Using ground penetrating radar (GPR) to image the Bald Spot: A test of concept for the use of GPR in Carleton geology classes

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March 9, 2018

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ABSTRACT

Ground penetrating radar (GPR) is a non-invasive technique that uses electromagnetic waves to image the subsurface (Annan, 2009). It has applications not only in geological settings, but also in archeology and construction (Bristow and Jol, 2003). The purpose of this study is to use GPR to explore the underground character of Carleton College’s Bald Spot with an eye towards the applicability of the technique in Carleton geology classes. Using GPR at a frequency of 50 MHz, I found interfaces between the depths of 0 and 5 m. I compared my GPR results to borehole data and facilities electrical maps to get a better sense of what types of sedimentary transitions and discrete objects can be identified using this technology. Despite successfully obtaining interpretable data, the time required for set up, the sensitivity of the equipment to external conditions, and the complexity of the data processing software, make GPR cumbersome for classroom use.

Keywords: ground penetrating radar; Northfield; glacial till; common offset reflection.
INTRODUCTION

Ground Penetrating Radar (GPR) is a technique involving the use of electromagnetic (EM) waves to image the shallow subsurface (Baker and Jol, 2007). It is similar in theory to seismic imaging, but instead of using vibrational waves with a frequency of 10-100 Hz (Burger, 1992), GPR uses radio waves with frequencies ranging from 10 to over 1000 MHz (Jol and Bristow, 2003). These higher frequencies are what make GPR useful for shallow, high resolution projects (Jol and Bristow, 2003). In a typical GPR survey, an EM pulse of known frequency is sent into the ground via a transmitting antenna (Baker et al., 2007). This pulse is reflected where it encounters a change in dielectric constant and its travel time is recorded by a receiving antenna (Baker et al., 2007). When a series of pulses are emitted along a transect, a cross sectional image of the subsurface emerges (Jol and Bristow, 2003).

Research regarding the use of radio waves as a method for subsurface exploration began in the early 1900s and has continued to the present (Annan, 2001). In 1956, the first attempt was made to image the water table by these methods. In this study electromagnetic interference patterns were used to accurately predict water table depth in the Egyptian desert (El-said, 1956). Then, in the early 1960s, Waite and Schmidt used reports of altimeter errors from the 40s and 50s to study high frequency wave penetration into thick layers of ice (1962). It wasn’t until the 1990s, however, that GPR technology was widely popularized due to increased knowledge and successful commercialization (Annan, 2001). Since then GPR has been used for a number of different tasks including locating undetonated mines, assisting in archaeological digs, answering geologic questions, and performing subsurface utilities surveys (Jol, 2009).
In this study, I used GPR on the Carleton College Bald Spot to gain an understanding of the basic principles of this technique where a general picture of the subsurface was already known. Thanks to borehole data obtained in preparation for the installation of a geothermal well field, approximate boundary depths between stratigraphic layers were available, as were plans showing the location of electrical cables and chilled water lines. The purpose of this study was to assess the practicality of using GPR as a learning tool in a classroom setting and possibly to inform the College geothermal efforts regarding any shallow subsurface anomalies.

**GEOLOGIC SETTING**

The Carleton College Bald Spot is an open plot of sodded ground central to campus, and used informally for recreation and college social functions (Fig. 1). It is also the future location of a geothermal well field that will contribute to the campus’s goal of becoming carbon free by 2050. This past summer (2017), 77 vertical bores were drilled in the Mini Bald Spot and 95 horizontal bores were completed beneath Bell Field. This coming summer (2018) will see the installation of 133 vertical bores in the Bald Spot (https://apps.carleton.edu/geothermal/). In the process, the electrical lines that provide power to the ice rinks and that are currently buried beneath the Bald Spot will have to be removed and re-interred after drilling has been completed (Larson, 2018). Therefore, it is important to know with precision the location of these electrical lines and the character of the material surrounding them. Soil samples from previously drilled boreholes indicate that the subsurface is comprised of a layer of glacial till ~30 m thick. One such borehole, drilled in the southern end of the Bald Spot at N 44° 27’ 37.4” (latitude), W 093° 09’ 3.4”
Figure 1. Map of MN showing the location of Rice County outlined in red and the city of Northfield (Left). Carleton College is located in Northfield, MN and a map of the campus is shown on the right. The Bald Spot is outlined in red.
(longitude) on August 11, 2017 encountered the Prairie du Chien Formation (bedrock) at a depth of 29 m, overlain by gravel and boulders (FTC Test Report, 2016). Understanding basic ground characteristics prior to using GPR allows the operator to make informed choices regarding instrument setup and parameters.

