaches had some success but there was interference between the EM and GPR systems. The latter system operated at up to 50 m from the surface. As flying altitude rises the GPR system's returned echo strength decreases and the background noise levels increase (Lalumiere, 1999b).

Appendix A includes plots of past results showing ice and snow echoes collected in the vicinity of the Ice Road near Tuktoyaktuk. This fieldwork was documented in Lalumiere, 1992.

3 GPR System Design Parameters

3.1 Helicopter Constraints

The GPR system will be hard-mounted to a helicopter. For use with the BO-105 helicopter, the GPR antennas must fit inside a 25-cm pod. For a Bell 206 helicopter the GPR antennas must fit in a 27-cm tube. The tube length could be variable. The centre of tube is approximately 0.4 m over the surface when helicopter is on the ground.

Flying conditions have changed as the EM-induction-based *Ice Pic* system has replaced the *Ice Probe* system. The helicopter is now operating at low altitudes (from 1 m to 6 m). Also, there is the option of soft-landing on the ice where the helicopter's skids touch the ice but the helicopter holds its weight off the ice.

While the helicopter velocity is likely to be slow when flying very low, the GPR should operate fast enough to provide a thickness measurement every few metres when operating at normal cruising speed.

3.2 Resolution

Commercial GPR systems are differentiated by their centre frequency.
The pulse length of the GPR system is inversely proportional to its centre frequency. To resolve fine layers, one specifies a GPR with the highest available centre frequency to obtain the shortest possible pulse length. Higher frequency units do trade-off system performance due to lower transmitted voltage (signal strength), small antenna aperture area and increased attenuation in conductive sea ice. A 500 MHz GPR system has a pulse length of approximately 3 ns and a 1 gigahertz (GHz) GPR system has a pulse length of approximately 1.5 ns.

As a GPR system provides the two-way travel time between layers, multiplying half the time measured between the layers times the velocity in the layer provides the layer thickness.

The minimum GPR layer resolving capability is approximately two thirds of the pulse length. For a 500 MHz system and with snow with a velocity 0.23 m per ns, the minimum detectable separation of echoes would be 2 ns, representing a minimum snow layer thickness of 0.23 m. For a 1 GHz system, the expected minimum snow thickness layer would be 0.12 m.

Practical experience with a 500 MHz GPR snow thickness system showed that the minimum snow thickness layer was 0.25 m (Lalumiere, 1998).

3.3 Scale factor and datum errors

Using GPR for the accurate measurement of ice and snow depths requires calibration of the instrument electronics and the calibration of the method used to convert travel time to layer thickness.

3.3.1 Calibration of the Electronics

For a 1 GHz GPR unit, the typical time interval between each sample in a scan is 100 picoseconds. If this value drifts or is biased, then the overall range return window length may vary. The sampling interval is specified by the window length and the number of points in a radar scan. If the window length and the sampling interval are in error then the reported layer thickness would be in error.

Also, the position in the radar scan where the transmitter is seen to fire can drift over time. This position is called the time-zero location. Sensors and Software reports that for the Noggin model the time-zero position drifts approximately 0.2

ns from a room temperature start to its steady state operating temperature. The Sensors and Software pulseEkko Pro model has temperature compensation and the time zero position varies less that 0.1 ns over a temperature range from -30 to +50 degrees Celsius.

With an airborne array it may be possible to do automatic time zero and window length calibration. As the geometry is fixed, the arrival time of the direct signal (travelling at the speed of light) from the transmitter to each receiver can be used to calibrate the time zero position. The relative arrival time of the direct signal from the transmitter to each receiver can be used to estimate the sampling interval

3.3.2 Velocity of GPR waves in Ice and Snow

The dielectric constant of snow varies from 1.5 to 3.2. This variation is related to the density of the snow. While the value for the dielectric constant of heavy wet snow needs to be determined, it is expected to be a much larger value than the dielectric constant of dry dense snow. Radar velocity is calculated by dividing the speed of light in free space by the square root of the dielectric constant.

With the radar velocity in snow ranging from .25 m/ns to 0.17 m/ns, the two way travel of the radar signal through 0.5 m of snow would range from 4 to 5.9 ns.

If a mid-range velocity is chosen (0.21 m/ns), the measurement error of a 0.5 m thick layer of dense snow would be 0.12 m and the measurement error of a 0.5 m thick layer of light dry snow would be 0.08 m.

A worst case scenario would be obtained by using either end of the velocity range. For example, the error in the measurement of a 0.5 m thick layer of dense snow using a radar velocity in light dry snow would be 0.24 m.

The dielectric constant of ice varies from 3.2 to 8, with ice types ranging from fresh water ice to electrically conductive sea ice. The dielectric range for ice produces a similarly wide range of velocities as with snow, with the radar velocity in ice ranging from .17 m/ns to 0.1 m/ns. If a mid-range velocity were chosen (0.14 m/ns) the measurement error of a 1 m thick layer of fresh water ice snow would be 0.22 m.

Section 4 below describes a GPR technique to measure the velocity to provide more accurate thickness measurements.

3.3.3 Physical Interface versus the Electrical Interface

The depth to the physical sea ice-water interface may differ from the depth reading from the GPR system (Campbell and Orange, 1974). The electrical interface seen by a GPR system has been reported to be approximately 8 cm from the ice water interface. The early GPR systems used for sea ice thickness were typically in the 100 MHz range. Some field data collection will be required to determine the difference between the physical ice/water interface and the interface observed by a 500 MHz or 1 GHz GPR system.

3.3.4 Peak Locating

Automatic snow and ice thickness processing must locate the radar echoes from the top of the snow, the top of the ice and bottom of the ice. The radar systems relative range accuracy is determined by the pulse length and system noise. Typically this specification is taken as one tenth of the pulse length. For a 500 MHz system, with a snow velocity of 0.23 m per ns, the relative accuracy due to peak locating would be approximately 0.035 m. A consistent position in the echo must be selected and distortions in the pulse shape due to interference from nearby echoes will cause a bias in the measurement.

Practical experience with a 500 MHz GPR snow thickness system showed that the accuracy of the automatic peak locating software was 0.05 m (Lalumiere, 1998).

3.4 Performance

3.4.1 Antenna size

The size of a GPR system's antenna is a function of the system's centre frequency. A 1 GHz GPR antenna is approximately a quarter the size of a 500 MHz unit but its layer resolution is twice as fine.

From the radar range equation (Annan and Davis, 1977), the received voltage (signal strength) of the radar signal is linearly proportional to the antenna's area. This corresponds to a linear relationship to centre frequency of the radar system. The amplitude of a received radar signal for a 1 GHz system would be half that of the amplitude received with a 500 MHz system (with all other system parameters being the same) as the area of the 500MHz antenna is 4 times larger than the 1GHz antenna.

When comparing systems, the amplitude of the received signal is compared with the receiver noise level. Averaging radar returns from multiple receivers increases the signal to noise ratio (as a voltage) by the square root of the number of receivers. The signal to noise level is improved by lowering the effective receiver noise level by averaging together the radar signals from each receiver. As a result, a 1 GHz GPR system with 1 transmitter and 4 receivers would have the same performance as the larger 500 MHz GPR system (with all other system parameters being the same).

3.4.2 Attenuation versus the Electrical Conductivity and Frequency

Electrical conductivity is a key material property affecting the ability of ground penetrating radar to probe into a given material. The GPR signal attenuates as it travels through an electrically conductive material such as sea ice. The DC electrical conductivity of sea ice is reported to vary from 0.001 S/m to 0.050 S/m (Rossiter et al., 1988). The electrical conductivity is proportional to the sea ice salinity.

The GPR signal also attenuates as function of frequency. Figure 1 (adapted from Rossiter, 1980) shows the combined effects of both frequency and salinity providing GPR signal losses ranging from approximately 1 dB/m to as much as 70 dB/m.

Snow and fresh water ice are low loss dielectric materials. GPR signals will propagate through them with very low attenuation.

3.4.3 Surface Reflections

Reflection and transmission coefficients

Surface losses vary with the dielectric contrast between the adjacent layers. The dielectric contrast determines the reflection and transmission coefficients regulating the signal strength reflecting back off the surface and the signal strength of the penetrating signal. The one-dimensional modeled data shown below in Figures 8 and 9, shows the strong return from the high contrast ice/water (3.2/81) interface and the weaker return from the low contrast air/snow (1/1.5) and snow/ice (1.5/3.2) interfaces.

Flying height and surface conditions

Many ice snow and ice conditions will include surfaces that are too rough for coherent specular reflection (Moray, 1975). Moray reported detection of the sea ice/water interface when the air/ice interface could not be detected when flying above 40 m.

Radar signal losses are also a function of altitude. Annan et al., 1977 provides equations for signal losses as a function of height for smooth, plane, specular reflectors and rough, plane, specular reflectors.

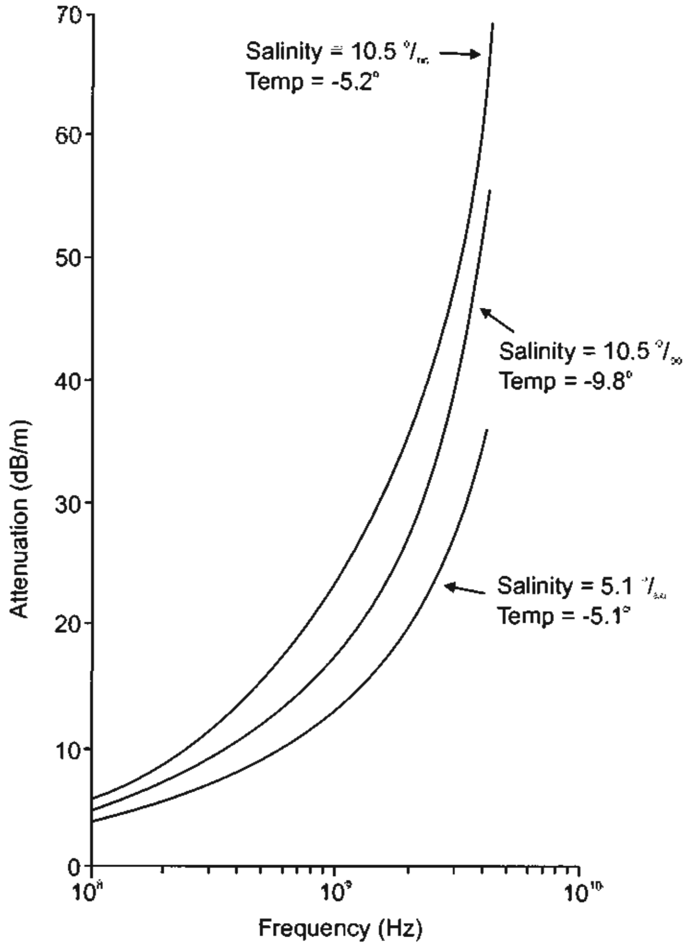


Figure 1 **GPR signal attenuation through ice as a function of frequency and salinity**

Figure 2 (adapted from Moray, 1975) shows the losses versus flying height over a smooth, plane, specular reflector and a rough, plane, specular reflector.

3.4.4 Electrical Anisotropy of Sea Ice

First year sea ice forms with a preferred horizontal c-axis orientation (Lewis et al. 1987). This horizontal anisotropy of the sea ice crystals affects the performance of GPR ice thickness measurements. Echoes with the GPR antennas oriented parallel to the c-axis are strong while echoes with the antenna perpendicular are weak or not even detectable (Rossiter, 1980). As a result, current GPR systems can not reliably profile first year sea ice unless the system has two transmitter-receiver antenna pairs oriented perpendicular to each other.

