Ground Penetrating Radar Validation of Seasonal Snow Depth Variations in Forested and Non-Forested Transects

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Abstract

The purpose of this study was to review how Ground Penetrating Radar (GPR) operates and apply it to a snowpack to distinguish how snow depth changes with respect to changes in vegetation. Three transects were taken in areas with differing vegetation patterns at Hogan Park, Steamboat Springs, CO. These transects were correlated with probe measurements at varying distances and also used as reference depths for applying the wave settings. A 1.6GHz antenna was used for all three transects and exceeded depths of 2m. This study shows a successful application of GPR on a moderate depth snowpack, finding distinct differences in snow accumulation under changing canopies. While also assessing the limitations to the technology and providing preliminary solutions for future improvements for the varying field of GPR.

1. Introduction

Today approximately 1/6th of the world population relies on snow as a natural water storage mechanism (Barnett et al., 2005). Climate studies have shown that precipitation is falling more frequently in the form of rain, not snow, removing the ability for it to be stored efficiently and naturally for later consumption (Bales et al. 2006). From these observations new techniques for water management are crucial to improve the efficiency of water management throughout the dry spring and summer months. One way to understand and help manage snow and water resources is to develop standardized techniques that map the spatial variability of snow distribution.

Today, a strong interest regarding the impact of climate change on snowpack accumulation and metamorphism is present. Studies have shown that in the northern hemisphere, snow covers about 14% of the land (Pielke et al. 2004). This coverage has consistently been depleting from earlier spring warming in the West. Because of this the Western US is experiencing more transient zone conditions. Meaning snow will accumulate and melt out repeatedly throughout the winter months instead of remaining until maximum accumulation around the April 1st date (Mote 2006). With these warming trends we will see an amplified metamorphic response from the snowpack. Higher temperatures in the atmosphere will increase the temperature gradient from within the snowpack, causing higher vapor fluxes. With these higher vapor fluxes snow grains will grow more rapidly forming faceted crystals, decrease in albedo, thus causing more rapid melt (Domine et al. 2007). From this positive feedback loop we can conclude that with increasing climate change we will see a decrease in snow accumulation and greater snowpack stratigraphic change from increasing grain metamorphism.

One way to predict water availability in spring and summer, after the accumulation season, is by assessing how much water is contained in a given watershed's snowpack. This is known as the snow water equivalent (SWE) which is a function of the depth of a given snowpack multiplied by its density (Custer and Birkeland 2006). Most commonly, SWE is determined by conducting point-based measurements using methods such as snow pit analysis, Federal Sampling, snow depth probing, and data collected from SNOTEL sites. SNOTEL stations provide SWE information by sensing snow pressure differences on a pillow like surface (NRCS 2009). Federal Samplers are aluminum tubes of a known weight and size that core out snow samples to be weighed on a spring loaded scale in the field. They use the known volume of snow and its weight, minus the weight of the tube, to derive SWE (Geo Scientific ltd. 2001). These remain the primary, and most accurate techniques to estimate water yield in a given snowpack, but they fail to address the depth variations of snow across a large areal extent. Elder et al. (1991) explains that the overall variance of SWE across a watershed, due to different topography and vegetation patterns, is proven to be difficult to map correctly when applying solely point based measurements. And so, from these conclusions, in order to address the diminishing snowpack brought by climate change, it is beneficial to look at other techniques that can supply continuous measurements of snow depth in order to get a more accurate idea of the amount of water that actually resides in a watershed for consumptive use.

Currently there is research being done on the use of remote sensing techniques to quantify these variations. These techniques produce very accurate depictions of the spatial variation of snow distribution; they rely on communication with satellites. Satellites work best in clear atmospheric conditions. This communication has improved over the years. However, signals have tendencies to be lost in mountainous terrain, and either cannot take images through

clouds or do not image frequently enough (Christopher & Gupta 2010; Molotch and Margulis 2008). Ground based radar systems, such as GPR, are complimentary with satellites and aircraft, providing spatial information through rugged, mountainous terrain, where snow storage and distribution is becoming more critical to understand.

Ground penetrating radar (GPR) is used to observe the stratigraphy of the subsurface by sending electromagnetic pulses into the ground and measuring the return time. This instrument is widely used in fields such as geology, archeology, glaciology, and others, but has recently been applied to study the stratigraphy of snow accumulation zones. According to Conyers (2002), GPR is not a method that can be readily used for any subsurface problem, but with thoughtful modifications in acquisition and data processing, GPR can be utilized for many different site conditions.

1.1 History of GPR

The study of microwaves began to develop from the 1900's to the 1950's. El Said (1956) completed the first successful subsurface mapping to observe the water table and its depth. This came after an Austrian, whose name is unknown in the literature, made an attempt to determine the thickness of an arctic glacier in the 1920's. His preliminary study came up inconclusive and thus was essentially forgotten until El Said's study (Miljatovic 2012). Then, a discovery from the US air force formed. Their signals were penetrating the Greenland ice sheet and messing up their landings. This spiked their interest in subsurface mapping of glaciers, coalmines, and the moon.. However, at this time GPR systems were extremely complex and not very user friendly (Annan 2002). It wasn't until the 1980's that GPR systems were commercialized and subsurface studies rapidly increased (Neal 2004). These new instruments were lightweight, hand held, and digitized with low frequency signals. In tandem with the commercialization of GPR products, from 1980-'85 there was a lull in application because as the instrument became easier to attain, people realized the difficulty of GPR usage in certain environments. Also non-experts were using the technology creating confusion with system failures and a knowledge gap of how to mitigate them.

However, after this period of adaptation an intrigue to attain a better understanding of the technology was motivated by the possibility for multi-fold data acquisition, with higher frequency antennas, easier digital data processing, and 2D numerical simulation (later to become 3D modeling) (Annan 2002). Today, it is relatively simple to obtain a GPR system and apply it in any desired subsurface problem.

1.2 Mechanics of GPR

GPR instruments rely on the electromagnetic properties of different subsurface materials to produce a cross sectional image. Radar waves are propagated in distinct pulses from a surface antenna and returned depending on the conductivity of the subsurface material and its respective dielectric permittivity. The dielectric permittivity is a unitless value that is otherwise known as the dielectric constant of a given material that characterizes the displacement of charge it holds in the presence of an electric field. This constant is the mechanical basis of how the GPR returns information (Jol 2009). As the radar pulses are transmitted through varying subsurface materials, the velocity of the wave changes with respect to these dielectric properties; And so, the greater the contrast between materials the greater the strength of the reflected signal(Conyers 2002). For snow, the measured dielectric constant is approximately 1.4. Depending on the presence of discontinuities in the subsurface, the reflection of differing pulses is measured (Maurer 2006; Bjorklund & Johnsson 2005). The composition of the subsurface, and whether or not it has a high electrical conductivity, is a function of the presence of liquid water in a saturated soil or snowpack, a high liquid content has the ability to remove the electrical portion of the radar waves and attenuate all subsurface propagation. This is because fresh water has a dielectric constant of 80, causing high attenuation, while ice and snow range from 1.4-4. However, if the wave is not attenuated fully it will continue to penetrate the subsurface until it dissipates with depth. This progression is dependent on the initial frequency of the wave (Conyers 2002).

