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Application of Ground Penetrating Radar for River Ice Surveys

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A pilot project was conducted on the Lower Athabasca River, Alberta, to explore the feasibility of ground penetrating radar (GPR) technology for river ice survey work. The goal of the pilot project was to evaluate the potential for this technology to acquire spatial information on bed and bottom of ice location under the range of working conditions presented at the study location. Also, the capacity for GPR technology to delineate the location of the water's edge was assessed – a particularly challenging task using conventional manual survey measurement methods.

For a comparable level of effort, a significant increase in total areal coverage of both ice thickness and bed profile information is expected with the application of GPR technology. Successful application of GPR technology is meant to complement (not supplant) existing survey methods. A basic methodology or approach for incorporating GPR methods into future field programs is suggested; the methods are based on experience gained in the field and during data post-processing. Initial findings of this study are presented and further improvements for future work are recommended.

Introduction

A pilot project was initiated during February, 2007, on the Lower Athabasca River to assess the feasibility of applying ground penetrating radar (GPR) technology for the purpose of obtaining river ice survey information – specifically, ice thickness and depth of the water column below the ice-water interface. Another beneficial application of this technology, identified during the early stages of the program, was the identification of the *waters edge*. The waters edge is defined by the intersection of the ice-water and water-bed interfaces. Location of the waters edge is typically found by probing through the ice with a series of auger holes. This exercise is not a trivial task and represents a significant consumption of survey production time. Also, the ice auger invariably encounters the bed during this process causing excessive wear on the auger blades.

This paper presents some of the initial findings of the GPR pilot project. To provide a means for comparison, GPR data was collected adjacent to locations where information on ice thickness and water depth were obtained by direct measurement. What follows is a basic background on GPR technology, a brief outline of the methods used to collect and process the data, initial results of the program, and recommendations for future programs.

Background

Ground penetrating radar is a general term to describe methods that use radio waves to probe subsurface objects or geologic features; it is a non-invasive electromagnetic geophysical technique for subsurface exploration and characterization. In a manner akin to radar principles, GPR systems transmit impulses of electromagnetic energy (radio waves) into the ground and detect their corresponding echoes reflected from interfaces of varying electromagnetic properties beneath the surface. The application of GPR technology for the purpose of estimating ice thickness is not especially novel. During the 1950s, some of the earliest reported GPR applications were conducted for the purpose of determining sea ice thickness in Polar Regions (Bogorodsky, Bentley, and Gudmandsen 1985). Airborne GPR applications in riverine environments have also been investigated for the purpose of estimating river ice thickness (e.g. Arcone 1991; O'Neill and Arcone 1991) and open water river depth and flows (e.g. Okamoto 1999). A simplified introduction to the type of GPR technology applied during this study is provided below. For a more comprehensive introduction on GPR technology and seismic data analysis, the reader may refer to publications on seismic data processing (e.g. Sheriff and Geldart 1985a, 1985b).

Figure 1 provides a simplified schematic illustrating the basic concepts of GPR. An electrical charge is produced from within the transmitter electronics and directed through the transmitter antenna where it transforms into electromagnetic wave energy propagating into the subsurface. Electromagnetic wave front returns (reflections) are subsequently detected at the surface by the receiver antenna, where the reflected electromagnetic energy transforms back into an electrical charge that is measured and recorded by the receiver electronics. Return energy amplitude strength and elapsed wave propagation travel time, also measured by the GPR, forms the basis of subsurface characterization.