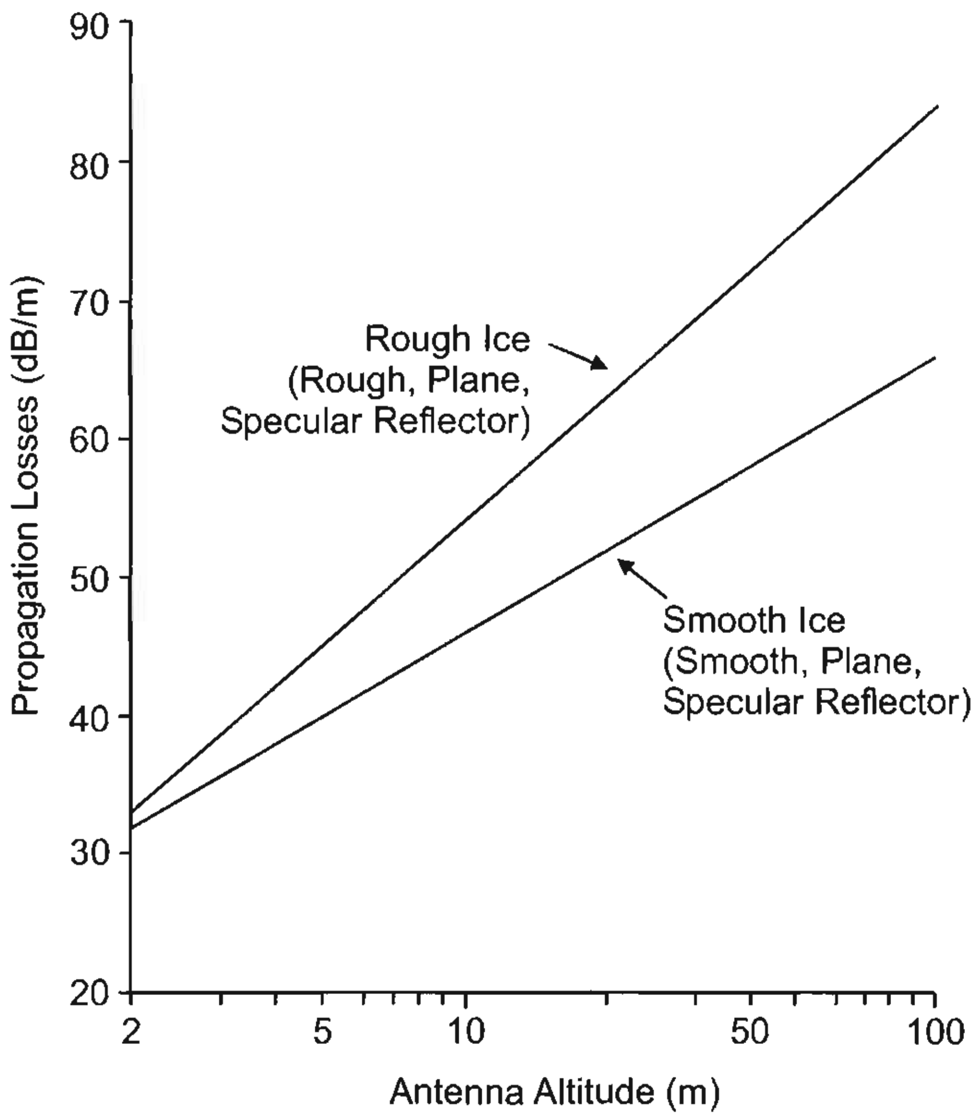


Figure 2 **GPR signal attenuation over a smooth specular reflector and a rough specular reflector as a function of flying height**

3.4.5 Stacking versus operational flying speed

Lowering the receiver noise level can increase a GPR system's performance factor. One method to reduce noise levels is the stacking (averaging) of multiple scans into one to reduce receiver noise by the square root of the number of scans stacked together.

On a helicopter moving at 50 knots, the time required to form the stack will could result in the an average of over an area of approximately 5 m. With current GPR systems, stacking will only be practical on a slow moving or stationary platform.

3.4.6 GPR System Noise

Shielded GPR antennas provide reduced sensitivity to echoes that might come from the back of the antennas. When the GPR antennas are placed near a metal surface the transmitted pulse will reverberate for many tens of nanoseconds.

Previous GPR systems developed for snow thickness operated at a fairly long distance from the ice surface. This provides a lot of time for the reverberations to diminish before the echo from the snow/ice surface would arrive. The new helicopter operating conditions with the *Ice Pic* position the helicopter much closer to the ice surface and as a result these reverberations will play a larger role in overall GPR system performance.

A plot from the 1999 ground tests (page 15 in Lalumiere, 1999b) shows the clean GPR record when the antenna was hand held in front of a metal target. A plot from the 2000 helicopter tests (page 25 in Lalumiere, 2000) shows the added reverberation when the antennas were mounted under the metal helicopter body.

Signal processing can be performed to remove most of the reverberations but this requires a very stable mounting platform and stable electronics. Under these conditions, a background reverberation pattern that is collected at high altitude (approximately 15 m or more) must remain valid when the helicopter is operating at survey altitude.

3.5 Regulatory Control

GPR performance has been restricted in the United States by the U.S. Federal Communications Commission's (FCC) Ultra-Wideband (UWB) regulations. These regulations prohibit the operation of GPR system above the ground. Some GPR manufacturers have had reduce the transmitted power level and increase the shielding of their antennas to get their systems approved for use. Systems sold before the UWB rules came into effect can still be used in the U.S.A.

It is expected that similar rules will come into effect in Canada. The effect of these rules on GPR operation in remote locations is not known.

4 Advanced GPR Processing Techniques

Processing techniques developed for seismic data can be applied to GPR data. Conventional seismic systems have a single source "shot" generator (equivalent to a GPR transmitter) and multiple geophones (each equivalent to a GPR receiver). The seismic industry has benefited from the large rewards from the discovery of oil and gas deposits resulting in the need for complex equipment configurations and continuous advancement in processing techniques. Due to the relatively high costs involved for both GPR equipment and the field time for data collection, GPR systems are generally used with a single transmitter-receiver pair.

With the recent introduction of commercial GPR system's with an antenna array capability and the ability to hard-mount a small array on a helicopter, the equipment and operating costs have been reduced so that a seismic-like hardware configuration is now feasible.

In the report "Review of Impulse Radar Sounding of Sea Ice" (Rossiter, 1980), a list of obstacles to successful airborne sea ice thickness measurements were listed. They are summarized as:

1. Improvements in processing, display and interpretation
2. Observe ice dielectric variability
3. Research types of ice that have eluded successful sounding
4. The effect of horizontal anisotropy of sea ice
5. The need for higher performance systems
6. Reducing antenna beam width

Obstacles 1, 2 and 6 are addressed by applying seismic processing techniques. Obstacle 5 has been addressed with commercial manufacturers now producing higher performance GPR systems with significantly reduced system noise compared with GPR systems available 25 years ago. Future enhancements of commercial GPR array systems will permit averaging across the multiple receivers to lower receiver noise levels.

The problem of the horizontal anisotropy of sea ice (obstacle 4 above) is not addressed with advanced processing techniques. In the past, custom dual-polarized antenna units were developed (Butt and Gamberg, 1980) to solve this problem. As the present system development goals (outlined in the introduction) do not include profiling conductive sea ice, this problem can be avoided for now. If this obstacle becomes important then either custom antennas or a dual array with perpendicular polarization will be required.

The main drawback with current commercial GPR array systems is that they are not configured for stand-alone operation. An operator is required to start logging and data is stored within the GPR control unit on a removable compact flash card.

Examples of the combined effect of the application of seismic processing techniques to GPR (normal moveout processing, velocity analysis and migration) can be found in Fisher et al., 1992 and in Appendix C of Lalumiere, 1999a.

4.1 Layer Velocity and Thickness Determination

With a single transmitter-receiver antenna unit, the velocity of the radar wave in snow and ice must be estimated. Typically, the velocity values are determined by manually probing for snow depth and drilling holes in the ice. The area where the manual measurements were taken is then survey with the GPR system. The manual thickness measurement is divided by the GPR travel time to obtain the radar velocity in the snow and ice at one particular surface position.

As the velocity in the snow and ice changes with location and temperature, the ground calibration measurements are valid for a limited time and area. An automated technique to determine the radar velocity in ice and snow will make ice and snow thickness practical and provide greater accuracy.

The automated technique requires a special GPR antenna array configuration along with normal moveout processing, velocity spectra processing and the application of the Dix equation. The steps for developing software to perform these steps can be found in Taner and Koehler, 1969.

4.1.1 WARR GPR Configuration

A Wide Angle Reflection and Refraction (WARR) survey has a transmitter at a fixed location with receivers placed at a number of offsets from the transmitter. A sketch of a WARR survey with 1 transmitter position and multiple receiver locations is shown in Figure 3. For each transmitter-receiver offset the radar signal travels a different travel path through the underlying layers.

In 1991, a field trial was undertaken for a snow thickness radar system for the TDC ice thickness sensor prototype (Lalumiere, 1992). Data collected during that field trial included airborne profiles and land profiles and WARR surveys. Figure 4a) shows a plot of a WARR survey taken on the snow bank on the side of the ice road near Tuktoyaktuk. Figure 4b) is an annotated version of the same plot.

4.1.2 Normal Moveout Processing

Normal moveout (NMO) processing uses the WARR survey data and processes a GPR scan for each transmitter-receiver offset. A range of velocities (from the lowest expected velocity to the highest expected velocity) are used for each antenna offset. When the velocity is correct for a given layer, the echoes for each antenna offset will align horizontally. Figure 5 shows a plot of a normal moveout for a test velocity that closely matches the actual velocity.

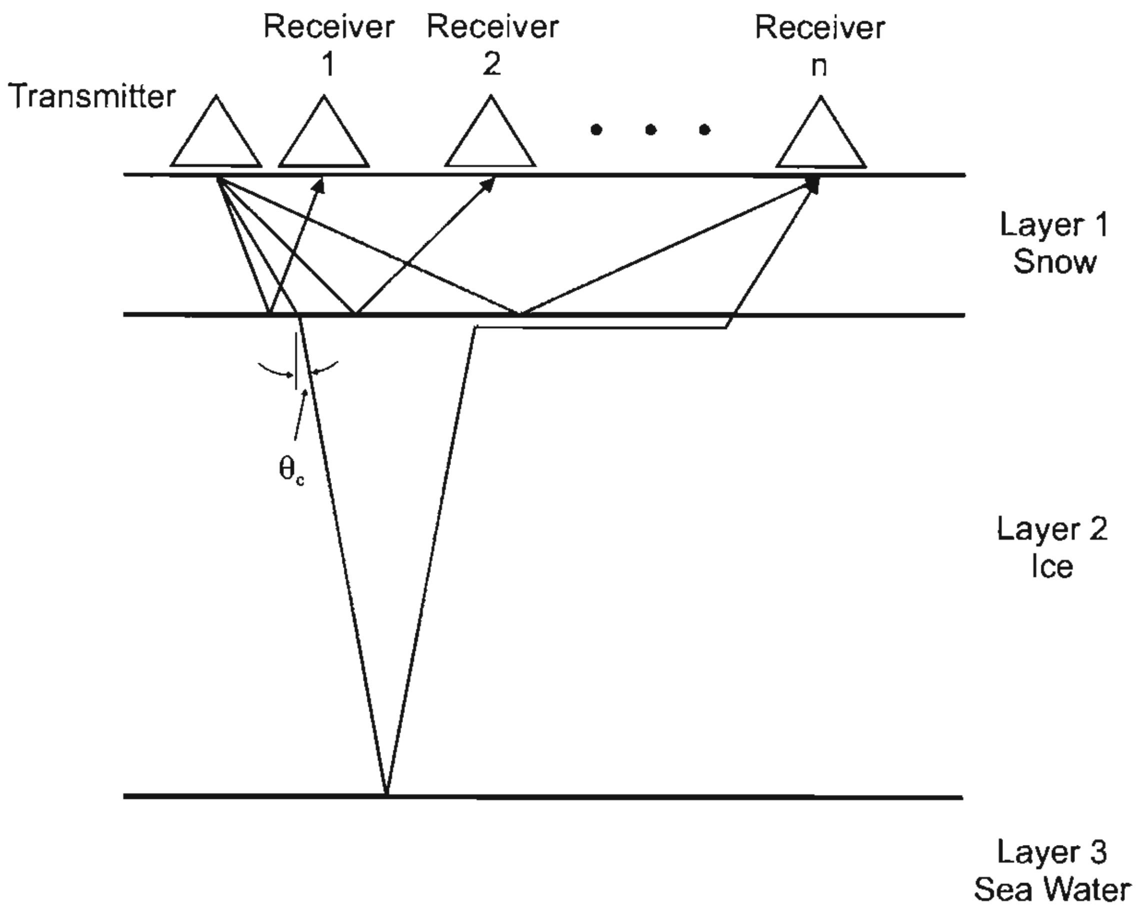


Figure 3 A sketch of the GPR antenna configuration for a WARR survey

Normal moveout processing highlights direct reflections from each layer and attenuates direct airwaves, direct ground waves and multiple reflections. The greater the number of receivers that are available, the greater the correlation gain provided by the normal moveout processing.

4.1.3 Velocity Spectrum

A velocity spectrum produces a two-dimensional data set that has maximums where a given velocity has aligned all the echoes for a given layer from each antenna offset to maximize the echo strength. A plot of the velocity spectrum is shown in Figure 6. The two areas with dark responses indicate the correct velocity for the snow and the average velocity through the snow and ice. The determined velocities and the time for each layer's dark response are used to measure layer thickness using the Dix equation as described in the next section.

