POLSCAT Ku-band Radar Remote Sensing of Terrestrial Snow Cover

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ABSTRACT

Characteristics of the POLSCAT data acquired from five sets of aircraft flights in the winter months of 2006-2008 for the second Cold Land Processes Experiment (CLPX-II) in Colorado are described in this paper. The data showed the response of the Ku-band radar echoes to snowpack changes for various types of background vegetation in the study site in north central Colorado. We observed about 0.15 to 0.5 dB increases in backscatter for every 1 cm of snow water equivalent (SWE) accumulation for areas with short vegetation. Based on a simplified radiative transfer model, the change detection technique is used to convert the temporal change of radar backscatter into SWE accumulation for dry snow conditions. The resulting SWE accumulation estimates are consistent with the in-situ SWE measurements, with about 2 to 3 cm Root-Mean–Square (RMS) difference for regions with sagebrush or pasture.

Index Terms— Snow water equivalent, radar

1. INTRODUCTION

In past studies ground-based microwave radar measurements at 5 to 35 GHz frequencies were obtained for snow with different wetness, depth, and SWE [1-4]. These historic measurements demonstrated the microwave radar response to snowpack for limited and/or artificial snow conditions. However, the impact of various vegetation covers, nominally present in natural environment, has not yet been explored. Within the United States, the second Cold Land Process Experiment (CLPX-II) was conducted during the 2006-2008 winter seasons in Colorado and winter 2007-2008 in Alaska [5]. The objective of the CLPX-II experiment is to acquire extensive Ku-band radar backscatter from various types of snow and vegetation cover together with extensive in situ snow measurements for the development of snow water retrieval algorithms and to test radiative transfer models for a variety of snowpack.

2. POLSCAT/CLPX-II

From December 2006 through March 2008, we deployed the Ku-band polarimetric scatterometer (POLSCAT) built by the Jet Propulsion Laboratory (JPL) for five sets of aircraft flights (Table 1) in north central Colorado. For the flight campaigns, we installed POLSCAT on a Twin Otter aircraft, and operated the antenna at a 35 degree elevation angle.

Table 1. CLPX-II POLSCAT Flight Summary in Colorado

Campaign	Year	Date	General Snowpack conditions
IOP1	2006	December 2, 3, 4, 5	Dry snowpack
IOP2	2007	January 25, 26, 28, 29	Dry snowpack
IOP3	2007	February 22, 23	Melting snow pack over the day time and refrozen over night
Background survey	2007	November 8, 9	No snow, except in the Park Range and Medicine Bow Mountains
Validation	2008	March 10	Snow over all sites.

Each flight imaged an area of 9 km wide by 90 km long (Fig. 1) from the Quarry and Thorpe Mountains on the west to the Medicine Bow Mountains on the east. The Park Range (elevation approximately 12,000 ft) is a mountain range of the Rocky Mountains in north central Colorado, separating the watersheds of Yampa River and Oak Creek from the North Park, which is a sparsely populated basin (about 8800 ft in elevation) between the Park Range and Medicine Bow Mountains. North Park encompasses several smaller tributaries, including the Michigan River and Illinois River. South of North Park is the Rabbit Ears Range, stretching east-west along on the continental divide. This study area consisted of a variety of land use / land cover characteristics, including coniferous and deciduous forests, sagebrush, and pasture fields.

3. DATA CHARACTERISTICS

The POLSCAT data were binned and averaged on 200 m grids for each observation period (Table 1). The VV radar image for the data acquired on 8 and 9 November 2007 (top panel in Fig. 2) shows distinct backscatter levels for