As electromagnetic waves propagate through the ground, energy is reflected when changes in electrical impedance (or permittivity) are encountered. The velocity of the wave is determined by the material's electrical properties. There is a relationship between the material's electrical properties and wave velocity. Electromagnetic waves pass through air near the speed of light, *c*, or 2.998 m/ns (1 ns = $1x10^{-9}$s). Assuming the relative permittivity of air is 1, the electromagnetic wave velocity, *v*, can be expressed as an inverse proportion of the material's relative permittivity normalized to that of air, *K*, as follows:

$$v = \frac{c}{\sqrt{K}}. \qquad [1]$$

K is commonly referred to as the dielectric constant of the material. Where a noted change in dielectric constants is encountered a portion of the energy within the wave is reflected back to the surface. GPR technology performs well in detecting the interfacial boundary between horizontal strata of distinct relative permittivity. The horizontal stratums of interest to this investigation exhibit very distinct dielectric properties. For fresh water ice, water, and wet sand the corresponding dielectric constants are approximately 4, 80, and 30, respectively.

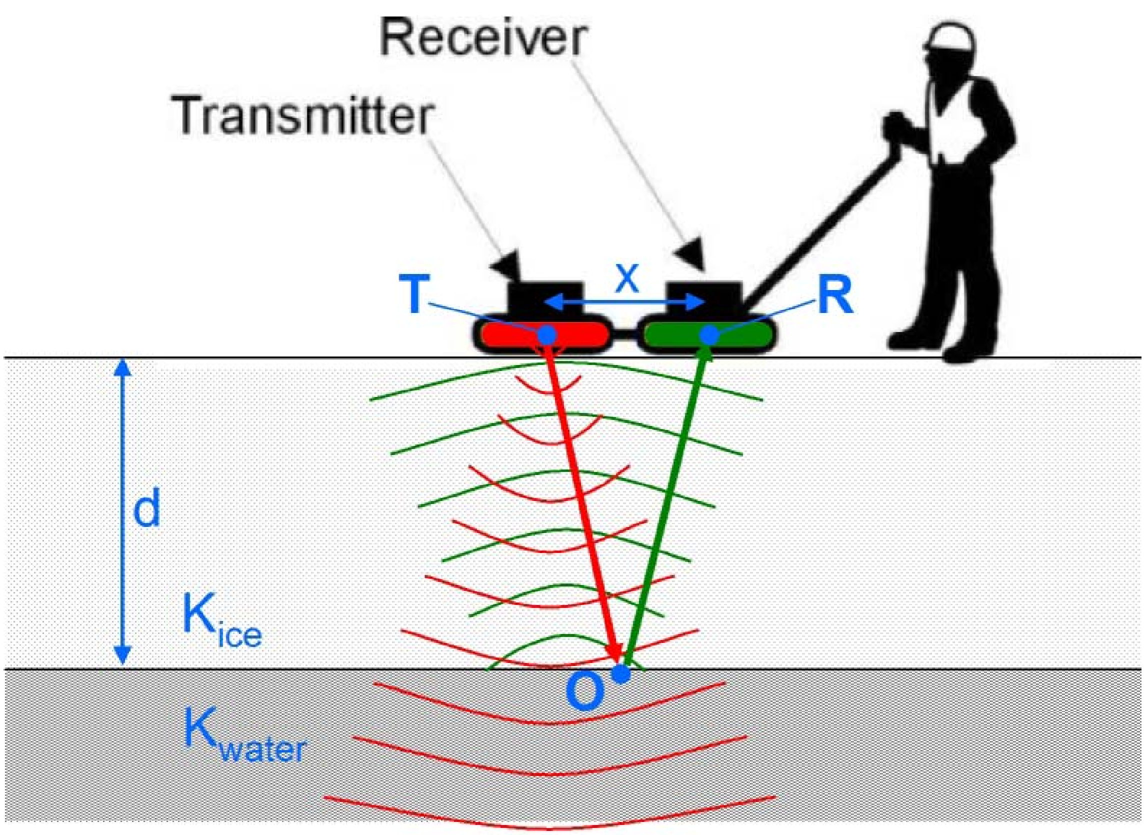

Figure 1. GPR Application Schematic.