Automatic processing can be employed to search for the peaks in the velocity spectrum results to determine the travel time and the corresponding average velocity to each layer.

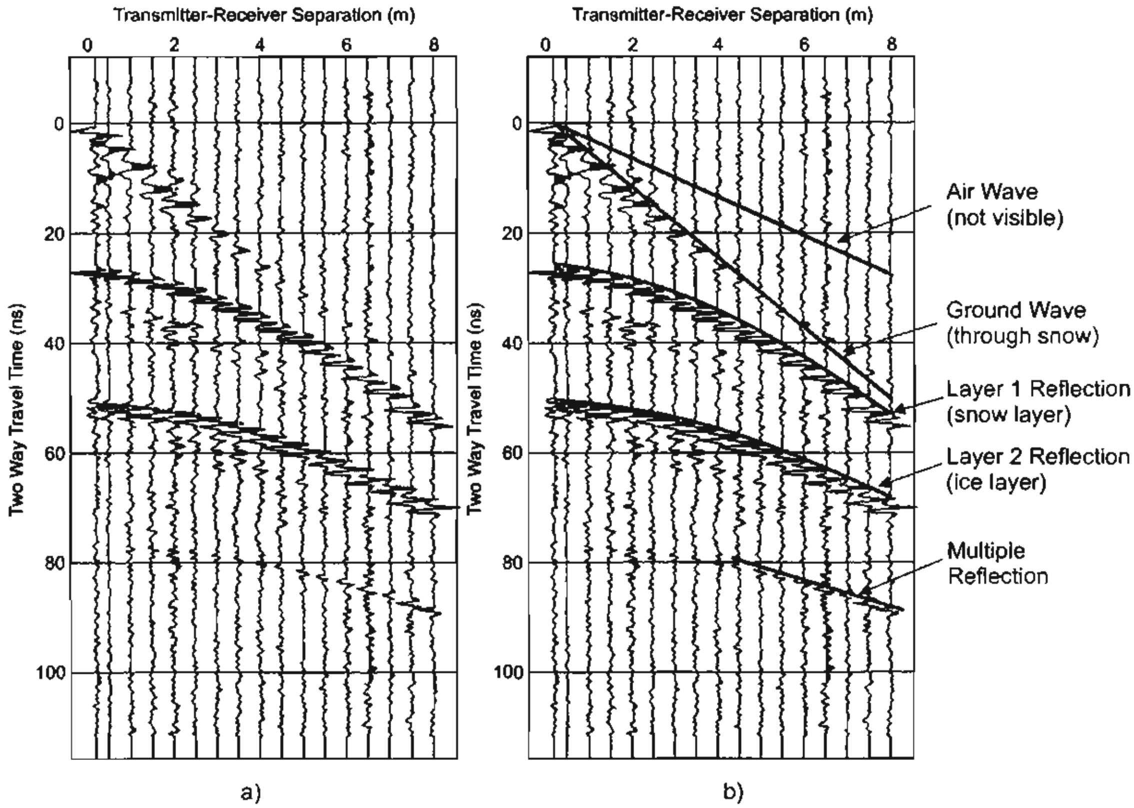


Figure 4 a) WARR survey on the ice road near Tuktoyaktuk
b) Annotated version

4.1.4 Determining the Layer Thickness

The Dix equation (Eqn. 1) is used to convert the average velocity from the antenna to each layer to the individual layer velocity. In the case of two layers, the equation is applied once using the velocity for the first layer and the average velocity over the two layers taken from the velocity spectrum.

$$v_i^2 = \frac{\tau_i V_i^2 - \tau_{i-1} V_{i-1}^2}{\tau_i} \qquad \text{Eqn. 1}$$

where:

τ is the time between each layer (i)
V is the average velocity from the antenna to each layer (i)
v is the velocity within each layer (i)

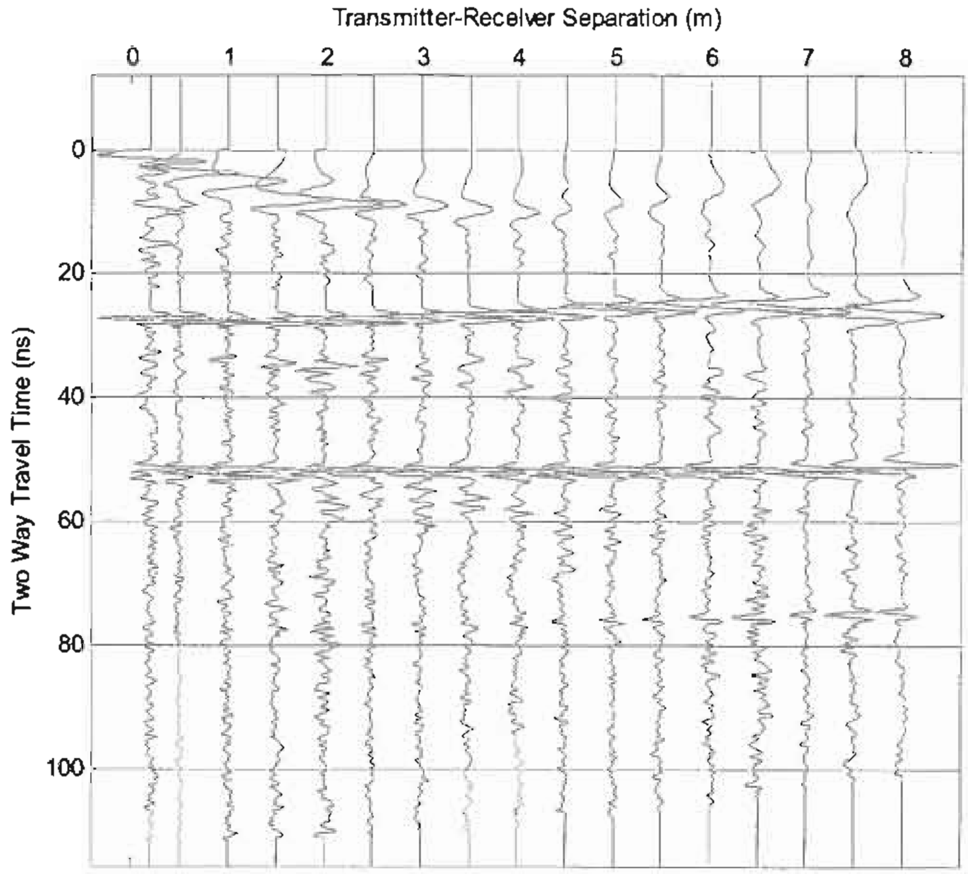


Figure 5 **Normal Moveout plot using a velocity of 0.16 m/ns using the 1991 Tuktoyaktuk ice road WARR**

Layer thickness can be determined at this point from the layer travel times between each layer and the individual layer velocities.

The dielectric constant for each layer can be by the following equation.

$$k_i = \left(\frac{c}{v_i} \right)^2 \qquad \text{Eqn. 2}$$

where c is the speed of light in free space.

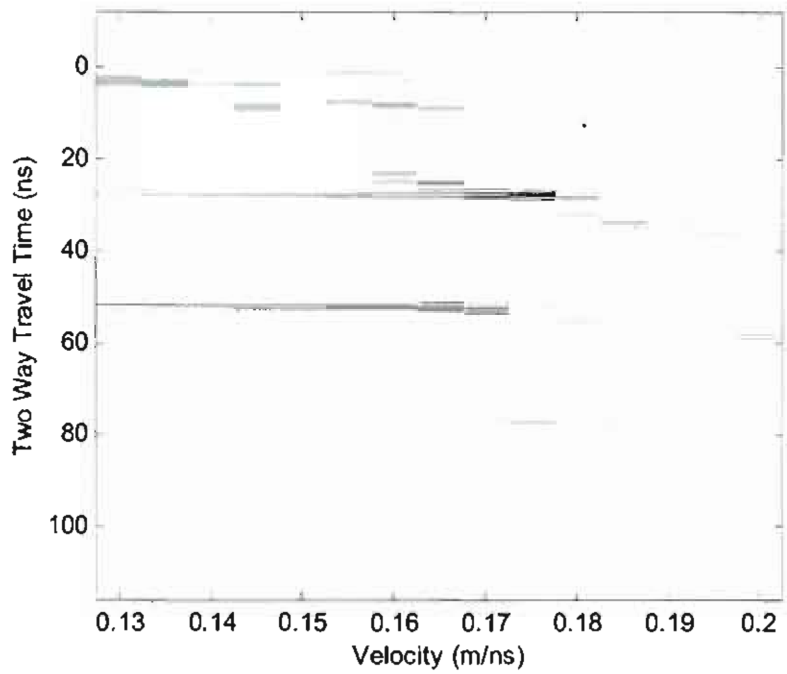


Figure 6 Velocity Spectrum using the 1991 Tuktoyaktuk ice road WARR

4.2 Migration Processing

One of the obstacles mentioned at the beginning of this section is the need to reduce the antenna beam width. The surface footprint of a GPR system is approximately equal to flying height. Point targets on the surface are seen well ahead and behind of an airborne GPR system.

A point target on the surface produces a series of echoes over a number of GPR traces along the GPR profile. The echo series appears as a hyperbola with the top of the hyperbola appearing at the point when the GPR system is directly over the point target as seen in Figure 7. Echoes coming from the point target before and after the GPR system crosses overhead come at a time later than echoes from the surface. This causes confusion for automatic snow and ice thickness processing routines as there are the echoes from the bottom of the snow (and perhaps the bottom of the ice) and the echoes from the hyperbolic response of the point target to process.

Migration processing uses the two-dimensional nature of a GPR profile to reduce the hyperbolic returns obtained from point scattering targets (rubble fields, ridges, and edges of rafted ice) into a single small response at one along track position and at one time. This effectively narrows the GPR system's antenna beam width.

Migration processing requires a model for layer velocity and thickness for each along-track GPR data point. The seismic approach (demonstrated with GPR data in Fisher et al, 1992) uses the WARR survey data collected at each profile point to develop a velocity and layer location model automatically. When a single transmitter-receiver antenna unit is used, the layer velocities and locations must be estimated manually.

5 GPR Configuration Options

5.1 Issues for Snow and Ice Thickness Measurement

The main issues for snow and ice thickness measurement are:

1. Automatic processing
2. Stand alone operation
3. GPR velocity in snow and ice
4. Surface roughness/ice types
5. Sea ice conductivity and anisotropy

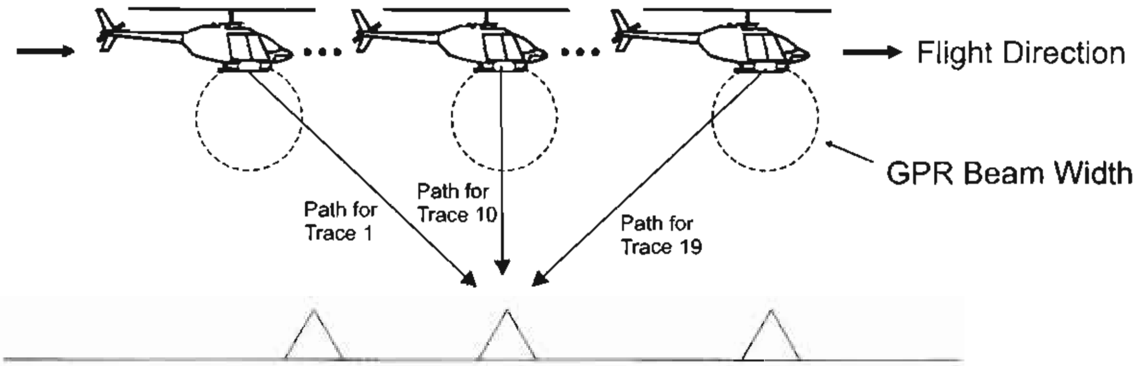
Automatic processing requires techniques to locate the top of the snow layer and the snow ice interface and to know when only ice is present. GPR system performance specifications limit minimum snow layer thickness and the maximum ice layer thickness.

For stand alone operation, the GPR system is required to start automatically when power is applied and output data by a communications link. Most commercial GPR systems require that an operator push buttons to configure the GPR unit and to start and stop logging.

