GPR profiling avalanche senior design

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Contents

1 Executive Summary

This project looks at the use of ground penetrating radar(GPR) to differentiate layering in snow-pack for use in avalanche forecasting. The applications used in the field were continuous profiling for understanding lateral continuity of the snow-pack and common midpoint for deriving the layer by layer density. This data can be used for use in looking for weak layers that different magnitudes of slab avalanches correspond to. Slab avalanches are the core focus considering they are frequently the most destructive. In making the assumption of looking for only these sort of avalanche conditions, the assumption of dry snow-pack also applies. This is essential in the use of the GPR because dry snow-pack can rely purely on variations in layer to layer permitivity. Where wet snow-pack would also have to more seriously take into account the signal attenuation of the GPR transmitter.

The actual results from this project were inconclusive due to a series of errors in the field. Three survey days were taken to achieve data, the first was faced with adverse weather conditions and poorly charged GPR batteries. The second survey day was faced with adverse weather conditions and a laptop that died in the cold weather and the third survey day dealt with a default setting parameter that resulted in NAN values. The project did produce an effective survey design for use on snow in the field and also yielded very good snow-pit data. Along with future recommendations for how this could be improved.

2 Introduction

The overall structure of snow pack is intimately tied to the density of each layer. Low or high density portions of the snow will favor either high heat conduction or diffusion and convection relatively [Harper and Bradford, 2003,]. These variations are directly tied to the elastic properties of the snow pack. Currently most applications for identifying these density variations are relatively destructive and labor intensive. Including methods like snow pit correlations, that take discrete in field data of the snow pack in search for characteristics like; hardness, snow type, and snow temperature. Continuing to use these characteristics to extrapolate into larger areas for prediction of spatial variability throughout the snow. The issue with this being that these discrete point measurements have very poor spacial and temporal resolution. [Schmid et al., 2014,] Although these prediction are not of the highest quality they are necessary for use in avalanche prediction, flooding prediction, and water resource management. To improve the quality of the data used in these types of predictions remote sensing methods can be applied instead.

One application of remote sensing that is non-invasive, is the use of upward-looking ground penetrating radar (GPR). This method is effective because the GPR can be buried months before the snow pack is established and can give consistent, real time data. This data has amazing temporal resolution and leaves the snow pack completely untouched [Schmid et al., 2016,]. The downside to this method is that its spatial resolution is very poor and faces the same issue as using a snow pit in regards to a discrete sampling problem. The method that compensates for this lack of spatial resolution is airborne or on-ground GPR. This project focuses on ground based GPR application with both continuous and common point survey methods.

2.1 Project Goal

The overall goal of the project was to accomplish three things. The first of which was simply to use GPR to identify snow pack. This could be done through a multichannel, singe channel, or common midpoint survey. The next goal was to take the GPR data acquired and correlate it to the physical snow pit data acquired in the field. Moving on to use whats discovered to try and build a simple avalanche prediction model. This model would be very basic, but hopefully the correlated data provides enough information to build a a worthwhile model.

This project also includes several aspects of survey implementation and data analysis identified as objectives. The initial layout of the GPR components require modification to account for the slope of the terrain and remoteness of the field site. The modified GPR sled set up is to be lowered and raised along a slope at a constant rate, while being isolated from potential sources of internal and external noise. Physical characteristics of the snow pack will be recorded by digging a snow pit and visually recording the internal layers. These measurements, in conjunction with the various stress tests, will be used to identify the weak layers in the snow pack and risk of a slide occurring. A GPR survey will be conducted over the area to image lateral continuity of layers and contrast of permittivities between them. The permittivity measured by the GPR will be correlated to the physical characteristics measured in the snow pit in order to determine if the GPR is able to identify the weak layers. This can create a way to remotely image the snow pack and identify weak layers that doesn't require the time and risk of sending people into the field.

2.2 Motivation

The overall motivation for the project came from a joint interest in winter recreational activities. The idea of aiding in any knowledge that could be used to help make it safer for people to travel in the winter for recreational activities is very enticing. An example of the shear destructive nature f avalanches can be seen in figure 1. There is also economic incentive, a study in 2012 has shown that the winter sports economy is worth about 22 billion dollars from ski resort contributions alone. Along with aiding in ski resort safety, any improvements in the application of GPR to snow-pack can be used in a large variety of applications. For example attenuation analysis of GPR can be used for the estimation of the Snow Water Equivalent. [Bradford et al., 2009,]. The SWE estimation can allow for areas to have a better approximation as to what their water storage in snow-pack is.