Figure 1 presents a representation of the relationship defining the round-trip travel time of an electromagnetic wave from transmission through reception. The following simplified relationship estimates the elapsed wave propagation time, *t,* for a GPR system with fixed antenna separation, *x*, over a continuous horizontal stratum of depth, *d*, and characteristic wave propagation velocity, *v*.

$$t = \frac{2\sqrt{(x/2)^2 + d^2}}{v}. \qquad [2]$$

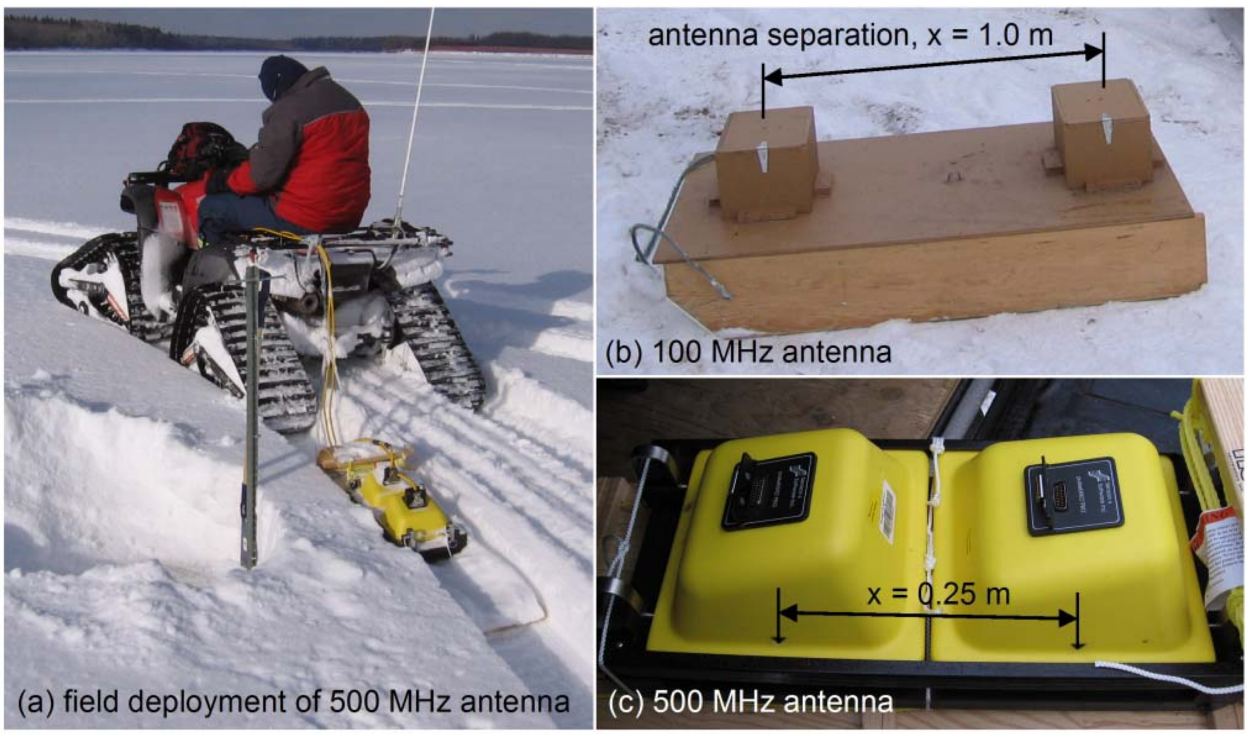

Figure 2. Field deployment and antenna arrangements.

Field Data Collection

Field data was collected using a PulseEkko Pro™ ground penetrating radar system. Two separate antenna arrangements were used to generate "low" and "high" frequency waves (100 MHz and 500 MHz) for the purpose of detecting the water-bed and ice-water interfaces, respectively. Each antenna arrangement was housed in protective enclosures that were towed behind an all-terrain vehicle (ATV) equipped with specially adapted snow tracks. Figure 2 presents photographs illustrating the deployment method and antennae used for both the high and low frequency antenna arrangements. Use of an ATV was preferred over a snowmobile since sufficiently low and constant speeds are more easily maintained. The snow depths encountered at the site (20-60 cm) were easily navigable by the ATV; for greater snow depths a more suitable vehicle may be necessary.

