Snow Depth Measurements using Ground-Based FMCW Radar Measurements of Dry Snowpacks During December of the 2006-07 NASA CLPX-II

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ABSTRACT

Ground-based microwave radar measurements of snowpacks were made during the December Intensive Observation Period (IOP) of the 2006-07 NASA Cold Land Processes Experiment (CLPX). Measurements, which covered a wide range of sensor parameters (4-18 GHz, multiple incidence angles, polarizations, bandwidths), were made at 5 different locations within the 100 km x 10 km study region in Northern Colorado and spanned a wide range of dry snowpack conditions.

Recent improvements in the portability and accuracy of our Frequency Modulated Continuous Wave (FMCW) radar system, incorporating a new lightweight sled for improved mobility, allowed continuous measurements to be made from the centimeter to the kilometer scale. Measurements were made with the radar mounted 0.5 m above the snow surface, which with post-processing can be used to estimate snow depth, SWE, and the location of major stratigraphic boundaries. The radar was also mounted at a height of 2.3 m (far-field) at oblique incidence angles of 30 and 45 degrees to simulate backscatter as measured over the study site by a coincident airborne Ku-band scatterometer, as well as to make backscatter measurements covering a wide range of sensor parameters. All radar measurements were geo-located with survey-grade GPS (2-10 cm accuracy). As an initial step in the interpretation of this large database, in this paper we focus on radar-derived snow depth estimates at three different sites with depths spanning more than an order of magnitude (0.05 – 0.98 m), and compare them quantitatively with the coincident manual depth measurements.

Keywords: snow depth, snow water equivalent, remote sensing, microwave radar, snow hydrology

INTRODUCTION

This paper discusses preliminary results from FMCW radar measurements of snowpacks made as part of the Cold Land Processes Experiment-II (CLPX-II), during the December 2006 Intensive Observation Period (IOP) in Northern Colorado. General objectives of CLPX-II are to advance air- and spaceborne snow measurement capabilities, by testing and developing high frequency radar techniques for estimating snow water equivalent (SWE). Improving our ability to remotely estimate SWE is an important objective for hydrological, cryospheric, and climatological research.

The specific objectives of CLPX-II are to collect high frequency (X- and Ku-band) radar observations of snowpacks coincident with in-situ observations of snow depth, SWE, and grain size at multiple locations throughout a 100 km x 10 km study region. Our work has focused on

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using a ground-based FMCW radar (4-18 GHz) to measure snow depth and SWE at high resolution, and to simulate measurements from air- and spaceborne remote sensors.

FMCW radar has long been recognized as a useful tool for snow research (e.g. Ellerbruch and Boyne, 1980; Gubler and Hiller, 1984; Holmgren et al, 1998; Gogineni et al, 2003; for detailed review see Marshall and Koh, 2007), and has more recently been used as a ground-truth tool for remote sensing campaigns (e.g. Marshall et al, 2004; Demuth et al (this issue)). Commercial impulse radars have also been used to study spatial variability of snow on glaciers (Harper and Bradford, 2003) and in deep maritime snowpacks in Scandanavia (e.g. Lundberg, 2000). Our ground-based FMCW measurements, using a recently developed highly maneuverable system (e.g. Marshall and Koh, 2007), spanned the frequencies of coincident Ku-band airborne (POLSCAT) and X-band spaceborne (TerraSAR-X) observations to support these specific objectives. Primarily, FMCW radar measurements were made to (1) estimate far-field radar backscatter as measured from air and space, covering a wide range of frequencies (4-18 GHz) at multiple polarizations and incidence angles; and (2) to provide high resolution estimates of snow depth, SWE, and stratigraphy from nadir radar measurements, coincident with the backscatter measurements. Our FMCW radar system mounted to the light-weight sled is shown in Figure 1. In this paper we focus on the nadir radar measurements (2), and quantify the accuracy with which they can be used to estimate the distribution of snow depth at a given site.

Figure 1. Aluminum radar sled, with FMCW radar (4-18 GHz) mounted on far side at a height of 2.3 m and an incidence angle of 30 degrees. Radar is also mounted in center of sled at 0 deg. to measure snow between skiers. Sled is attached to skiers with a rigid harness system, and also contains a survey-grade GPS system.

