HELICOPTER-BASED MICROWAVE RADAR MEASUREMENTS IN ALPINE TERRAIN

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ABSTRACT: Due to the time-consuming nature of traditional snowpit measurements, and the large spatial variability that often exists in alpine snowpacks, tools which can rapidly characterize snowpack properties are in great need. Microwave radar has an additional advantage in that it is non-destructive and measurements can be made remotely, providing the opportunity to make measurements over large areas rapidly from an airborne platform. Signal interpretation can be difficult, however recently several ground-based studies have shown that the technique can be used to accurately measure snow depth, snow water equivalent, and snow stratigraphy. Accurate measurements of these properties from the air is much more challenging, especially in steep terrain. We present results from two field campaigns near Valdez, Alaska, in which measurements in mountainous terrain were made from a helicopter with two different FMCW radar systems. Snow depth and stratigraphy was visible at altitudes of less than 100 feet, while steep terrain made interpretation difficult at typical flying altitudes, due to the footprint size of the radar. Refinements of helicopter-based radar measurements may eventually provide a useful tool to assist in stability evaluations for helicopter ski operators.

KEYWORDS: snow instrumentation, snow remote sensing, radar, spatial variability

Figure 1. Helicopter-mounted FMCW radar measurements. 2-10 GHz radar is white box on outside of ski basket, yellow case contains rugged tablet computer.

1. INTRODUCTION

Snowpack properties often are highly variable over short distances, especially in complex mountainous terrain. This variability can make accurate estimates of slope stability difficult, as manual measurements are time consuming and therefore performed only at a limited number of locations. Despite these challenges, point measurements of failure interface properties, combined with stability tests have been shown to be correlated with local skier-triggered avalanche activity (Schweizer and Jamieson, 2003; Schweizer et al., 2007).

Snow stability is a difficult snowpack property to estimate, and currently no instrument exists that provides a direct measurement of this essential property for avalanche forecasting. Emperical relationships for estimating strength

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from snow density have been used (e.g. Conway and Wilbour, 1999), since density is a much easier property to directly measure and model, however these empirical density/strength relationships show wide scatter, as strength is very sensitive to snow crystal morphology and microstructure.

In practice, the most useful in-situ test or measurement for estimating stability is a small-scale stability test such as a Rutschblock or compression test. Recently other tests have been developed to measure the fracture propagation properties (Simenois and Birkeland, 2006; Gauthier and Jamieson, 2006). Spatial variability studies using these tests have shown substantial variations at the slope scale, however quantifying the geostatistics even at slope scales is difficult due to the limited number of observations possible with these time-intensive tests.

Recent comparisons with SnowMicroPenetrometer (SMP) measurements (e.g. Schneebeli and Johnson, 1998) have shown strong correlations between stability estimated from stability tests and the SMP micro-strength estimates (Pielmeier et al, 2006; Pielmeier and Marshall, 2008; Lutz et al, 2008, this issue) derived from applying an improved SMP analysis described by Marshall and Johnson (submitted). These new studies provide a promising foundation for studying spatial variability of SMP-estimated stability.

While stability is a very difficult parameter to measure, other much more basic snowpack properties such as total snow depth and new snowfall are much easier and faster to measure. The spatial variability of snow depth and new snowfall are closely tied to the spatial variability of stability, however our knowledge of how new snow as well as total snow depth varies in space is still very limited. Elevation, topography, aspect, wind, and microclimate all combine to produce variations in new snow, snow depth, and stability at a wide range of scales.

It is highly unlikely that a measurement of the snowpack, made remotely or automatically, will ever produce a direct estimate of snow stability. Stability tests and other in-situ mechanical measurements (e.g. SMP) will always be necessary for strength estimates. However, other parameters that are much easier to measure, such as new snow and total snow depth, also provide useful information for avalanche forecasting, and these measurements made at automatic weather stations are used daily in practice.

Measurement of snow depth using ultrasound allows measurements to be made automatically at a ***temporal resolution*** that was not previously possible, and has now become standard on many weather station installations. Portable microwave radar has recently been shown to produce accurate depth estimates at a ***spatial resolution*** not previously possible (e.g. Gubler and Hiller, 1984; Sand and Bruland, 1998; Marshall and Koh, 2008). The locations of major layer boundaries in the snowpack such as large density contrasts and ice layers, which are often associated with potential failure interfaces, have been shown to produce radar reflections that agree with the locations of these transitions in SMP measurements (Marshall et al, 2007). Portable microwave radar is therefore a powerful tool for studying spatial variations in layer thickness and snow depth, which may further our understanding of the spatial variations that influence stability.