**METHODS**

Soil samples collected from a 1.7 m deep borehole in the northeast corner of the Bald Spot confirmed that the gravel and boulder layers described in the FTC report are glacial till.

Figure 2 is a simplified depiction of the layering found in the 1.7 m borehole. The most obvious trends are seen with regards to color, clay content, and grain size. Soil color lightens with depth from dark brown (10YR 3/3 dry) to dark yellowish brown (10YR 4/6 dry) to yellowish brown (10YR 5/6 dry). Additionally, although containing little clay overall, clay content seems to generally decrease with depth. Grainsize increases with depth from clay sized particles near the surface to medium grained sand deeper down. Furthermore, centimeter scale cobbles occur around 160 cm. These ground truthed results are relevant not only as a comparison for the GPR results, but also as a parameter in data collection, because the dielectric constant of a material effects the signal’s transmission.

A 60 x 65 m rectangular grid was established on the Bald Spot with a center at approximately 44°27′39.48″N, 93° 9′16.95″W by marking out 27 transects: 13 North/South and 14 East/West (Fig. 3). Parallel transects were spaced 5 m apart and their
Figure 2. Soil profile from NE corner of the Bald Spot showing a general coarsening of sediments with depth. The allochthonous clasts indicate that these sediments were transported and deposited by glaciers.
Figure 3. Google Earth image of Carleton College’s Bald Spot overlain with the locations of subsurface electrical lines (in red) and transect endpoints, spaced 5 m apart, along the edge of the survey area. Adapted from Google Earth, 44°27'39.55"N and 93°09'16.99"W, Imagery date 5/31/17.
end points were indicated using athletic field marking paint. Transect separation was determined by calculating the area of the Fresnel zone at a depth of 8 m using the equation $A = \frac{d}{\sqrt{\varepsilon_r - 1}} + \lambda$, where $A$ is the signal’s footprint at a certain depth ($d$) based on wavelength ($\lambda$) and dielectric constant ($\varepsilon_r$) (Baker, 2007). Accordingly, transects should have been spaced less than 2 m apart to achieve uninterrupted coverage of the subsurface at a depth of 8 m. However, due to time constraints and also considering the purpose of the survey, it was determined that a separation of 5 m would be sufficient to capture general subsurface character.

An antenna frequency of 50 MHz was chosen based on the desired depth and resolution of the survey. Because the survey was focused on identifying planar stratigraphic boundaries that might impede digging, high penetration depth was prioritized over high resolution (Jol and Bristow, 2003). In order to reduce survey time, antenna separation was set at the minimum of 2 m and step size was set at the maximum of 0.5 m. Antennas were arranged in a broadside perpendicular configuration per the advice of Harry Jol (2017).

A common midpoint survey (CMP) was performed along transect A in order to determine wave propagation velocity through the subsurface. This velocity, which is dependent on material and wave frequency, is necessary to construct a cross section based on travel time. A common offset reflection survey was then performed along each transect.

Data in the form of DX1 files were imported from the pulseEKKO console into an RGPR package designed by Emmanuel Huber and available on github (https://emanuelhuber.github.io/RGPR/). To improve data quality, each transect
underwent minimal manipulation that involved a time zero correction, signal amplification, and trace averaging. Because even direct waves take time to travel between the transmitter and the receiver, when travel time is converted into distance and graphically displayed, the ground surface will appear deeper than 0 m. To remedy this, the first break time for each trace in a transect was averaged and this average was used to shift the traces up. Next, low frequency components of the signal were removed by dewowing where a median absolute deviation filter was used with a length of 50 ns. Then, a 60 to 80 MHz band pass filter was applied to remove high frequency noise. An automatic gain control (agc) correction was subsequently applied to account for signal attenuation. Finally, a median spatial filter was used to remove noise and smooth the signal. Signal velocity was determined at 0.06 m/ns by taking the slope of the ground wave signal from the graph of the CMP survey.

