Analysis of the Effectiveness of geophysical methods in the locating of snow avalanche victims

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ABSTRACT: Hundreds of people worldwide are killed in snow avalanches each year. (Adkins, CAIC) A small percentage of victims remain missing after the use of traditional techniques including probe lines and cadaver dogs. (Aspen Grove avalanche, 2003) Geophysical methods may provide an effective means by which to locate victims before the summer thaw. Research focused on the locating of metallic debris that could remain attached to a buried victim. Three geophysical tools used in the research include the Geonics EM-31 and EM-61 and a Pulse EKKO 1000 GPR equipped with 450MHz antenna. A survey grid was set up at Loveland Ski Area, Colorado during the winter of 2004. The survey included various backcountry objects commonly accompanying a victim as well as objects known to give false victims indications with geophysical tools. Data suggest that EM-31 and EM-61 tools are not able to uniquely locate single metallic debris and should not be used for victim location unless perhaps the victim is known to be carrying a large amount of metal. The data also suggest GPR can be used to uniquely resolve debris orientation and material composition. GPR was effectively utilized to uniquely identify debris based on material composition and shape. Shape was determined by varying the azimuth of data lines about a target and observing changes in moveout. Material composition was determined through wavelet polarity analysis. GPR data was also collected in April 2004 at the Aspen Grove avalanche site in Provo Canyon, Utah. The purpose of the Aspen Grove survey was to locate the lone remaining victim of the December 26, 2004 Elk Mountain avalanche. Data collection revealed challenges that include the resolving of ice layers, identifying rocks, trees, and ice blocks, determining high-probability targets, and coordinating with the search and rescue team. Both processed and real-time singe-stack data were used in the search, which was performed with cross-line spacing of 3ft and inline flag spacing of 6ft. Trees, rocks, and metallic debris were uniquely identified and classified as low probability targets. One high probability target was identified during the search and remains unidentified. The victim later melted from the snow-pack a short distance from the survey grids; the victim was not imaged in the survey. More than $12,000 and 7000 man-hours were spent searching. (Utah Avalanche Information Center) The time and money spent by Utah County Search and Rescue illustrates the potential for GPR to streamline searches and save valuable time. Aggregate results of the research suggest EM-31 and EM-61 instruments cannot detect single objects commonly carried on the victim while GPR may function effectively when data interpreters are versed in debris identification.

KEYWORDS: Avalanche, Victim Recovery, GPR, Ground Penetrating Radar, Electromagnetic

1. NOMENCLATURE

Debris: Any object caught in an avalanche including man-made material, natural material, and ice.

Target: Debris identified with electromagnetic tools.

Normal Wavelet: GPR wavelet characterized by a trough-peak-trough shape, same shape as the air-snow reflection.

Inverse Wavelet: GPR wavelet characterized by a peak-trough-peak shape, opposite shape as the air-snow reflection.

1.1 Introduction

Around the globe, several geophysical instruments have been used to locate snow avalanche victims. (Broken River, 1995)(Guardsman Pass Bulldozer Burial)(Bountiful Peak, 2003)(Scotland victim recovery, 1994) The most published include the use of the Geonics EM-31 and ground penetrating radar (GPR). Several examples detail the use of the EM-31 and GPR in recovery situations, to date, the number of victims located with these instruments can be counted on one hand. Even worse, there are no baseline data to compare the signature of a ski, for example, against that of a tree. In our research, 280 man-hours were utilized to collect baseline EM-31, EM-61, and GPR data over common avalanche debris under controlled experimental conditions. In addition, 60 man-hours were spent on the Aspen Grove avalanche site in Provo Canyon, UT using GPR to locate one missing victim. Research goals included:

- *Determine the effectiveness of EM-31, EM-61, and GPR in the locating of victims.*
- *Develop a search method for use with GPR*

The common themes in debris detection and debris identification throughout our research are identifying signature variation with varying azimuth about a target and deducing debris composition by the polarity of the reflected wavelet.

The Geonics EM-31 is a frequency-domain electromagnetic instrument commonly used to detect large ferrous metallic objects and pipelines. The instrument measures the difference between the sinusoidal-source magnetic field and the induced magnetic field, which yields information about the conductivity values below the surface.