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MEASUREMENTS

We designed and built a custom-made microwave radar system that operates between 4-18 GHz, at HH and HV (or VV and VH) polarizations simultaneously. It has a range resolution of less than 1.5 cm, and can sweep the entire frequency range 20 times per second. An aluminum sled was built to improve mobility in complex snow-covered terrain and so that backscatter measurements could be made at a height of 2.3 m, which is in the far-field for all frequencies used. In the far-field, the radar could be positioned at an incidence angle of either 30 or 45 degrees. In addition, the radar could also be mounted in the near-field, at a 0 degree incidence angle and a height of 0.5 m, which allowed measurement of snow depth, stratigraphy, and SWE, at high vertical (~1.5 cm) and horizontal resolution (~50 cm x 50 cm footprint).

Specific site locations within the 100 km x 10 km study area were chosen by the CLPX-II coordinators in order to span a variety of snowpack types and background terrain. Radar profiles up to 1 km were performed pulling the sled by hand, and longer profiles were made possible with the use of a snowmobile where motorized access was allowed. The FMCW radar recorded independent measurements 20 times per second, resulting in a horizontal spacing of 5-50 cm depending on the traveling speed. The CLPX-II field campaign in Colorado resulted in 16 successful days of ground-based radar measurements throughout the 2006-07 winter, however here we focus only on measurements during 3 separate days during the December IOP. In addition, as a first step, we concentrate only on radar-derived estimates of snow depth, and compare them with the coincident manual depth and SWE measurements. These manual measurements were necessary to quantify the radar accuracy, and also add to the database of in-situ measurements for comparison with the air- and spaceborne radar measurements.

ANALYSIS

Frequent radar calibration measurements throughout each day were made using a metal sphere and by clear sky measurements (where the radar is pointed skyward away from any targets). These calibration measurements were used to accurately remove instrumentation-related signals, and to account for signal drift caused by changes in ambient air temperature.

All ground-based FMCW radar measurements were processed using a windowed Fast Fourier Transform (FFT), after calibration, as described by Marshall et al. (2007). The radar reflection from the snow surface was easily detected automatically after calibration, since this was the first dielectric contrast that the radar signal encountered. Due to the large dielectric contrast between snow and the ground surface, a large reflection from this interface was almost always observed since our system does not penetrate into the ground, due to its high frequency range. In addition, ground-truth depth measurements through regular probing of these seasonal snowpacks provided an ideal data set for evaluating the uncertainty of the radar snow depth and SWE retrievals, particularly in comparison to polar firn where ground-truth is difficult.

Building on the semi-automatic layer picking routine described in Demuth et al (this issue), we improved this software into a fully-automated snow depth picking algorithm, which located the surface reflection and the ground reflection without any further user input. Due to the large amount of radar data we collected (6,500-12,900 separate measurements in a day), this was a necessary development to facilitate processing such a large database, and helped advance the instrument further towards becoming an operational tool.

The two automatic picks of the surface and ground reflections at each measurement point were differenced to calculate the two-way travel time (TWT) of the radar wave in the snowpack. The TWT was next converted into a snow depth, using only the mean manual measured density at the site. This means the manual measured snow depths are completely independent from the radar estimated depths, i.e. the velocity of the radar waves were *not* adjusted to fit the mean measured depths.

RESULTS AND DISCUSSION

The accuracy of estimating depth and SWE from FMCW radar depth profiles is quantified using data from 1-3 December 2006, at three sites spanning a wide range of snowpack depths (5-98 cm). Table 1 summarizes the radar dataset and coincident in-situ measurements from this period and Figures 2-5 and Table 2 directly compare radar and in-situ data.

Table 1. FMCW radar and manual depth measurements at 3 sites during the first 3 days of CLPX II, covering a range of depths and densities.

Study Area	Date	Depth [cm]	Density [kg/m^3]	# manual	# radar
Brenner Farm	12/01/06	15-30	85-135	126	12,914
North Park	12/02/06	5-32	105-170	65	7,510
Rabbit Ears Pass	12/03/06	55-98	88-317	216	6,511

Figure 2 shows a radar profile of more than 6,000 measurements in a deep (0.55-0.98 m) snowpack measured on Rabbit Ears Pass. Red represents a large reflection, and blue shows very little backscatter. The left side of Figure 2 indicates the surface and ground reflections are well above background noise. In addition, one of the stronger internal layers is also indicated. The white vertical lines show locations where ground-truth snow depth measurements were made.

