Ultra-broadband portable microwave FMCW radars for measuring snow depth, snow water equivalent, and stratigraphy: practical considerations

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Abstract

The properties of seasonal snow and near surface polar firn can be measured using radars operating at the microwave frequencies. These frequencies offer an optimal combination of bandwidth and penetration required for snow studies. Because the velocity of microwave signals in dry snow and firn is primarily controlled by density, wave travel times can be converted to snow depth, snow water equivalent (SWE), and layer thickness, which are the main snow properties of interest in hydrologic and climatologic studies. The accuracy with which depth, SWE, and layer thickness can be determined varies with environment and snow properties. Sharp dielectric contrasts between snow layers and the underlying ground produce excellent results, while gradational boundaries and low contrasts can be problematic. Liquid water can also make penetration and interpretation difficult. Nevertheless, mobile microwave radars represent one of the most promising methods for mapping snow properties at landscape scales. Here we discuss some practical considerations that must be accounted for when using radars to measure snow properties.

1. Introduction

Ground-based microwave radar to measure snowpack properties have indicated that the technique has great potential, as measurements can be made rapidly and non-destructively. The natural properties of snow (frozen water) are such that in dry snow radar can penetrate more than 2 meters even at Ku-band frequencies (14-18 GHz), while in wet snow C-band (2-6 GHz) frequencies or lower are required for 2-meter penetration. In shallow Arctic snowpacks, Ka-bands (26-40 GHz) can be used. Impulse radars have been used to measure snow depth (e.g. Sand and Bruland, 1998; Lundberg et al, 2000; Lundberg et al, 2006) with success, but because many seasonal snow packs are shallower than 1 meter, the timing of the impulse signal can be challenging for typical frequencies of commercial systems (100-400 MHz). Small scale snow stratigraphy is difficult to interpret due to insufficient vertical resolution. Recent improvements in technology, however, are increasing the commercially available center frequencies and bandwidths, improving the ability of impulse radar to measure snow (e.g. Harper and Bradford, 2003). As a result, Frequency Modulated Continuous Wave (FMCW) radars have been favored in the majority of previous ground-based radar measurements in snow.

The FMCW radar technique allows an ultra-broadband signal to be used, producing very high (1-3cm) vertical resolution. Previous studies have shown that the two-way travel time of microwave signals can be used to estimate snow depth and snow water equivalent (e.g. Ellerbruch and Boyne, 1980; Gubler and Hiller, 1984; Holmgren et al, 1998; Sturm et al, 2002; Yankulien et al, 2004). Snow stratigraphy in polar firn has been measured with FMCW radar at lower frequencies (Kanagaratnam et al, 2001; Richardson et al, 1997) as has snow depth on sea ice (Sturm et al, 2002, Gogenini et al, 2003). More recent studies showed that a multi-frequency approach was required for a wide range of snow conditions (Koh et al, 1996), and that the reflection from the snow-ground interface, although usually obvious, was often ambiguous in arctic tundra environments and had to be locally calibrated (Holmgren et al, 1998). Many snow studies have used FMCW radars experimentally in the past (for a review see Marshall and Koh, in press), however cost, the need for specialized knowledge to operate the system, and practical difficulties in interpretation of the signal, has limited widespread use. On the other hand, recent improvements have simplified FMCW construction, and have drastically decreased the weight of this type of radar, allowing high resolution measurements at the kilometer scale with portable, and even hand-carried systems. Microwave FMCW radars span a frequency range that includes most satellite radars currently in orbit, and we have used these systems for ground-validation during numerous remote sensing campaigns. This paper discusses practical considerations for using FMCW radars for measuring snow depth, SWE, and stratigraphy, derived from our experience in a wide range of environmental conditions.

2. Methods

Frequency Modulated Continuous Wave radars transmit a continuous sinusoidal wave, with a frequency which changes linearly with time. A small portion of this transmitted signal is multiplied by the received signal with the use of directional couplers or a circulator, resulting in a sampled signal containing the sum and difference in frequency between the two signals. After low-pass filtering, the digitised signal has a frequency content determined by the difference in frequency between the transmitted and received signals, which is constant across the entire bandwidth for a given reflector. This frequency difference can be used to calculate the two-way travel time to the reflector, since the form of the transmitted signal is known (e.g. Marshall and Koh, in press).