Figure 1: A picture of avalanche debris taken near Leadville, Co

3 Understanding Snowpack

3.1 Primary Deposition

For understanding how snow-pack actually accumulates and builds density variations, two primary driving processes must be understood. The primary deposition and the primary density system of the snow-pack. The primary deposition is the general deposition of the snow as it leaves the atmosphere and falls to the ground. This deposition will be dependent on the atmospheric conditions in the area and will vary region to region. For example the Cascades will generally yield a snowflake with a higher SWE that will tend to have a very good cohesion between snowflakes. While the rocky mountains will have larger snowflakes with a lower SWE that will have much worse cohesion overall. The other aspect of primary deposition is how the wind changes the distribution of the snowflakes as they fall from the sky. This aspect may also alter the shape of the snowflake, turning a more crystalline shaped snowflake into a rounded finer grain snowflake.

The primary deposition of the snowflake also will cause variations in the density of the snow-pack once it has fallen to the ground. For example the snow deposited from a fresh snowfall will have a semi consistent density property. While the older snow that the storm snow is falling on will have a different density contrasts. Note that undisturbed storm snow will also vary in its density in relation to the fresh untouched storm snow.

3.2 Secondary Deposition

In contrast to primary deposition, Secondary deposition is dependent on the in situ metamorphosis that a snow flake goes through once it has been deposited on to the snow-pack. This processes will cause higher or lower density variations in the original snow-pack over time. Note that high density favors heat conduction through the ice-grain lattice, while low density favors a processes of diffusion and convection. [Schmid et al., 2014,]. These processes are dependent on the composition of the surface that the snow falls on. For example there can be up to a 24X increase in depth hoar over rock a outcropping, given that the rock will favor a different heat flow process in contrast to the vegetation. [Harper and Bradford, 2003,] The secondary deposition and density variation drivers are the main culprits for the largest avalanches that occur in Colorado. This is because Colorado often forms a deep persistent slab avalanche problem. This problem is dependent on on the secondary deposition system that created large faceting at the base of our snow-pack. This sort of faceting should be easy to identify because there is a very large reflection that occurs right at the snow ground interface. Large facets almost always sit on this interface in Colorado. A description of this interface can be seen in bottom layer of figure 5 in the snowpit results section. A picture showing the approximate size and shape of depth hoar and faceting can be seen in figure 2.

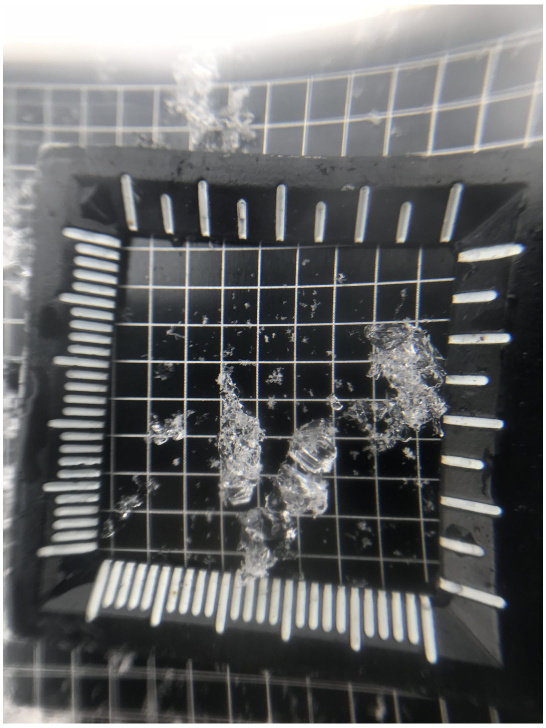


Figure 2: Depth Hoard under snow hand lens

3.3 Avalanches

This project focuses mainly on slab avalanches because they are the largest and the most deadly type of avalanche and also are the most frequent killers in Colorado. A slab avalanche is a cohesive slab of snow that slides on a weaker layer of snow below it. These avalanches can be triggered either naturally or through human activity. When the avalanche is caused naturally the overburden weight of the snow-pack will build up and eventually cause the lateral stress to overcome the supporting layers ability to support the new snow. Naturally occurring slab avalanches usually occur in situations where there is heavy snowfall for prolonged periods of time. The fast snowfall does not allow for enough time for the new snow to attach itself to the older snow-pack that has already solidified on the ground. It is during these primary and secondary deposition and density building events that builds the recipe for an avalanche.

Another important snow property that an avalanches depends on is the elastic moduli of the snow-pack. Variation in these elastic moduli may not be visible with the naked eye, but are the culprit for weak layers that avalanches slide on. As seen in the governing seismic exploration equations, elastic moduli depend directly on density. This is an especially important property because GPR in snow is dependent on variations in permittivity which translates to density through well known petrol-physical relationships.