RESULTS

There are a few trends evident in data from all of the transects (Fig. 4; Fig. 5). For example, layering beneath the Bald Spot is largely horizontal at least down to a depth of about 4-5 m. Additionally, horizontal layers maintain a fairly constant thickness across each transect. Below 4-5 m there is some evidence for thinner, dipping layers, but signal attenuation is great enough at this depth to make this interpretation uncertain. Near 0 m, the air wave and the ground wave nearly merge to create a solid darker signal marking the top of the first layer. Other interfaces are at 3-4 and 4-5 m.

There are, however, a few significant differences between transects A through G and transects H through AA. Firstly, the layers in H-AA appear to be shifted down by
about a meter in relation to the layers in A-G (Fig. 5). Upper interfaces appear in A-G at depths of 0 and 3 m, whereas upper interfaces in H-AA are at depths of 1 and 4 m. Additionally, data from A-G show small hyperbolic bulges near the edges and in the center of the transects (Fig. 4). These hyperbolas are absent in data from H-AA. Furthermore, transect U shows reflections only down to a depth of about 4 m, which is about 4 m shallower than the reflections from other transects (Fig. 6).

DISCUSSION

While useful independent of other sources, GPR data are especially illuminating when referenced in conjunction with other data sets. In the case of the Bald Spot, it is possible to compare the GPR results to geothermal exploration reports, borehole data, and facilities maps. This comparison not only offers a check on the GPR data, but also reveals some limitations inherent to GPR technology.

The thermal conductivity report created by Geothermal Resource Technologies Inc. (GRTI) interprets a transition from topsoil to gravel between 5 and 6 ft. (1.5 and 1.8 m), and a transition from gravel to cobbles/boulders between 13 and 14 ft. (3.9 and 4.3 m) (FTC Test Report, 2016). Neither of these interfaces is present at the reported depths in the data from GPR transects A-G. Both interfaces, however, are seen at depths approximately matching those in the FTC report in data from transects H-AA. Additionally, the augered hole provided a higher resolution look at the top 1.7 meters of soil. The transition between soil and gravel was observed at around 1.6 m in the auger data, but was only present in GPR transects H-AA.
Figure 4. Panel A shows the corrected but uninterpreted data from a representative EW transect. Panel B shows the interpretation of this data. The air wave is shown in blue. The ground wave is shown in green. A thin layer around 3 m is shown in orange. Two hyperbolas have been identified and circled in the orange layer.
Figure 5. Panel A shows the corrected but uninterpreted data from a representative NS transect. Panel B shows the interpretation of this data. The air wave is shown in blue. The ground wave is shown in green. A layer at around 4 m deep is shown in orange. Note that in contrast to the EW transect in figure 4, the signals are darker and there are no obvious hyperbolas in the orange layer.
Figure 6. Panel A shows the corrected but uninterpreted data from transect U, a NS oriented transect positioned directly above and running parallel to buried electrical lines. Panel B shows the interpretation of this data. The air wave is shown in blue. The ground wave is shown in green. It is possible that the gap in data at the southern end of the transect shows where the batteries in the receiver died. Also note, the maximum depth of this cross section is just over 4 m as opposed to just over 8 m in other transects.
One reason why layers in A-G and H-AA do not appear at the same depths may be because the data were taken on different days. The data from A-G were collected on a drizzly day, but after a week or so of little rain. Data from H-AA, however, were taken after a few days of rain. Because GPR relies on wave velocity through subsurface materials to approximate depth, travel time graphs are sensitive to ground conditions (Baker et al., 2007). The wave velocity, obtained during the CMP survey through dry ground, was likely not the same as the wave velocity on subsequent, wetter days. Because EM waves travel more slowly in saturated material (Baker et al., 2007), a travel time graph made using the original, faster velocity would make layers appear deeper on days when the ground was wet. This could explain why an air and ground wave were observed around 0 m in A-G and not in H-AA. If, however, subsurface conditions have shifted data from H-AA, then the borehole data and GPR data do not show interfaces at the same depths. Additionally, it shows that GPR does not recognize the transition between topsoil and gravel.