The Geonics EM-61 is a time-domain electromagnetic instrument mostly used to detect unexploded military ordinance. A current loop 1m by 1m induces a primary magnetic field, which causes small currents in conductive objects. The primary current is then turned off and the receiving antennas record the secondary field.

Ground penetrating radar (GPR) is commonly used to image material inhomogeneities in the shallow subsurface. A transmitting antenna emits a constant-frequency electrical impulse that travels with a velocity that depends on subsurface electric properties. A reflection of the impulse occurs when a change in electric properties is encountered. The receiver records the reflected wave time, and a simulated cross-section of the subsurface is displayed.

2. EXPERIMENTATION, STATIC GRID

A static grid was set up at Loveland Ski Area near Loveland Pass in Colorado to test instrument detectability of debris commonly caught in an avalanche. The layout of the grid is shown in figure 1. A total of eighteen metallic and non-metallic items were buried in the static grid and data was collected on four separate occasions from December through April. Acceptable experimental conditions were maintained with no tampering of the grid from December through April. Snow pack conditions within the grid were also monitored periodically and compared to snow pit records and informal observations on Loveland Pass, CO and Jones Pass, CO. Good correlation was observed. Parameters included snow depth, temperature gradient, hardness, and layering and indicate similar deposition rate, metamorphism, and snow type in all areas.

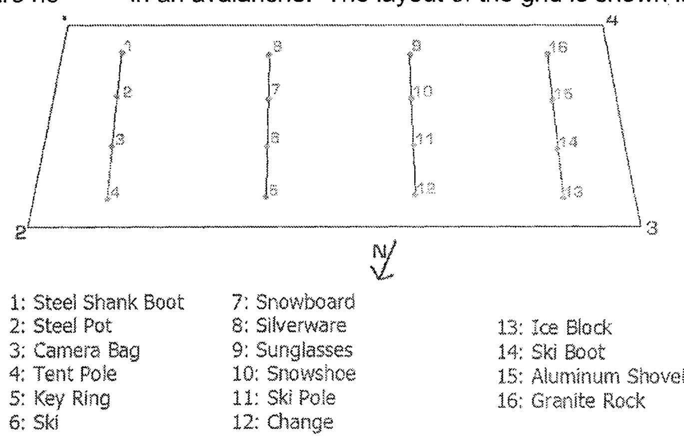

Figure 1: Static grid 100x100 ft, located at Loveland Ski Area, CO

Each item was buried below 1.5 feet and depth to ground and from snow surface was recorded with each day of data collection. Every object with an elongate shape was oriented with the larger dimension striking Northward. Every item maintained a twenty-five feet buffer of separation to the next object to eliminate electrical interference. Good experimental conditions allowed isolation of the variables: snow quality, homogeneity, and depth, and allowed experimentation to focus on signature amplitude, polarity, and signature variation with azimuth.

2.1 EM-31

The EM-31 was used on the static grid purely as a metal detector. With a 9ft boom separation between transmitter and receiver, data resolution is too course to determine object width and signal variation with azimuth. Construction of the instrument allows the source and receiver coil orientation to be changed to obtain vertical and horizontal components of the induced secondary magnetic field. A total of 46 different lines of data were collected on the static grid throughout the winter. The lines of most interest were the vertical and horizontal component lines in both the grid East-West and North-South directions over the buried objects. Lines were also run around the perimeter and in between objects to ascertain background conductivity levels.

The EM-31 data acquisition is fairly rapid, but does require repetitive input into the data logger, which records both the in-phase and out-of-phase portions from the receiver coil. The instrument is extremely dependent on a tight, controlled grid system, making data collection and detection of potential anomalies a challenge. On the contrary, a successful field technique for victim recovery needs to be independent of a rigid grid system, fairly rapid, easy to use, and easy to interpret/understand.

During data acquisition, each data line was marked with flags to denote the start and end points. Markers were added manually within the data to indicate debris locations and to aid in rubber-sheeting of the data. Figure 2 above shows the vertical and horizontal component graphs over as sampling of objects, traveling approximately South to North.