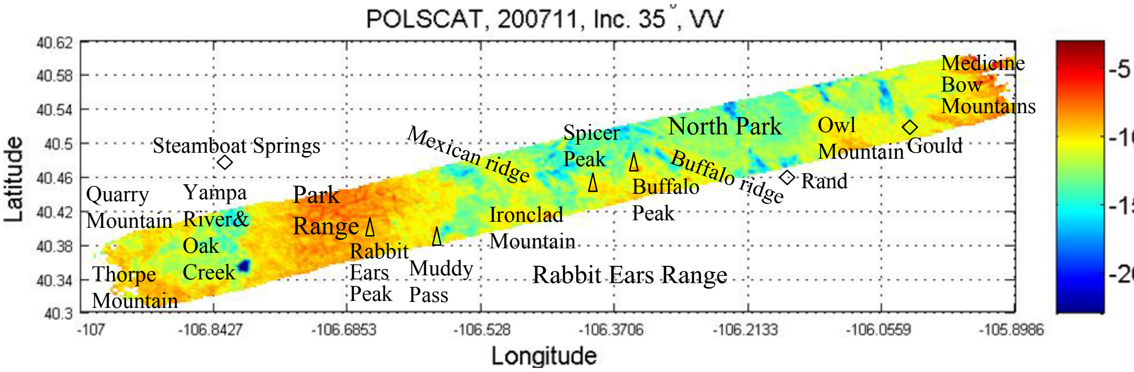

Figure 1. The test site is about 90 km long from west to east and 9 km wide from south to north. The panel shows the color-coded POLSCAT VV radar data in dB, acquired in December 2006.

different terrain covers. The backscatter from the forests in the Routt National Forest (Park Range and Rabbit Ears Range), Owl Mountain and Medicine Bow Mountains showed strong radar backscatter of about -5 to -10 dB (yellow to orange colors). Inside the triangular region with the corners marked by three small triangles are deciduous forests with lower backscatter (green-yellow color) than the coniferous forests (orange color in Fig. 2). The areas with sagebrush cover or grass pasture in the North Park and the Yampa River/Oak Creek watersheds had weaker backscatter of about -10 to -15 dB (green to light blue colors). The weakest backscatter (deep blue) came from Lake Catamount, several lakes and the riverbeds of Illinois River and Michigan River in the North Park.

Comparison of the VV data from three IOP campaigns (the middle three panels in Fig. 2) and the November 2007 data (top panel) shows the impact of snowpack on Ku-band radar backscatter over time. The December 2006 radar backscatter was stronger by about 1-3 dB than November 2007 across the entire study site, including the forested areas in the Routt National Forest and the Medicine Bow Mountains. From IOP1 (2-5 December 2006) to IOP2 (25-29 January 2007), the radar backscatter showed further increase by about 2-3 dB over the sagebrush and grass pasture areas in the North Park and the Yampa River/Oak Creek watersheds. From IOP 2 to IOP 3 (22-23 February 2007) the sagebrush and pasture fields had more dramatic VV increases of about 3-5 dB. Interestingly, the radar backscatter of the snow-covered sagebrush and pastures in the Yampa River/Oak Creek watersheds and North Park exceeded or became comparable with the forested areas in the Park Range in February, and remained strong in March 2008 (bottom panel in Fig. 2).