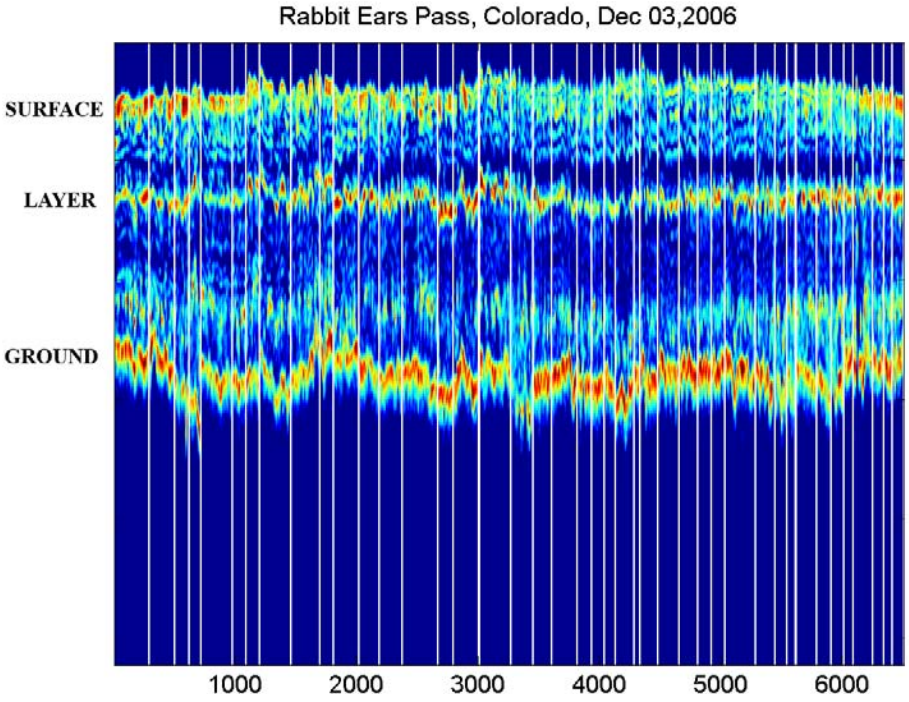

Figure 2. Radar image showing over 6000 measurements and location of 54 manual snow depth probe sites; 4 manual depth measurements were made at each site.

Figure 3 shows the automatically picked surface reflection (white circles), and the surface profile from these picks with a smoothing filter applied (red line). The black circles show the automatically picked ground reflection, and the white line shows the smoothed version of this data.

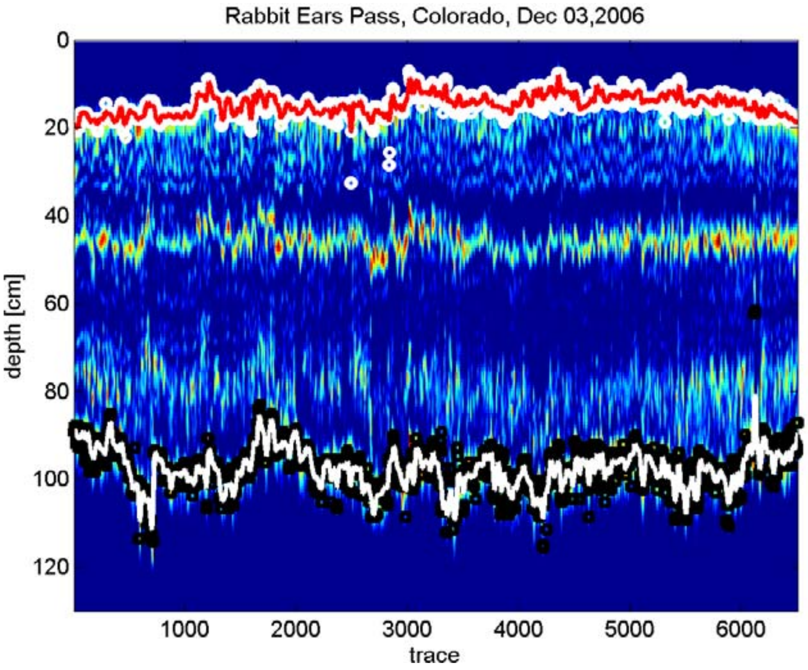

Figure 3. Radar image showing more than 6000 measurements, with automatically picked surface and ground locations. Rabbit Ears Pass, 12/3/06.