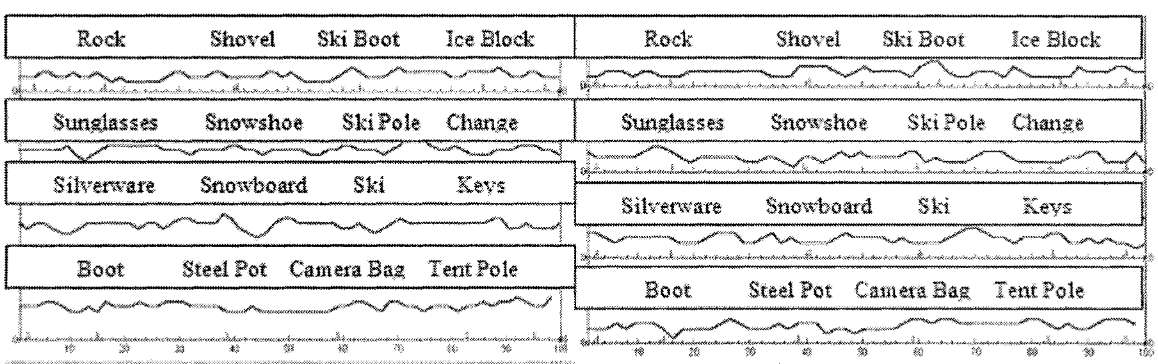

Figure 2: Quadrature (red) EM-31 data with the objects surveyed above the arrow representing their location in the grid. The data on the left is the vertical component if the induced magnetic field, while the horizontal component of the induced magnetic field is shown on the right (mS/m).

Evident in the data is the lack of detectability in both the in-phase and out-of-phase components. None of the 44 EM-31 data lines run over the objects yielded information that indicate positive object identification. Correlation between buried objects and plotted data appears to be nil.

While the EM-31 has useful applications in other situations, we feel that the EM-31 would not be the best geophysical tool for avalanche scenarios. If attempted, it is our recommendation that use of the EM-31 for victim recovery be limited to situations where the victim is known to have a large amount of metal on their person.

2.2 EM-61

The EM-61 was also used purely as a metal detector on the static grid. The instrument is an electromagnetic induction tool, which is used to detect both ferrous and non-ferrous metals. Like the EM-31, the EM-61, records the induced secondary field produced by metallic objects in the presence of a primary field. The EM-61, however, records the relaxation of the secondary field after the primary field is turned off. The top receiver's magnitude is subtracted from the bottom receiver's magnitude to yield the rate of change, or gradient of the field, for each point. Twelve lines of data were collected with the EM-61 including two of our grid perimeter, four East-West lines over objects, and six similar lines in the North-South direction. The goal was to determine a background field with the grid perimeter lines and then examine object detectability as well as signature variation with azimuth about the object. Due to time restrictions, a dense grid was not acquirable, so data presented are one-dimensional lines of our grid, not contour maps.

For data acquisition, we used the factory wheelbase available for the EM-61. The instrument was then pulled across the snow along the grid lines as each data point was taken manually approximately every foot. Due to the rough surface of the snow and error involved in the one-foot acquisition measurements, some lines had more data points then others. The lines were rubber-sheeted to fit a distance of 100 feet. Plotted data show the difference in the measured induced current recorded by the two receivers on the EM-61. Figure 3 shows two of the lines of data collected on the grid.

As seen in Figure 3 the aluminum shovel shows a significant anomaly but is the only object to be detected. High frequency noise associated with the data is likely due to the rough nature of the snow pack causing the instrument to be positioned at slightly inconsistent distances above the ground. Again, a lack of detectability leads us to conclude that the EM-61 should not be used for victim detection unless the victim is known to be carrying a large amount of metal on their person.