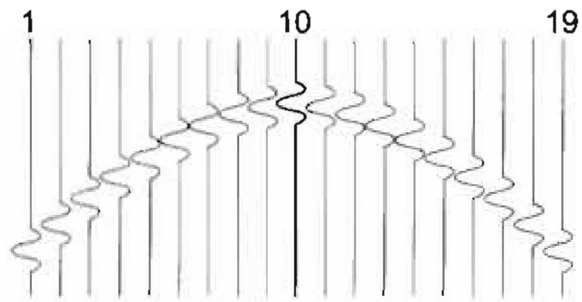
As GPR units provide the time to the return echoes, echo times are converted to layer thickness by multiplying by the velocity in the layer. Incorrect estimates for the velocity give incorrect layer thickness measurements.

A rough ice surface provides many surface reflectors, which produce echoes that clutter up the GPR response. A GPR antenna has a broad beam width (approximately equal to flying high) and reflectors not directly below the GPR antenna will still produce an echo. The echoes from the side will arrive at a later time than the echo from the top surface (either snow or ice). This results in confusion between the echo from surface clutter and the echo from the snow/ice interface or the ice/water interface.

For the measurement of sea ice thickness, the electrical conductivity level and anisotropy of the ice will determine whether or not the GPR system will be able to penetrate the sea ice and provide an observable echo from the sea ice water interface.



a) Sketch of an Airborne GPR Profile



b) Hyperbolic GPR Response over a Point Target

Figure 7 Sketch of Airborne GPR Profile flying over an ice rubble field. Plot a) shows the helicopter passing over a point target on the ice surface. Plot b) shows the hyperbolic GPR response for the point target.

5.2 The Previous Snow Thickness Sensor Developed for Ice Probe

The snow thickness sensor developed for the Ice Probe system attempted to meet the first 2 points above. Automatic processing detected the top two echoes and applied a predetermined value for the velocity of the radar signal in snow. The processing results were valid only over smooth snow and ice surfaces and undetermined results would be obtained when flying over ridges, rafted ice or rubble fields. The unit operated in a stand-alone configuration and it used a modified version of Video/Laser system logging system to display the results. When at high altitude, the operator was required to press a button on the Video/Laser System software to tell the radar unit to collect a new background average to remove system noise.

5.3 A New Snow Thickness GPR System - Single Transmitter - Single Receiver Antenna Unit

A new single antenna unit snow thickness system would build on the capability of the previously developed system described above.

Improvements could include:

- A higher centre frequency to provide finer layer measuring capability. By operating at a lower altitude, the system can trade off system performance for greater resolution.
- A commercial GPR system is now available for incorporation into a real-time snow thickness sensor. Sensors and Software's Noggin OEM (Original Equipment Manufacturer) GPR units can be operated using custom software.
- Provision for the snow thickness sensor controller to accept a laser altimeter height measurement for automatic triggering of the collection of a background average.
- The signal processing could be enhanced to do a two-dimensional layer tracking to reduce the number of erroneous snow thickness readings.
- With GPS position information, migration processing (as discussed in Section 4.2) could be applied the GPR profile to reduce the echo strength from radar scattering targets on the surface. The migration processing would provide limited improvement as the values such as accurate velocities and layer thicknesses (obtained from WARR processing) would not be available.

The thickness measurement of low conductivity ice may also be possible with the single transmitter – single receiver configuration. This would be possible with the helicopter flying low over the snow/ice surface. During the 1991 trial, the ice road on the Mackenzie River delta near Tuktoyaktuk was profiled from the air and on the surface with a 500 MHz GPR system. The surface-based profiles and the airborne profile (see Appendix A) show echoes from the bottom of the ice.

This system could provide automatic data collection, but the operator is required to provide a radar velocity estimate for snow and ice. The ability of automatic processing to filter out echoes from surface clutter is unknown at this time so the operator may be required to determine when the results are valid.

5.4 Expected Results based on Modeling

Modeled GPR profiles were created for a surface-based and airborne GPR system using 500 MHz antennas. Figure 8 shows the surface-based profile and Figure 9 shows the airborne profile. The model is based on the GPR range equations provided in Annan and Davis, 1979. The model calculates echo return strength based on the distance to each layer and the reflection coefficient at each layer. The model also includes some multiple reflections.

Layer thicknesses along the profile are shown in Table 1. The dielectric constant for snow was chosen to be 1.5 and the dielectric constant for ice was chosen to be 3.2. The ice conductivity was very low. For the airborne profile, the flying height over the ice layer is held at approximately 5 m.

5.5 A New Snow/Ice Thickness GPR System - Single Transmitter - Multiple Receiver Antenna Unit

In addition to the improvements for the single antenna GPR unit mentioned in the above section, additional performance improvements for a GPR system configured as a WARR array could include:

- The automatic estimation of layer velocity and layer return times
- Reducing the effect of surface scatters by using migration to narrow the antenna beamwidth
- Calibration of time zero and window length

Combined, these improvements greatly increase the accuracy of snow and thickness measurements.

Also, an airborne WARR array has the advantage over a ground WARR performed with only one transmitter and receiver. As the geometry for the airborne system is fixed, system noise can be subtracted before coming down to the surface to make the measurements.

Table 1 - Layer Thicknesses for the Modeled GPR data

Section Number	Snow Thickness	Ice Thickness	WARR #
1	2 m	2 m	4
2	1 m	2 m	3
3	0.3 m	2 m	2
4	0 m	2 m	1
5	0 m	0.3 m	5
6	0.3 m	0.3 m	6
7	1 m	0.3 m	7
8	2 m	0.3 m	8

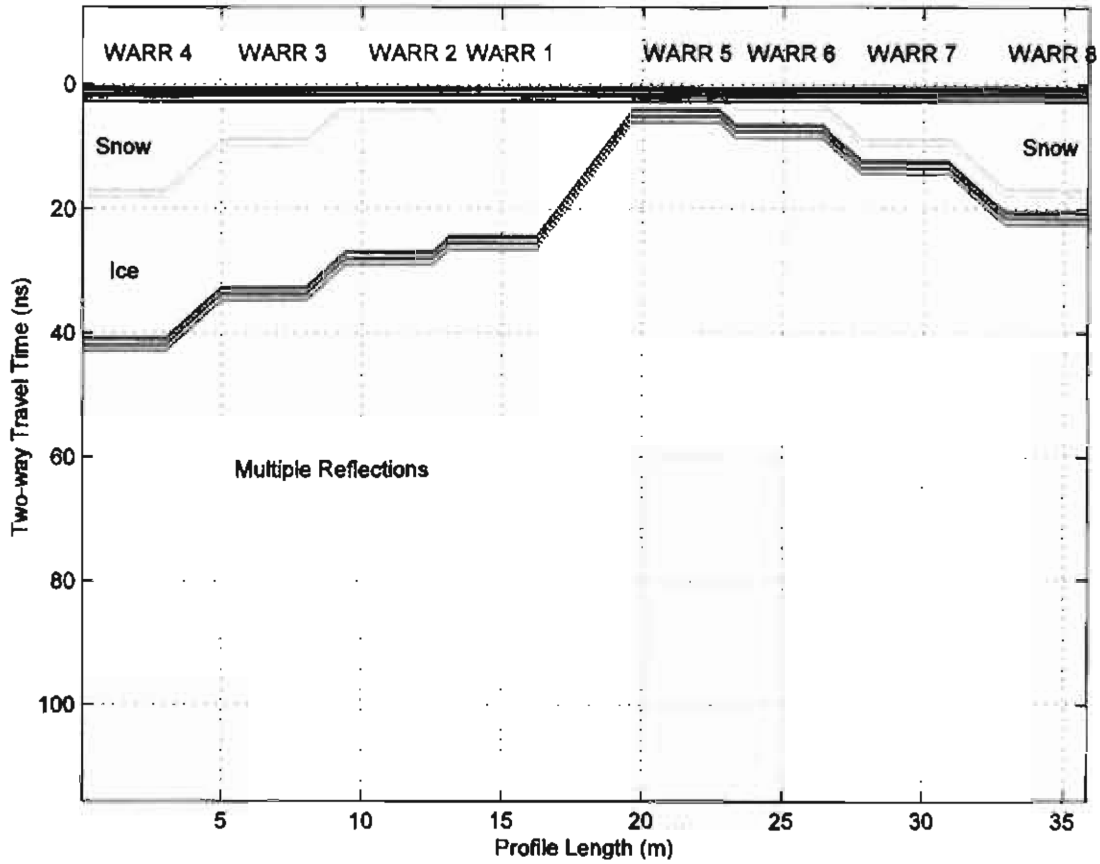


Figure 8 Modeled data for a surface-based GPR system using 500 MHz antennas.

5.6 WARR Array Configuration

The WARR array system configuration is specified by the number of receiver antennas and the distance between the transmitter antenna and each receiver. The greater the number of receivers that are available, the greater the improvement (the correlation gain) provided by the normal moveout processing. For the best-case scenario, the correlation gain is equal to the number of receivers in the WARR array.

The best separation spacing for a WARR array has the echoes positioned so that the normal moveout processing results will maximize the reflected response from each layer and minimize unwanted radar echoes arriving from direct airwaves and multiple reflections.

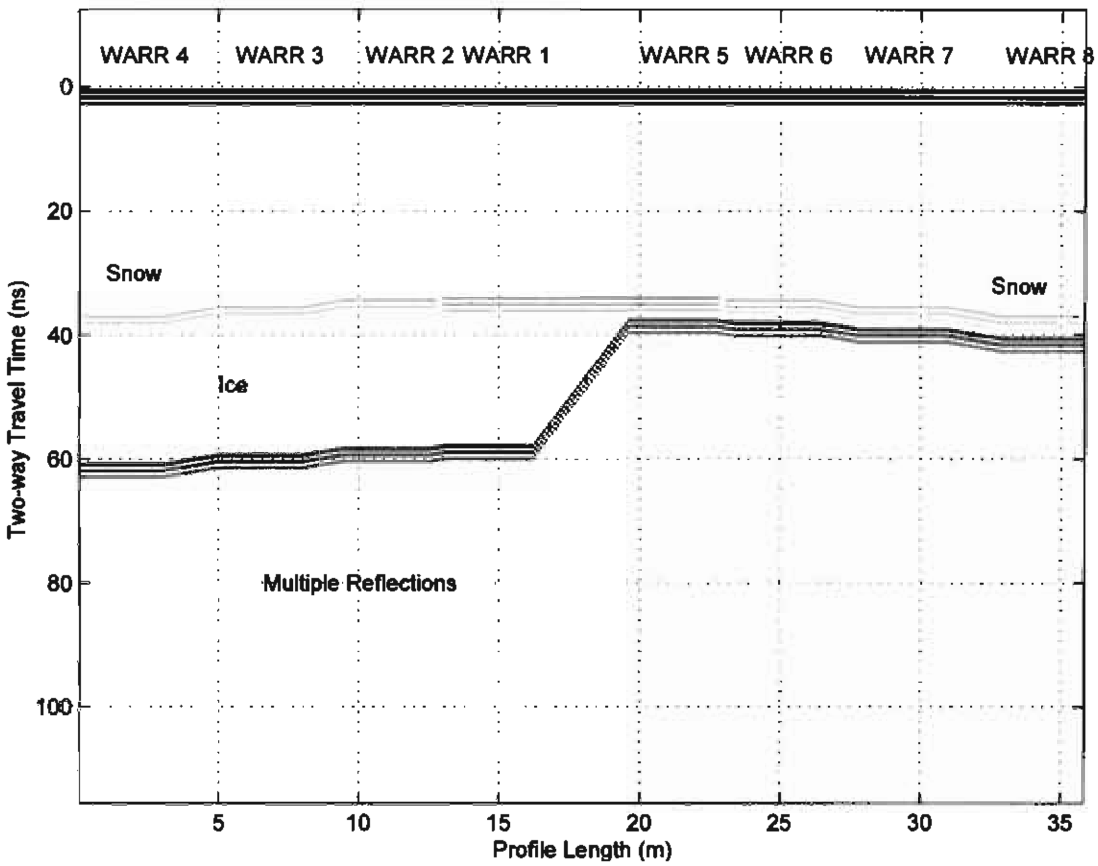


Figure 9 Modeled data for an airborne GPR system using 500 MHz antennas. Flying height maintained at 5 m over the ice surface

5.6.1 Expected Results based on Modeling

Figures 10 and 11 compare the responses from surface-based and airborne WARR configurations. The snow and ice conditions for each plot in these figures are listed in Table 1 above. These figures plot the arrival time versus antenna separation. Figure 8 and 9 above show the surface-based and airborne single-antenna profiles using the same snow and ice conditions.