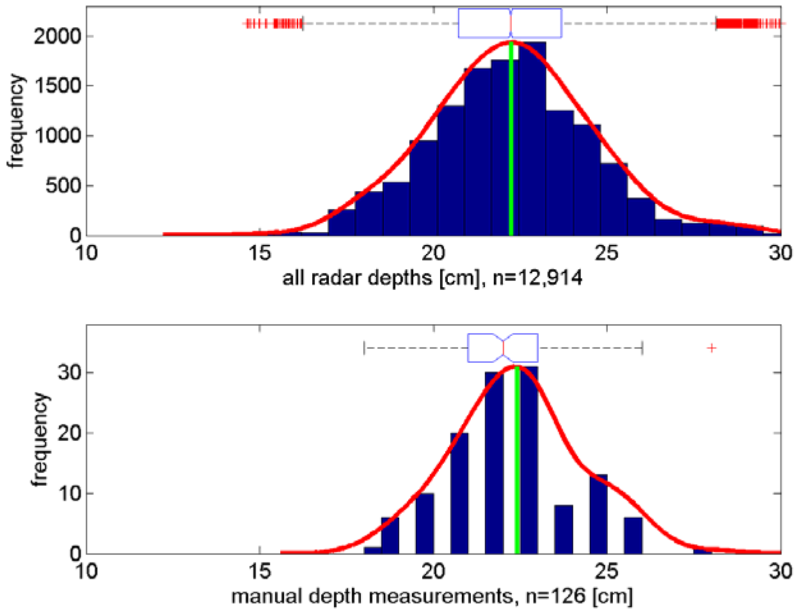

Figure 4. Distribution of radar and manual snow depths, Brenner Farm, 12/1/06.

Figure 4 shows the comparison of histograms and box plots of radar depths and manual depths at the first site visited, Brenner Farm on 12/1/06. Note how well both the mean, as well as the entire distribution of the data agree, and that the large radar dataset shows a very smooth underlying distribution. In order to interpret manual point measurements of depth and SWE, and extrapolate them to locations where we do not have information, we must have information not only on the mean values but also the variability, and the length scales over which that variability exists. Accurately quantifying the overall distribution of depth and SWE requires many more measurements than quantifying the overall mean, especially in areas where the variability is large.

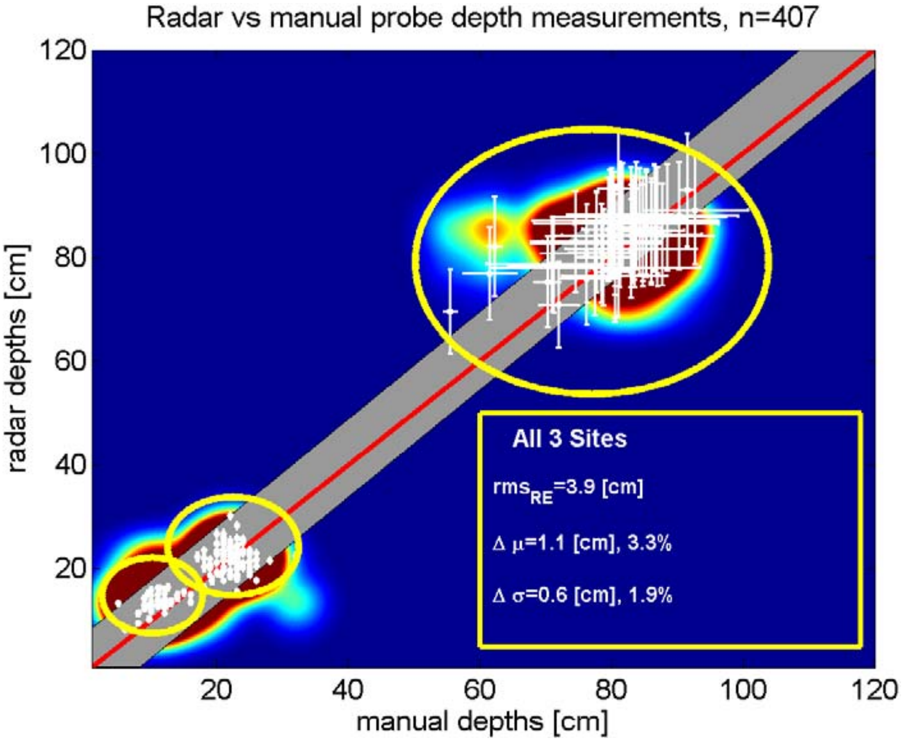

Figure 5. Comparison of manual and radar snow depths.

