Snow stratigraphy measurements with high-frequency FMCW radar: Comparison with snow micro-penetrometer

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Abstract

The stratigraphy of an alpine snowpack is very important for avalanche danger assessment, as well as interpretation of remote sensing measurements for hydrological purposes. Since spatial variability is often widespread, due mainly to wind, micro-climatic and topographic effects, extrapolating point measurements can be difficult. Tools which can quickly characterize snowpack stratigraphy, such as high frequency radar and mechanical probes, will be required for a complete understanding of the effects of spatial variability, however interpretation of these kinds of measurements still remains challenging. We compare measurements from a portable 8–18 GHz Frequency Modulated Continuous Wave (FMCW) radar with SnowMicroPenetrometer (SMP) and standard snowpit measurements. Although significant variability existed at the sub-meter scale, major stratigraphic horizons could be followed along radar profiles and identified in SMP measurements. A very thin hard crust (0.2–0.4 mm) that was continuous caused strong signals that were identifiable in both the SMP and the radar measurements at five different sites along a 10 m traverse. Two other more subtle transitions in the SMP signal were highly correlated with the locations of radar reflections. This work suggests that combining FMCW radar measurements, to characterize snowpack geometry, with SMP measurements, to characterize mechanical properties of layers, may be a useful technique for quantifying the spatial variability of the snowpack.

Keywords: Snow stratigraphy; Radar; Penetrometer; Spatial variability; Avalanches; Snow hydrology

1. Introduction

Mechanical properties of snow control the snowpack’s response to the forces present in its environment. Making accurate predictions of the behavior of snow under a wide range of conditions is important for avalanche hazard assessment as well as many engineering problems. Snow is a very complicated material to model, however, due to variability both temporally and spatially on a wide range of length scales (e.g. Kronholm et al., 2004). In order to accurately characterize the length scales at which variations exist and to attempt to better understand the length scales which are important in the avalanche formation process, there is a need for a technique which can measure large areas rapidly at high resolution. Radar measurements can be made many times per second, and in addition the measurement is non-destructive allowing temporal measurements at a
fixed site. Many previous studies have shown correlations between snowpit and radar measurements, however signal interpretation remains challenging. Previous studies (e.g. Gubler and Hiller, 1984; Marshall et al., 2005) found the depths of major reflections occurred at transitions visually observed in an adjacent snowpit, however quantitative interpretations of the magnitude of reflections are much more difficult (e.g. Yamamoto et al., 2004). Although the location of layer boundaries can be accurately estimated from radar measurements, it is very unlikely that information about mechanical properties of snow will ever be obtained.

Currently avalanche professionals make mechanical measurements at many different length scales, from micrometer scales (SMP) (e.g. Schneebeli et al., 1999) to studies on entire avalanche slopes (e.g. Sovilla and Bartelt, 2002). Recent studies have shown that large spatial variability can exist on length scales ranging from less than a meter to hundreds of kilometers (Sturm et al., 2004). Mechanical tests are time consuming (SMP measurements take approximately 3 min per profile), therefore it is impractical to make measurements over large areas but also with high resolution to address the question of what length scales are important for the avalanche formation process. When the minimum length scale at which variability exists is unknown, it is very difficult to extrapolate accurately from careful point measurements of mechanical properties.

A transmitted radar signal will reflect from large changes in dielectric properties, which often exist at layer boundaries in the snow stratigraphy, due to changes in physical properties. Large changes in density, hardness, grain size and type, which cause discontinuous dielectric properties that radar is sensitive to, are often observed at sliding layers in slab avalanches. The ability to track these transitions over large areas would allow characterization of the geometry and variation of layer thicknesses. Although the dielectric and mechanical properties of snow are related in an unknown and complicated way, high frequency radar may be a useful tool for following important layers and transitions that can be characterized with mechanical tests such as the SnowMicroPen (SMP).

2. Background

The scientific study of snow stratigraphy began in the 18th century, however only recently have tools become available which can measure stratigraphy quickly and non-objectively. Pielmeier and Schneebeli (2003a) thoroughly review the development of snow stratigraphy research, and point out that recent technological advancements in instrumentation are providing evidence that challenges the traditional assumption of a snowpack consisting of discrete, homogeneous layers. To accurately characterize the spatial variability of snow stratigraphy, detailed, high resolution, quantitative measurements are required, due to the large variability that exists at sub-meter length scales. FMCW radar and the SMP are two instruments which together make such a sampling strategy feasible.