Once the wave has penetrated the subsurface, the GPR measures the travel time it takes for the magnetic pulse to reach a target and be reflected back. This is known as its two-way travel time (TWT) measured in nanoseconds. In order to convert this to a respective depth, the velocity of the pulse must be set (D=VT). As mentioned above, this velocity is determined by the dielectric permittivity of the material in question (Maurer 2006). Air has a high dielectric constant and so it does not attenuate a given signal, while water has a very low constant, so its ability to reduce the signal is more effective. Because of these properties, when studying shallow ice and snow layers, a short wavelength should be used because it does not penetrate as far beneath the surface, giving more precise measurements and avoiding deeper, negligible, layers (Zirizzotti et al. 2010). These higher frequency waves dissipate in the subsurface quicker because of their short wavelengths versus low frequency waves that penetrate deeper but do not show small stratigraphic changes. Once the wave frequency is set, the steps to calculate snow depth are performed using calculations that incorporate the two-way-travel time and the ground velocity, determining how fast the radar pulses travel through the subsurface (Bjorklund & Johnsson 2005).

$$Depth(m) = twt \times \frac{c}{2} \sqrt{er}$$

Where twt is the signal travel time (ns), c is the speed of light in a vacuum (299,792,458 m/s), and er is the dielectric constant (unitless).

Today, because of the intrigue in GPR application, there are sophisticated programing languages that can calculate the depth for you when the right parameters are indicated regarding the TWT and dielectric constant of the penetrated material. Some of these include Interactive data language (IDL) code written by Maurer (2006) to be used with an ENVI interface. This program allows the data to be filtered and calculated for depth, as well as many other functions.

Another usable program was developed in executable files by Lucius and Powers (2002). These were first written in 1990 because there were no commercially available software programs that met USGS processing and display requirements. Since then, the programs have been updated annually but are not superior to commercially provided software today. The biggest benefit of the executable files is that they require no license or special installation in order to be executed, rather than the codes written by Maurer (2006) that need specific software.

1.3 GPR applications on snow and glaciers

In recent years techniques using GPR have been applied to measuring not only extensive glaciers and ice sheets, but also the spatial variability of a surface snowpack. The benefit of conducting GPR analysis is the ability to obtain continuous measurements of depth, and in some cases density, of a variable snowpack. Classic techniques such as snow pit analysis and depth probing have become standard procedures to determine characteristics of snow but they only produce data at point locations (Harper and Bradford 2003). Variables such as topography, and vegetation create complex mosaics of meteorological conditions. These variations result in heterogeneous distribution of snow cover. As a result, these observations do not adequately characterize a given watershed's annual snowpack (Bewley et al. 2010). However, while studies show that GPR analysis produces more accurate depictions, it has not yet distinguished itself as a primary measuring technique and so it is still coupled with point source validations.

Dunse et al. (2008) conducted a study on the Greenland Ice sheet using GPR to observe trends of thinning at different elevations. Their goal was to show that extrapolating point-based results can misconstrue data and continuous profiling gives a more accurate portrayal. They found that there was significant thinning at elevations lower than 2000m and a mass-gain above. The importance of understanding spatial characteristics of glaciers and snow accumulation, as

mentioned above, is to be able to develop more accurate atmospheric models and improve

predictions of future snow conditions (Richardson-Naslund 2004).

In the past 15 years, studies have shown that GPR analysis could be a superior method of

measuring continuous snowpack stratigraphy. In the Palli et al. (2002) study on the Svalbard

glacier in Norway, it was shown that the GPR signals could penetrate deeper into the subsurface

than ice cores giving their data more consistency. Studies performed in Antarctica and

Greenland showed that when using a high frequency signal, (i.e. > 800 MHz), GPR imaging can

produce stratigraphic consistencies in the subsurface, which was a major focus of this research.

In these studies, different accumulation layers were detectable, especially those from previous

years and with different densities such as fern ice. In many of these it was concluded that

accumulation distribution on the glacial surface is not just a function of altitude but topography

as well, and the accuracy of using GPR is superior to the older traditional methods (Dunse et al.

2008, Harper and Bradford 2003, Marhsall and Koh 2008, Maurer 2006, Naslund 2003, Palli et

al. 2002, Singh et al. 2011).

Some techniques used for the transport of the GPR range from air-borne to ground based.

Many have used sleds to transport the antenna (Harper and Bradford 2003; Dunse et al. 2008;

Galley et al. 2009). This is the most cost efficient way and produces the clearest onsite data.

Those who used snowmobiles (Palli et al. 2002; Maurer 2006; Naslund 2003) ran into the

problem of noisy signal returns. The benefit of the snowmobile is its speed allowing greater

distances to be covered quickly, but it is necessary to account for that in the signal settings. One

way to reduce noise is by increasing how many trace stacks there will be. A stack takes the

average of several scans at the same point in a profile. This helps preserve the signal while

removing noise produced by the instrument. The higher the signal to noise ratio the more crisp

the image (Bjorklund and Johnsson 2005). Another limitation to using snowmobiles for antenna transport is that their weight disturbs and compresses the underlying snow causing it to change its natural structure. This is not as detrimental when used on glaciers but if the desire is to run the GPR over an undisturbed snowpack, sleds pulled by hand are more effective. Finally, Maghuth et al. (2006) used a helicopter- borne GPR to conduct their research on Alpine glaciers in Switzerland. The benefit of using airborne, or any elevated mechanisms, for transporting the antenna signal is that the near field effect does not play a role. For snow, this means the occurrence of spreading and attenuation. The attenuation of for snow ranges from $0.1 - 2$ dB/m, which is higher than freshwater but can still cause spreading and attenuation in the area of the near field.

The near field is the surface in the immediate vicinity of the GPR antenna. The GPR does not collect good data until it has penetrated 1.5 times the center of the wavelength into the subsurface. This zone directly below the GPR has direct ground waves and direct airwaves. This energy is transmitted and received along the ground-air interface, producing black and white banding across the top of the radargram (Ernenwein 2006).

From these studies application of a more time efficient way to determine snow depth and variability on a large scale can be obtained using GPR. The analysis can be utilized to understand the relationship between other factors that affect precipitation accumulation rates. These can include canopy structure and vegetation variations, changes in topography, and the characteristics of the terrain. For this study a comparative analysis of snow depth variations from vegetation changes was the primary focus, as well as showing the precision of Ground Penetrating Radar.