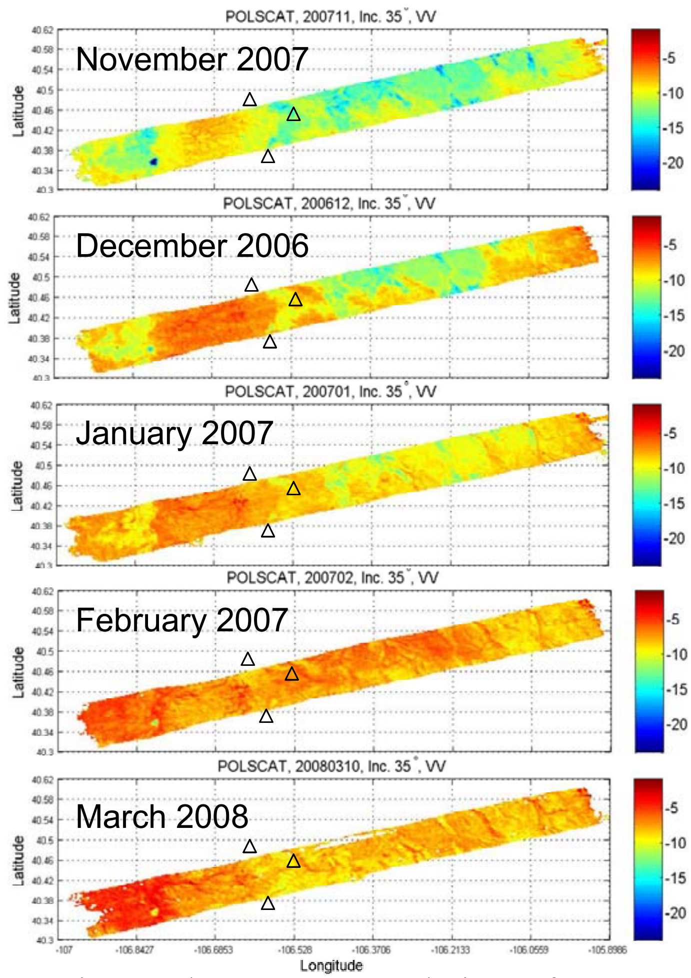

Figure 2. The POLSCAT VV radar images from top to bottom are for 8-9 Nov 2007 (background survey), 2-5 Dec 2006 (IOP 1), 25-29 January 2007 (IOP 2), 22-23 February 2007 (IOP 3) and 10 March 2008. The VV data are color-coded with the color key in dB shown in the color bar. The three small triangles mark a triangular area of deciduous forest with lower backscatter than other coniferous forest areas.

4. CORRELATION WITH IN-SITU DATA

During the three IOP field campaigns, several "hourglass" (HG) test sites were selected with intensive in-situ sampling. The size of each HG site was about 500 m by 500 m. The ground team made snow pits at the center and corners to

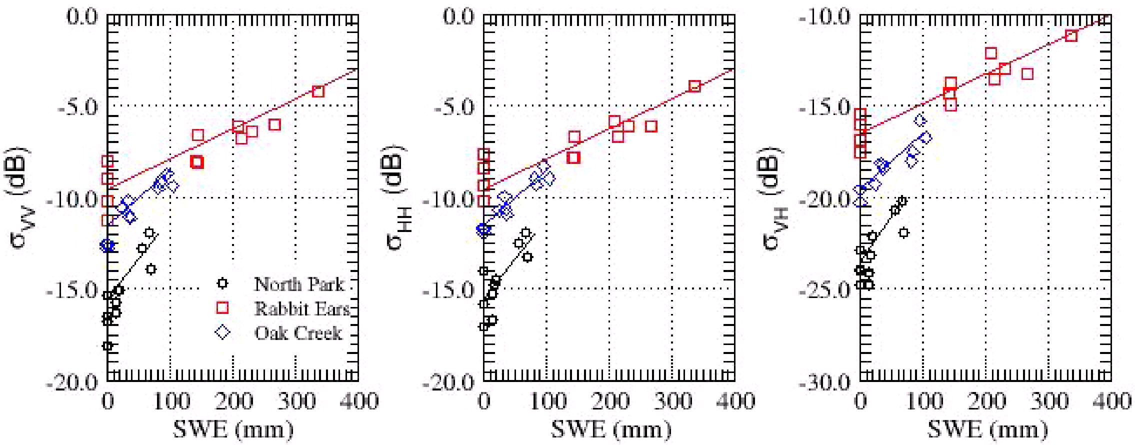

Figure 3. Comparison of POLSCAT radar data with the snow water equivalent samples from the hourglass test sites.

measure the snow density, SWE, depth and stratigraphy. The team also sampled the snow depth at about every 10-20 meters along four transects in the shape of an hourglass. Two of the four transects passed through the center to reach opposite corners and two along the edges of each site. The SWE for the HG sites were estimated as the product of the average snow density from the pit data and the average snow depth from transects. For consistent comparison with the averaged SWE data, we included the radar data for averaging only if the center of the radar footprint was within 200 m from the center of the HG sites.