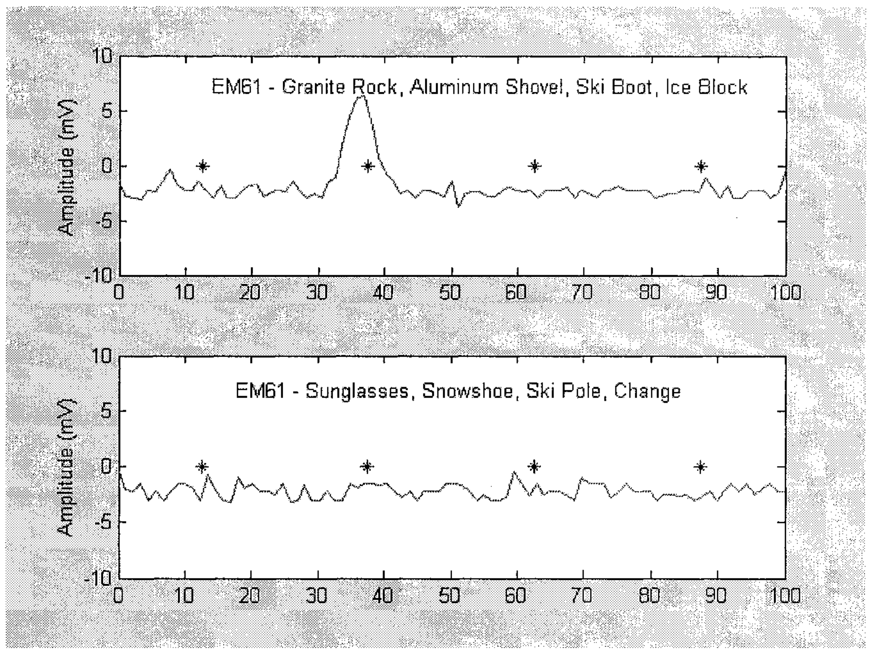

Figure 3: EM-61 data plotted by taking the difference in magnitude of the two receivers; the blue stars represent the approximate location of our objects

2.3 GPR

Ground Penetrating Radar (GPR) was used to detect all debris and sought to determine debris material composition through wavelet analysis and debris shape by varying location of data lines about a target. Data was collected in the controlled static grid for purposes of building a baseline database of debris signatures within a snow pack. In the next section, limited data is presented from a victim search at the Aspen Grove avalanche site, April 2004. Data from Utah are used to illustrate some of the problems with victim searches using GPR as well as to suggest a method of coordinating a victim search using GPR with that of search and rescue.

3. ADAPTING GPR FOR ON-SNOW CONDITIONS

The Sensors and Software^{TM} Pulse Ekko 1000 GPR unit consists of a transmitter-receiver pair, laptop interface running Pulse-Ekko software, and 12V battery. The use of GPR on snow necessitates improving coupling and stability of the transmitter-receiver unit. Typical avalanche debris consists of blocks and chunks of ice or extremely hard snow. Good coupling is therefore difficult to achieve and orientation of the unit receiver is difficult to maintain. These conditions were simulated in the static grid by the addition of chunks of hard snow in data lines. The dielectric similarity of snow and air allows the antenna to periodically lose contact the snow/air interface with minimal loss of energy. Considering the ability of the antenna to function a short distance above the snow and the nature of the debris, the antenna unit was fixed inside a 4' plastic sled, resulting in the ability to collect data with a fixed orientation antenna over mildly rough debris.

450MHz and 900MHz antennas were used for data collection on the static grid. Both antennas allowed for adequate imaging with depth. The 900MHz antenna provides increased detail but contains significantly more noise. The 450MHz data is cleaner but shows less object-

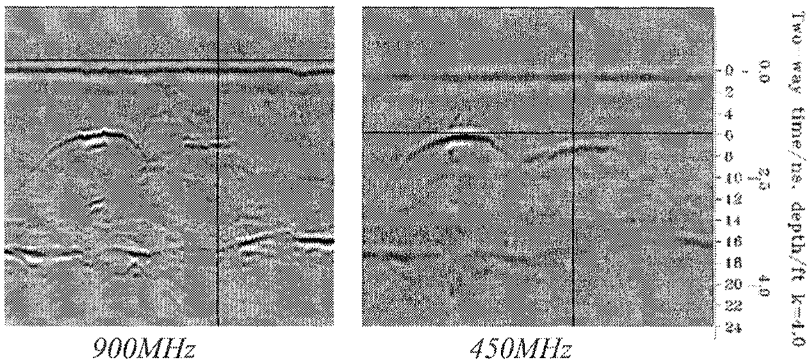

Figure 4: GPR image of warm pig (right), metal plate (left) buried in snow. Courtesy Justin Modroo, CSM 2003

wavelet resolution. Figure 4 shows a comparison of 900MHz versus 450MHz data collected by Justin Modroo and Doug Klepacki at Loveland Ski Area, November 22, 2003. Note the better resolution of the wavelet but increased noise in the 900MHz sample.