4 Theory

4.0.1 Ground Penetrating Radar

GPR detects changes in the electromagnetic properties of the subsurface, which include permittivity and conductivity. Since snow of all types is relatively non-conductive, the primary response is changes in the permittivity. Permittivity is a complex value, with a real and imaginary component. The real component relates to the rotation and alignment of a polar molecule. As the molecule aligns, it stores potential energy that is captured by this term. When the field is released, so is the energy. The imaginary term is related to the frictional energy lost by the rotation. These terms are frequency dependent, as molecules have finite rotation speeds. For low frequencies, materials have relatively constant permittivity as they are able to align and hold their positions. As frequency increases, the molecules are no longer able to fully align, and the energy stored in their rotations decreases. The frictional energy loss begins low, as the time spent moving compared to holding alignment is minimal. As more rotations occur, the imaginary part increases until the frequency is too high to allow sufficient time for alignment to occur. The point at which the imaginary component reaches its maximum is called the relaxation frequency.
Liquid water content and porosity, and by extension density, are the primary controls on this property. Porosity affects permittivity by affecting the percent of air through which radar waves can travel. Since electromagnetic waves prefer the path of least resistance, they tend to travel though air and therefore are not affected by the water present in the snow. As porosity decreases and density increases, the radar waves interact more with the snow and become affected by the water content. Liquid water, being a highly polarized molecule, is greatly affected by the electromagnetic waves. There are several equations that govern the relationship between density, water content and permittivity. The Complex Refractive Index Method (CRIM) Equation. This is a mixing law that relates the volume fractions (theta) and relative permittivities of subsurface components to the effective permittivity.

$$\sqrt{\epsilon_{ef}} = \Theta_1\sqrt{\epsilon_1} + \Theta_2\sqrt{\epsilon_2} + \Theta_3\sqrt{\epsilon_3}$$

A second empirical equation has been put forth which relates density and liquid water content (W) to the dry and saturated snow permittivites [Tiuri et al., 1984], [Sihvola and Tiuri, 1986].

$$\epsilon_d = 1 + 1.7\rho + .7\rho^2$$

$$\epsilon_s = (0.1W + 0.8W^2)\epsilon_w + \epsilon_d$$

The impedance contrast between two layers of varying physical properties causes a reflection of the radar waves, which is picked up by the receiving antenna.

4.0.2 Snowpit Identification

While traveling in the winter back-country, historically the best method created for analyzing the stability of snow-pack is a snow-pit test. In general a snow pit is a method that exposes a vertical face of snow from ground level up until the top of the snow pack. This method can be useful in identifying layers of the snow pack that are potentially prone to causing avalanches and also can be useful in identifying the water potential of the snow for watershed predictions. In general a snow pit will be topped with snow that is relatively fresh from the storm layer. This can be identified first hand by observing the shape of the snowflake, if the snowflake still has maintained its full crystal shape it is most likely from a primary transport event

Figure 3: An image of a snow pit dug during the first survey on Colorado Mines Peak

The next layer that is usually found below the primary deposition layer is known as the firn layer. This layer consists of snowflakes that are more rounded from the natural heat diffusion and convection in the snow pack. This layer is usually very well bounded, but displays weakness between historic freeze thaw events or unusual precipitation events that occurred throughout the winter. In an overly simplified snow pit the next layer would be the base snow that has been heavily metamorphosed by the convection of heat from the ground contact. The base snow will often have a very sugary consistency and is usually referred to as depth hoar. These snowflakes will often be greater in size than 1mm and have a much more robust crystal appearance in comparison to a standard storm snowflake. The snow pit classification system will allow the observer to classify the overall thickness of each of these three layers and also classify other layers that may be mixed in with these layers. As a side note for consistency with scientific standards we will be using the *International Classification for Seasonal Snow on The Ground* for all observations in fields snow-pit assessment.

5 Methods

5.1 GPR Procedure

5.1.1 Equipment List

- 100 meters climbing rope
- 4 locking carabiners
- 10 meters 7mm rope
- Small plastic sled
- GPS

- 1000 Hz GPR antennas
- Laptop

5.1.2 GPR Setup

The survey design used for this project had two main components; the antennas were mounted to a plastic sled while the SPIDAR system, laptop, and batteries were mounted on the back end of a SmartCart and dragged behind. The sled had a hole cut out in the middle, through which the antennas sat and were suspended 2cm above the snow surface. Climbing rope was used to connect both parts as to ensure no tension occurred on the cables. A secondary rope was connected to the front of the sled and was used to either lower or pull the configuration depending on direction relative to the slope. The SPIDAR system does not include a display, so a laptop was connected via an ethernet cable which controlled the GPR and gave real-time outputs of data.