Continuous GPR measurements were recorded as the antenna arrangements were towed separately over the river adjacent to manual measurement locations. The GPR data measurements were taken approximately every $1/10^{th}$ of a second and viewed in real-time on the portable PulseEkko Pro data logger. A differential global positioning survey system (DGPS) was coupled with the GPR data logger to provide horizontal (and in some instances, vertical) positions for the GPR data measurements. Both the GPR and DGPS data were recorded to a digital media card for post-processing.

Data Processing and Results

The GPR data was processed using the EkkoView Deluxe™ and Ice Mapper R4™ software produced by the PulseEkko Pro GPR system manufacturers (Sensors & Software Inc.). MATLAB© software was also used to facilitate further post-processing and data plotting. Figure 3 presents samples of the GPR data depicted graphically as grayscale images. The x-axes in Figures 3a and 3b, represent individual GPR trace measurements stacked side by side to form the data profile. The y-axes represent the elapsed time window corresponding to reflection events recorded by the GPR receiver electronics. Whitened pixilated areas represent positive amplitude signal responses (wave peaks), recorded in milliVolts, and whitened pixilated areas represent negative amplitude signal responses (wave troughs).

Water Depth and Ice Thickness

On Figures 3a and 3b, the red lines represent the arrival of the peak energy of the wave traveling directly across from the transmitting to receiving antenna (direct impulse arrival). The yellow lines represent the arrival time of the peak energy of the wave reflected from the water-bed and ice-water interfaces – Figures 3a and 3b, respectively. The elapsed time between arrivals of these peak energies was used to estimate the corresponding "material" thickness by Equation 2. Estimates on the thicknesses of the ice and water layers assumed associated dielectric constants $K_{ice} = 4$ and $K_{water} = 81$, respectively. These constants were adopted from common values reported in the literature for water and fresh water ice (no "calibration" on these constants was exercised).

GPR data was collected adjacent to direct measurement locations at a distance of approximately 1-3 meters. The GPR system was not passed over top of direct measurement locations since the presence of holes in the ice (and water over the ice surface) obscured GPR images sufficiently to restrict meaningful interpretation of the data. Figure 3c presents a visual comparison of the GPR interpreted ice and water layer thicknesses to thicknesses obtained by direct measurement. The horizontal axes is representative of the transverse distance along a line projected between the GPR interpreted locations and direct measurement locations. The vertical axis, defining layer thickness, has been reversed to facilitate visual reference to the GPR image data. At the top of Figure 3c, the location of the signal traces associated with the 100 MHz (water layer) and 500 MHz (ice layer) data are also indicated. These signal traces correspond to the horizontal axes of Figures 3a and 3b.