Frequent measurements are made with the directional horn antennas pointed at the sky, and these calibration measurements are used to remove instrumentation-related signals. In addition, measurements are made over an excavated snowpit while a metal reflector is inserted horizontally at various depths for velocity calibration. Changing the height of the antennas over the same location can also help identify important internal snowpack reflections.

2.1 Snow depth estimates

The two-way travel time to a reflector in snow depends on the actual distance and the velocity of the signal. The velocity of microwave signals in dry snow is controlled primarily by snow density, as the dielectric constant can be approximated, over the range of typically observed snow densities, by

$$\varepsilon_{snow} \approx 1 + 1.75 \rho_{snow} / \rho_{ice} \tag{1}$$

where ε_{snow} is the dielectric constant of snow, and $\rho_{snow,}\rho_{ice}$ are the densities of snow and ice respectively. Since the velocity of microwave signal is $v = c / \sqrt{\varepsilon}$, a $\pm$ 25% uncertainty in mean snow density results in less than a $\pm$ 5% uncertainty in the radar estimate of snow depth.

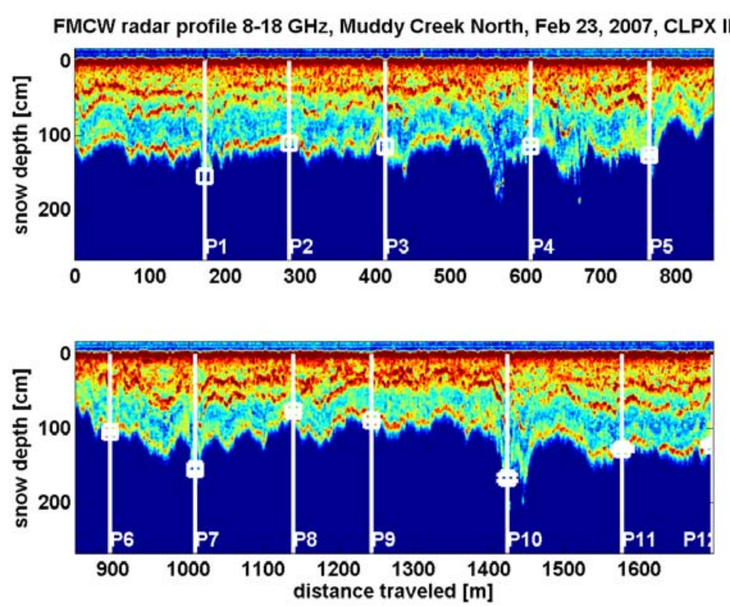

Figure 1: Typical FMCW radar profile from N. Colorado. Red indicates a strong reflection, blue indicates no reflection, and white vertical lines show locations of manual depth measurements. White boxes show the mean snow depth from 5 manual measurements at each location, showing good agreement (rms=4.7 cm, 3.7%)

The surface of the snowpack can always be seen clearly in the radar measurement, as even a very low surface snow density causes a reflection well above our signal-noise ratio. The reflection from the bottom of the snowpack can be much more ambiguous, particularly when that bottom consists of low density mosses, lichens and grasses, (e.g. Holmgren et al, 1998). If the snow is shallow (<50 cm), errors in identifying the bottom return can lead to a large errors in radar-derived snow depth estimates. In many areas, however, the ground is not frozen beneath the snow and a damp soil layer causes a very clear reflection that is easily identified, as shown in Figure 1. In these conditions the ground reflection can be located in the radar image using an automated picking algorithm.

2.2 Snow Water Equivalent Estimates

Snow hydrologists are often more interested in the snow water equivalent (SWE), rather than snow depth. Unfortunately, manual measurements of SWE are extremely time consuming, as snow samples must be weighed. Therefore a traditional snow survey includes SWE measurements at a few points, combined with many manual depth measurements. The estimated mean density is used with the manual depth measurements to estimate SWE at many locations, through

$$SWE = d\rho_{snow} / \rho_{water} \tag{2}$$

where d is the snow depth, $\rho_{snow}, \rho_{water}$ are the densities of snow and water respectively, and SWE is the equivalent amount of liquid water. Therefore, a 25% uncertainty in mean snow density causes a 25% uncertainty in snow water equivalent. However, since the radar velocity has an inverse relationship with snow density, a 25% uncertainty in mean density results in a less than 12% uncertainty in radar derived SWE. These radar-derived SWE estimates are also subject to uncertainties in location of the snow-ground interface, however, which depends on environment. Using a typical mean density of 250 kg/m^3, at several locations in Colorado during the NASA Cold Lands Processes Experiment (CLPX) in 2003, we found the radar SWE estimates were within less than 10% (Marshall et al, 2005). In practice, a few measurements of snow density are made manually and are used to produce SWE values from the radar.