The MATLAB-based modeling software consists of models to generate the airwave, the ground wave (for the surface-based WARR only), the reflection from the bottom of the first layer and the reflection from the bottom of the second layer. This model does not incorporate spreading losses or losses due to high ice electrical conductivity. The model uses the dielectric constant to determine when the antenna separation reaches the critical angle for a smooth specular reflector.

Suggested WARR Configuration

Symbols are placed on the plots in Figure 10 and 11 to indicate the antenna separation where the received echo is one pulse length later than the zero-offset location. An o is used to indicate when the echo is delayed 1.5 ns for a 1 GHz system and an x is used to indicate when the echo is delayed 3 ns for a 500 MHz system.

For an airborne WARR system flying at 5 m, the modeling results suggest that the minimum separation of the transmitter to the outer-most receiver is 3.2 m for a 1 GHz system and 4.6 m for a 500 MHz system.

For a ground-based WARR system, the modeling results suggest that the minimum separation of the transmitter to the outer-most receiver is 2.2 m for a 1 GHz system and 3.2 m for a 500 MHz system.

The greater the number of receivers that are placed between this overall transmitter-receiver separation, the greater the noise canceling performance of the array but with increased system cost. Based on the author's experience with ground-based WARR arrays, it is expected that the minimum receivers would be 4.

Critical Angle Effects

In Figures 10 and 11, the echoes for separations beyond the critical angle point are plotted in red. With a real WARR survey the echo reflection continues to be visible beyond the point when the critical angle has been reached. This suggests that the interface layer is not a smooth specular reflection. Field collected WARR surveys over snow and ice have shown that a critically refracted ground waves begin to appear with a transmitter-receiver separation of 8 m or more. When this point is reached, the slope of the response from a layer switches from the hyperbolic response of the normal reflection to the slope of the critically refracted ground wave.

Comparing Figures 10 and 11, the critical angle for the ice layer in the surface-based WARRs is reached with a smaller antenna separation than in the airborne WARRs. For a surface-based WARR array, the antennas are directly on the snow or ice surface. When the snow layer is thin, the radar signal travels mostly through ice and reflects of the ice/water interface. The large dielectric contrast between the ice and water results in a large critical angle, which is reached with relatively small antenna separation. For the airborne WARR, the air/snow/ice layers provides some impedance matching from air to the ice/water interface significantly reducing the critical angle.

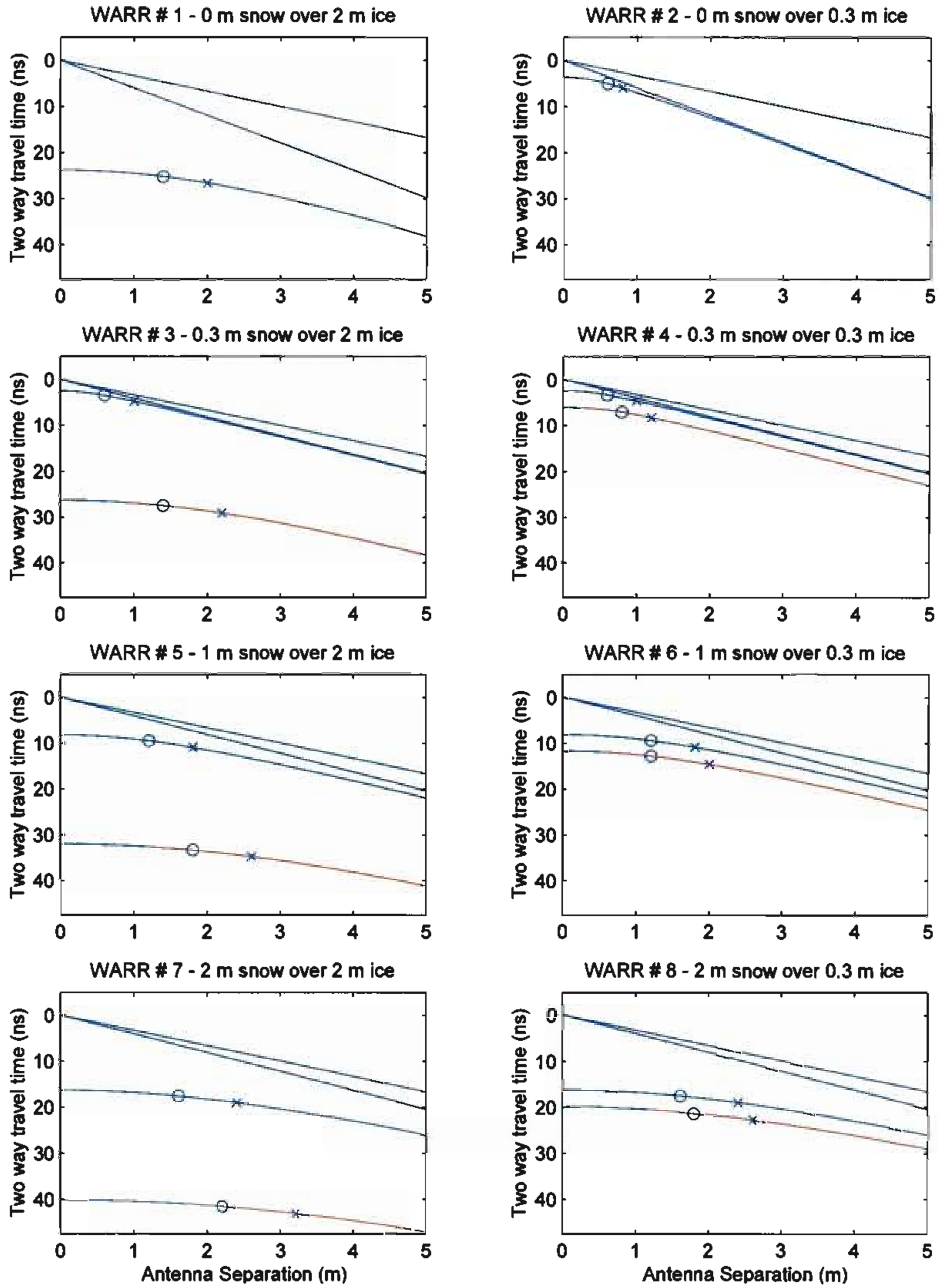


Figure 10 Modeled WARR data for a surface-based GPR system

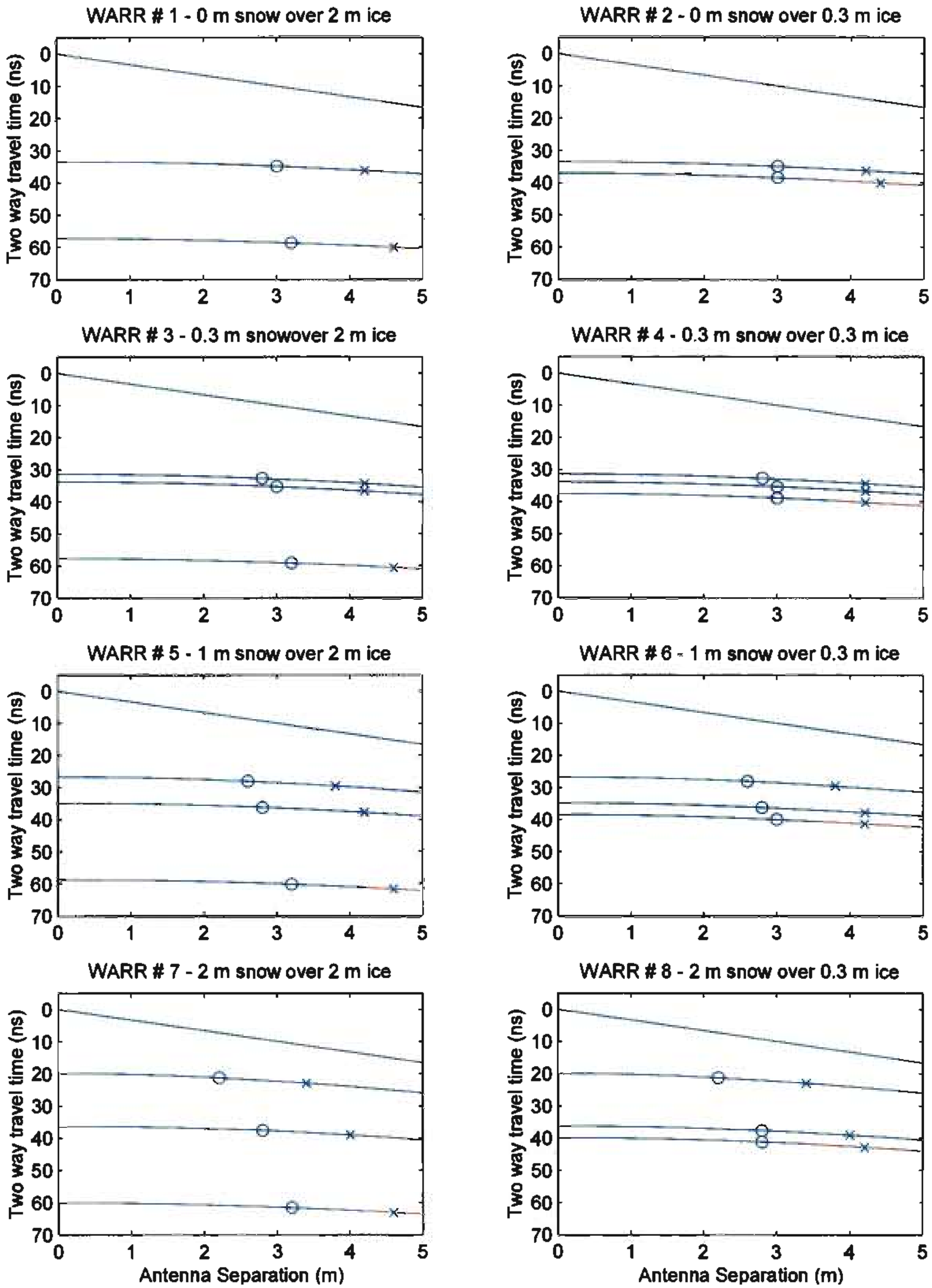


Figure 11 Modeled WARR data for an airborne GPR system

6 Commercial GPR Manufacturers

There are three commercial GPR Manufacturers, Geophysical Survey Systems, MALÅ GeoScience and Sensors and Software. The report for the 1999 helicopter hard-mount system (Lalumiere, 1999a and Lalumiere, 1999b) compared the GPR systems from these manufactures on the ground and in the air. The new capabilities of importance to this study are Sensors and Software's Noggin 1000 OEM unit and their multi-channel pulseEkko Pro unit.

Geophysical Survey Systems Inc.

12 Industrial Way
Salem, NH 03079 USA
Tel: 603-893-1109

Web site: http://www.geophysical.com

The shielded antenna units available from GSSI have not changed since the 1999 hard-mounted GPR system report (Lalumiere, 1999a).

MALÅ GeoScience AB

Based in Malå, Sweden
Web site: http://www.malags.com

Canadian Distributor
Terraplus Inc.
52 West Beaver Creek Road, Unit #12
Richmond Hill, Ontario, Canada, L4B 1L9

Tel: 905-764-5505

Web site: http://www.terraplus.ca

The shielded antenna units available from MALÅ have not changed since the 1999 hard-mounted GPR system report (Lalumiere, 1999a).

Sensors and Software Inc.

1040 Stacey Court
Mississauga, Ontario
L4W 2X8

Tel: 1-800-267-6013

Web site: http://www.sensoft.ca

Since the 1999 hard-mounted GPR system report (Lalumiere, 1999a), Sensors and Software has release several new GPR systems. Appendix B has photographs of the Noggin 1000 OEM system and the pulseEkko Pro 1000 system. Appendix C has the brochures for these units.

6.1 Product Summary

6.1.1 For a Single Unit Snow Sensor

The three main commercial GPR manufacturers provide GPR systems in the 800 MHz to 1 GHz range. This high frequency range appears to be the most desirable as it give the ability to resolve finer snow thickness layers compared with the previous snow sensors developed for the *Ice Probe* System.

All three manufacturers produce antenna units with the receiver antenna and transmitter antenna in a single package. For the single antenna package, the Sensors and Software Noggin 1000 OEM unit would be the most advantageous as custom software can be used to control the unit and log the data. All other systems require the operator to press buttons on the control unit to start data collection.

The dimensions of the Noggin 1000 OEM unit are 30 cm by 15 cm by 11 cm. and its weight is 2.3 kg. This unit would have no trouble fitting in any convenient location in the *Ice Pic* boom. A small view port in the carbon-fibre tube will be required.

The approximate cost of a Noggin 1000 OEM unit is $US 20,000.

6.1.2 For a Multiple Antenna System

All three manufacturers produce units with multi-channel data collection capability.