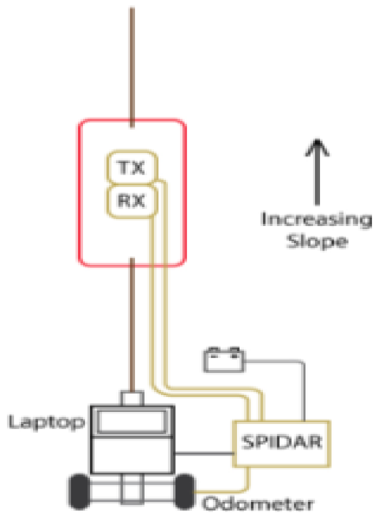


Figure 4: Illustration of the assembly used for our final GPR assembly

5.1.3 Field Procedure

The survey was conducted on Colorado Mines Peak near the summit of Berthoud Pass. The area is at an elevation of around 3470m, which is just below tree line. A northwest facing slope of 10-20 degrees was used, with the wall being on the uphill side of the pit. A 70m line was chosen, and position data for both ends was recorded. A tape measure was ran down the length of the survey line to ensure consistent positioning while the sled and cart were being moved.

When the GPR was started, an issue occurred that prevented us from saving data to the laptop. The system could still run and record data, which was outputted to the laptop screen. A decision was made to use the image of the data for analyzing. The full 70m line was recorded using constant time to control traces, which allowed the full section to be visible on the laptop. The bottom quarter of the section was recorded again using the odometer wheel and again screen shotted. At where the snow pit was to be dug, a single trace was recorded.

5.1.4 Field Location

Our initial survey location for testing was on Loveland pass, this location did not yield any usable data. The next location used was up in Guanella Pass, Co. A large storm moved in on this survey location and made it necessary to turn around. The final location used was off of Colorado Mines Peak at the summit of Berthoud pass. This location was easily accessible and allowed for fast access from Colorado School of Mines. The slope aspect for this survey location was also WNW which minimized sun exposure and preserved the snow-pack from going through heat conduction phases that would solidify the snow-pack. The survey location can be seen in the figure below.

Figure 5: Survey Line on Colorado Mines Peak at the summit of Berthoud pass

5.2 Snowpit Procedure

An undisturbed area in the middle of an open slope was chosen, and a pit several meters wide was dig to the base of the snow. Starting at the top, the side of a credit card was slid vertically down the face of the pit until the force needed to drive the edge changed. The depth of this interface was recorded, and a sample of snow flakes were taken from the middle of the interval and identified. Hardness was measured using either a knife blade, end of a pencil, one or four fingers, or a fist which was driven into the side. The hardness of a layer is recorded as the largest object that can be inserted into that layer. This process is repeated for every change in either the force needed to drive the credit card or visual appearance of the snow pack.

Stability of the snow pack was measured using a compression test and Rutschblock test. The compression test used a 30cm square column, and the flat end of a shovel was placed on top. The shovel was tapped with a hand of moderate force 10 times by moving the wrist, 10 times by moving the elbow, and 10 times by moving the shoulder. When fractures occurred, the number of taps and depth were recorded then the layer was removed and taps continued. The Rutschblock tests used a 1.5m wide by 1m deep column, in which a skier stood at the crest of the block and repeatedly jumped until a fracture occurred. After the initial fracture, the skier moved closer to the center of the block and continued to jump until the entire column collapsed.

Figure 6: Picture of storm layer that failed during extended column test

Figure 7: Extended Column used for understanding slide prone layers. This is created by digging to the base of the snow-pack. Then isolating a 30cm by 30cm region of snow for in field stress test. Which essentially work to help understand how the elastic moduli are fluctuating throughout the snow column.