In addition to ground truthing using borehole data, I was also able to compare my results to facilities maps. These maps show electrical lines branching from a single point at the south end of the Bald Spot and eventually running North-South along its edges and center (Fig. 3). Because discrete objects appear as hyperbolas in GPR data, I initially thought that the hyperbolas in my A-G transect data corresponded to buried electrical lines. Figure 4 shows what I thought were electrical lines at approximately 30 and 58 m. These positions are in agreement with the locations of electrical lines on the facilities map. However, based on this map there should also be a hyperbola in the data around
3 m. Transect G was not the only transect where hyperbolas seemed to be missing or wrongly placed. For example, data from transect B indicate that there should be electrical lines at 10, 35, and 50 m. But, only the line at around 35 m actually exists. Small discrepancies between the GPR data and locations on the facilities map could be due to the fact that neither dataset is tied to a GPS coordinate system. Instead, transects were overlain on a Google Earth map based on an approximate starting point and distance between transects. Similarly, electrical lines were placed on the Google Earth map based not on GPS points, but instead on tree locations.

The discrepancies between the GPR data and the facilities map are, however, too large to be attributable only to poor map alignment. It is more likely that hyperbolas in the data mark points where the GPR electrical equipment (including the console and batteries) was closest to the antennas. The GPR electrical equipment was set up on a crate. The crate had to be picked up and moved once or twice per transect due to the length of the fiber optic cables. Therefore, the electrical equipment was much closer to the receiver at the beginning and in the middle of the transect. The absence of hyperbolas in data from transects H-AA could be explained by a larger gap between the equipment crate and the antennas after the first day. Unfortunately, this gap was never measured.

Still, electrical lines seem to have some effect on the data. Transect U data show wave penetration only up to 4 m, which is significantly shallower than penetration along other transects. Transect U was also located directly above and parallel to the center electrical line. It is unclear why electrical effects would be present in this case and not in others, but there is also no obvious alternative explanation for the transect U data.
CONCLUSION

Using GPR, I was able to image the Bald Spot down to a depth of approximately 5 m. The data showed meter scale, horizontal bedding in the glacial till punctuated by what might have been electrical lines. It is, however, beyond the scope of this project to identify the composition of those layers or postulate on the manner of their formation.

Despite some success in terms of obtaining real, interpretable data, finicky instrumentation and complex data processing make GPR unsuitable for use in a classroom setting at this time. Equipment set up is time-consuming and delicate. Additionally, the equipment is highly sensitive to ground conditions, especially saturation. If data cannot be collected on a dry day, attenuation, at least in the material setting of Carleton’s campus, will prevent data from being collected at depths greater than a few meters. Furthermore, easily available GPR processing software is either outdated or requires at least minimal programming knowledge.

With regards to informing geothermal efforts on campus, my GPR data is inadequate. This is due to the low resolution of the survey and my current limited understanding of instrument nuances.
ACKNOWLEDGEMENTS

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REFERENCES


Larson, M., 2018, personal correspondence via email regarding geothermal plans.


Background to Understanding Ground Penetrating Radar (GPR)

Ground Penetrating Radar (GPR) uses radio signals to probe the subsurface (Baker et al., 2007). When an electromagnetic (EM) pulse from an antenna is sent into the ground it travels through the ground material until it encounters a change in dielectric constant (Baker et al., 2007). The dielectric constant is reflective of a material’s ability to store electrical energy (Cassidy, 2009). EM waves that encounter such a change will be reflected back to the surface and recorded by the receiver (Cassidy, 2009). A 2D image of the subsurface emerges when EM pulses are sent into the subsurface along a transect (Jol and Bristow, 2003; Fig. 7).

Considerations Prior to Surveying

Survey design should be tailored to reflect the surveyor's purpose (Jol and Bristow, 2003). This will nearly always involve weighing the relative importance of depth versus data resolution in a specific material (Jol and Bristow, 2003). In general, as maximum survey depth increases, resolution decreases (Jol and Bristow, 2003). So, in deeper surveys, small objects might be lost. The maximum depth of a survey is often limited by the type of material through which the signal must travel, but can be varied within material constraints by changing the frequency of the radio signal (Jol and Bristow, 2003). Higher frequencies, although providing greater resolution, are attenuated more quickly than lower frequencies, reducing the depth of the survey (Jol and Bristow, 2003). One way attenuation is measured is by computing the skin depth, or the depth at which an EM signal’s amplitude has decreased by 37% (1/e) (Baker et al., 2007). Skin depth ($\delta$) depends on the angular frequency of the signal ($\omega$) and the absolute
Figure 7. A simplified schematic of a GPR reflection survey. Panel A shows the position of the transmitter and receiver (T and R respectively) at the start of a survey. Panel B shows the next step in the survey where the transmitter and receiver are both moved a certain distance along a transect, but maintain a constant separation. Panel C shows idealized data from such a survey with one reflector layer. Adapted from Jol and Bristow, 2003.
permeability ($\mu$), absolute permittivity ($\varepsilon$), and conductivity ($\sigma$) of the material through which the signal travels (Cassidy, 2009). Rarely will all of these values be measured, but those that are not can be estimated from literature. The following equation was used to calculate skin depth in Table 1. In most cases, however, it will be unnecessary to have a detailed understanding of skin depth prior to surveying.