At the slope scale, these variations in snow depth and stratigraphy can be studied using a ground-based radar, if the slope is stable. To study more regional variations in these properties, a faster mode of travel is required. In flat Arctic snowpacks, snowmobiles have been used to perform radar surveys over large distances (e.g. Holmgren et al, 1998).

Airborne radar surveys provide much greater spatial coverage, and in addition allow access to terrain unsuitable for snowmobiles. Unfortunately, the difficulties involved in making radar measurements from the air have prevented successful measurement of seasonal snow stratigraphy. The vertical resolution required and radar footprint issues make application in mountainous terrain very difficult. A recent ground-based study with an elevated impulse radar indicated that avalanche victims may be detectable from an airborne platform (Heilig and Schneebeli, 2006). Another study using a FMCW radar mounted on an ski lift successfully measured snow depth (Yankielun et. al., 2004).

Airborne radar measurements must be made at a much faster rate, and with a very focused beam, due to the rapidly changing topography. A helicopter's ability to fly at a slow speeds and at low elevations makes it much more advantageous than an airplane, for application in mountainous terrain.

Though helicopter-based radar measurements are challenging, and many problems remain, such measurements might someday provide useful, real-time data on snow depth and layer thickness across slopes for helicopter ski operators. This paper presents our initial efforts to test and refine a helicopter-based radar system for estimating snowpack properties.

2. METHODS

The two Frequency Modulated Continuous Wave (FMCW) radars used in this study have been used and calibrated extensively in ground-based applications, for estimating snow depth, snow water equivalent, and snow stratigraphy in alpine and polar snowpacks in Colorado, Montana, and in the Arctic. It has been shown to estimate snow water equivalent to within 10% alone, with more accurate results if an estimate of mean density is available (Marshall et al, 2005). Radar-derived snow depth estimates are typically within 5 cm, with differences within the range expected based on the variations in depth within the radar footprint and uncertainties in variations in snow density. FMCW radar has previously been used from an airplane for measuring snow stratigraphy in polar firn (Kanagaratnam et al, 2001). For a review of FMCW radar studies in snow, see Marshall and Koh (2008).

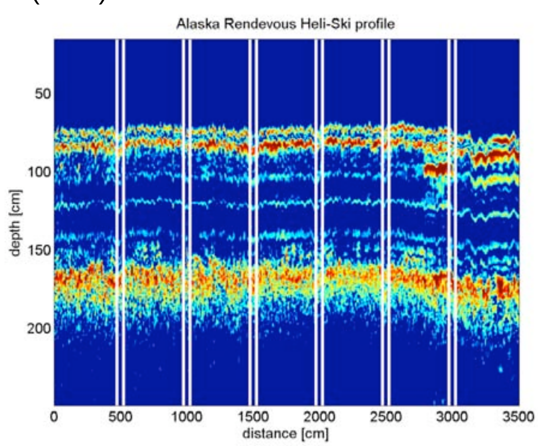

Figure 2: Ground-based FMCW radar profile in flat field. Vertical white lines show locations of arrays of SMP measurements. Red indicates a strong reflection, and blue indicates no reflection, with the surface at a depth (y-axis) of ~70 cm and the very rocky ground at ~170 cm Note the very strong reflection at a distance (x-axis) of 3000 cm and a depth (y-axis) of 100 cm, which was determined to be a buried snowmobile track.

3. RESULTS

In February 2007 we made helicopter-based measurements with a 2-10 GHz FMCW radar, mounted to the ski basket of a helicopter used by Alaska Rendezvous Heli Guides. An initial attempt was made with the radar inside the basket, however the metal basket caused large radar reflections resulting in a very noisy signal. We next bolted the radar to the underside of the basket, which provided a much cleaner signal. Figure 1 shows the light-weight portable 2-10 GHz FMCW radar attached to the helicopter.

To isolate problems caused by steep terrain from problems caused by making radar measurements attached to the helicopter, we began with measurements over a flat field. The helicopter slowly landed and then took off in a flat field next to the Alaska Rendezvous Lodge. Next the radar was removed from the helicopter, and used for ground based measurements in the field, for comparison with the helicopter measurements. Figure 2 shows a ground-based profile in the field, showing little variability in snow depth.