6 Expectations

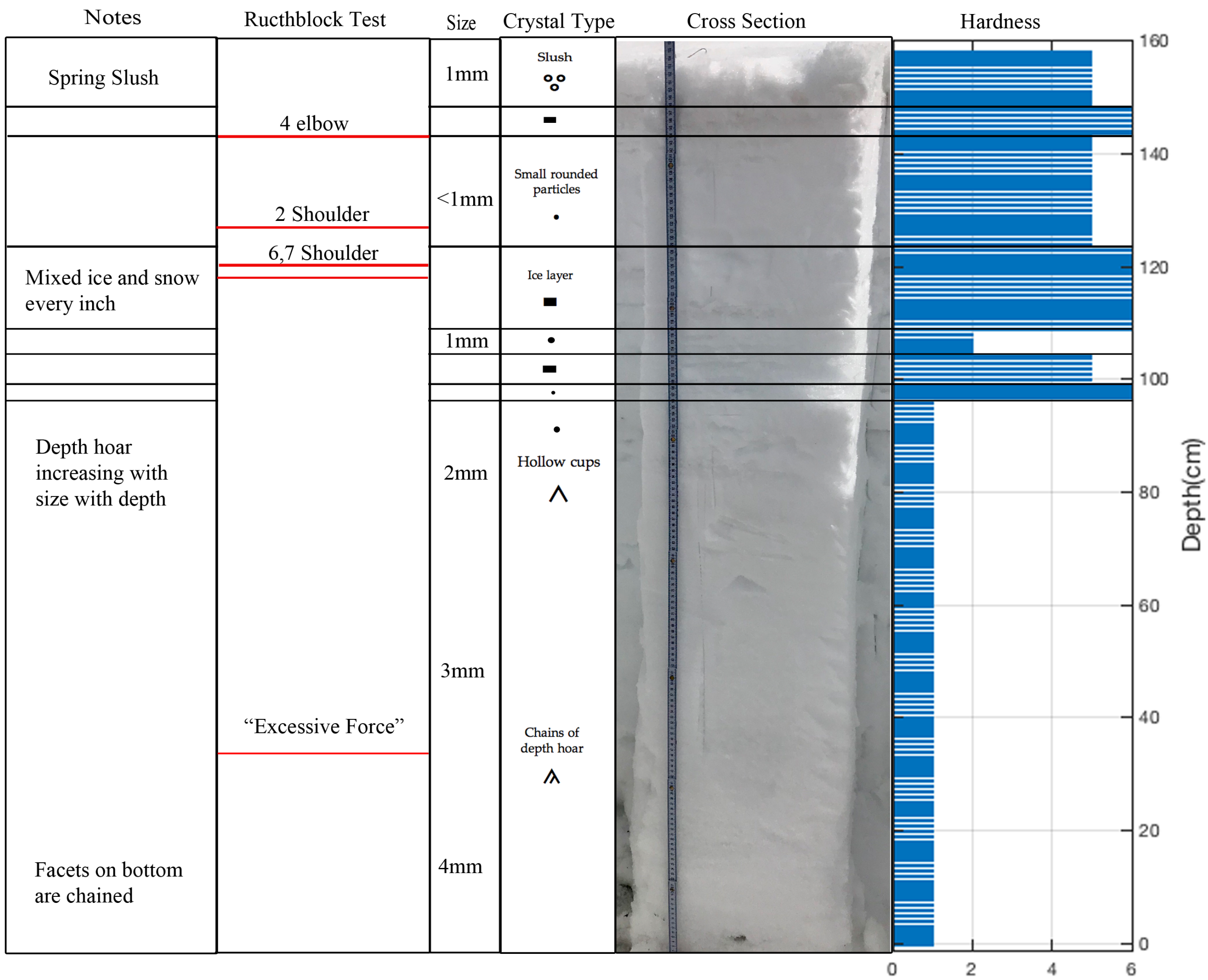


Figure 8: Snowpit results, including descriptions of each layer, stability test results, crystal size, crystal type, an image of the snowpack, and hardness. Horizontal lines indicate layer changes that were used for the forward model.

Using the snowpit results seen in Figure 8, a forward model of the GPR data was created. Values for conductivity were held constant for the snowpack, and permittivity varied depending on the crystal type and relative liquid water content seen. Ice layers were given slightly higher permittivity values as they were not perfectly crystallized and still retained some snow.
The forward model shows two high amplitude peaks of opposing polarity in the early time. There is also a strong ground reflection at .02 nanoseconds. The interval between these two events shows little response, save for a small reflection occurring at .016 nanoseconds.

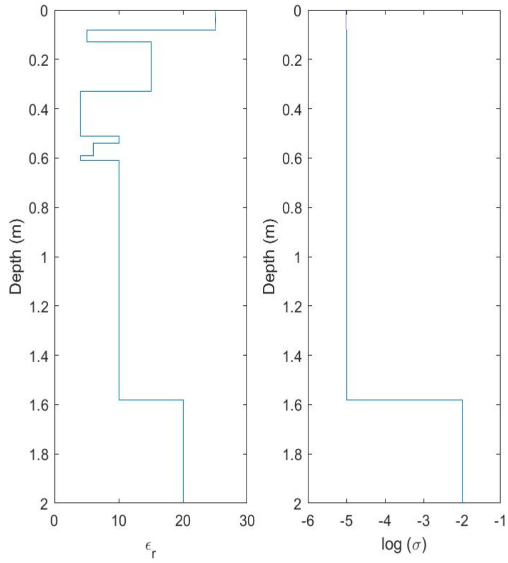


Figure 9: Permittivity and conductivity values for the forward model.