The systems from each manufacturer differ in several ways. The GSSI and Mala multi-channel units work only with single transmitter/receiver pairs, while the Sensor and Software pulseEkko Pro model has individual packaging for the transmitter antenna and the receiver antennas. A multi-channel pulseEkko Pro system can be configured with 1 transmitter and up to 7 receivers.

None of the multi-channel units come in OEM versions and require either their own operating software on a laptop or their own logging/control unit.

GPS position and time information can be recorded by the logging systems for these units for post flight merging of the GPR data with Video/Laser or *Ice Pic* system data.

The dimensions of a single pulseEkko Pro 1 GHz antenna are 15 cm by 15 cm by 12 cm and its weight is less than 1 kg. A WARR array system with 4 receiver antennas spaced over a maximum distance of 3.2 m from the transmitter would fit inside boom sections 21 and 22 (see Figure 12).

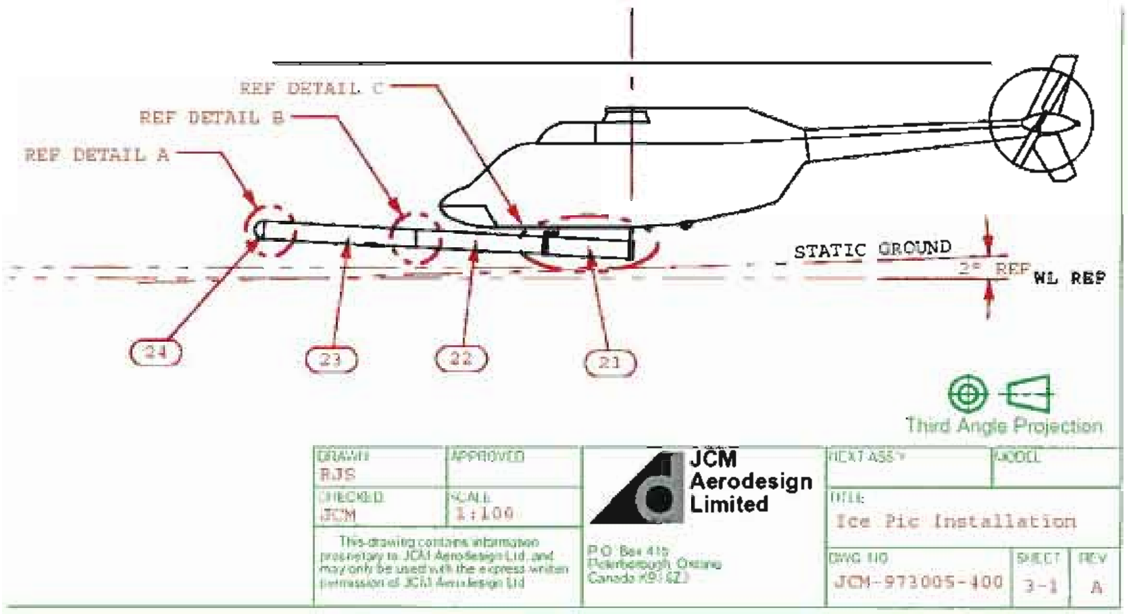


Figure 12 Ice Pic Helicopter Boom Mount

The approximate cost of a multi-channel pulseEkko Pro unit with 1 transmitter antenna and 4 receivers is approximately $US 45,000.

7 Conclusions

A Sensors and Software Noggin 1000 OEM unit would be appropriate for snow thickness measurement with improvements in the accuracy of the results when compared with the snow sensor developed for the *Ice Probe* system.

A field trial with a rental unit will be needed to prove the feasibility of a snow and ice thickness sensor based on the Noggin 1000 OEM unit due to the following factors:

- Its actual performance over snow and fresh water ice needs to be proven
- The performance improvements using new implementation and processing techniques need to be demonstrated
- The GPR antenna will likely be mounted within a tube made of conductive material and underneath the metal skin of a helicopter

- It will be operating near an EM-induction system which has cause some interference with GPR systems in the past (Lalumiere, 1992) but the interference was minimized for a later field trial (Prinsenberg et al., 1993)

To obtain a greater level of snow and ice thickness performance over a wider range of surface conditions, a field trial with a helicopter WARR array should be performed, as the author is unaware of any previous airborne GPR in a WARR configuration. The University of Manitoba has offered the use of their multi-channel pulseEkko Pro unit (personal communication with Bob Hodgson). This system has a one 1 GHz transmitter and one 1 GHz receiver. Extra receivers could be rented from Sensors and Software for a fairly low cost. A borrowed (or extra) non-conductive *Ice Pic* boom section 23 would be required to mount the WARR array with a 2 m total separation.

For real-time measurement, an updated version of the snow thickness signal processing will be needed. It is expected that the Video/GPS laptops will log the GPR data to start with. These laptops may even have enough available processing performance to provide a real-time snow thickness result.

8 References

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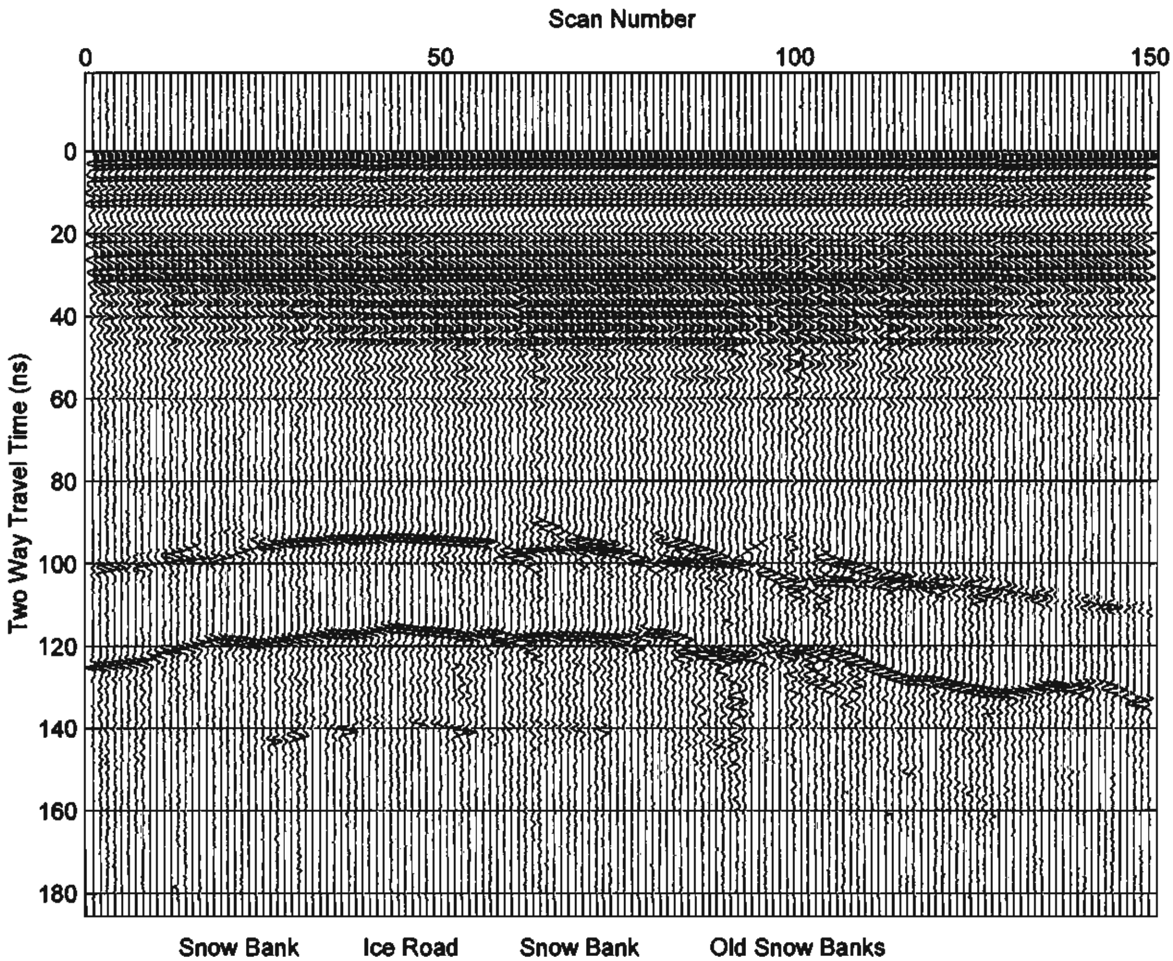
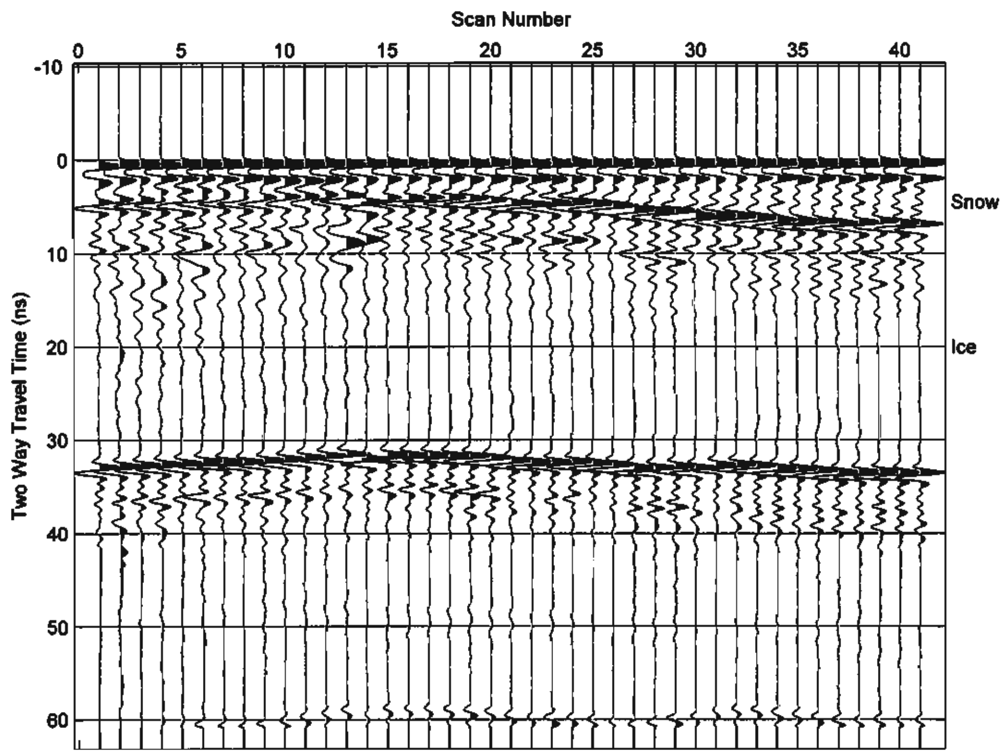
Appendix A - Plots of Past Results

Plots of Ice and Snow in the Vicinity of the Ice Road near Tuktoyaktuk

Airborne Profile



Surface Profile - Over Snow near the Ice Road



Appendix B - Photographs of GPR Equipment by Sensors and Software

The Noggin 1000 OEM system

The pulseEkko Pro 1000 system

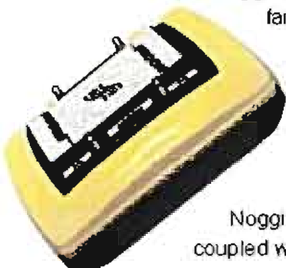
Appendix C Sensors and Software brochures

NOGGIN®

by Sensors & Software Inc.

subsurface imaging solutions

NOGGIN®

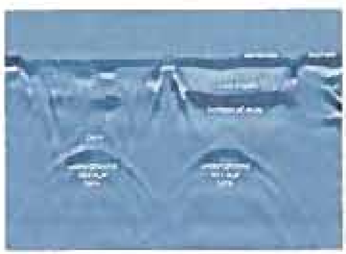


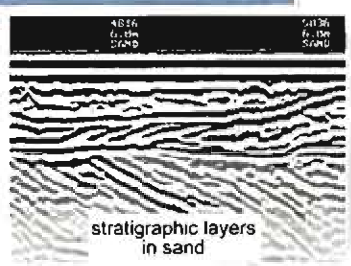
Noggin® subsurface imaging instruments are a fast, affordable and easy-to-use family of Ground Penetrating Radar (GPR) systems from Sensors & Software Inc. The rugged, weather-proof assembly combined with low power, compact, cutting edge digital electronics make Noggin® the most advanced GPR system ever developed. Experience from years of practical field operations has been exploited to enhance the functionality and simplicity of Noggin®.