2.1. Snow radar studies

In comparison with radar work in other media, relatively few experiments have been performed in snow. Previous impulse radar studies (Vickers and Rose, 1972; Sand and Bruland, 1998; Lundberg et al., 2000) have shown that the technique is sensitive to snowpack layering and that total snow water equivalent could be estimated to 5–10%. Harper and Bradford (2003) made 3D impulse radar measurements in a 20 m × 20 m study plot on a glacier, saw little spatial variability in the radar measurements and found general agreement between manual density measurements and a low resolution Common Mid-point (CMP) inversion of radar measurements done at one location (3 layers in 250 cm). The resolution of the commercially available impulse radars limits their use for avalanche applications, however.

Frequency Modulated Continuous Wave (FMCW) radar measurements have the advantage of much higher frequency than commercially available impulse radars, as well as much larger bandwidth which results in higher resolution and greater sensitivity to thin layers and more subtle transitions. Early work by Ellerbruch and Boyne (1980) and Gubler and Hiller (1984) showed that surface and ground reflections were clearly visible, so that SWE could be estimated to within ±5%. Reflections from depth hoar layers were observed, and changes due to surface melting could be seen. Gubler and Weilenmann (1986) made static measurements while removing layers sequentially from the surface, and also qualitatively compared FMCW radar measurements with ram and morphological profiles. Fujino et al. (1985) and Forster et al. (1991) observed snow stratigraphy that related to snowpit measurements at one site, and Gubler and Rychetnik (1991) present profiles that indicate significantly less snow layering in forest stands than in open fields.

More recently, Koh and Jordan (1995) were able to detect a subsurface melt event predicted by a thermal snow model, Holmgren et al. (1998) measured snow depth along very long traverses, and Gogineni et al. (2003) have used an FMCW radar to measure snow thickness on sea ice.
internal snow layers in Greenland from aircraft, and Yankielun et al. (2004) successfully measured snow depth from an aerial tramway. Marshall et al. (2005) located the depths of major reflections with metal reflectors, which agreed with layer boundaries observed in an adjacent snowpit, and found that the location of reflections occurred at large changes in dielectric properties that were measured with an in-situ dielectric sensor. This study found that spatial variability in the radar signal occurred on length scales less than 1 m, and that the measurement of this spatial variability was repeatable. Marshall et al. (2004a) document FMCW radar measurements in a wide range of snowpack types in both wet and dry conditions, with depths from 40 to 350 cm, at a wide range of frequencies (2–18 GHz), incidence angles (0–45°), and bandwidths. Marshall et al. (2004b) found that a high center frequency (Ku-band, 14–18 GHz) provided the most information in a dry snowpack, whereas C-band frequencies (2–6 GHz) were optimal for deep, wet snowpacks.

2.2. Snow penetrometer

Various mechanical probes have been used in attempts to develop an index useful for predicting the stability of a snow slope (Bader et al., 1939; Bradley, 1968; Dowd and Brown, 1986; Birkeland et al., 1995; Mackenzie and Payten, 2002). The SnowMicroPenetrometer (SMP) (Schneebeli and Johnson, 1998; Johnson and Schneebeli, 1999) has become the most widely used mechanical probe, and has been thoroughly tested during the last decade. Previous work demonstrates its ability to accurately discriminate between layers with different properties (e.g. Schneebeli et al., 1999; Pielmeier and Schneebeli, 2003b; Kronholm et al., 2004; Birkeland et al., 2004). The SMP accurately measures penetration force and distance every 4 μm while the sensor is driven into the snowpack at 20 mm/s with a stepping motor. Force measurements, accurate to less than 0.001 N, are made with a piezo-electric force sensor at the SMP tip, which is a cone with a maximum diameter of 5 mm and a 60° included angle.