2.3 Snow Stratigraphy Estimates

Since snow stratigraphy typically is more variable than total snow depth, radar measurements at higher horizontal resolution are required to produce images in which continuous snow layering can be followed over significant distances. Figure 2 shows a profile in which complete radar traces were acquired every 3 cm. Note that several layers can be followed through most of the profile, and that significant variability occurs in a distance of less than 30 m. When underlying vegetation causes variations at smaller scales, much higher horizontal resolution is required. Due to limitations on sweep rates of the radar system (~50 Hz), much slower travel speeds are therefore required in these conditions. Our previous work has shown that internal snowpack reflections in the radar signal are highly correlated with changes in hardness as measured with a high resolution penetrometer (Marshall et al, 2007).

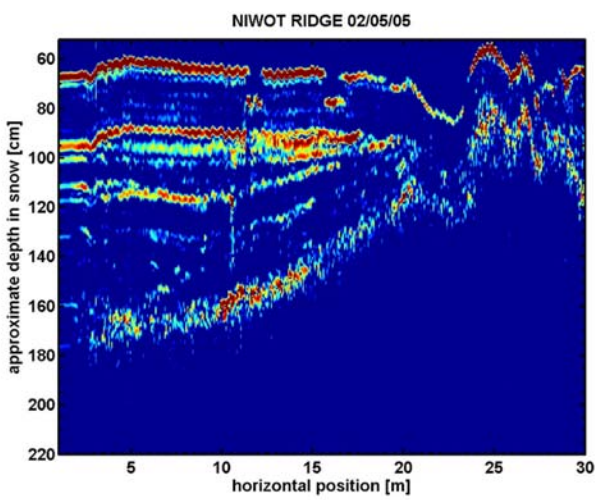

Figure 2: Snow stratigraphy variations as seen in FMCW radar profile. Note several layers can be followed over 20 m but pinch out and disappear where the snowpack is shallow. The two surface indentations between 10 and 20 m are ski tracks.

3. Geometric effects

One major difficulty one encounters when comparing ground-based radar measurements with manual measurements is a difference in support, or the area over which the measurement is averaged. Most ground-based FMCW systems have a footprint on the order of 2500 cm^2, while manual measurements sample a horizontal area of 1 cm^2 (depth probe) to 100 cm^2 (SWE sample). These different types of measurements can be rectified when multiple manual measurements are made within the radar footprint. This captures, within the manual measurements, the natural variability at the sub-meter scale. We have integrated a survey-grade GPS system with our radar to improve our ability to co-register measurements, thereby improving the reliability of the radar results. Even with frequent radar-manual checks, errors can enter the radar results due to rocking of the antennas. If the antenna is rocked off vertical by incidence angles greater than 15 degrees (not unusual if the antenna is mounted on a towed sled) , inaccurate radar estimates can result.

4. Conclusions

Microwave FMCW radar is an important tool for measuring snow depth, snow water equivalent, and snow stratigraphy. The accuracy of the radar estimates depends largely on the local environment, as small dielectric contrasts can be present at the snow-ground interface in some environments, such as Arctic tundra. In highly variable conditions, it is important to maximize the horizontal and vertical resolution, especially if the more variable snow stratigraphy is desired. In optimal conditions, radar estimates of snow water equivalent may be more accurate than estimates based on snow depth measurements, due to the radar's lower sensitivity to mean snow density. When comparing radar measurements to other instruments, the difference in support must be taken into account, as there is often significant variability at the scale of the radar footprint. When the limitations of this rapid, non-destructive ground-based technique are carefully considered, FMCW radar can be a powerful tool for detailed snow studies.

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