Noggin® provides subsurface image output directly in digital form. Whether coupled with a PC using SpiView® or operated with a Digital Video Logger (DVL), the subsurface images appear in real-time and are recorded for scroll-through review. Printing hard copy or exporting data images to include in reports is quick and easy. All systems provide marker input as well as time and date stamps on each record.

The basic Noggin® family provides the convenience of "point and shoot" operation. The systems are designed to make you productive immediately. Once you try a Noggin® you will never do a GPR survey any other way.

NOGGIN® Applications





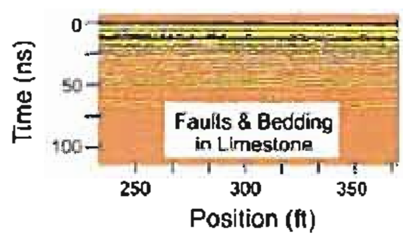
Use your Noggin® for: **Forensic & Archaelogy** **Geotechnical & Environmental**

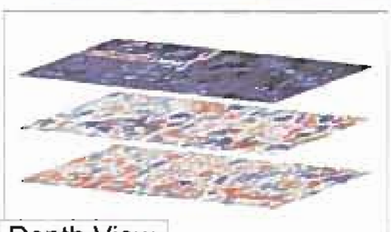
NOGGIN^{plus}

The Noggin^{plus} family of subsurface imaging instruments extends the power of the Noggin® group. All Noggin® systems acquire data and timing information in digital form internally. Noggin^{plus} systems are enhanced to export the raw digital data. To fully exploit the power of Noggin^{plus}, use a Sensors & Software Inc. DVL system to control, display, and record data.

Noggin^{plus} is designed for the professional GPR user who needs fast and simple operation combined with full digital data acquisition for enhanced imaging. Combine Noggin^{plus} with a SmartCart™ or SmartHandle™ system to rapidly create maps and 3D visualizations using EKKO_Mapper, EKKO_Pointer and EKKO_3D Windows based software.

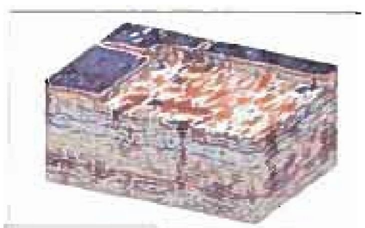
NOGGIN^{plus} Applications





Depth View

2D and 3D views of Old Foundations



3D View

Mining & Quarrying **Buried Utilities** **Structure Assessments (NDT)**

Systems and Peripherals

SmartCart™

The SmartCart™ provides the perfect platform for rapid surveying The collapsible cart is constructed from tough fiberglass components With quick release removable wheels and a fold down handle, the SmartCart™ is easily loaded into a vehicle or neatly stored The integrated DVL, battery and wheel odometer make controlled surveys easy. From arrival on site to beginning surveying, start up time is less than a minute The computer managed power system allows survey operation all day using a single rechargeable battery Integrated data management makes surveying of grids for maps and 3D visualization quick and easy Downloading data to a PC or making hard copy records directly to a printer are standard features of the integrated system software

SmartHandle™

The SmartHandle™ provides a compact platform for surveying in confined areas with a Noggin® Building on Sensors & Software Inc.'s ergonomic designs, the integrated odometer and intelligent control button, light indicators, and beeper accelerates remote data acquisition A SmartHandle™ system includes the same DVL data acquisition and power management features as the SmartCart™

DVL (Digital Video Logger)

The DVL provides for control, display and recording of data for the family of Noggin® systems The robust, waterproof package enables easy survey operation in any weather condition The wide temperature range, high contrast, sunlight visible LCD screen makes outdoor operation practical No more squinting at screens through tunnel hoods to see your data in the field Large capacity data storage, easy integration with peripherals, and support of GPS operation make the DVL an indispensable part of the Noggin®

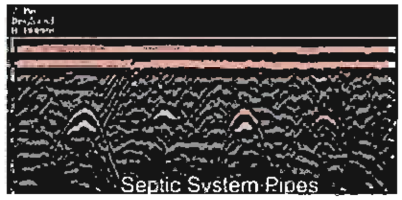
*Sensors & Software offers a complete range of accessories that complement the Noggin® family of GPR systems From shipping cases to battery packs to cables, visit www.sensoft.ca or contact us to find out more

Military, Law Enforcement & Espionage   Bio Applications   Snow & Ice

Software

SpiVIEW ®

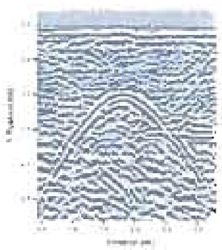
SpiView™ turns a DOS-based PC into a control, display, printing, and data storage system for the Noggin® family. Simple time-based operation of Noggin® with on-the-fly gain, depth, colour, and speed adjustments make for an inexpensive entry to the exciting GPR field.



NOGGIN^{plus}

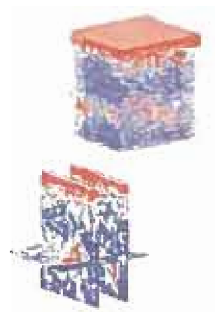
EKKO_View

For Noggin^{plus} users with raw digital data, EKKO_View provides a powerful Windows® based data editing, display, and plotting capability. EKKO_View acts as a pre-processor for the EKKO_Mapper, EKKO_3D and EKKO_Pointer imaging software modules.



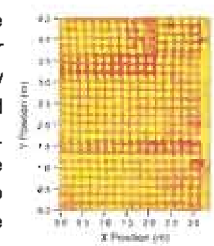
EKKO_3D

EKKO_3D provides 3D visualization of GPR grid data obtained using the SmartCart™ or SmartHandle™ Systems. EKKO_3D enables fascinating 3D slice, cube, and chair presentations and movies to be created quickly and easily.



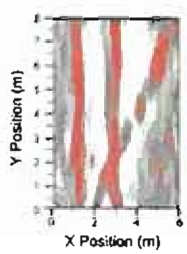
EKKO_Mapper

EKKO_Mapper converts the Noggin^{plus} SmartCart™ or SmartHandle™ grid survey data into GPR time and depth slice maps. The DVL and Noggin^{plus} output merge seamlessly into EKKO_Mapper to enable rapid map creation. Map outputs ease the understanding of complex 3D structures.



EKKO_Pointer

EKKO_Pointer uses pattern recognition to identify localized target responses in GPR data and creates a statistical output representation. Output aids in identifying features such as pipes and cables. Processing is highly automated and operates on the same grid data sets used by EKKO_Mapper and EKKO_3D.



NOGGIN® Technical Specifications

	NOGGIN® 1000	NOGGIN® 500	NOGGIN® 250
Size	12 x 6 x 4.5 in (30 x 15 x 11 cm)	15 x 9 x 6 in (39 x 22 x 16 cm)	25 x 16 x 9 in (63 x 41 x 23 cm)
Weight	5 lbs (2.3 kg)	6.5 lbs (3 kg)	16 lbs (7.3 kg)
Power	8 watts 12 V @ 0.7A DC	8 watts 12 V @ 0.7A DC	8 watts 12 V @ 0.7A DC
Performance Factor	>160 dB	>160 dB	>160 dB
Transducer Patented Dipole	500 - 1500 MHz	250 - 750 MHz	125 - 375 MHz
Shielding Front to Back	>20dB	>20dB	>20dB
Noggin® to PC	115KB, RS232	115KB, RS232	115KB, RS232
Default Depth Windows (User Definable)	0.25, 0.5, 1, 2, 4m (6.25, 12.5, 25, 50, 100ns)	1, 2.5, 4, 6, 8m (25, 50, 75, 100, 150ns)	2.5, 5, 7.5, 10, 15m (50, 100, 150, 200, 300ns)
Acquisition Rate (depends on control system)	100,000 samples/s	100,000 samples/s	100,000 samples/s
PC & DVL Output	Digital image in .PCX Format	Digital image in .PCX Format	Digital image in .PCX Format
DVL Output	Digital (raw) 16 bit 2's complement*	Digital (raw) 16 bit 2's complement*	Digital (raw) 16 bit 2's complement*
Integrated GPS	Point mark or continuous recording	Point mark or continuous recording	Point mark or continuous recording
Operating Temperature	-40 to 40°C	-40 to 40°C	-40 to 40°C
Environmental	IP66	IP66	IP66

* In Noggin^{plus} only

Sensors & Software Inc. is recognized globally as the technical leader in GPR products. Our name is synonymous with technical excellence, continuous innovation and responsive customer service. Our products and systems have been designed for a broad range of customers and markets. Contact us for more information on our application areas.

subsurface imaging solutions

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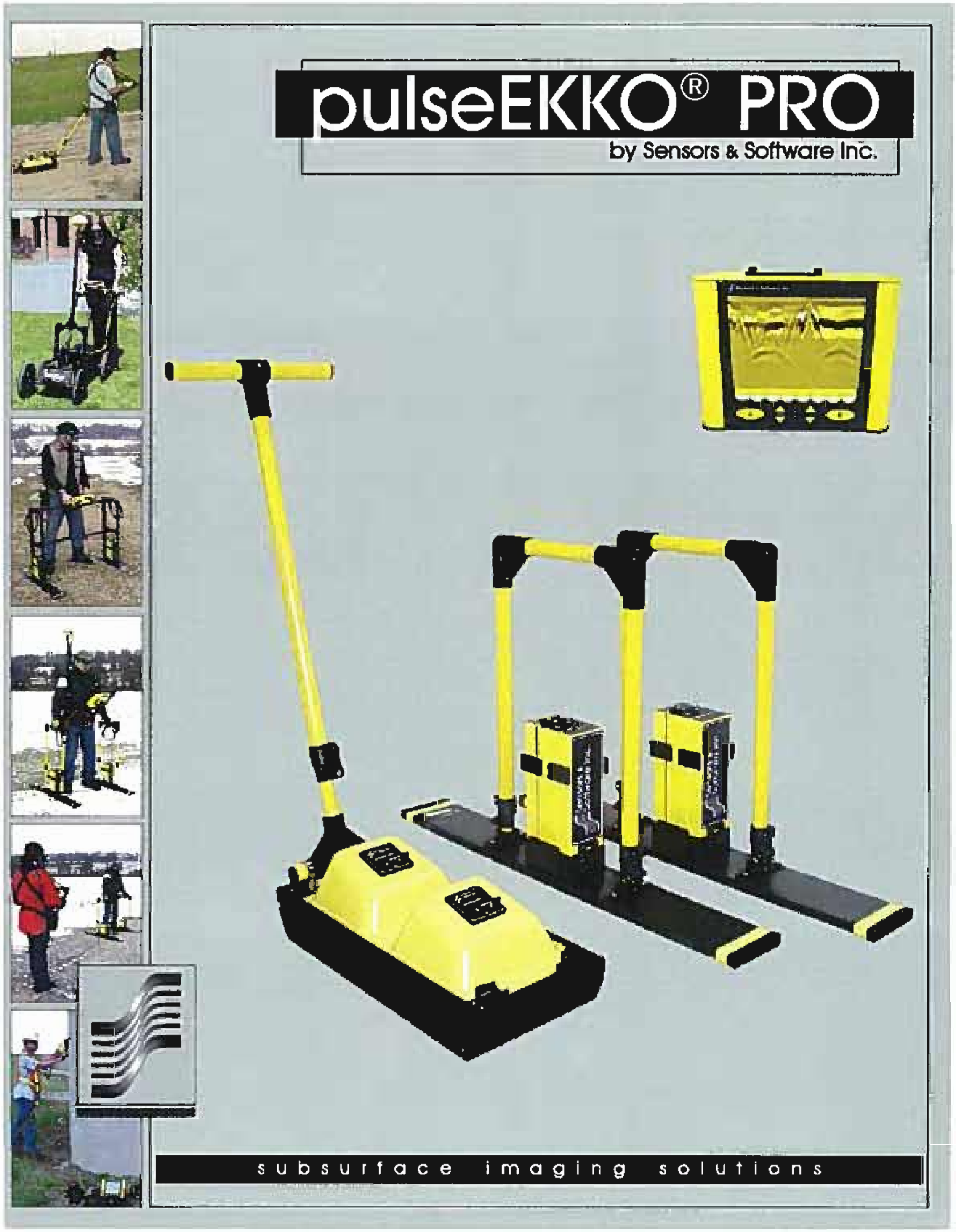
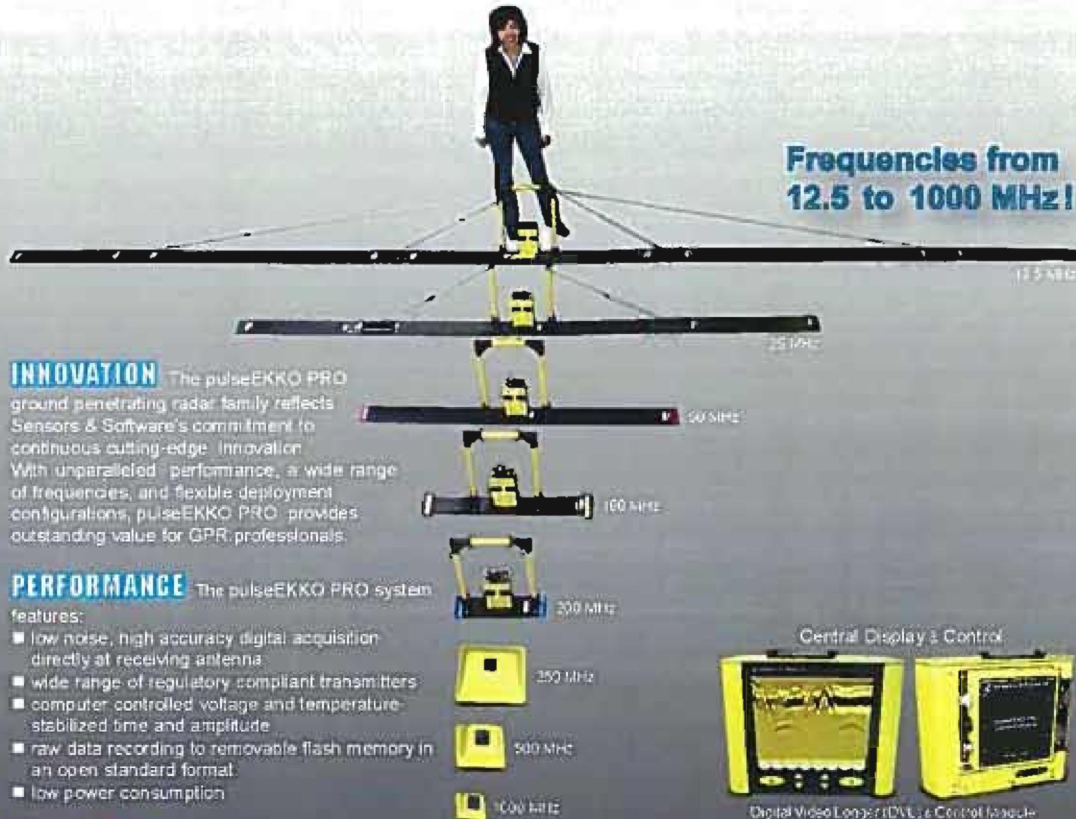