3. Methods

3.1. Portable high-frequency FMCW radar

Here we give just a brief summary of the FMCW radar technique, as it has been described previously (e.g. Stove, 1992). A voltage-controlled oscillator is used to transmit a continuous sinusoidal electromagnetic wave, whose frequency \( f(t) \) varies linearly with time over a wide bandwidth \( B = f_{\text{high}} - f_{\text{low}} \). The transmitted wave spans a length of time \( T_{\text{pl}} \) which is several orders of magnitude larger than the two-way travel time \( T_{2w} \) to reflectors of interest.

Consider first the simple case of two semi-infinite media, with dielectric constants \( \varepsilon_1 \) and \( \varepsilon_2 \), respectively. A portion of the transmitted wave is reflected from the boundary, and returns to the receiving antenna. This received wave also has a frequency which varies linearly with time, and this signal is mixed (multiplied) by a portion of the transmitted signal and low-pass filtered before it is digitally recorded. The mixed signal contains the frequency sum and frequency difference of the transmitted and received waves, and the low-pass filter removes the frequency sum component. Due to the linearity in frequency of the two waves, the frequency difference \( \delta f \) is constant over the entire bandwidth \( B \). Since the slope of \( f(t) \) is known, the frequency difference \( \delta f \) can be used to calculate the distance \( d \) to the boundary, if the velocity of propagation \( v \) is known:

\[
d = \frac{1}{2} v T_{2w} = \frac{1}{2} v \delta f \frac{T_{\text{pl}}}{B} = \frac{1}{2} \frac{c}{\sqrt{\varepsilon_1}} \delta f \frac{T_{\text{pl}}}{B}
\]

where \( c \) is the speed of light in a vacuum, and the velocity of propagation in the upper medium is \( v = c/\sqrt{\varepsilon_1} \).

The recorded signal is voltage as a function of time \( V(t) \) which, for our simple case of two semi-infinite media, contains just one frequency component. To calculate the frequency spectrum of this signal, we use a windowed fast-fourier transform (FFT), to minimize spectral leakage:

\[
\text{PSD}(f) = \int w(n) V(t) e^{if \delta t} \, dt
\]

where \( w(n) \) is the window function defined over the range of data points \( n = -N/2:N/2 \), for \( N \) total samples. After experimenting with many different window functions, we chose to follow Harris (1978) and used the Kaiser-Bessel window, as it contains a parameter \( \alpha \) which is proportional to the time-bandwidth product and can be adjusted depending on whether minimizing spectral leakage or minimizing resolution is more important. Harris (1978) defines the Kaiser-Bessel window as

\[
w(n, \alpha) = \frac{I_0 \left( \pi \alpha \sqrt{1 - (\pi n/N)^2} \right)}{I_0(\pi \alpha)}
\]

where \( I_0 \) is the zeroth-order modified Bessel function of the first kind. A small value of alpha can be used to accurately locate reflections (higher resolution), and a
large value can subsequently be used to calculate an accurate magnitude (reduce spectral leakage).

3.1.1. Magnitude of reflections

For our simple two-medium case, the magnitude of the reflection is proportional to the elementary reflectivity \( r \) given by

\[
r = \frac{\sqrt{\epsilon_1} - \sqrt{\epsilon_2}}{\sqrt{\epsilon_1} + \sqrt{\epsilon_2}}
\]

In theory, we can use the magnitude information to estimate the change in dielectric constant at the boundary. Since the dielectric constant is primarily a function of density \( \rho \) in the microwave frequency range for dry snow (Ulaby et al., 1986), this could potentially allow an estimate of the change in density at the boundary.

The physical properties of snow, such as density, are highly sensitive to the meteorological conditions during formation and after deposition. This results in a layered and heterogeneous snowpack, as many different types of snow are observed in the course of one winter, due to the wide range of environmental conditions which occur each season. The next logical complexity to introduce into the simple two-medium example is a stratified snowpack with multiple homogeneous parallel layers. Real snowpacks, however, are unfortunately far from a simple homogeneously layered material. Observable layers, although they can mark major, often storm-related boundaries, often show a large degree of variability in physical properties (e.g., Conway and Abrahamson, 1984; Sommerfeld, 1980; Kronholm and Schweizer, 2003). Planar sections and SMP tests show many transitions but relatively few clear boundaries. A thorough review of snow stratigraphy is given by Pielmeier and Schneebeli (2003a).