$$\delta = \frac{1}{\sqrt{\mu\varepsilon \left[ \frac{1}{2} \sqrt{1 + \left(\frac{\sigma}{\mu\varepsilon}\right)^2 - 1} \right]^2}}$$

Table 1 also includes the theoretical resolving limit at a certain frequency in a specific material. Resolving limit refers to the smallest object or thinnest stratigraphic layer that can be detected, and is calculated as a quarter to a half of the wavelength (Jol and Bristow, 2003).

It should also be noted that surveys done over a dipping reflector will underestimate the actual angle of dip (Jol and Bristow, 2003). This is because the signal returns perpendicular to the reflector rather than from a point directly beneath the antenna (Jol and Bristow, 2003). The actual dip ($\alpha$) can be found by taking the inverse sin of the tangent of the measured angle ($\beta$) (Jol and Bristow, 2003). $\alpha = \sin^{-1}(\tan \beta)$. 
Table 1: Skin depth and theoretical resolving limit for selected materials at three frequencies

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Material ((\varepsilon))</th>
<th>Skin Depth (m)</th>
<th>Theoretical Resolving Limit (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 MHz</td>
<td>Freshwater (78-88)</td>
<td>0.3</td>
<td>0.15-0.3</td>
</tr>
<tr>
<td></td>
<td>Freshwater Ice (3)</td>
<td>300</td>
<td>0.8-1.6</td>
</tr>
<tr>
<td></td>
<td>Wet Clay (15-40)</td>
<td>0.01</td>
<td>0.33-0.65</td>
</tr>
<tr>
<td></td>
<td>Wet Sand (10-30)</td>
<td>0.3</td>
<td>0.35-0.7</td>
</tr>
<tr>
<td></td>
<td>Dry Sand (3-6)</td>
<td>4</td>
<td>0.73-1.45</td>
</tr>
<tr>
<td>100 MHz</td>
<td>Freshwater (78-88)</td>
<td>0.2</td>
<td>0.075-0.15</td>
</tr>
<tr>
<td></td>
<td>Freshwater Ice (3)</td>
<td>300</td>
<td>0.4-0.8</td>
</tr>
<tr>
<td></td>
<td>Wet Clay (15-40)</td>
<td>0.008</td>
<td>0.17-0.33</td>
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<td>4</td>
<td>0.37-1.45</td>
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<td>200 MHz</td>
<td>Freshwater (78-88)</td>
<td>0.2</td>
<td>0.038-0.075</td>
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<td>Freshwater Ice (3)</td>
<td>330</td>
<td>0.2-0.4</td>
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<td>Wet Clay (15-40)</td>
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<td>Wet Sand (10-30)</td>
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<td></td>
<td>Dry Sand (3-6)</td>
<td>4</td>
<td>0.19-0.37</td>
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</tbody>
</table>
Figure 8. The top photo shows how the antenna and receiver fit together. The bottom photo shows antenna and receiver configuration while surveying. When performing a common offset reflection survey, they are kept at a constant separation. Data points are taken at set intervals along the transect (shown with a measuring tape).
Description of PulseEKKO 100 RUN

Hardware Components

- pulseEKKO 100 radar console unit
- pulseEKKO 100 hub
- RS232 cable (connects console to computer)
- Antenna pair (transmitter and receiver) for chosen frequency
- 2 antenna handle assemblies
- 2 12-volt batteries
- 1 single fiber optics cable (for transmitter)
- 1 dual fiber optics cable (for receiver)

Antenna Assembly (Fig. 8)