pulseEKKO® PRO
by Sensors & Software Inc.
subsurface imaging solutions

For the GPR professional



INNOVATION The pulseEKKO PRO ground penetrating radar family reflects Sensors & Software's commitment to continuous cutting-edge innovation.
With unparalleled performance, a wide range of frequencies, and flexible deployment configurations, pulseEKKO PRO provides outstanding value for GPR professionals.

PERFORMANCE The pulseEKKO PRO system features:

- low noise, high accuracy digital acquisition directly at receiving antenna
- wide range of regulatory compliant transmitters
- computer controlled voltage and temperature-stabilized time and amplitude
- raw data recording to removable flash memory in an open standard format
- low power consumption

Central Display & Control

Digital Video Logger (DVL) & Control Module

VERSATILITY pulseEKKO PRO's broad frequency range (12.5 to 1000 MHz) enables users to address any scale of GPR application from deep mineral exploration and glaciology to high resolution geotechnical investigations and concrete imaging.
Analyze data and create presentation quality images with EKKO_View, EKKO_Mapper and EKKO_3D.

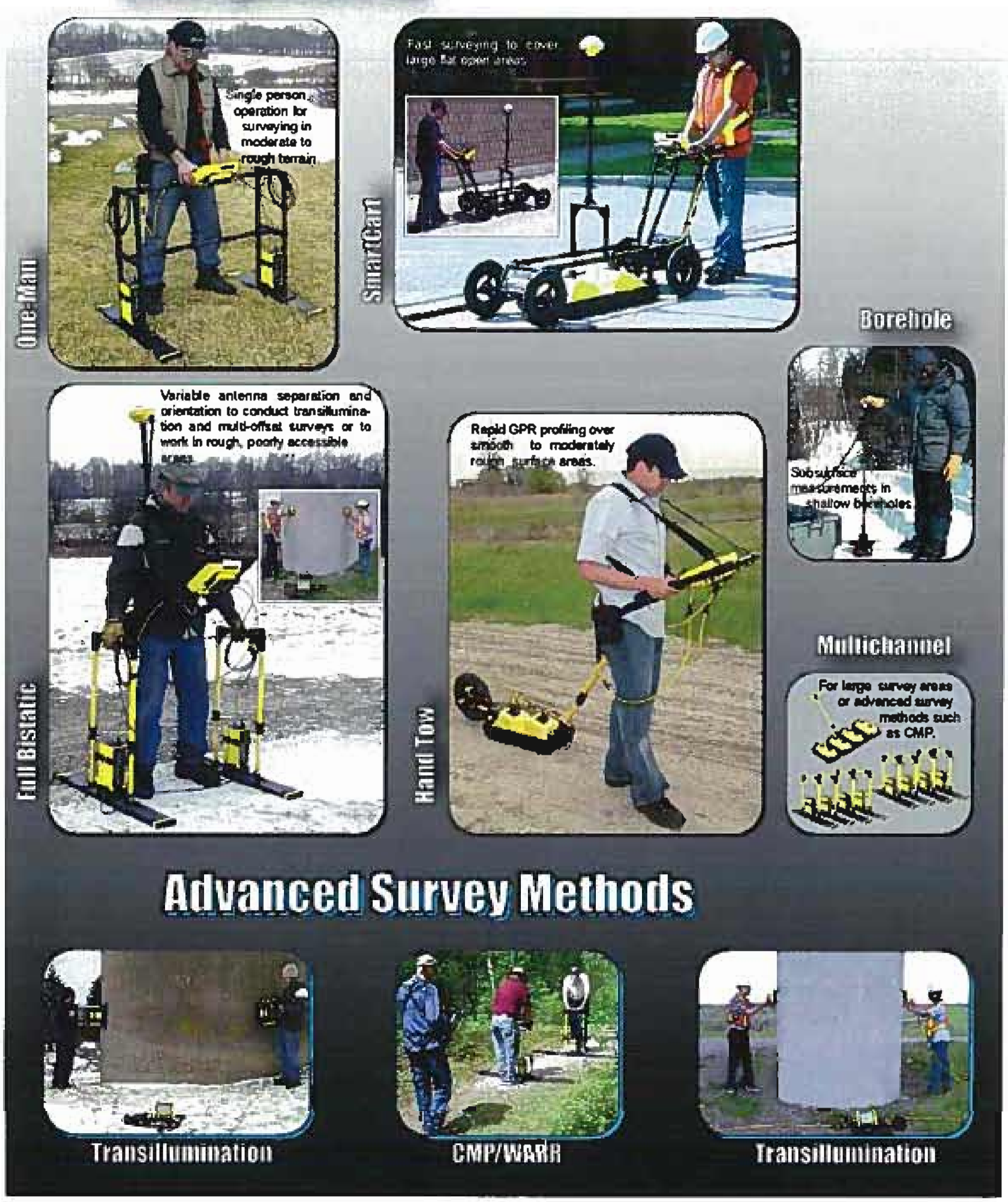
FLEXIBILITY Ergonomic deployment configurations - Full Bistatic, Hand Tow, SmartCart, One-Man, Borehole and Multichannel - enable GPR deployment for reflection profiling, transillumination, or CMP/WARR surveys.

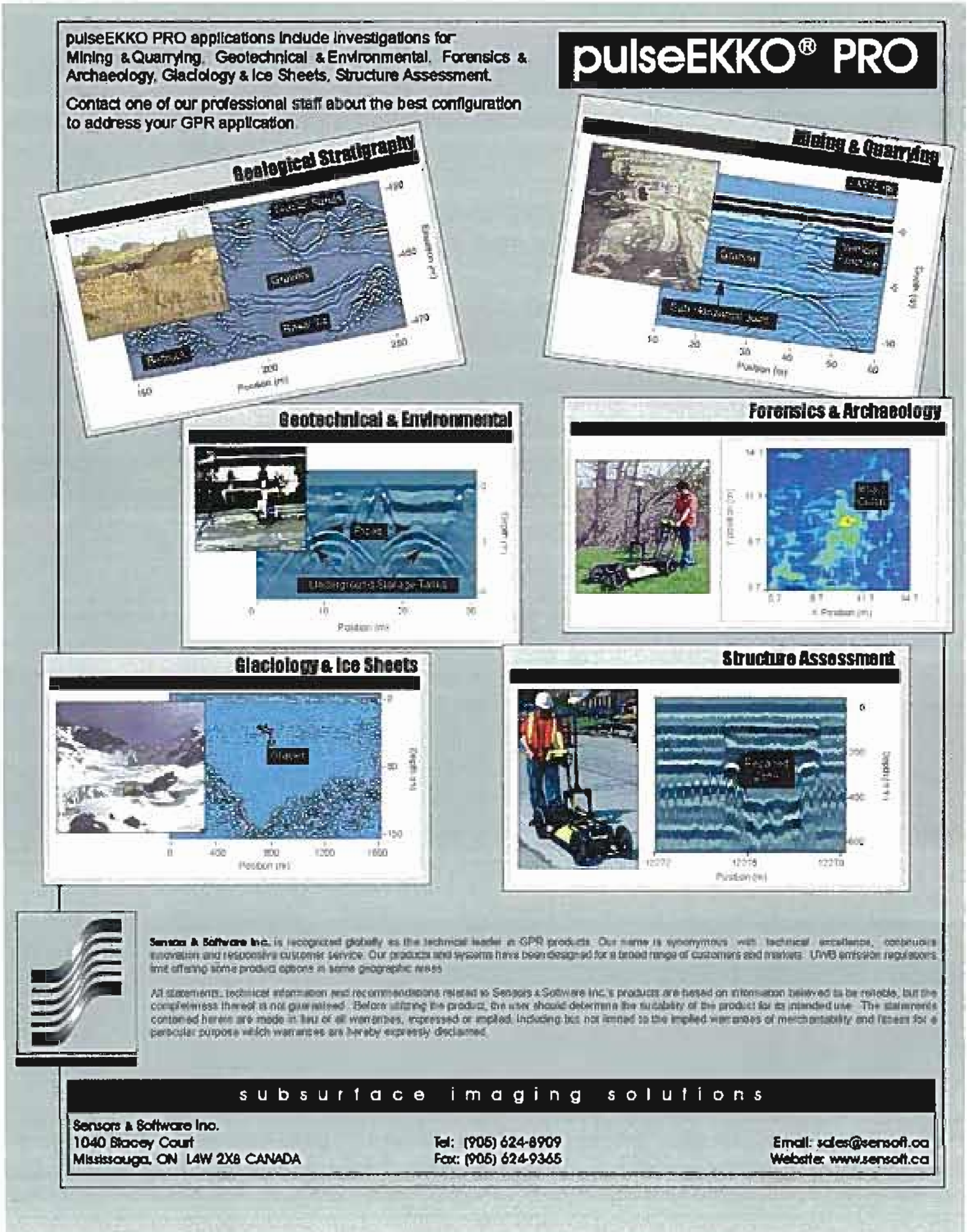
Quick release fastenings and interchangeable components enable rapid system reconfiguration.

Integrated support for GPS, odometers and fiducial markers with triggering from a wide range of inputs provides accurate spatial positioning.

CUTTING EDGE specifications:
Maximum system performance: 186 dB
Programmable time window: 500 ps to 200,000 ns
Points per trace: 10 to 31,000
Hardware stacking: 2 - 1 to 32,768
Receiver Sensitivity: 1.5μV lsb
Data Recording: 16 bit
Environmental: IP66

Configurations




pulseEKKO PRO applications include investigations for Mining & Quarrying, Geotechnical & Environmental, Forensics & Archaeology, Glaciology & Ice Sheets, Structure Assessment.
Contact one of our professional staff about the best configuration to address your GPR application.
pulseEKKO® PRO
Geological Stratigraphy
Mining & Quarrying
Geotechnical & Environmental
Underground Storage Tanks
Forensics & Archaeology
Glaciology & Ice Sheets
Structure Assessment
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