2. Methods:

2.1 Study Area:

The main radargrams used for GPR analysis were acquired from Hogan Park in Steamboat Spring, Colorado. Steamboat is located in the upper portion of the Yampa river valley in the Rocky Mountains. The park sits at a low point of 9440ft just outside the boundary of the Steamboat Springs ski resort, and is situated in Routt National Forest just south of Mt. Werner and extending to the top of Rabbit ears pass on U.S. 40. The access to Hogan Park was through a gate directly below the inbound Morningside Lift in Steamboat Resorts. This area has low sloping terrain with even proportions of forested and clear areas, providing untouched plots in their natural setting. GPR transects were taken between two adjacent tree wells, from an open canopy to a forested area, and under a full forested canopy.
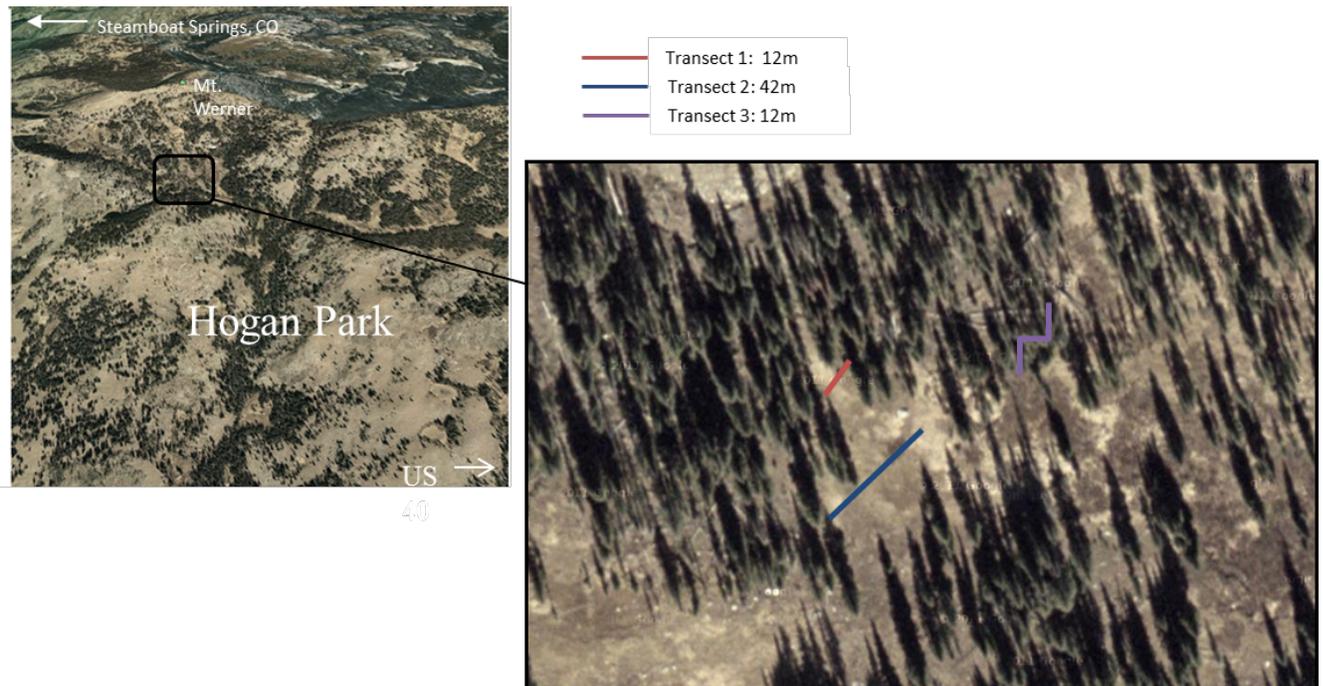

Fig. 1 Hogan Park, Steamboat Springs, CO. The transects indicated in color are not to scale but are meant as a reference to where the radargrams were taken from.

2.2 Equipment:

The entire GPR instrument consists of three major components. The first is the ProEx control unit. This is the main part of the GPR system and is the interface between the antenna and monitor. It sends out a timing signal, designated by the XV monitor, to the transmitter and receiver antenna. Once the pulse returns to the antenna it passes it on to the ProEx where it is collected into a trace. Once the trace is complete it is then sent to the monitor where it can be displayed and saved (Mala Operating Manual 2.0).

The module attachment used for this application was a high frequency antenna of 1.6 GHz using a coaxial connection, which exhibits precision and non- destructive accuracy when observing the subsurface because of its compact nature. This antenna in particular is monostatic, meaning the transmission and reception of the EM waves is propagated and received from one antenna (Basson 2000). Three primary transects were used to show the precision of the microwave penetration. The GPR was run over a snowpack of varying depths from roughly 1.5m to 2.5m. The decision to use such a high frequency was based on previous successful studies on snow accumulation that used a range of frequencies from 500MHz -1000MHz (Naslund 2003, Macguth et al. 2006, Maurer 2006, Dunse et al. 2008, Harper and Bradford 2003, Peterson et al. 2012). By using this high frequency antenna, crisper images can be obtained with better stratigraphic differentiation. Also the antenna was pulled along the snow surface in a sled and so there was negligible separation between the snow surface and the antenna.
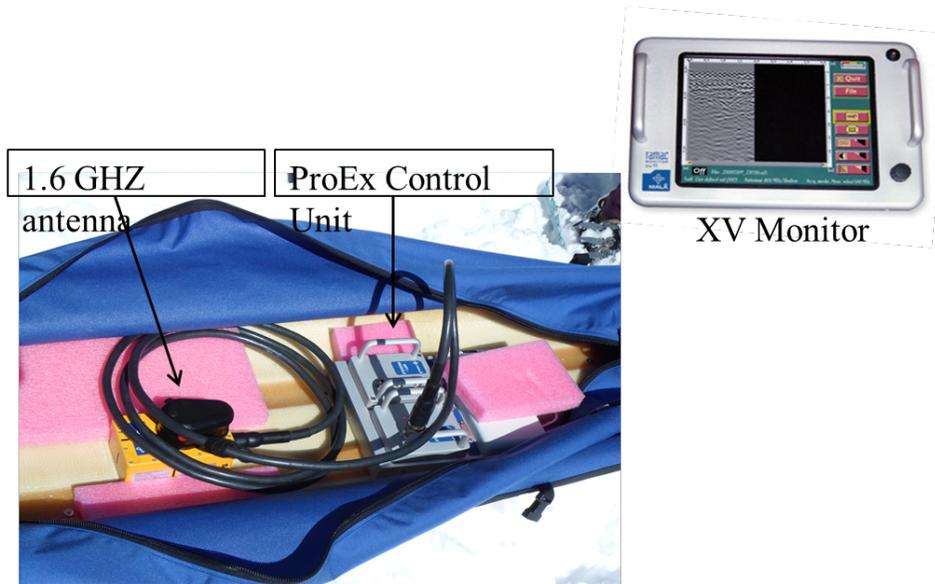
Fig. 2 1.6GHz antenna connected to the ProEx unit and connected by a coaxial
connection. This shows the set up in the skipulk sled and connected
to the right by the Ethernet cable is the XV monitor.