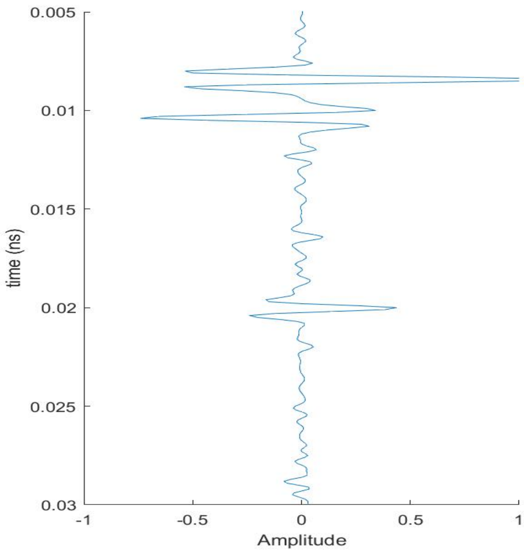


Figure 10: Forward modeled data using snowpit results. The time axis is scaled to match the output of the GPR data display.

7 Discussion

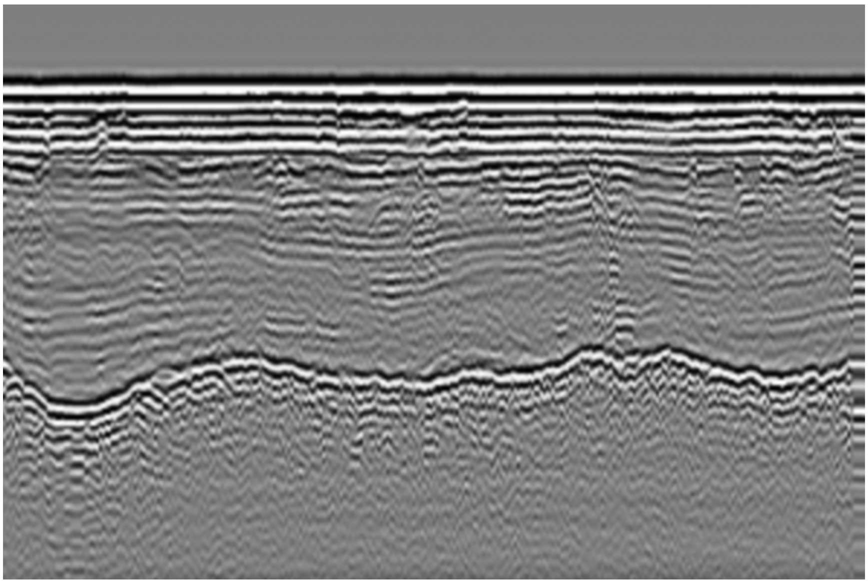


Figure 11: Full survey line as recorded by the GPR. Orientation is uphill to the left, and the time is 30 microseconds.

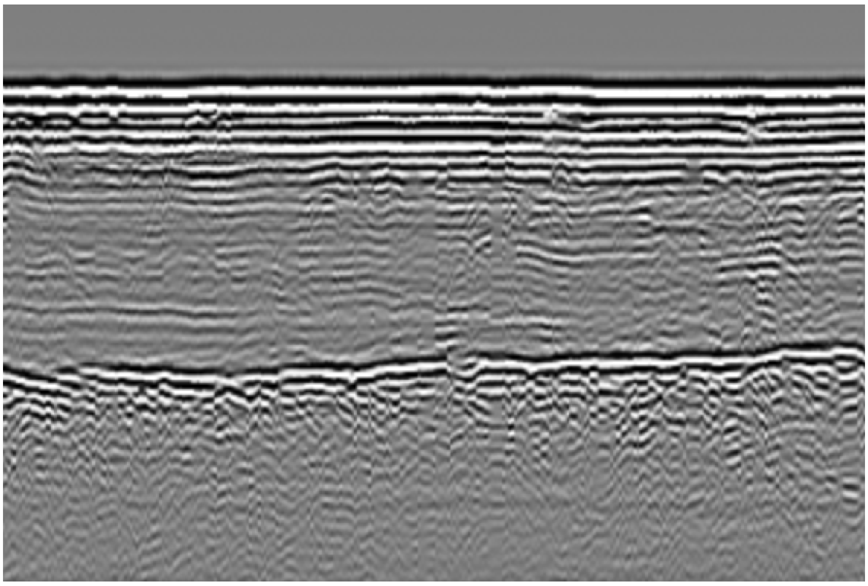


Figure 12: GPR results for the right-most quarter using the odometer wheel.