For multiple parallel layers, the reflectivity \( R_i \) at the \( i \)th boundary is

\[
R_i = |\Gamma_i|^2
\]

where \( \Gamma_i \) is the reflection response, which can be expressed with the recursion relation

\[
\Gamma_i = \frac{r_i + \Gamma_{i+1}e^{-\beta_i \delta z_i}}{1 + r_i \Gamma_{i+1}e^{-\beta_i \delta z_i}}
\]

where \( k_i \) is the wavenumber in the \( i \)th layer, \( \delta z_i \) is the thickness, \( \Gamma_{i-1} \) is the reflection response of the uppermost (air-snow) boundary, and \( \Gamma_{i-1} \) is the value for the lowermost boundary (snow-ground), where the ground is assumed to be semi-infinite. The recursion relation is initialized at the lower boundary by setting \( \Gamma_m = r_m \).

This causes the reflectivity in the upper layers to be a function of frequency (due to constructive and destructive interference), such that for our case we must then average the reflectivity over the range of transmitted frequencies. For layers which are much thicker than the wavelength, this results in a reflectivity that depends only on the relative dielectric contrast at the boundary. For layers which have a thickness less than the wavelength, the reflectivity also depends on the layer thickness.

Our FMCW radar system operates from 8 to 18 GHz, resulting in a range of wavelengths from 1 to 4 cm over the range of observable densities. Since crusts can often be less than 1 cm in the snowpack, we calculated the variation in reflectivity of the upper boundary of an ice layer (\( \rho = 918 \text{ kg/m}^3 \)) embedded in a homogeneous snowpack (\( \rho = 200 \text{ kg/m}^3 \)), as a function of ice layer thickness. The reflectivity was calculated using Eq. (6) for a wide range of ice layer thicknesses, averaged over our operating frequency range. The resulting reflectivity is shown as a function of ice layer thickness in Fig. 1.

Gubler and Hiller (1984) presented a similar calculation for their X-Band (8–12.4 GHz) system, and used the results to infer that a crust less than 0.5 mm could be detected given the sensitivity of their system. This inference holds for our system as well, however here we also point out that for layers less than 5 mm thick, interpretation of the magnitude of the reflection becomes very difficult. If, for example, an ice layer’s thickness changed from 1 to 2 mm along a traverse, the magnitude of the reflection would change by 275%. Between a thickness of 1 and 2 cm, the reflectivity oscillates approximately ±15%. This highlights the difficulty in interpreting the magnitude of reflections from thin
crusts and layers, as changes in thickness could be misinterpreted as changes in the degree of density contrast. A similar effect would occur for a more subtle density transition, such as a weak layer, although the mean reflectivity would be much lower. This kind of simple reflectivity model allows the study of the potential effects of any given layered snowpack, improving our interpretation of the radar signal.

3.1.2. Vertical resolution

Our FMCW radar uses hardware similar to previous work (e.g. Stove, 1992; Gubler and Hiller, 1984). Higher frequencies are much more sensitive to snowpack layer transitions, but at the expense of decreased penetration. Marshall et al. (2004b) made measurements at C-band (2–6 GHz), X-band (12–14 GHz), and Ku-band (14–18 GHz) frequencies and found that in a dry snowpack Ku-band frequencies provided the most stratigraphy information and still penetrated to the ground. Marshall et al. (2004b) also illustrated the relationship between bandwidth $B$ and vertical resolution. The theoretical vertical resolution, or the minimum separation of two layers such that they can be independently identified, is

$$\delta z_{\text{min}} = \frac{c}{2\sqrt{\varepsilon_1 B}} \quad (7)$$

which was shown to correspond to the separation at which two reflectors, differing in magnitude by less than a factor of 20, could be identified. If the reflectors differ by a factor of two or less, the minimum separation was shown to be $0.5\delta z_{\text{min}}$.