The settings for the antenna are controlled on the XV monitor that is communicating with the ProEx unit by means of an Ethernet cable. This controls the parameters to which the antenna propagates the wave. For the three transects, the parameters were standardized each day of use. This requires first establishing the time domain to collect the reflections. All frequencies are emitted at the same time and use the echo of the wave strength versus the travel time delay to determine the properties of the subsurface (Sensors & Software 2013). The radargram produced is then based on a time- time comparison rather than time- distance. This means the GPR measures the distance into the subsurface in nanoseconds, which later can be converted into a depth (m), and also the time in seconds that the GPR is traveling on the ground. The time-distance method still reports the wave propagation in nanoseconds but, with the help of a wheel, measures the distance the GPR travels on the ground in meters and not as a time function. Either method is acceptable, but because I used the GPR on snow a wheel would have been unreliable and thus was not used. Instead the plot distances were measured by hand using a tape measure.

Another parameter that must be set is the time window. This determines the total trace length of the transmitted wave. The time window is dependent on the number of samples and their frequency. However, after these are set, the time window can be altered allowing the wave to penetrate greater depths if the ground velocity is known. Stemming from this, the sampling frequency was set according to Nyquist's sampling frequency theorem that states the sampling frequency should be *at least* twice the antenna frequency (Marshal 2001). In the MALA manual, they propose that you use a sampling frequency *ten times* the antenna frequency for more accuracy.

The sled that was used to transport the GPR was a 6'4" fiberglass ski pulk provided by Grant and Ashley Schnell through skipulk.com. The use of this particular sled allowed for easy transportation of the multiple components that make up the MALA GPR ProEx system.

2.3 Processing:

As mentioned before, depth analysis can be done through hand calculations, but today sophisticated software is available to convert the TWT into depths using the header information stored in the files. For this application, the program used was RadExplorer 1.4, provided by Mala GeoScience. In this program the user is able to process the radargram using specified filters to sharpen and clear up the image and calculate depth from the TWT.

For figures 3,4, and 5 both the DC and Background removal filters were applied. The DC- Filter applies to the offset in the amplitude of the trace and removes the DC component. The trace is the digitized image of the waveform (Mala manual). The background removal eliminates the noise in the data so it is not mistaken from the actual reflections.

2.4 Point based validation measurements:

The three transects used in this study did not rely on snow pit analysis for validation but only probe measurements. These were taken at varying distances as depth references to gauge how the GPR settings should be set. A 264cm Black Diamond avalanche probe, graduated at 5 cm intervals, was used to obtain these measurements.

3. Data Settings:

Three transects were taken in different concentrations of vegetation to show the variability of snow depth. The first shows a transect between two isolated lodgepole pine trees (Pinus Contorta), the second was in an open clearing to a group of trees, and the third displays depth under a healthy tree canopy.

The first transect was between two tree wells and had a maximum probe depth of 2.34m which was used to determine the GPR settings. This transect was taken on the 26th of March, 2013. The antenna frequency was 1.6 GHz with a time window of 41.9ns. This provided the wave to penetrate a maximum depth of 2.69m with 1992 SPM. The velocity of the wave was 127 m/uS and a default time interval of .5s. The wave was stacked 8 times with a sampling frequency of 46792.8MHz, which was automatically set by the instrument.

The next two transects were taken the next day on the 27th of March, 2013. The first was taken from a clearing into a forested area and the next was in a completely forested area to observe the changes in depth. Again the 1.6 GHz antenna was used with a time window set at 42.6ns allowing the wave to penetrate 2.74m at 2024 SPM. The maximum measured probe depths at these sites were 2.40m in the clearing to 2.04m in the trees. The velocity of the wave for these tests was 127m/uS, the default time interval of .5s, and stacked 8 times at a sampling frequency of 46792.8MHz.

4 Results:

For each transect snow depth variations were observed by the changes in depth of the predominant ice lens indicated in each image. The three transects vary in length and location to provide a comprehensive understanding of the complexity of snow depth under different vegetation circumstances.

4.1 Transect 1: Tree-Clearing-Tree

The first transect performed was located between two adjacent trees with a short clearing in between. The line was roughly 12m in length and contains 28 traces stacked 8 times each; each stack represents an individual wave pulse. From the radargram below (Figure 3) a distinct ice lens is shown about 1m from the snow surface. For clarity, in all of the images, the x-axis is the inverse of normal. Zero depth is located at the top of the image, indicating that depth increases down through the image. This lens was verified visually after the run by digging down beneath the snow surface until it was reached. The change in trace wave amplitude verifies the change in the dielectric permittivity of the ice. Ice attenuates the microwave signal more than snow because of the higher liquid water content. The depth hoar (at the bottom of the snowpack and radargram) is also very distinguishable because of its higher liquid content due to the formation of facets. These changes are indicated in figure 3 by the white arrow and *trace wave* title. This wave is also present in figures 4 and 5. The top of the image also shows a spike in the trace wave because of the change from signal attenuation in the sled to the snow surface, and shows tight dense layering that is most likely due to the compaction of the snow beneath the sled. From this transect, and specifically the observable ice lens, it is shown that snow depth is a function of canopy distribution. The depth of the lens correlates to a greater depth in the total