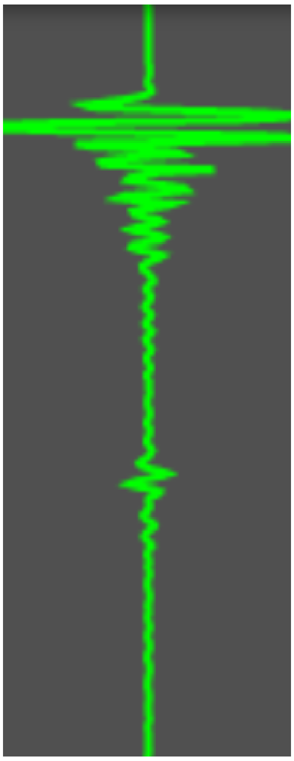


Figure 13: Single trace captured over the pit location

The 2-D data captured shows several interesting features. There is a large section of high amplitude oscillation in the upper part of the data. This is likely caused by the close proximity of the antennas and surface. Although this oscillation seems to mask the underlying reflections in this section of the snowpack, several instances of lateral variation within this seen in Figure 8 shows the presence of change in the depth of reflections. The snow layers appear to follow the ground topography closely at deep intervals, and gradually begin to conform to the surface topography as you get closer to the surface. Several strong reflectors are present in the snowpack which appear to be discontinuous as you move down the slope. There is also the presence of diffractions, as seen by the downward facing curves that transect reflection layers. These could possibly be solid disks of ice that were seen while excavating the pit. Since the system was unable to save data, no further processing could be done on this data set. Some potential
When the single trace in Figure 10 is compared to the forward model, there is a good match in the time of initial and ground reflections. The bottom half of the snowpack again shows little activity, except for a small disturbance at 16 microseconds. The upper half shows the high amplitude oscillations seen in the 2-D sections. The two peak response seen in the forward model is not present in the recorded trace, and no discernible information about reflections can be made for this section. Relative amplitudes for the single trace decrease with time compared to the forward model. This can be attributed to the geometric spreading and attenuation caused by liquid water in the snowpack.

8 Conclusion

The GPR survey conducted was unsuccessful in determining the presence of weak layers in the snowpack. Snowpit data was recorded to determine risk of the snowpack producing an avalanche, and at what depths these weak layers occurred at. The data was then used to produce a forward model to be compared against, but since we were unable to record and process data, visual inspection was used. The data and model matched in time, however high amplitude echoes in the upper subsurface made identifying ice layers difficult.

8.1 Suggestions For Future Work

- Make forward model used for snowpit data to take multiples into account.
- Measure snow density in field
- Measure permitivity with "Swedish Fork"
- Process Data via time migration, invert for permitivity, use psychophysical equations to solve for velocity.
- Future sled design should elevate antenna a least 1 wavelength off of the snow.

9 Acknowledgements

We would like to acknowledge Dr. John H Bradford for his guidance and for his supply of data used to teach us how to process and interpret GPR data on snow. We would also like to acknowledge the effort that Adam Mangel put in when driving us up to Loveland for our fist survey. Along with the support and answering our barrage of questions.

10 Appendix

10.1 Field Notes

March 29th, 2018

These were the field notes used as reference for setting up the GPR survey each time in the field. Some survey

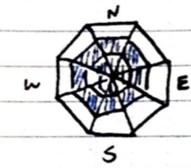
3-28-18 Jonny Morsicato Pg 53

Daily Conditions

- Weather high 20°F Low -5°F Snow Showers after 1pm, snow accumulation 1-3 in
  - 30-70% chance snow
  - Humidity 89% · Wind Speed W 9mph

Avilanche Forcast

- avilanches can be triggered on new & wind loaded snow
  - new snow has made storm slabs a potential on any aspect of snow slope. Particularly above treeline



* Field Avilanch Observations *
  - Skier activated avalanch on headwall of lift gully berthoud pass
  - Snowboarder commented on starting avalanche on opposing slope above "the fingers"

Crew Erik Knipple & Jonny Morsicato

Location Colorado Mines Peak "North western slope" facing parking area by summit of CO 40

Terrain Steep & Snowy

Emergency Contact 720-833-9818 Joanna Morsicato

Risk Assesment

- generally safe avilanche conditions, but should avoid loaded slopes for duration of survey

Method Information

GPR

$$\vec{\nabla}^2 \vec{E} = \mu\varepsilon \frac{\partial^2 \vec{E}}{\partial t^2}, \quad \frac{\sigma}{\omega\varepsilon} << 1 \text{ For GPR}$$

* if there is a very high conductivity gpr will not work

$$V = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = c \text{ in free space, but not in matter}$$

- GPR is generally pretty similar to seismic except we are using an EM source.