4. DEBRIS IDENTIFICATION

Ice blocks, trees, rocks, backpacks and skis/snowboards are the debris most common in avalanche debris as well as the objects most likely to be misinterpreted as the victim by GPR (Adkins, CAIC, 2003). The ability to discern between a singe ski, a victim, and a ski attached to a victim, for example, is critical. Elimination of low probability targets and rapid interpretation of probable targets can save valuable time in the recovery effort.

4.1 Debris I.D. using wavelet shape

A large range in size and material composition of the objects placed in the static grid was crucial. This study revealed that objects as small as sunglasses could ultimately be imaged and resolved into their wavelet shape. Differentiation between objects carried on the victim and natural debris objects located in the snow, based on material composition, is the most successful avenue of this study. Metallic objects such as the ski, metal shovel, and snowshoe have a high amplitude normal wavelet with a trough-peak-trough shape. In addition, ringing of the metallic wavelet is commonly observed as is shown in Figure 4; note also the normal wavelet shape.

The wavelets produced by ice, trees, and a body are internally similar but are markedly different than those produced by metallic objects such as skis or snowshoes. First, trees, ice, and a body produce a peak-trough-peak wavelet that is the inverse of the metallic wavelet. Second, no ringing is observed with the ice, tree, or body mass equivalent (BME).

The wavelet shape produced by the rock used in the survey was normal. This is likely due to the high iron content of the rock used. A more resistive rock would likely produce an inverse wavelet. (Modroo, J., 2004) Unique field identification of a rock based on wavelet shape is difficult since it can produce either a normal or inverse wavelet. (J. Modroo, 2004)

The wavelet produced by a BME has been shown to be an inverse, peak-trough-peak. (J. Modroo, G. Olhoeft, 2004) The wavelet form has been shown indicative of partial melting of snow above and below the BME creating a snow, ice layer, air, BME sequence with depth. (J. Modroo, G. Olhoeft, 2004)

In summary, metallic objects (including skis, snowboard) produce a normal trough-peak-trough wavelet and often exhibit "ringing." Natural objects (tree, ice, body) produce an inverse peak-trough-peak wavelet. Rocks may produce either wavelet. Clearly, in order to uniquely identify objects, something must be known about size and shape.

4.2 Object I.D. by varying azimuth

Once a piece of debris has been located, collecting several lines of data at various azimuths about the object is helpful in identification of the debris shape, size, and orientation. Small objects tend to have no azimuthal variation in signature. Figure 5 shows the azimuthal variation for the ski. The left image is of 450MHz data collected in-line with the long axis of the ski. The signature is that of a composition of hyperbolas and appears elongate with approximate length 6ft. The right image is of 450MHz data collected across the

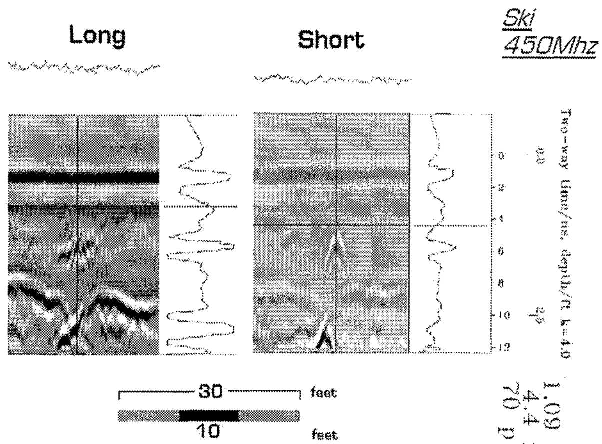

Figure 5: Azimuthal variation of ski, data parallel to ski (left), across ski (right), static grid.

short axis of the ski. The signature is that of a metallic point source. Azimuthal variation is observed to decrease with depth, as the debris effectively becomes a point reflector, although width has been calculated, albeit with some error, for debris at depths below 10ft. For shallow objects buried less than about 5 ft, visual inspection of the wavelet is sufficient to discern signature variation with azimuth. Below about 5ft depth, the use of GRORADAR software is helpful in determining object width. (J. Modroo, 2004) (Free download at www.g-p-r.com)

Determining if objects have a long axis is instrumental in debris identification. Backpacks, skis, snowboards and ski poles are objects most likely remain attached to victim caught in an avalanche. (Adkins, 2003) These objects in addition to the victim produce strong azimuthal variations in wavelet shape. Debris identified with strong azimuthal variation and ringing is considered a high probability target, especially multiple targets in close proximity.