- Screw brass pins into the threaded holes in each antenna and hand tighten (do not overtighten)
- Screw brass sockets into the threaded holes on the bottom of the transmitter and receiver boxes and hand tighten (do not overtighten)
- Attach the antenna mounting block to each antenna by tightening the quarter-turn fasteners with a flathead screwdriver (double check that each fastener is tight before continuing)
- Insert two 12V camcorder batteries into each transmitter and receiver box (retail batteries are slightly too large and will need to be sanded down)
- Attach the transmitter and receiver boxes to the antenna mounting blocks by aligning them so that the brass pins are inserted into the brass sockets
- Secure the transmitter and receiver boxes with the latch connectors located on each side of the box
- Attach the handles to the antennas by tightening the quarter-turn fasteners

*Cable Connections (Fig. 9)*

- Connect the transmitter to the hub using the single fiber optics cable (the black end should be connected to the transmitter and the gray end should be connected to the hub - note: labels on the hub are located beneath the ports)
- Connect the receiver to the hub using the dual fiber optics cable (match gray to gray and black to black)
- Connect the console to the hub using RS232 cable
- Connect the fast port to the computer and the console
- Use alligator clip cable assembly to attach two 12V car batteries to the hub power port
- Connect beeper device (optional)

Note: While flexible up to a point, fiber optics cables are made of glass and thus should be handled with care. This includes being cautious when rolling and unrolling cables as well as taking care not to step on them during the survey.

**Conducting a Generic Survey**

*Setting Data Collection Parameters*

- Turn on the console by pressing ‘B’
- Select “Run pulseEKKO GPR” from the menu screen
- Select “pulseEKKO 100”
- Under **Options** make sure that Correction is set to DEWOW and Depth Axis is ON
- Under **Field Line** set Type to CMP if performing a common midpoint survey or to Reflc if performing a reflection survey, Mode should be STEP, define Separation and Step Size based on chosen frequency (use chart on console)
- Under **Gains** select Agc
- Under **Velocity** m/ns can be set either based on the results of the CMP survey or based on material (use chart on console)
- Under **System** set Antenna Frequency to chosen value

Selections will only be saved if Return is pressed. If ESC is used no changes will be saved.

Note: If the beeping stops and the screen remains blank or shows only black lines when the console is turned on, the console will probably need to be opened up to adjust the internal connection. To do this, carefully unscrew the bottom panel of the console. Once open, find the wire connected to the display and fiddle with it. It may be necessary to turn the console on so that it is obvious once a good connection is restored. Then, carefully reattach the bottom panel.
Figure 9. Diagram showing GPR cable connections. Colored lines represent cables except in the case of the red line where an image of the actual cable is shown. For the most part, however, it is unnecessary to include images of the cables because they can only be connected a certain way. For example, there is only one cable with alligator clips on the end, so that cable must be used to connect the battery to the hub. Note that two 12 V batteries are required even though only one is pictured here.
Common Offset Reflection Survey

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Common Midpoint Survey

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<th>T2</th>
<th>T1</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
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<td>d2</td>
<td>d3</td>
<td>d1</td>
<td>d2</td>
<td>d3</td>
</tr>
</tbody>
</table>

Figure 10. Two types of survey configurations. In a common offset reflection survey, stepsize (a) and antenna separation (d) remain constant along the transect. The transmitter is labeled ‘T’ and the receiver is labeled ‘R’. Numbers beside T and R indicate discrete timesteps. In a common midpoint survey, antenna separation increases by the stepsize after each timestep.
Establishing Transects

Transects should be established along which data will be collected. For best coverage, a grid is recommended, but transects will likely be constrained by topography. Ideally, transects should be spaced such that there are no gaps in coverage. To calculate this use the equation \( A = \frac{d}{\sqrt{\varepsilon_r - 1}} + \lambda \), where \( A \) is the signal footprint at a certain depth \( d \) based on wavelength \( \lambda \) and dielectric constant \( \varepsilon \) (Baker et al., 2007). The maximum depth can be based either on results from a preliminary transect or from published experimental data. Alternatively, a shallower depth may be chosen based on the survey’s purpose.

For example, when using a 50 MHz antenna in saturated sand to image down to 8 m, transects must be spaced at most 1.5 m apart. If, however, the surveyor only needs to see down to 2 m, the transects can be placed 5 m apart. Note that it may not be necessary based on the purpose of the survey to image an uninterrupted zone.