pack which increases as you get farther away from the tree and its canopy as the lens is located at the deepest depth between the two trees.
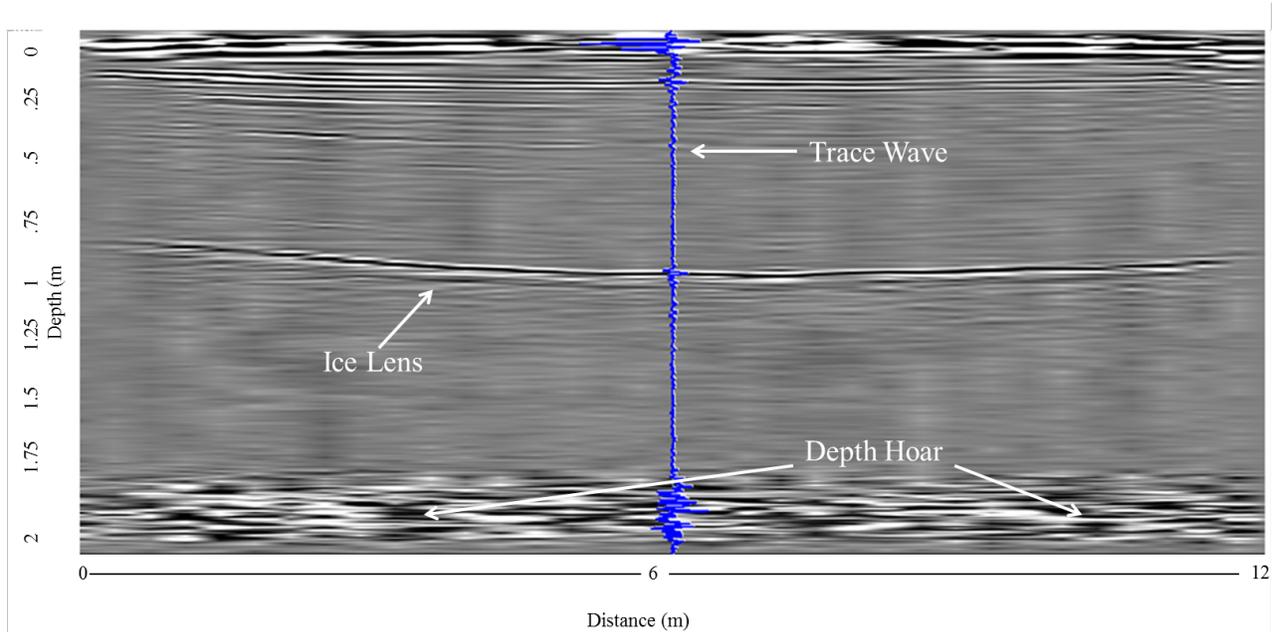

Fig. 3 Tree to Tree transect 1. Ice lens located between .9m and 1m. The trace wave indicates the change in dielectric permittivity. The ice lens contains more water to is attenuates the signal more as well as the observable depth hoar located between 1.8m and the bottom of the snowpack.

4.2 Transect 2: Clearing to Trees

In this transect there is a clear point where the antenna reached a line of trees and then came out of it again at the end of the GPR run. Again the depth of the ice lens that is present throughout the snowpack in Hogan Park is the reference for the depth variations of the entire snowpack. Below it is shown that depth decreases as you reach the edge of the forested portion of the transect, noted by the white arrow and tree well. Subsequently, it can be seen that snow depth increases as you get further away from the forested area because depth is increases as the lens indicator dips down. The variability in the depth measurements from the probe are most likely a function of natural ground undulations, or the presence of ground debris such as rocks or fallen logs. The black arrow indicates the decrease of ice lens depth when the transect intercepted the tree for the probe measurement and the radargram.
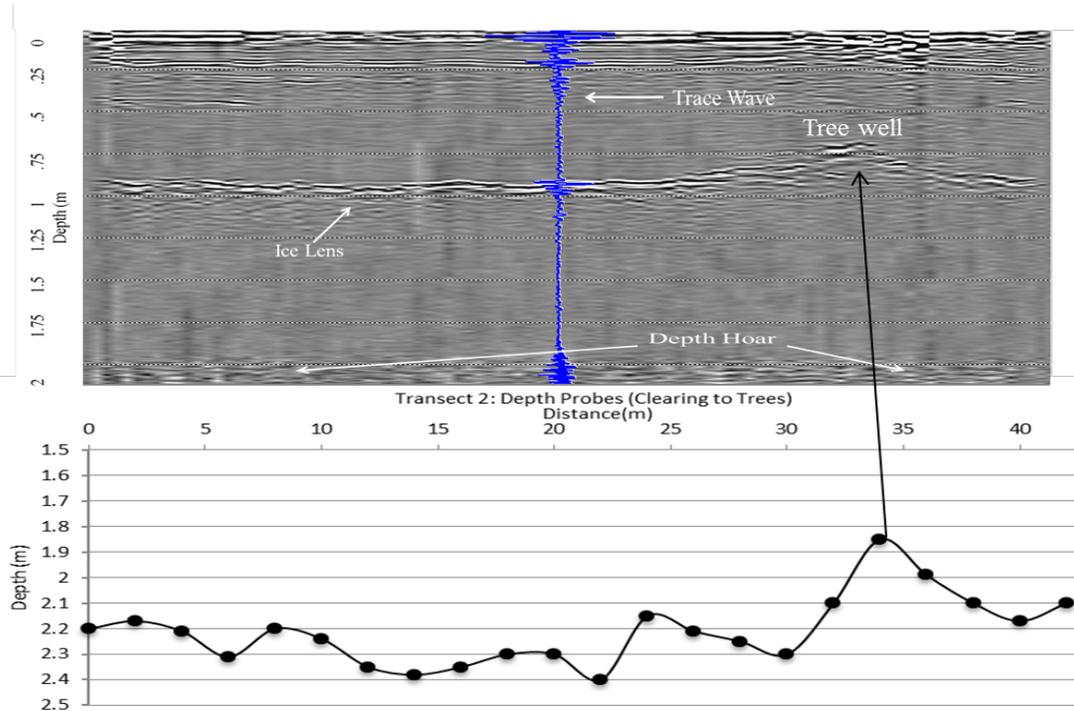
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Fig. 4 This transect was taken from a clearing into a tree well and then back out again on the other side. Depth- probe measurements taken every 2m on 3/27/13. At 34m there is a distinct decline in the depth of the ice lens where the antenna transected a tree well.