4.3 Object I.D. summary

Initial identification of an object can be based on the appearance of a hyperbole. With the use of GRORADAR software, the data can be further analyzed on the basis of wavelet polarity, to determine if the object is metallic. Table 1 provides a wavelet summary for various debris commonly caught in an avalanche. Then, multiple data lines at various azimuths about the debris can reveal width variations. Width modeling is easily accomplished with GRORADAR software in the field. Based on whether the object is metallic or not and whether it exhibits signature variation with azimuth, objects may at least be classified as low or high priority or potentially even identified uniquely. By properly classifying debris by priority, deceptive targets can be greatly reduced, which is essential in rapid locating of the victim.

5. DATA COLLECTION AT ASPEN GROVE AVALANCHE SITE, APRIL, 2004

Utah County Search and Rescue, Utah County Sheriff's office, and Colorado School of Mines combined efforts for two days over the weekend of April 10, 2004 in an attempt to recover a single remaining victim from a large December avalanche. On December 26, 2003, six snowboarders were hiking "Roberts Horn Chute" in the Aspen Grove recreation area when a series of 4 massive avalanches cascaded down the mountain sweeping away all the victims. The avalanche danger on December 26, 2003 was rated extreme by the Utah Avalanche Center. Three victims were partially buried and survived but three were buried completely and went missing in a debris field larger than 16 acres. None of the victims was wearing an avalanche transceiver beacon and initial search efforts were fruitless.

The first observation of the debris field is that numerous rooted trees have been forced down parallel to the avalanche path and partially buried. The rooted trees have a strong orientation down-slope due to the slide direction. The large mass of trees was still partially buried and gave numerous false targets when lines were run across the avalanche path. Running data lines parallel to the avalanche path reduced the number of targets significantly. According to Dale Adkins of the Colorado Avalanche Information Center (CAIC), avalanche direction has no correlation with debris orientation so data lines oriented along the slide path still allow for detection of debris suspended in the snow pack while reducing the number of false targets due to rooted trees.

Data were collected with two separate techniques. A quick look analysis was used in snow less than 10 ft deep as shallow depths were deemed low probability due to the increased ability of cadaver dogs to locate a shallow victim. In addition, shallow areas had already been probed extensively by search and rescue. A more extensive data analysis technique was used for snow greater than 10ft deep. This involved gaining of the data and width modeling with GRORADAR software. GPR is most helpful in deep zones since

Man-Made, Metallic

item	steel sh boot	snowshoe	ski pole	alum shovel	steel pot	ski	snowboard	silverware	sunglass
confidence									
wavelet	normal	normal	normal	normal	normal	normal	normal	normal	normal
|	low	low	low	low	low	low	low	low	low
shape	high	high	high	high	high	high	high	high	high
|	low	low		low	low	low	low	low	low
	high			high	high				high
	low								

Natural Items

item	tree trunk	pine boughs	ice block	rock	pig body
confidence					
wavelet	inverse	not app	inverse	normal	inverse
|	high		high	low	high
shape	low	not app	low	high	low
|	high		high	low	high

Table 1: Wavelet signatures for various debris; wavelets shown for metallic and natural objects.

Man-made, non-metallic

item	ski boot	backpack	tent pole
confidence			
wavelet	normal	normal	inverse
|	low	low	high
shape	high	high	low
|	low	low	high
	high		

cadaver dogs lose effectiveness in deep snow and avalanche probes are only 10ft long (Utah County Search and Rescue). Deep snow zones with scent indications by cadaver dogs were considered high probability zones.

For both techniques, data lines were collected at 3 ft cross-line spacing with marker flags at in-line increments of 6ft to allow for rubber sheeting of data. The cross-line spacing allows for imaging of a debris buried to 1.5ft depth, located exactly between data lines.