Collecting Data

First conduct a common midpoint (CMP) survey to establish wave velocity through the study site’s ground material (Fig. 10). To do this, create a transect by laying out a measuring tape. Place the transmitter and receiver in the center of the transect. Their spacing will depend on the frequency being used and can be determined by referring to the chart on the PulseEkko console under the survey type – CMP tab. Once a shot is taken with this starting configuration by pressing B on the console, the antenna and receiver are moved apart a specified amount. This amount can also be found by using the
PulseEkko console chart. Another shot is taken and the antennas are moved again. This continues to the ends of the transect. So long as the ground material remains fairly constant throughout the survey area, it is only necessary to perform one CMP survey for the entire region. Using the data from this survey, calculate the slope of the ground wave to determine velocity. This velocity can then be input into the console for the remainder of the survey.

A series of common offset reflection surveys can then be performed (Fig. 10). This type of survey is like a CMP survey except the transmitter and receiver start at one end of the transect instead of in the center. Additionally, the separation between the transmitter and the receiver should remain constant as they are moved along the transect. This separation and the distance moved between shots can be determined using another chart on the PulseEkko console under the Survey Type – Reflection tab. To begin the survey, the console holder should select Run – Collect - Input File Name – Enter on the console. Like with the CMP survey, pressing B collects data at one location. The antennas must then be moved before pressing B again. This pattern continues until the end of the transect.

The console holder should be able to view the traces as they are collected. If the traces change their appearance in the middle of a transect, check the lights on top of the transmitter and receiver. It is likely that one has run out of battery. It is best at this point to put in fresh batteries, but if no fully charged batteries are available, shuffling the batteries between the transmitter and the receiver will likely provide a little extra time since only one good battery is necessary for each to function.
If the screen displays CONSOLE ERROR #1, unplug the connection between the console and the hub’s power port. Then, restart the console.

If the screen displays RECEIVER ERROR, the receiver is probably not turned on or the battery needs to be replaced.

Other Considerations

Cell phones and radio signals can interfere with the data (Annan, 2009). If the interference is constant throughout all the data, it can essentially be ignored. It is, however, good practice to remove cell phones from pockets or shut them down while collecting data.

GPR equipment is robust and data can be collected in nearly all weather conditions (Jol and Bristow, 2003). However, batteries will die more quickly in cold temperatures. Also, it is best to cover batteries in heavy rain to avoid short circuiting.

Data Analysis

Although there are a number of open source programs available for analyzing GPR data, one relatively user friendly option is an R package created by Emanuel Huber called RGPR. It is available to install from GitHub, and a series of tutorials can be found at https://emanuelhuber.github.io/RGPR/.

Corrections

There are very few corrections that are necessary prior to being able to interpret GPR data (Jol and Bristow, 2003). Those described here are a basic selection used to
make the data more readable. Be careful in applying corrections, because too much
manipulation can create patterns that do not really exist (Jol and Bristow, 2003).

Time Zero Correction: averages the first arrival times for traces in a transect and adjusts
all traces so that they begin at this averaged time zero.

Dewow: removes low frequency components of the signal

Frequency Filter: removes high frequency noise

Time Gain: compensates for signal attenuation down trace

Spatial Filter: removes noise by averaging across traces

Topographic Correction: relevant if the survey is performed on uneven ground

Interpretation

Interpretation will depend on the purpose of the survey. In an archaeological
survey, for example, identifying hyperbolas caused by buried objects will be more
important than noting the depth and character of stratigraphic changes (Jol and Bristow,
2003). One way to learn to interpret GPR data is to study the interpretations made by
more experienced researchers. The next few pages contain examples of data that have
undergone analysis.

Cross Bedding/Progradation (Johnston et al., 2007; Fig. 11)

This data was collected in a study on the preservation of beach ridges in the Great
Lakes Region. 250 MHz antennas were used at a separation of 0.3 meters to obtain a
resolution of about 30 cm at a depth of 3-8 m. The data were corrected using DEWOW,
AGC, and a topographic correction. In this case, data interpretation was focused on the identification of stratigraphic features such as cross bedding and bounding surfaces. Cross section A shows the uninterpreted data along a 90 m transect. Above 1 m the reflections are mostly horizontal. Between 1 and 4 m the reflections dip to the left. Below this, not much is discernible. In Cross section B, the authors of the study have labeled the water table as the boundary between the horizontal and dipping layers, probably based on core analysis. Ravinement surfaces are drawn in the dipping layers based on the reflection data as well as on topography. The inset shows how the dipping layers are further divided into offlapping progradational wedges. Where the boundaries of these wedges are drawn is based on grain size changes seen in core samples.