Snells Law Review

$$\frac{V_1}{V_2} = \frac{\sin\phi_1}{\sin\phi_2}$$

* This will govern how EM wave travels through snow layers

* FOR Full method information see method info in write up of report

Method Information Continued

Snow Pit Classification

* This method is just used to classify the crystal type, temperature, density, and layers in reference to a cross section of snow

Equipment list

- snow hand lense
- snowflake card
- thermometer FAILED REPLACE BATTERIES
- snow ruler
- shovel
- snow saw
- x2 probes
- field notebook
- Tape Measure
- map
- compass
- GPS
- GPR controller
- GPR antenna (1000 MHz)
- Cables (optical to connect controller to antenna, parallel to computer, charged battery packs Died in field)

Using Equipment

- choose antenna. We will use 100 MHz antenna which should be acceptable for up to a few meters of snow

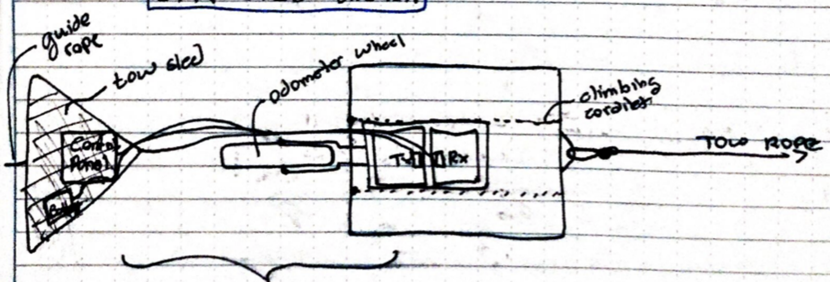
field frequency calculation

$$f(\text{MHz}) = \frac{150}{d\sqrt{\varepsilon_r}} = \frac{150}{2\sqrt{0.7}} \approx 100\ \text{MHz}$$

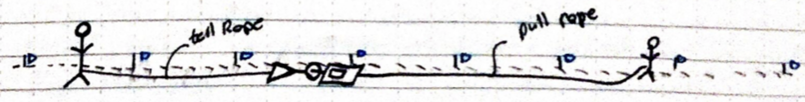
* there is a lot of air in snow so the permittivity should be pretty low. $\varepsilon_r = 0.7$ for dry snow and 0.6 for wet snow

- For Set up and configuration of GPR see field documentation on start up procedure

GPR SLED SKETCH



SLED PROCEDURE



Method Information Continued

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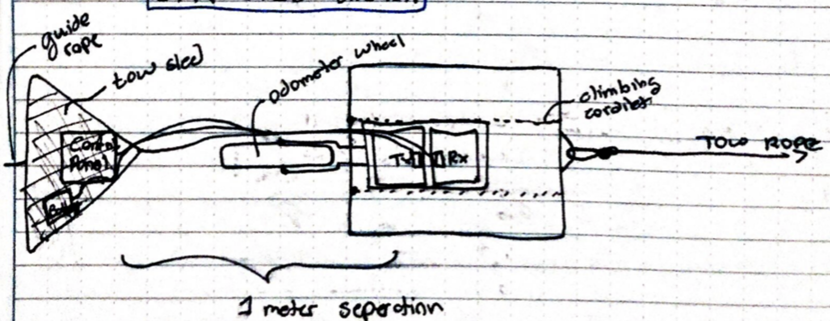
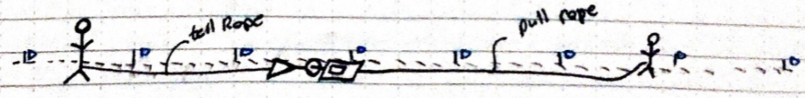


SLED PROCEDURE



Scale: 1 square = ______

10.2 Field Pictures

Figure 14: Design for sled mounted GPR antennas.

Figure 15: Sled mounted antennas and SmartCart back-end which housed SPIDAR, laptop, and battery.

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