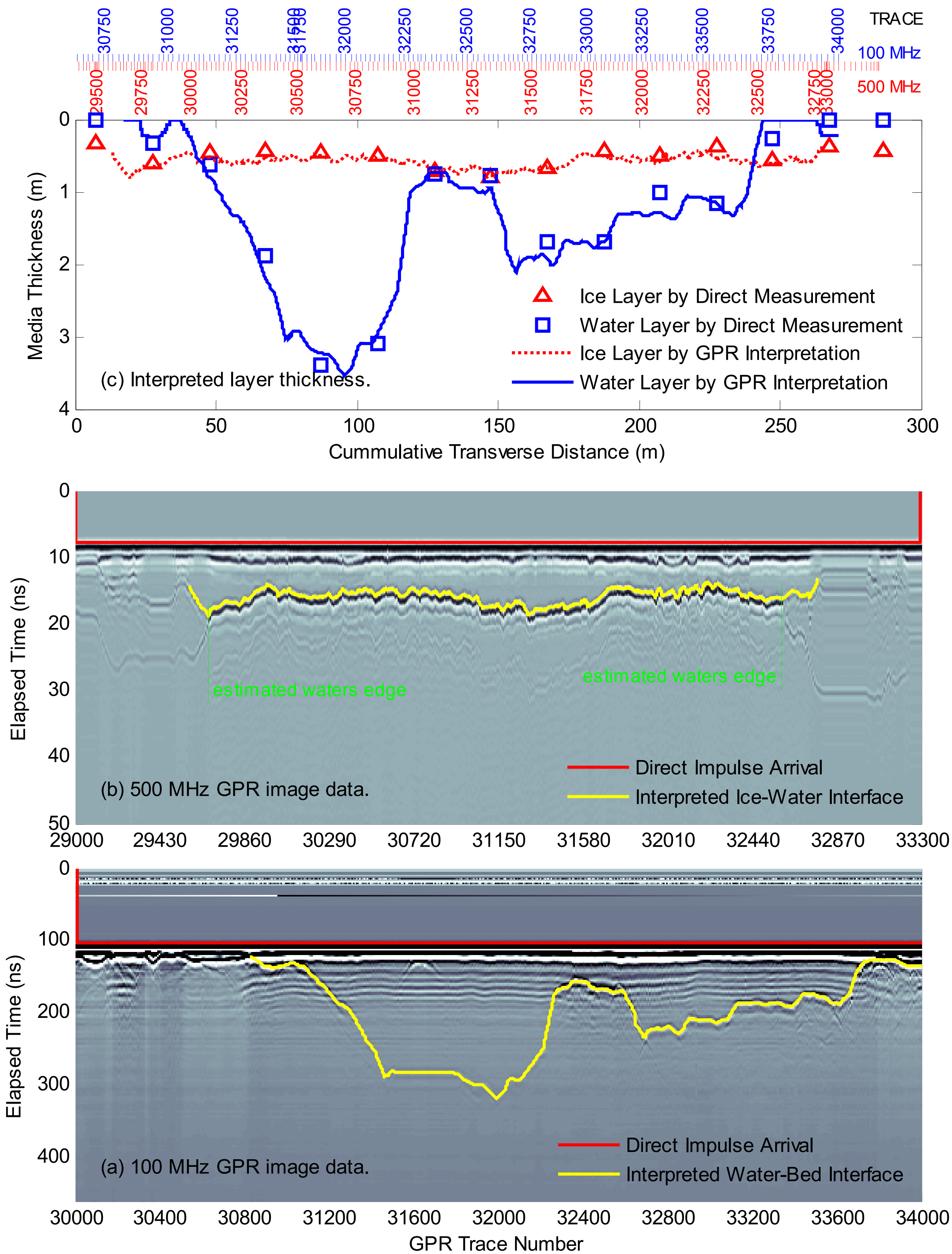

Figure 3. Sample data set and post-process results.

Waters Edge

Figure 3 also illustrates how the GPR arrangement may provide a means for delineation of the waters edge. The waters edge is indicated by the appearance of a second interface that diverges from the ice-water interface. It is believed that this diverging interface relates, in part, to reflections returning from the phreatic water surface that extends into the sandy bed material. While the phreatic surface remains constant, the thickness of the overlying "dry" (and/or possibly frozen) bed material increases. The travel time for the wave passing through the bed material to the phreatic surface may cause a downward progression of the line that diverges from the ice-water interface since the wave travels at a comparably lower velocity through the "dry" bed layer than the ice layer. The downward progression may also be associated with reflection geometry distortion caused by lateral changes in layer velocities and layer thicknesses (moving from ice over water onto ice over the "dry" bed layer). Among these uncertainties, the paramount observation remains: the amplitudes of waves returning from the interpreted ice-water interface were clearly greater than the amplitude of waves returning from the ice-bed interface. The interpreted waters edge is identified on Figure 3b with vertical green lines.