Data were saved to hard disk in addition to being monitored in real-time using Pulse Ekko™ software. Debris identified in real time was noted by the observer for later identification with GRORADAR software. After every 5-10 lines, the data were analyzed with GRORADAR software and high-probability targets marked with flags for recovery by search and rescue. Search and Rescue personnel were on hand to dig at target locations.

A total of .6 acre was searched using GPR and the victim was not located after two days of searching. The GPR team was confident that the victim was not located under any of the grids. Hikers located the victim the day after GPR searching ceased; the victim was located near the bottom of the debris field a small distance from the GPR search area. A total of 42 man-hours were accumulated with GPR. To search the entire debris field would have taken about 1100 man-hours. According to Alan Wakefield of the Utah County Sheriff's Office, Search and Rescue personnel accumulated 7000 man-hours. In the case of Provo Canyon, the equivalent search method of using GPR to search the field is seven times faster than conventional search methods with dogs and probe lines.

5.1 Lessons Learned from Aspen Grove Avalanche:

- Data collected parallel to the avalanche path are less cluttered due to the down-slope orientation of rooted trees. Since avalanche debris is oriented independently of avalanche direction, collecting data parallel to the avalanche path reduces the number of false targets.
- Cross-line spacing of data lines of 3 ft is adequate to image 100% of the sub-snow surface below a depth of 1.5 ft.
- Most high-probability targets can be detected in the real-time and may be further analyzed in the GRORADAR software after gain application and width modeling.
- GPR avalanche victim surveys are most effective when trained personnel are on-hand to investigate debris identified with GPR.
- Buried ice layers are the largest source of false targets and can be identified since they usually appear parallel to the ground reflection.

6. EFFICIENT FIELD TECHNIQUE FOR GPR SYSTEMS

The suggested grid system, to be used with a standard 450MHz or 900MHz antenna, has cross-line spacing of 3ft with marker flags every 6 ft along data lines. 3 ft cross-line spacing coupled with the conical shape of the transmitter signal allows for imaging of 100% of the subsurface below 1.5 ft depth. Figure 6 shows the suggested grid layout.

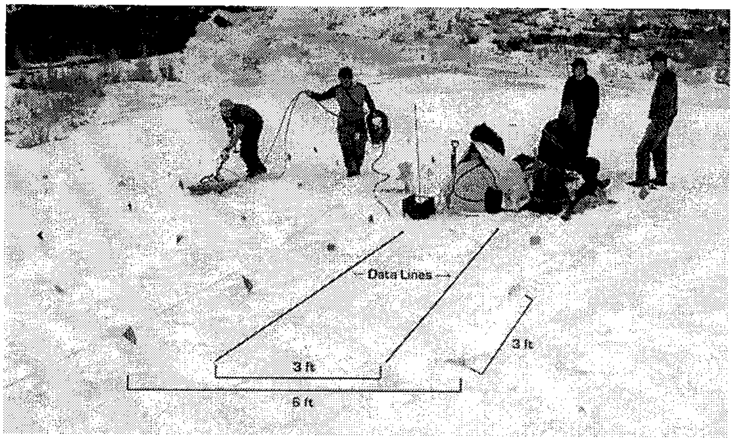

Figure 6: Grid Layout at Aspen Grove avalanche site

6.1 Deciding on an antenna

1: Both 450MHz and 900MHz antennas allow for adequate depth imaging of deep avalanche debris
2: 450 MHz antenna is our antenna of choice for avalanches with numerous non-snow debris and buried ice layers such as the Elk Point avalanche
3: 900 MHz antenna may be used for recent avalanches with few debris and no buried ice layers

6.2 Coordinating with Search and Rescue

1: All evidence of victim locations should be discussed in order to determine high-probability search locations. *(Surface debris, slide direction, cadaver dog indications, etc)*
2: Search and rescue should form probe lines and search areas with snow depths less than 10 ft.
3: GPR should be used first in high priority areas with snow depths greater than 10 ft.
4: Search and Rescue teams should be on-hand to investigate high probability targets identified with GPR.

6.3 Quick Look Technique – For GPR users proficient with on-snow data analysis

1: Setup grid with 3 ft cross-line spacing using minimal marker flags
2: Configure Pulse Ekko software for 450MHz antenna and medium with expected Dielectric Permitivity, k = 1.5 – 4.
3: Data should be collected continuously with a single stack with and no filters or gains applied.
4: Upon initial I.D. of debris, multiple lines of data at multiple azimuths should be analyzed in real time to determine the surface location of the debris and to classify the debris as low or high probability. Surface locations of high-probability debris should be marked with spray paint or marker flags.
5: Search and rescue should be dispatched to investigate high probability debris.