4.3 Transect 3: Forested

This transect was located amongst a completely forested area. The antenna was taken along a sinuous path through a section of Lodgepole pine trees to show the variability of snow depth under a healthy canopy. An ice lens is apparent in the snowpack with significantly greater height variability than in the first or second transects. The total variability of the lens is from about 0.58m to 0.9m indicated by the black arrows and correlated with the probe depth measurements at the same locations. The 32cm of variation in the ice lens shows that underneath a canopy the distribution of snow is highly variable due to the heterogeneity of canopy cover and tree density and distribution; associated primarily with snow interception. This variability was also noted by the large variation of total depth, provided by the probe measurements below.
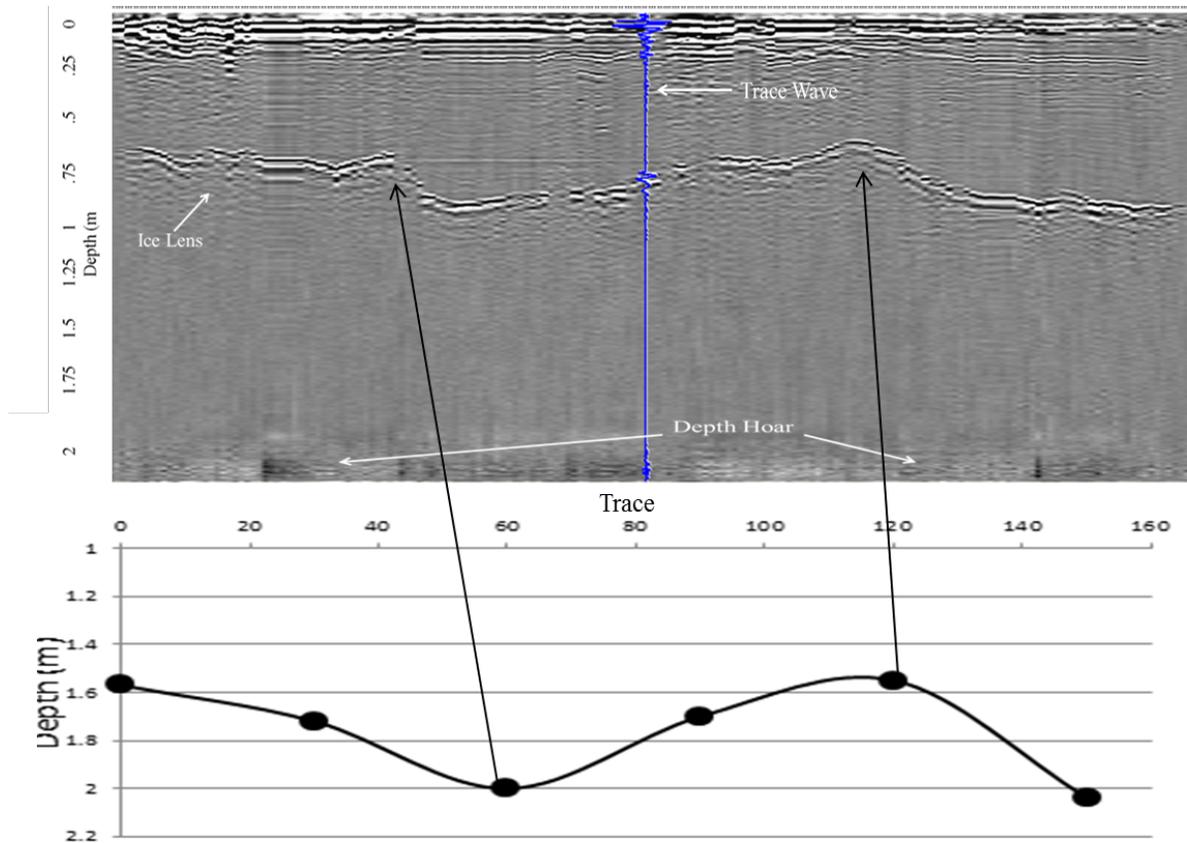
Fig. 5 Canopy covered transect 3. The sled was drug sinuously through the trees to show the large variation in snow depth located beneath a covered canopy. Actual depths underneath the forested canopy taken every 30 traces and correlated with the ice lens depth at the same trace.

5. Discussion:

Research regarding the importance of snow structure and stratigraphy supports the importance of further GPR usage. As shown here high frequency antennas have the potential to distinguish between discontinuities in the subsurface. The major discontinuity found in this study was the prevailing ice lens, present throughout each transect. This distinct stratigraphic layer, and other smaller layers, plays an important role in understanding the spatial extent of density changes within a snowpack. The radargrams in each transect presented here indicate density differences by their change in reflection according to the dielectric constants. These constants again are affected by the presence of liquid water, which in turn is a factor in the density. By distinguishing these changes you can efficiently assess what layers within a snowpack are

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necessary to obtain density validations from, rather than sampling the entire profile. Also, by being able to track these minute changes in the stratigraphy, more accurate parameters for models can be set, by this I mean in regards to different snowpack structures. For example, GPR would be able to distinguish the many ice lenses in a maritime snowpack and on the other hand be able to address the more prominent presence of depth hoar in a continental pack.

GPR is an extremely universal tool that can be applied to many types of subsurface changes. In just the past year the *Journal of Applied* Geophysics has published studies regarding the use of GPR that encompass imaging of sand dune aquifers (Rejiba 2012), water volume and sediment characterization (Sambuelli 2011), propagating pavement cracks (Diamanti and Redman 2011), and many more. This small sample size of published papers does not begin to encompass the extent of GPR use but shows that it is not confined to one application. But as shown, even in one discipline, such as snow stratigraphy, GPR is not confined. Other assets to using radar techniques, whether it is air or ground based is the non-destructive, in terms of environmental or topographic, techniques required for measuring and its relatively easy and rapid data collection.

However, along with this universality comes discontinuity in data acquisition and processing. Neil (2004) suggests that GPR analysis is analogous with the wave propagations of seismic reflections. With seismic readings there are large assumptions made in regards to the reflection data which unfortunately applies to GPR analysis as well. These assumptions can lead to misinterpretation of GPR radargrams and erroneous conclusions. The use of radargrams can also lead to multiple contradictory conclusions. Because of this possibility, only the most distinct and indisputable assumptions were made from the reflections in this study. It seems that with the use of the GPR, unless coupled with other measuring techniques, making rigid conclusions about

wave reflections is risky. For example, it would seem that the bottom portion of figures 3,4, and 5 show the change from snow to soil because of the change in the way the reflections. But in fact, it is known that this is not the snow-ground interface because the probe-measured depths were greater than the reflection shows.

Some factors that influenced the data collection included the time-zero drift, near field effect, and penetration depth (Neal 2004). The time-zero position of the antenna is not a constant value and has to be determined for each surface material on-site. This occurs when the waves change from trace to trace during the collection time which can cause misalignment of the radar waves. For example, in figure 4 it can be seen that the second transect, at about 37m at the top of the radargram, there is a discontinuity. It does not exist throughout the entire profile but is prominent between 0 and .25m The MALA GPR calculates the time-zero automatically but, as seen, is not 100% precise throughout the entire profile. This setting, when not done manually, does not take into consideration the near-field effect so the zero location is corrected but data acquisition does not begin to give readable returns until it has reached 1.5x the wavelength (Ernenwein 2006). For studies on shallow snowpack the near field effect has a very large influence. There is no definable minimum depth for GPR to function properly as a snow depth gauge but depending on the purpose of the study a depth of about 30-40cm is necessary. This near field effect posed a problem during the onset of data acquisition for this study. Colorado has experienced a very dry year in terms of snow fall; the total snowpack for 2013 is 77% of normal (NRCS 2013). The lack of significant snow accumulation earlier in the season inhibited data collection. However, when there is a sufficient snowpack, a way to combat the near- field problem is to suspend the antenna above the ground surface at a height 1.5x the wavelength, or higher, so it begins reflections right at the surface and not below. A model to follow in future

studies could mimic Bradford et al. (2009) where they performed two different studies that used GPR on the snow surface and GPR suspended 7m above the surface. By suspending the GPR the air and snow interface is easier to distinguish and the stratification of the upper portion can be detected because the reflections are not being interfered with by horizontal antenna communication along the ground surface, such as when it is operated in a sled.