Vertical Positioning of GPR Data

Information interpreted by the GPR data represents the thickness of the two primary layers of interest –ice thickness and depth of water below the ice. A vertical reference for these layers is required to achieve a river ice topography model. The method used was to add the cumulative ice and water layers found through application of the GPR system to a known vertical position. The following two basic approaches were explored for the purpose of providing a vertical reference to the GPR data: reference to measured elevations on the ice surface and reference to DGPS elevation data collected during the GPR survey. Figure 4 presents the river bed and ice thickness profiles derived by these two approaches (profiles found by direct measurement are included for comparison).

For the first approach, the average elevation of the top of ice across the flow area was defined as the vertical reference. Then, the thickness of the water and ice layers were referenced or "hung" from this vertical reference (Figure 4a). For the second approach the elevation of the bed was estimated by subtracting the cumulative thickness of the ice and water layers from the elevation of the bottom of the sled housing the 100 MHz antenna system. Continuous elevation data for the bottom of the sled was obtained through the use of a DGPS antenna mounted on top of the antenna housing. The DGPS data stream containing the horizontal and vertical position (elevation) was synchronized with the GPR data stream during data collection. Each GPR trace was then assigned a reference elevation during post-processing. For each GPR trace the profile elevation of the ice and water layers were found by subtracting the ice thickness and water layer thickness from the recorded elevation of the bottom of the sled.

The first method resulted in profiles found through the GPR system that approximated the measured profiles well. The second approach resulted in profiles that overestimated the vertical position of the measured profiles by approximately 20 cm. This difference relates reasonably well to the snow thickness and speaks to the challenges that require attention during future programs (discussed further below).