Water Table (Peterson et al., 2007; Fig. 12)

These data were collected during a groundwater study designed to show that groundwater surface reflections can be traced laterally using GPR. 100 MHz antennas were used to reach depths of 10-15 m. In this cross section, the groundwater surface reflection is labeled and is shown to rise beneath the dune crest. In this case, the groundwater reflection is clearly distinguishable from other reflectors, but in many cases it is difficult to discern without core data.

Diffractions (Clement and Murray, 2007; Fig. 13)

Diffractions are interference patterns produced when waves pass through a small opening or encounter an edge. In GPR surveys, diffractions often occur at the edges of fractures or dikes. In their study, Clement and Murray took advantage of these
diffractions to characterize the geometry of clastic dikes in Washington. 100 MHz antennas were used at a separation of 1 m. Data were corrected using a bandpass filter and trace averaging. The diffractions can be clearly identified as broken hyperbolas.

Buried Object (Stevens and Robinson, 2007; Fig. 14)

GPR is not only useful when looking at subsurface geometry, but can also be used to identify the location, shape, and surrounding material of discrete objects. In a study done by Stevens and Robinson looking relict lacustrine deltas in northern New York, they were able to identify drop stones in their GPR data. In cross section, drop stones, and other buried objects, show up as hyperbolas. This is because EM waves propagate conically from the transmitter and can thus detect buried objects that are not directly below the antenna. As the transmitter nears the object, the EM wave’s travel time from the transmitter to the object and back to the receiver decreases. This translates to a shallowing when time is converted to distance on a cross sectional plot. When the survey line is positioned directly above the object, the object’s location can be determined by looking at the hyperbola’s apex. Furthermore, algorithms exist that allow researchers to fit the shape of the observed hyperbola to a set of standards, and through this say something about the geometry of the buried object.
Figure 11. Interpreted GPR data with water table, ravinement surfaces, and progradational wedges identified. The vertical lines in panel A show the locations of boreholes. One such borehole appears in the panel B inset. Adapted from Johnston et al., 2007.
Figure 12. Example of interpreted data where the water table has been identified as a continuous, nearly horizontal layer below the surface. In this case the water table can be seen to rise slightly beneath a dune crest. Adapted from Peterson et al., 2007.
Figure 13. Interpreted GPR data showing diffractions around the edges of a dike. The relevant region of the graph has been boxed and the approximate location of the dike has been illustrated in red. Adapted from Clement and Murray, 2007.
Figure 14. Interpreted GPR data showing a cross section of a delta. Note that discrete objects, such as dropstones, show up as hyperbolas in GPR data. Where the dropstone appears in this cross section is boxed, and the hyperbola it forms is traced in red. The actual location of the stone is probably near the hyperbola’s apex. Adapted from Stevens and Robinson, 2007.
APPENDIX B: RGPR CORRECTION CODE
# Installation
myDir<-"D:/RealSurvey"
setwd(myDir)
getwd()
library(devtools)
devtools::install_github("emanuelhuber/RGPR")
library(RGPR)

# Raw data
A<-readGPR(fPath="rawGPR/Filename.DT1")
vel(A)<-0.06 # velocity value from CMP
plot(A) # add ,type="wiggle" for wiggle trace plot

# Time zero correction
time0(A)
tfb<-firstBreak(A)
t0<-firstBreakToTime0(tfb,A)
time0(A)<-t0
t0=mean(tfb)
A2<-time0Cor(A,method="pchip")
plot(A2)

# Dewow
A3<-dewow(A2, type="MAD", w=50)
plot(A3)

# Frequency filter
spec(A3) # use plot to determine c(_,_) values
A4<-fFilter(A3,f=c(60,100),type="low",plotSpec=TRUE)
plot(A4)

# Time gain
A5<-gain(A4, type="agc")
plot(A5)

# Spatial Filter
A6<-filter2D(A5,type="median3x3")
vel(A6)<-0.06
plot(A6)

# Save
writeGPR(A6,fPath=file.path(getwd(),"processing",paste0(name(A6),",.rds")),format="rds",overwrite=TRUE)