The averaged radar data are illustrated in Fig. 3 against the SWE data from the HG sites for the data acquired from IOP1, IOP2 and November 2007. We do not include the data from February 2007 in the scatter plot because of the significant metamorphism of snowpack due to several melting and refreezing events in February. The POLSCAT HH, VV and HV radar echoes increased by about 0.5 dB per cm SWE for the HG sites in the North Park, 0.3 dB per cm in the Oak Creek watershed, and 0.15 dB in the HG sites in the open meadow near the Rabbit Ears peak. The Rabbit Ears HG sites had the strongest backscatter (about -17 dB for HV) in November, but the smallest backscatter-SWE slope (0.15 dB per cm SWE). The North Park HG sites had the weakest backscatter (about -23 dB for HV) in November, but the largest backscatter-SWE slope (0.5 dB per cm SWE). When there was no or little snow in November, the radar backscatter essentially represented the strength of vegetation scattering. If the characteristics of snow do not differ too much between Rabbit Ears and North Park HG sites, the same amount of snow accumulation will introduce the least change in dB to the backscatter from the Rabbit Ears HG sites and will produce the most change in dB to the North Park sites.

5. CHANGE DETCTION RETRIEVAL

Here we investigate the change detection technique for retrieving the SWE from the temporal change of radar backscatter. The model we assume is the one-layer radiative transfer model with several parameters, characterizing the scattering properties of snowpack.

$$\sigma_{0s} = A_0[1-\exp(-2k_e \cdot d/\cos\theta)] + \sigma_{0g}\exp(-2k_e \cdot d/\cos\theta)$$
$$= A_0 - (A_0 - \sigma_{0g})\exp(-2k_e \cdot d/\cos\theta)$$

The first term on the right hand side of the first equation accounts for the volume scattering from the snow, and the second term σ_{0g} represents the scattering from the ground surface and short vegetation under the snowpack. In the above equations, d is the snow depth, k_e is the extinction coefficient, and θ is the zenith direction of radar signal path in the snowpack. The parameter A_0 represents the volume scattering from the snowpack when the snow depth is much greater than the penetration depth, which equals $1/k_e$. The above equation ignores the double bounce effects between the snow grains and the ground cover with a nominal error of less than a few percent. This simplification is fairly accurate as long as the ground surface reflectivity is low enough. When the ground surface is smooth and has high reflectivity, it will be necessary to include the scattering interaction between ground and snowpack.

Introducing the normalized attenuation parameter, $C=2k_e/\rho\cos\theta$, we can recast the above equation into the following form,

$$\sigma_0 = A_0 - (A_0 - \sigma_{0g})\exp(-C \cdot SWE)$$

Here SWE=ρd.

If the bulk scattering properties of the snowpack do not change much through snow accumulation, let us represent the radar backscatter at two different times by σ_{01} and σ_{02}, corresponding to two different SWE1 and SWE2,