In regards to penetration depth, even when coupled with pit and probe measurements, the position of discontinuities in the subsurface is subject to the observer. The best way to distinguish subsurface changes is by the change in the trace wave. When the wave changes amplitude there is an indication of a change in the medium properties (Zirizzotti et al. 2010). However, this technique is not precise because wave changes could also be a function of water pockets present within the snowpack, which would be observed as a high change because of the high dielectric property of water versus snow. The image below is an example from readings conducted in the learning stages of GPR for this project and the red arrow indicates the large change in wave amplitude.
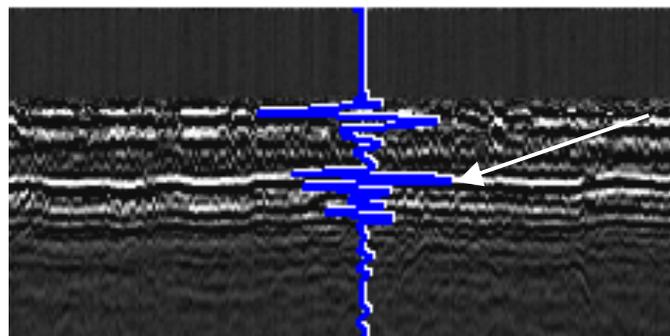

Fig.6 The white arrow indicates the change in trace wave amplitude indicating a change in dielectric permittivity.

Through this study, it was found that limitations regarding knowledge of certain factors could effect data acquisition surfaced. For example, I experienced a disconnect between product knowledge and its expanding applications. The technical experts knew the mechanics of

wave propagation through differing mediums, but lacked problem solving solutions that could have benefitted me in the field which. This proved to be very difficult because of the complexity of the instrument and its array of capabilities. It became apparent that because of its widespread commercial use, GPR needs some standardizations if it is going to continue to succeed as a tool that assess spatial variability in the subsurface (Neil 2004).

In this study, standardization of the frequency and time parameters were made in hopes of relieving field stress by reducing the time it takes to establish new parameters for each transect, and creating figures that could easily be comparable without alterations. This normalization helped when relating the radargrams but also reduced the potential accuracy of each plot. Another limitation to this method was that even though the set depths were initially greater than the snow depth for each transect, the program used for processing cut off the deepest depths. This eliminated the clear distinction of the snow-ground interface. This could also be due to a premature signal loss from the attenuation of the signal from the depth hoar facets.

To expand, there are specific changes that could be made to improve this study for the future. One includes increasing the time window for each transect to penetrate greater depths. This would eliminate the processing problem that the bottom portion of the cross-section gets cut off once uploaded into the program. Though the ice lens in this situation provided a very distinct reference for each of the transects, inferences were made that the ice lens is directly proportional to actual snow depth variations. However, this problem is not completely detrimental because the probe measurements correlate directly with the ice lens. And, it was not shown in this study but GPS tracking can be synonymous with GPR tracking, which would have allowed for spatially variable 3-D imaging. This could have allowed for better, larger scale correlations between snow depth and vegetation.

GPR holds a lot of promise in answering questions with regards to spatial depth variation in areas that have experienced high amounts of forest disturbance, precipitation change from the form of snow to rain, and many other inquiries. It is a proficient tool for reducing field research time in times of inclement weather and can be, but is not advised to be, done by one rather than many. Overall, for observers GPR provides a comprehensive depth analysis of the subsurface and a non-destructive way allowing better understanding of snow distribution across large areas and snow properties without destructive alterations.

5. Conclusion:

A successful application of Ground Penetrating Radar to asses changing snow depth as a function of vegetation distribution was achieved. The purpose of this study was to obtain an in-depth understanding of the potential to use microwave technology in order to address spatial variation of snow distribution and accumulation. This was shown by the prevailing ice lens in each transect and its changes in depth with regards to vegetation alterations. The most dramatic change that was noted occurred in the third transect located in the forested area. The depth varied about .5m, verifying how spatially inconsistent snow depth is across a large area. This study also validated the potential for GPR use in detecting subsurface discontinuities without destructive measures by reflecting both the ice and depth hoar layers. GPR is a maturing method for subsurface studies and it has the potential to assist Snow Hydrologist in forecasting snow accumulation changes with a changing climate. As well as addressing the overall water availability of the snowpack in its respective watershed. And as more improvements to the technology surface, GPR will be able to cater to specific subsurface problems, appealing to the array of disciplines it covers. The future is bright for GPR and now that this paper has presented a comprehensive review and simple application of its ability, future

studies can build upon this basis and concrete, long-term studies can be conducted in the pursuit of quantifying the changing global water resources.

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Bibliography:

1. Annan AP. 2002. GPR—History, trends, and future developments. *Subsurface Sensing Technologies and Applications* 3(4): 253
2. Bales R.C., Molotch N.P., Painter, T.H., Dettinger M.D, Rice R., Dozier J. (2006). Mountain hydrology of the western United States. *Water Resources Research.* 42(8): 1-3.
3. Barnett, T. P., Adam, J. C., & Lettenmaier, D. P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, *438*(7066), 303-309.
4. Basson, U. (2000). Imaging of active fault zone in the Dead Sea Rift: Evrona Fault Zone as a case study. *PhD, Tel Aviv University*, *195*.
5. Bewley, D., Alila, Y., & Varhola, A. (2010). Variability of snow water equivalent and snow energetics across a large catchment subject to Mountain Pine Beetle infestation and rapid salvage logging. *Journal of Hydrology*, *388*(3), 464-479.
6. Bradford J., Harper J., Brown J. (2009). Complex dielectric permittivity measurements from groud-penetrating radar data to estimate snow liquid water content in the pendular regime. *Center for Geophysical Investigation of the Shallow Subsurface.* DOI: 10.1029/2008WR007341
7. Björklund, N., & Johnsson, T. (2005). *Real-time Sampling of Ground Penetrating Radar and Related Processing* (Doctoral dissertation, Lulea, Sweden: Department of Computer Science and Electrical Engineering, Lulea University of Technology).
8. Christopher, S. A., & Gupta, P. (2010). Satellite remote sensing of particulate matter air quality: The cloud-cover problem. *Journal of the Air & Waste Management Association*, *60*(5), 596-602.
9. Colorado Ski Authority. (2012). *Morningside Park at Steamboat.* http://www.coloradoskiauthority.com/steamboat/morningside/
10. Conyers, L. B. (2002). Ground Penetrating radar. *Encyclopedia of Imaging Science and Technology*.
11. Custer S., Birkeland K. (2006). Snow-water- equivalent (SWE) measurement laboratory. Available at: http://www.montana.edu/uessc/esci450/SWEmeasure.html
12. Diamanti, N., & Redman, D. (2011). Field observations and numerical models of GPR response from vertical pavement cracks. *Journal of Applied Geophysics*.
13. Domine, F., Taillandier, A. S., Houdier, S., Parrenin, F., Simpson, W. R., & Douglas, T. A. (2007). Interactions between snow metamorphism and climate: Physical and chemical aspects. *Physics and Chemistry of Ice, edited by WF Kuhs*, 27-46
14. Duncan C. (2008). *Mountain Population : 200 Version.* University of Massachusetts. http://www.geo.umass.edu/faculty/duncan/iwonder/mtnpop.html
15. Dunse T., Eisen O., Helm V., Rack W., Steinhage D., Parry V. (2008). Characteristics and small-scale variability of GPR signals and their relations to snow accumulation in Greenland's percolation zone. *Journal of Glaciology.* 54(185).
16. Elder, K., Dozier, J., Michaelsen, J. (1991). Snow accumulation and distribution in an alpine watershed. *Water Resources* 27(7): 1541-1552. DOI: 10.1029/91wr00506.
17. El Said, M.A.H., 1956, Geophysical prospection of underground water in the desert by means of electromagnetic interference fringes, Pro. I.R.E., v. 44, p. 24-30 and 940.
18. Ernenwein, E. G. (2006). Imaging in the Ground-penetrating Radar Near-field Zone: a Case Study from New Mexico, USA.
19. Galley, R. J., Trachtenberg, M., Langlois, A., Barber, D. G., & Shafai, L. (2009). Observations of geophysical and dielectric properties and ground penetrating radar signatures for discrimination of snow, sea ice and freshwater ice thickness. *Cold Regions Science and Technology*, *57*(1), 29-38.
20. Geo-Scientific ltd. *Sampling Instruments: Federal Snow Sampler.* Watershed monitoring Instrumentation. 2001. http://www.geoscientific.com/sampling/
21. Harper J., Bradford H. (2003). Snow stratigraphy over a uniform depositional surface: Spatial variability and measurement tools. *Cold Regions Science and Technology.* P:289-298.
22. Jol, H. M. (2009). *Ground penetrating radar theory and applications*. Elsevier Science Limited.
23. Lucius J.E., Powers M.H. (2002). GPR Data Processing Computer Software for the PC. *USGS science for a changing world.* 02-166.
24. Macguth H., Eisern O., Paul F., Hoelzle M. (2006). Strong spatial variability of snow accumulation observed with helicopter-borne GPR on two adjacent alpine glaciers. *Geophysical Research Letters.* Vol33:3503.
25. Marshal, D. (2001). *Nyquist's Sampling Theorem.* http://www.cs.cf.ac.uk/Dave/Multimedia/node149.html
26. Marshall, H. P., & Koh, G. (2008). FMCW radars for snow research. *Cold Regions Science and Technology*, *52*(2), 118-131.
27. Mala Geoscience. (2008). *RAMAC GroundVision Software Manual: Version 1.3.* Sweden: MALA Geoscience.
28. Maurer IV, J. A. (2006). *Local-scale snow accumulation variability on the Greenland ice sheet from ground-penetrating radar (GPR)* (Doctoral dissertation, University of Colorado).
29. Miljatovic S. (2012). GPR Investigation at Saint Adriano Church, Brenna (CO). *Politecnico Di Milano.* pp: 10-16.
30. Molotch, N. P., & Margulis, S. A. (2008). Estimating the distribution of snow water equivalent using remotely sensed snow cover data and a spatially distributed snowmelt model: A multi-resolution, multi-sensor comparison. *Advances in Water Resources*, *31*(11), 1503-1514.
31. Natural Resources Conservation Services. (2013). *Colorado State-Wide Time Series Snowpack Summary.* ftp://ftpfc.sc.egov.usda.gov/CO/Snow/snow/watershed/daily/basinplotstate13.gif
32. Neal A. (2004). Ground-penetrating radar and its use in sedimentology: principles, problems and progress. *Earth-Science Reviews* 66: 261-330.
33. National Resources Conservation Service. *SNOTEL and Snow Survey & Water Supply Forcasting.* United States Department of Agriculture. March 2009.
34. Palli A., Kohler J., Isaksson E., Moore J., Pinglot J., Pohjola V., Samuelsson H. (2002). Spatial and temporal variability of snow accumulation using ground-penetrating radar and ice cores on Svalbard Glacier. *Journal of Glaciology.* Vol. 48:162.
35. Peterson I., Prinsenberg S., Holladay J., Lalumiere L. (2012). A comparison of ice thickness data from helicopter- borne sensors with SAR imagery for the Beaufort Sea and Labrador Shelf. *Geoscience and Remote Sensing Symposium (IGARSS), 2012 IEEE International.* (pp. 3281-3284).
36. Pielke R.A., Liston G.E., Chapman W.L., Robinson D.A. (2004). *Climate Dynamics.* 22:591.
37. Rejiba, F., Bobée, C., Maugis, P., & Camerlynck, C. (2011). GPR imaging of a sand dune aquifer: A case study in the niayes ecoregion of Tanma, Senegal. *Journal of Applied Geophysics*.

38. Richardson-Näslund, C. (2004). Spatial characteristics of snow accumulation in Droning Maud Land, Antarctica. *Global and planetary change*, *42*(1), 31-43.
39. Singh, K. K., Datt, P., Sharma, V., Ganju, A., Mishra, V. D., Parashar, A., & Chauhan, R. (2011). Snow depth and snow layer interface estimation using Ground Penetrating Radar. *Current Science(Bangalore)*, *100*(10), 1532-1539.
40. Sambuelli, L., Comina, C., Bava, S., & Piatti, C. (2011). Magnetic, electrical, and GPR waterborne surveys of moraine deposits beneath a lake: A case history from Turin, Italy. *Geophysics*, *76*(6), B213-B224.
41. Steamboat. (2013). *Mountain Stats.* http://www.steamboat.com/the-mountain/mountain-stats.aspx
42. Zirizzotti A., Urbini S., Cafarella L., Baskaradas J. (2010). Radar Systems for Glaciology. *Radar Technology.*
43. (2013). *GPR: Subsurface Imaging Solutions*. Sensors and Software. http://www.sensoft.ca/FAQ.aspx
44. (2007).*Ground Penetrating Radar.* Environmental and Engineering Geophysical Center. http://www.geo-sense.com/GPRmore.htm