Based on this study, we chose to design a system which operated within the Ku-band frequency range and with the largest possible bandwidth. Recent improvements in radar hardware allow us to operate over a broader bandwidth, resulting in greater resolution than previous work. Our current system operates over a 10 GHz bandwidth (8–18 GHz), resulting in a vertical resolution $\delta z_{\text{min}} \sim 1.5$ cm. We have developed MATLAB-based software which controls the data acquisition system and allows real-time processing of the measurements. Impedance mismatches in the radar cause constant instrumentation-related signals, which can make layer tracking difficult. In order to isolate these effects, we made measurements at one position while we varied the height of the radar. A measurement of this type is shown in Fig. 2. Note that signals that change position during this measurement are related to the snowpack, while constant signals are caused by the instrumentation and need to be accurately removed.

We have developed an efficient new signal processing algorithm to remove the instrumentation-related signals using measurements made with the horns pointed at the sky. The same measurement from Fig. 2 is shown after this algorithm has been applied in Fig. 3. Note that now the first major reflection is caused by the snow surface, and interior reflections can be clearly traced throughout the measurement. An automated algorithm is next used to pick the surface (first clear signal), as well as all of the internal reflections. Note that in both Figs. 2 and 3, no horizontal smoothing (i.e. stacking) has been performed; these are 250 independent measurements.

3.1.3. Continuity of radar reflectors

Since magnitude information is difficult to interpret and can be affected by layer geometry (Fig. 1), horn angle, system drift, and temperature, here we focus on the location of major reflectors. The depth below the snow surface reflection for each reflector that was picked by the algorithm was calculated. In order to determine which reflectors were the most continuous, we made measurements at each SMP location while varying the height of the radar at a fixed horizontal position. We next used the locations of the automatically-picked, major radar reflections, and subtracted their position from that of the snow surface (first major reflection). In order to quantify which depths showed a major reflection in the majority of the ~250 independent measurements (made while the radar height varied), we calculated a probability density function (PDF) of the depths of all measured reflections (e.g. Bowman and Azzalini, 1997). This is essentially a smooth histogram, where a weighted average is used to calculate the probability of observing a
strong reflection at a given depth. This is an improvement to the traditional histogram, as it is not effected by the choice of bin position. The width of the moving window for the weighted average is chosen as a parameter for the weighted average function, called the kernel.

We used a bi-square kernel, given by

\[
W(D) = \frac{15}{16} \left(1 - \left(\frac{D}{\kappa}\right)^2\right)^2, \quad D < \kappa
\]

\[
W(D) = 0, \quad D \geq \kappa
\]

where \(W(D)\) is the weight given to each data point, \(D\) is the distance from the point where the PDF is estimated, and \(\kappa\) is the smoothing parameter. We set \(\kappa = 1.5\) cm, as this is the approximate resolution of the radar.

Depths that always showed a reflection (continuous layers) have a large PDF, while reflections that had a spatially variable depth near this position have a low PDF. This PDF is therefore a measure of how continuous a given reflector is, while the horn height was varied at a fixed horizontal position.

3.2. Other instruments

We used several other snow science techniques to measure the snow stratigraphy. A standard snowpit was excavated after the radar measurements were finished, and density, temperature, grain size and type, and hardness were measured (Fig. 4). Density was measured with a
100 cm³ cutter at 5 cm increments, with three separate measurements made at each depth. The mean density was used to calculate the mean velocity of radar wave propagation, which has been shown to result in a depth scale accurate to within 2% (Marshall et al., 2005; Marshall, 2005). Small samples were also preserved for later laboratory analysis.

Mechanical measurements were made with the Snow-MicroPenetrometer (SMP), a highly accurate, very high resolution snow penetrometer, described above. Measurements were made at 5 equally spaced locations (every 2.5 m) along the radar profile. As this measurement is highly accurate and objective, here we focus on comparing the FMCW radar measurements with those made with the SMP.

The pit wall was also photographed with a near-infrared (NIR) digital camera. This type of measurement is known to be sensitive to grain size, however quantitative processing techniques are still being developed at this time (Matzl and Schneebeli, 2002). A comparison of NIR results with SMP and FMCW radar measurements will be the subject of a future paper.