Note the strong (red) reflection at a depth of 100 cm and a distance of 3000 cm, which was determined to be a buried snowmobile track after excavation. This track, which caused a density and hardness transition that the radar was sensitive to, also was evident in the SMP measurements at this location. Many other internal snowpack layers are clearly visible and can be followed across the entire 35 m profile.

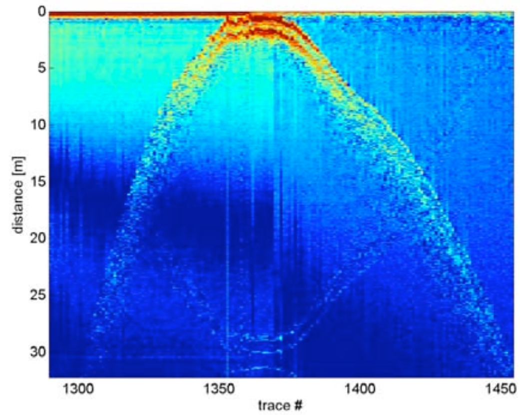

Figure 3: Helicopter radar measurement over flat field. Snow depth can be determined at the landing spot and to an elevation of ~10m, and agrees well with the ground measurements.

Figure 3 shows the helicopter radar measurement over the same flat field. The signal-to-noise ratio is too low to resolve the snow stratigraphy, however snow depth can be determined to an elevation of at least 10 m, and agrees with the ground measurements. The noise could be caused by vibrations, static and other environmental noise caused by the helicopter. The large beamwidth causes a large area to be averaged with increasing elevation with this system, and at a height of ~25 m the radar footprint likely includes trees and significant variations in the surface and ground locations.

Figure 4: Helicopter mounted FMCW radar measurements. 12-18 GHz radar is white box bolted to arm of skid.

In order to minimize the effect of radar footprint size, and increase sensitivity to snow stratigraphy, in March 2008 we made helicopter-based radar measurements using a 12-18 GHz FMCW radar system, shown in Figure 4. The white radar box is bolted to the arm of the back skid, again with a yellow case containing the rugged laptop (not shown). We added foam padding between the radar and the arm to minimize static noise, and used antennas with smaller footprints. We increased the speed of data collection to 30 complete profiles per second.

Figure 5 shows the results from measurements as the helicopter flew in low and hovered over the landing site on the shoulder of the run *Cry-babies*. Note that the signal quality with this new system is much greater, with a much higher signal-to-noise ratio. Not only is snow depth clearly visible while the helicopter is in the air, but at least 4 clear internal reflections are visible above the noise, caused by layering in the snowpack. These antennas still have a fairly wide beam (~40 degrees), therefore measurements at elevations above the surface of more than 10 m are difficult to interpret. These results, however, show that a very high quality radar profile can be obtained while the helicopter is in the air, showing both snow depth and stratigraphy.

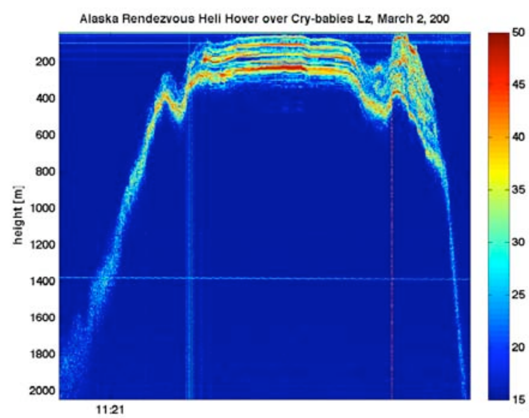

Figure 5: Radar profile from helicopter, over landing site on the run Cry-babies, Thompson Pass, Alaska. Note the clear stratigraphy and depth information when the helicopter is 2-6 m from the snow surface, with much higher signal-to-noise ratio than the lower frequency radar results.

4. FUTURE WORK

Now that we have developed a method for making high quality radar measurements from a helicopter during flight, the practical application of this tool is limited by the footprint size of the radar. Our current systems have beam widths of 40-60 degrees, therefore in steep terrain the radar measurement is averaged over locations with different elevations when the helicopter is more than 10 meters above the surface. Reducing the beam width will greatly reduce the footprint size, which should improve this problem dramatically. We have designed a system with a 1 degree beam width that we will begin building this fall, for tests in the spring of 2009. With this 1 degree beam width we should reduce our footprint size by a factor of 40. This is the next step toward developing a radar that may be able to begin to characterize the snowpack conditions on specific slopes from a helicopter.

5. ACKNOWLEDGEMENTS

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