6.4 Protracted Technique – For GPR users not proficient with on-snow data analysis

* Data should be collected in the same manner as the Quick Look Technique but should be analyzed in GRORADAR software after several lines have been collected to highlight wavelet polarity and ringing.

6.5 Prioritizing Debris

Low Probability: Regardless of wavelet polarity, targets with little or no azimuthal variation in wavelet signature
Medium Probability: Multiple targets in close proximity.
High Probability: Single targets with moderate to high azimuthal variation.
Very High Probability: Multiple targets in close proximity exhibiting high azimuthal variation.

7. CONCLUSIONS

Several distinct conclusions can be drawn from this study.

- EM-31 and EM-61 electromagnetic instruments may not be effective in the locating of victims. The study suggests that the amount of metal is too small to cause an anomaly greater than the background field variation. The only debris detected with the electromagnetic instruments was the aluminum shovel, which was detected only by the EM-61.
- GPR can become an even more powerful tool when polarity analysis and azimuthal variation in signature is used in favor of basic debris detection.
- GPR can image nearly 100% of the snow pack with cross-line spacing of 3ft and still save significant amounts of time and

money as opposed to probe-line search methods.

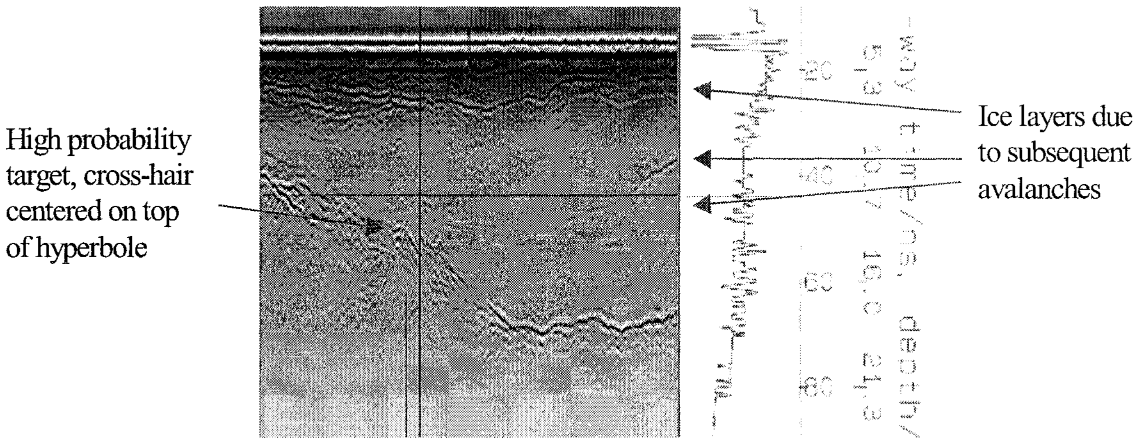

Figure 7: Illustrates some of the common difficulties interpreting field data. Source: Aspen Grove avalanche site, max snow depth=18 ft, depth to high probability target = 10 ft. Target is roughly hyperbolic with some width beyond a point reflector. GRORADAR indicates target has diameter 1.6m. Target is not a body and all large pieces of equipment have been recovered.

8. RECOMMENDATIONS

Regarding future research, conductivity contour plots should be created to further examine the detectability of metallic debris with electromagnetic tools.

Another potential experiment may include use of a newer EM-61, or the MK2 electromagnetic tool, which allows up to six recordings per coil. This would be advantageous because the time rate of decay for the secondary field could be better constrained and some noise attenuated, the result potentially being more resolute data.

To further differentiate between debris using GPR, we feel there is an opportunity for amplitude analysis to further aid in material determination from the raw data. In addition, some evidence exits suggesting frequency analysis may further aid in material determination. (J. Modroo, 2004)

Software improvements also have the potential to extract more information from raw data. An ideal field software package would automatically import field data lines, extract hyperbolic moveout, flag ringing events, and calculate debris width.

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