4. Results

In Davos on February 20, 2005 measurements were successfully made with high frequency radar, the Snow-MicroPen, a near-infrared camera, as well as traditional snowpit measurements with high resolution density samples. An FMCW profile was performed over a 10 m distance, and 5 sites along the profile were chosen for SMP measurements. At each of these 5 sites, we made static measurements. This profile is shown in Fig. 5. Note that the locations where we stopped moving are obvious due to the constant signal, and illustrates the repeatability of the measurement, as well as the large signal-to-noise ratio. Large spatial variability exists between stops, which span about 2.5 m.

Due to the large degree of variability, we felt it was important to accurately characterize the locations where the SMP measurements were made. We therefore made measurements at these locations while changing the antenna height (footprint), as shown in Figs. 2 and 3. The antenna height above the snow surface varied from approximately 20 cm to 180 cm, changing the antenna footprint from approximately 10 cm×10 cm to 1 m×1 m. This allowed us to focus on reflectors that were spatially continuous over a length scale between 10 cm and 1 m. The depths of these continuous reflections would most likely relate to transitions in the SMP measurement, which sampled a horizontal area of only 1 cm×1 cm.

4.1. Comparison with SMP

Fig. 4 shows the SMP measurement (solid line) and the processed radar PDF (dashed line) at site #4 on the left, and the snowpit measurements which were made between site #4 and #5 on the right. Peaks in the radar PDF above a threshold of 0.02 were automatically chosen, and the location of these peaks is shaded gray on both plots, with a thickness equal to the approximate radar resolution (1.5 cm). Note that the radar shows peaks that are highly correlated with peaks/transitions in the SMP signal throughout the snowpack, including those caused by numerous crusts, located below 40 cm, which were also visually observed in the snowpit (Fig. 4). Almost all major radar peaks could be associated with a mechanical signal from the SMP. All FMCW peaks could also be associated with features in the manual profile, except the peak at 47 cm. There is, however, a peak at exactly this depth in the SMP profile, so this was most likely caused by a crust that was missed in the manual measurements.

Transitions A, B and C are marked on the right side of each plot in Fig. 4, and are discussed below. Mean density from three separate measurements is shown in the plot on the right in dark gray, with error bars corresponding to the height of the 100 cm³ sampler. Note that the penetrometer measured a maximum resistance at approximately 80 cm and automatically ended the profile to protect the sensor tip. The radar measured a snow depth of approximately 83 cm. This difference could be caused by errors in the radar depth scale (~2%) combined with true spatial variability within the radar footprint. Between this measurement and the next SMP
measurement 2.5 m away, the snow depth changed from 80 cm to just over 100 cm. A depth of 80 cm was measured in the manual profile.

In the upper part of the snowpack, we also observed some consistent features in both measurements. At \( \sim 25 \) cm depth there was a very thin crust that was apparent in the SMP signal but not in the snowpit. This thin crust also caused a reflection in the radar signal at all 5 of the comparison sites, even though it was only 0.2–0.4 mm thick. Fig. 6 shows SMP measurements at 3 of the comparison sites, with the locations of the radar reflections shown again in gray. Note the crust at \( \sim 25 \) cm at site #2 and #4, and at \( \sim 29 \) cm at site #5, and the two transitions above 25 cm that also agree well at all 3 sites; the three transitions are labeled A, B, C on the far left side of the figure. These transitions were visible in both instruments at all 5 sites. Transitions A and C correspond to the top and bottom of layer 2 in the hardness profile, while the middle transition (B) is located at a peak in measured density (Fig. 4). It appears that these layer transitions, recognized in the SMP profiles and the manual measurements, can be tracked along a profile with the radar.

Next the locations of the three transitions in the SMP signal were picked automatically using the following rules. The first transition (A), which corresponds to the new snow/old snow boundary, was chosen as the first measurement in the SMP signal above 0.3 N at all 5 sites. The second transition (C), which marks the lower boundary of this older snow layer (see Fig. 4), was the thin crust. This transition was picked by finding the maximum force in the upper 30 cm at all sites. The third transition (B), which was located at a peak in measured density but not identified in the hardness profile, was found by picking the maximum force between transitions A and C, and corresponds to the peak in hardness within this older snow layer.