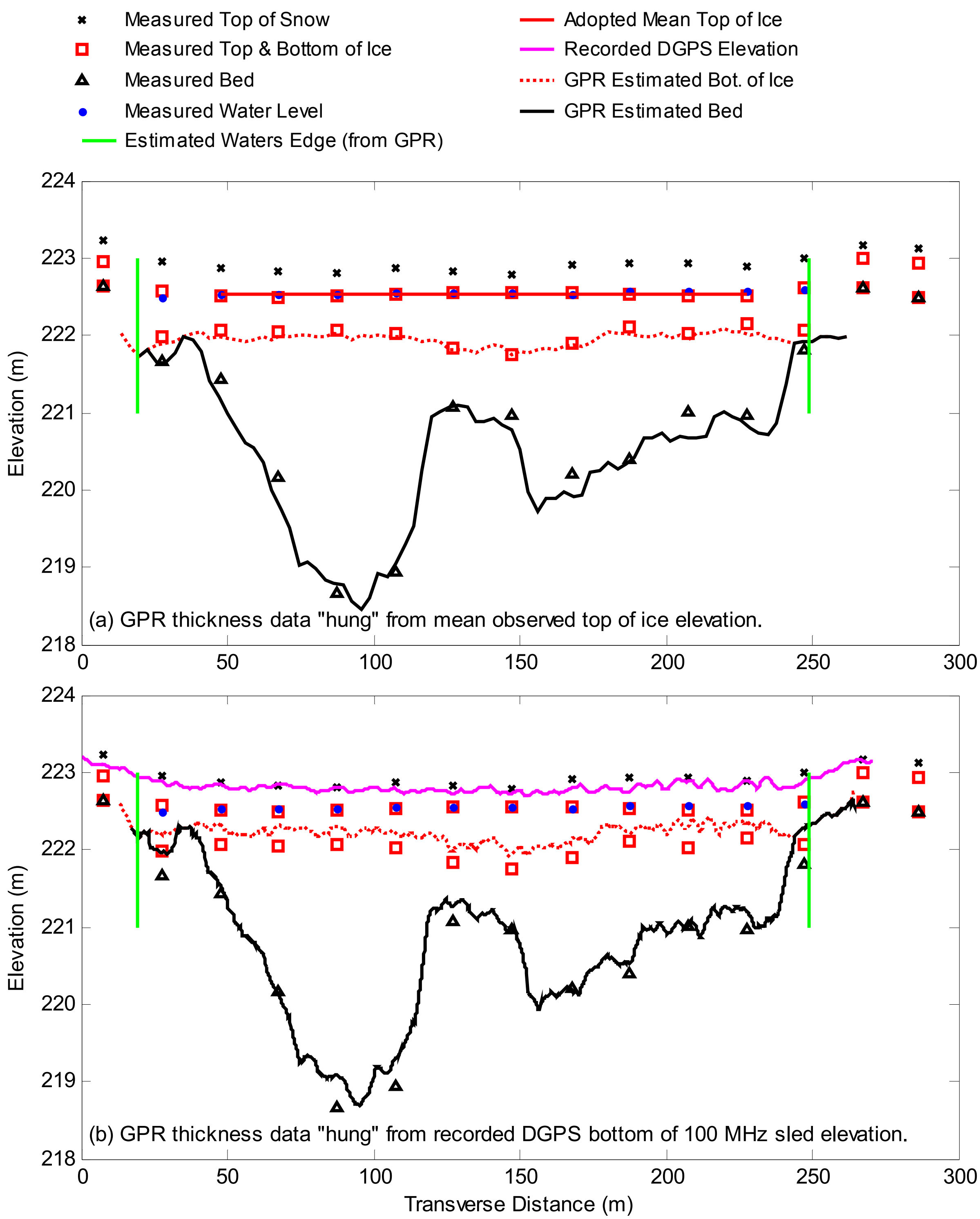

Figure 4. Comparison of measured and GPS interpreted river bed and ice section profiles.

Discussion and Conclusions

One may suppose that the GPR system devised for this project would function much like a typical river bathymetry survey using a boat, depth sounder, and DGPS system. However, from an operations perspective, they function quite differently. What separates a typical boat-based bathymetry survey from the GPR survey system deployed during this project is most simply described as follows. For a boat survey system, the point of vertical reference (the base of the depth sounder) is coupled directly to the medium of interest (water layer). While for a GPR survey system, the point of vertical reference (receiver base) is not coupled directly with the medium of interest and is separated by several strata with varied electromagnetic properties (e.g. air, snow, ice, sand).

The following list highlights: some of the major findings resulting from this study, identifies challenges to be addressed, and suggests operational considerations for future programs.

- Successful interpretation of the snow thickness layer may be achieved with a higher frequency antenna and will facilitate improvements on vertical orientation of data.
- Direct measurements would be required in future programs to facilitate analysis of the GPR data.
- Direct measurements on the top of ice elevation may provide an expedient means for establishing vertical orientation of GPR data.
- GPR methods would provide a means for approximating the horizontal location of the waters edge and increase field production.
- Maximum water layer thickness that is clearly detectable by the 100 MHz antenna is approximately 3.5 to 4.0 m.
- Electromagnetic waves emitted from the 100 MHz GPR (unshielded) antenna interfere with the DGPS system antenna. For future programs shielding of the 100 MHz antenna may be required.
- The average speed of the 100 MHz deployment system should be less than roughly 5 km/hr (or close to a very brisk walking pace) over gradually varying bed elevations – slower speeds should be observed where bed elevations changes are more dramatic. For the higher frequency deployments (500 MHz or more) speeds in excess of 5 km/hr are permissible.
- The GPR image data can not be interpreted without knowledge of the media/materials under investigation; that is, the amplitudes and their respective arrival times do not provide a means for identifying the type of material or related properties of the material.

Challenges remain with the application of GPR technology for the purpose of obtaining river ice survey information. However, a GPR survey system comparable to that deployed during this investigation still shows great potential for future applications. For a level of effort comparable to current river ice survey programs, a significant increase in the quality and quantity of spatial information is expected through the use of GPR technology. The intent of this program was to explore the capacity to which GPR technology may compliment (not supplant) existing river ice survey methods. Initial results of this study indicate that GPR technology provides a suitable means for interpreting the thickness of ice and depth of water below the ice bottom. With further operational improvements GPR survey systems will find increased use for river ice surveys in the future.

Acknowledgment

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