Figure 5 shows a point-to-point comparison of all of the coincident FMCW radar and manual depth measurements at the three sites (n=407). Comparison data points in white, overlaid on a 2-D non-parametric PDF. The red line is y=x and represents perfect agreement; the gray shaded area is the 95% confidence interval for the next observation. Yellow circles group the data by study site: the lowest circle highlights data from North Park, in a windy sagebrush environment; the middle circle highlights data from the Brenner Farm near Steamboat, a flat grass farm pasture; the upper circle highlights data from the deeper snowpack on Rabbit Ears Pass.

At the Rabbit Ears site (deepest snow depths), error bars are shown on each data point because these depth measurements are an average of 4 measurements within the radar footprint, at each of 54 probe sites. The horizontal error bars indicate the range of these 4 measurements, and the vertical error bars indicate the uncertainty in the radar estimate due to uncertainties in the mean snow density. Note that the major differences between specific coincident radar and manual depth measurements were likely caused by co-registration errors, the true variability of depth within the footprint of the radar, and uncertainties in mean density. Given the true variability in snow depth and density, and the difference in support of the radar measurement (~50 cm x 50 cm) and that of the manual depth measurement (~1 cm x 1 cm), the agreement between point-to-point comparisons of the two techniques is quite good.

The root-mean square (RMS) error of all 407 depth comparisons between radar and ground-truth was 3.9 cm. The difference in mean snow depth over all measurements was 1.1 cm, or 3.3% relative to the mean, and the difference in standard deviation of all measurements was 0.6 cm, or 1.9% relative to the mean. The mean and standard deviation values for the radar and manual depths, for each site, are given in Table 2. Note the good agreement of both mean as well as standard deviation values.

Table 2. Summary statistics of adar estimated snow depth and manual probed snow depth.

Study Area	Date	Radar mean	Probe mean	Radar std	Probe std
Brenner Farm	12/01/06	22.2 cm	22.4 cm	2.3 cm	1.8 cm
North Park	12/02/06	14.1 cm	11.8 cm	3.8 cm	4.7 cm
Rabbit Ears Pass	12/03/06	83.0 cm	80.5 cm	5.0 cm	7.1 cm

CONCLUSIONS

Preliminary analysis of ground-based FMCW radar measurements, during 1-3 December 2006 as part of CLPX-II, were used to quantify the accuracy of the radar for estimating snow depth. Comparing 407 independent manual probe depth measurement measurements, covering a range from 5-98 cm, with the radar estimated snow depth gave an RMS difference of 3.9 cm. On average over the 3 sites analyzed, the mean snow depth of the radar estimate was within 1.1 cm (3.3%) , and the standard deviation within 0.9 cm (1.9%) of the manual measured depths. Based on high-resolution manual measurements, most of the point-to-point differences can be attributed to true variability of point measurements within the radar footprint, and variations in mean snow density.

Our analysis only focused on comparing radar estimated snow depth with manual snow depth measurements, since the manual depth measurements are quick and easy to make. Snow hydrologists are far more interested in snow water equivalent (SWE), however manual SWE measurements are much more time consuming. Typically the SWE is measured at only a few locations, and then many more depth measurements are used to estimate the distribution of SWE, using an estimate of mean snow density.

Since a manual snow depth is easy to make accurately (to within 1cm), the error in the estimated SWE using this traditional method is mostly due to uncertainties in the true mean density - an error in the mean density estimate of 10% causes an approximate error of 10% in the estimated SWE from the manual depth measurement. Radar estimated SWE, in contrast, is less sensitive to errors in estimated mean density – if the density changes, the radar TWT changes in the same direction, somewhat self compensating. A 10% error in estimated mean density would lead to only ~5% error in the radar estimated SWE. We therefore expect our radar SWE estimates to be more accurate than our radar estimated snow depths.

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