In the FMCW signal, the depth below the surface reflection was found for the first three peaks in the PDF which were above 0.02. These three peaks were then labeled transitions A–C at each of the 5 sites. By using rules for picking the three transitions in each of the 5 SMP profiles and 5 radar PDF’s, we can more objectively compare the two measurements. The radar depths corresponding to transitions A–C at each of the 5 sites are plotted against the measured SMP depths in Fig. 7. A different symbol was used for each transition, shown in the legend. The agreement is remarkably good, with an \( r^2 = 0.923 \) and rms = 1.6 cm.

One data point at approximately (10,16), contributes most to the overall error, and is most likely caused by spatial variability of this layer transition within the radar footprint. The difference in horizontal scale of the two instruments (SMP: approx. 1 cm\(^2\), FMCW radar: 400–10,000 cm\(^2\)) makes quantitative comparison difficult, especially in light of the sub-meter spatial variability that exists.

5. Discussion

This preliminary comparison of FMCW radar measurements and other snow science instruments is very encouraging. The standard snowpit measurements
showed many hard crusts that were observed in the radar measurements, as well as in the SMP and NIR data. An accurate algorithm was developed for removing instrumentation-related signals in the radar data, which greatly enhances our ability to interpret the cause of reflections. A new method of interpreting the radar measurements was used, to prevent misinterpretation of the magnitude of the reflections caused by layers with a variable thickness less than the wavelength. This method focuses on the continuity of reflectors rather than the magnitude of the reflections, as the distance to a reflector can be determined accurately while the magnitude of the return depends on many unknowns and is difficult to interpret. This new method of interpreting the radar signal as a probability density function (PDF) reduces the difficulties in interpretation caused by variations in the magnitude of reflections.

A sub-millimeter crust was found in all 5 SMP measurements, and this caused a continuous reflection in the radar measurement at all 5 locations as well. The SMP depths of this crust, as well as two other transitions above the crust were found to be highly correlated with the first 3 depths of this crust, as well as two other transitions above the radar measurement at all 5 locations as well. The SMP measurements, and this caused a continuous reflection in caused by variations in the magnitude of reflections. A new method of interpreting the radar signal as a probability density function (PDF) reduces the difficulties in interpretation caused by variations in the magnitude of reflections.

The FMCW radar may have difficulty locating weak features in the SMP measurements were also correlated with the depths of major radar reflections, indicating that it is possible to track important snowpack layer boundaries with an FMCW radar. Discrepancies could have been caused by true variability within the footprint of the radar (400 cm$^2$–10,000 cm$^2$), as only one SMP measurement (1 cm$^2$) was made at each site. Note that these two high resolution methods are completely physically independent—the radar responds to changes in dielectric properties and the SMP responds to mechanical properties, however both methods detect the same major stratigraphic boundaries. Future work will incorporate many SMP measurements within many radar footprints, to accurately characterize spatial variability in stratigraphy at a wide range of length scales.

The FMCW radar may have difficulty locating weak layers associated with more subtle density transitions, however weak layers often have a hard crust or layer above or below, causing a discontinuity in the dielectric profile which the radar is highly sensitive to. Measurements of depths to important layer transitions, such as the thickness of a slab overlaying a weak layer, could be made with this type of radar. Combined with many SMP tests, this technique has great potential for identifying and quantifying spatial variability in the snowpack. The PDF approach to radar processing shows promising potential for filtering out effects caused by thin layers (<1.5 cm). Comparing the static radar measurements, which are extremely consistent and have a very high signal to noise ratio due to our signal processing techniques, with the dynamic radar measurements, which show a large degree of repeatable spatial variability in less than 1 m, it is clear that a very high spatial sampling rate is necessary for applying these statistical procedures. Our FMCW radar can record complete traces at 50 Hz when sweeping over the entire 10 GHz bandwidth, allowing measurements at high spatial resolution.

FMCW radar and the SnowMicroPen may be powerful tools to use together, as the SMP can find important transitions in the snowpack and characterize their mechanical properties, while the radar can be used to follow these transitions along profiles and characterize their variability. Many more comparison tests will allow a more quantitative comparison between the two instruments, and these are planned for the next few winters. This concept of interpreting the radar signal as a PDF could also be applied to other layered porous media, such as soils. This approach may allow more accurate detection of heterogeneities when compared with the original signal (e.g. detection of avalanche victims, landmines, and archaeological objects).

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