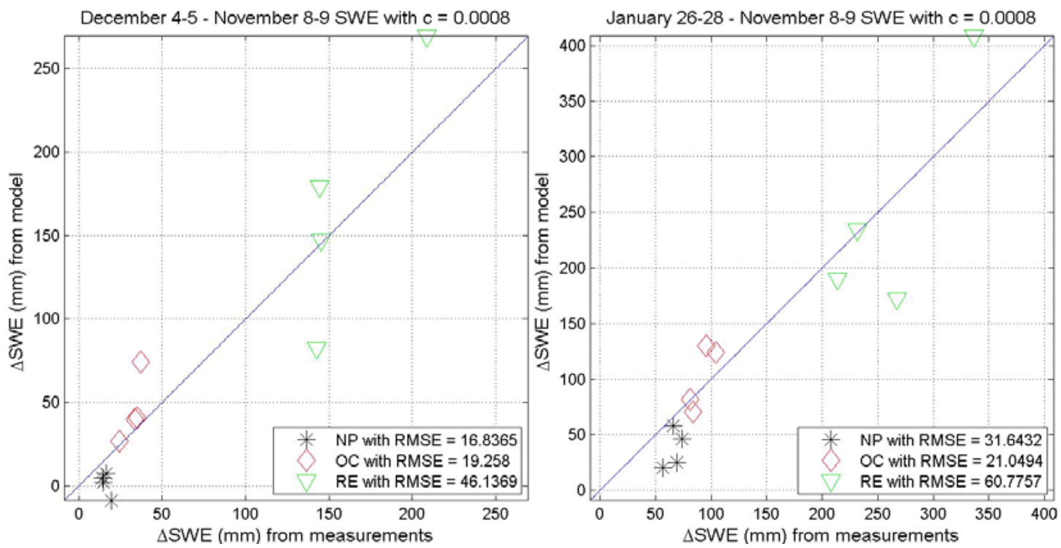

Figure 4. The estimate of SWE from the POLSCAT HH radar backscatter changes are compared with the measured SWE for three values for the C parameter. The panels in the right hand columns are for the SWE in January 2007, and the panels in the left hand column are for December 2006.

respectively. From the above equations, the SWE accumulation can be calculated by

$$\Delta SWE = SWE_2 - SWE_1 = -\frac{1}{C}\ln\left(\frac{A_0 - \sigma_{02}}{A_0 - \sigma_{01}}\right)$$

We applied the above equation to convert the POLSCAT HH radar backscatter change into SWE accumulation, using the data from November 2007 as the reference (σ_{01}). The SWE accumulation estimates using A_0=1 and C=0.0008 for Dec 2006 and January 2007 are calculated. The estimates suggest that there was 10-30 cm SWE in the open meadow in the Park Range and lesser SWE (<10 cm) in the North Park and Yampa River/Oak Creek watersheds. The overall spatial distribution of snow accumulation seems reasonable with more SWE near the Park Range than the North Park. Figure 4 illustrates the scatter plots of estimated SWE versus in-situ measurements for C=0.0008. The results are further divided into two columns with the left panel for Dec 2006 and the right panel for January 2007. For C=0.0008, the North Park SWE estimates from North Park and Oak Creek seem to agree with the measurements by 2-3 cm (RMS).

6. SUMMARY

The high resolution POLSCAT data acquired from the CLPX-II in the winter months in 2006-2007 and 2007-2008 showed the response of the Ku-band radar echoes to snowpack changes for various types of background vegetation. We observed about 0.15 to 0.5 dB increases in backscatter for every change of 1 cm SWE for dry snow conditions in December 2006 and January 2007. It appears that more vegetation biomass in the footprint, indicated by stronger radar backscatter in November 2007, resulted in weaker radar response in dB to the SWE. The SWE estimates from changes of radar backscatter show good agreement with the data.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

[1] Dozier, J., Remote sensing of the Alpine snow cover: A review of techniques and accomplishments from the visible wavelengths through the microwave, *CRREL Special Report 98-10*, Int. Conf. Snow Hydrol., eds. J. Hardy, M, Albert, and P. Marsh, Brownsville, VT, p. 33, 6-9 Oct. 1998.

[2] Ulaby, F.T., W.H. Stiles, and M. Abdelrazik, Snowcover influence on backscattering from terrain, *IEEE TGRS* 22(2), p. 126, 1984.

[3] Mätzler, M., Review of radar experiments of the seasonal snow cover, *CRREL Workshop on the Interaction of Microwaves with the Seasonal Snow Cover*, 56 pp., Inst. Applied Phys., U. of Berne, 1984.

[4] Kendra, J.R., S. Sarabandi, and F.T. Ulaby, Radar measurements of snow: experiment and analysis, *IEEE TGRS* 36(3), p. 864, 1998.

[5] Cline, D., K. Elder, S. Yueh, J. Entin, H. Rott, and T. Nagler, Overview of the Second Cold Land Processes Experiment (CLPX-II), IEEE Proc. International Geoscience and Remote Sensing Symposium, Barcelona, 2007.