SIR-C/X-SAR Investigations of Snow Properties in Alpine Region

Jiancheng Shi and Jeff Dozier*

Institute For Computational Earth System Science (ICESS)
*School of Environmental Science and Management
University of California, Santa Barbara, CA 93106, U.S.A
Tel: 805-893-8116, Fax: 805-893-2578, E-mail: shi@ices.ucsb.edu

ABSTRACT

In hydrological investigations, modeling and forecasting of snow melt runoff requires information about snowpack properties and their spatial variability. This study demonstrates the capabilities of the SIR-C/X-SAR, a multi-frequency and multi-polarization Spaceborne Synthetic Aperture Radar (SAR), on deriving snow wetness, and snow water equivalence. In contrast to a single-polarization SAR, this study shows that SIR-C/X-SAR has the capabilities to (1) estimate free liquid water content on the top of snowpack with C-band measurements quantitatively, and (2) infer snow density and ground dielectric and roughness properties with L-band measurements, in addition to map both dry and wet snow cover with the multi-frequency and multi-polarization measurements.

INTRODUCTION

The most important attributes of the snow cover that are necessary for modeling runoff and climate in alpine areas are: snow water equivalence, snow covered area, free liquid water content, and spectral albedo. Because of rough, irregular topography, all these attributes exhibit large spatial variability over alpine drainage basins. Except area extent, those snow physical parameters have not been generally used in snow melting prediction because it is difficult and costly to measure on a routine basis over large areas.

Active microwave sensors are highly sensitive to the most snowpack parameters interested by hydrologists. They are not affected by weather, day-night capability, and have a spatial resolution compatible with the topographic variation in alpine regions. Furthermore, Space-shuttle image radar - C and X-band synthetic aperture radar (SIR-C/X-SAR) with three frequencies L-band at 1.25 GHz (wavelength 24 cm), C-band at 5.3 GHz (wavelength 5.6 cm), and X-band at 9.6 GHz (wavelength 3.1 cm) and with multi-polarization: polarimetry at L-band and C-band, and VV polarization at X-band provide much more information per pixel than single-polarization data[1][2]. In this study, we show our recent progresses on mapping snow, deriving snow wetness, and estimating snow density using the SIR-C/X-SAR imagery obtained during its first mission in April, 1994 over one of our test site - Mammoth Mt., California.

The Mammoth Mt., one of our test site for SIR-C/X-SAR investigations of alpine snow properties, is located at 37°25'N and 118°45'W on the eastern slope the Sierra Nevada. The micrometeorological station is at Mammoth Mountain ski area at an elevation of 2930 m. A snow study plot has been maintained there since 1978. The site is an open, high altitude area characterized by high winds and dry snow. Vegetation is sparse with only a few large trees 50 to 200 m away. The site is typical of alpine region of the Sierra Nevada. Mean winter air temperature is about -5°C, and mean annual maximum snow water equivalence is about 0.8 m. Snowfall usually begins in early November and the snowpack often persist well into May. The site is instrumented with complete automatic meteorological capabilities, radiometers, a snow pillow, and snow lysimeters.

During SIR-C/X-SAR first mission in April, 1994, there were ten data-takes over this test site and we carried out an intensive field campaign to obtain snow properties for verification of the inversion models. Those ground measurements included both snowpack vertical profiles (temperature, density, wetness, gain size and size distribution) and snow survey (depth, wetness, and surface roughness) for each data-take. For radiometric and polarimetric calibration, we deployed triangle corner reflectors. For terrain correction of SAR image data, we used the Shuttle ephemeris information and digital elevation model (DEM) to generate the local incidence angle and the calibration factor maps for each data-take. In this paper, we will mainly summarize the results of estimation of snow wetness and density using SIR-C/X-SAR imageries. For capability of SIR-C/X-SAR on mapping snow cover is demonstrated in a separate paper in this proceeding [3][4].

MEASUREMENT OF SNOW WETNESS

The study [5][6] showed that the scattering mechanics for wet-snow at C-band is dominated by the first-order surface
and volume scattering. The relation between backscattering and snow wetness is controlled by the scattering mechanism. When the surface is smooth, volume scattering is the dominant scattering source. As snow wetness increases, both the volume scattering albedo and the transmission coefficients greatly decrease. This results in a negative correlation between the backscattering signals and snow wetness. When the surface is not smooth, increasing snow wetness results in greatly increased surface scattering interaction and surface scattering becomes the dominant scattering process. Therefore, a positive correlation between the backscattering signals and snow wetness will be observed. This complicates relationship makes it difficult to develop a statistical type of inversion model for estimating snow wetness.

Based on this identified scattering mechanics of wet snow-covered terrain from the model predictions and measurements of the polarimetric properties, we have developed an inversion model for snow wetness retrieval using C-band polarimetric imagery. This algorithm is based on the first-order scattering model with consideration of both surface and volume scattering. A simplified surface backscattering model was obtained from the numerical simulations for the conditions of most season wet snow covers. Through this simplified surface backscattering model and the property of the volume scattering ratios in co-polarizations, which is only a function of snow permittivity, we can estimate snow wetness and the surface roughness parameters using three C-band measurements: \( \sigma^v_w, \sigma^h_h, \text{and } \sigma^\lambda_{vhh} \). The algorithm is only applicable to the situations of incidence angle from 25° to 70°, and of the snow surface roughness - rms. height < 0.7 cm. The detailed description of this model can be found in [6].

As an example, we derive the snow wetness map using SIR-C's C-band Quad-polarization imagery, acquired on its 40th orbit, April 11, 1994 over the study site. The processed scene covers about 50.5 km x 11.6 km. Figure 1, shows C-band VV polarization SAR image on left and the inversion-derived snow wetness map on right. The image was taken at about 3 p.m. Snow has been started melting for several houses. On south slope, the SAR derived results of snow wetness were about 4 to 8 percent by volume. On top of the mountain ridge, the snow wetness was about 2 percent by volume. There is a clear separation between north and south slope. The snow wetness map on the north slope has also more clear dependence on elevation. As elevation decrease, the snow wetness increases up to 5 to 8 percent. The spatial distribution of snow wetness inferred from SAR image agrees well with what we understand about the characteristics of spatial distribution of snow wetness at this scale.

Figure 2. Shows the comparison of snow wetness between the ground measurements and the inferred from SAR images. The two SIR-C data-takes, both were afternoon passes, on its 40th and 136th orbits were used to derive snow wetness. The ground measurements of snow wetness included both from the snow pit profiles and snow survey transects. The ground measurements were all obtained from an average of five point measurements. Most SAR-derived snow wetness agreed well with the measured snow wetness on ground. The standard deviation of absolute error were about 1.3 % by volume which gives 2.5 % error bars at 95 % confidence interval for absolute error.

**ESTIMATION OF SNOW DENSITY**

Snow density has also great influence on radar backscattering. At high frequency such as C- or X-band, backscattering contribution from snow-pack with a same gain size is inversely related to snow density. This is because snowpack is a dense media where the coherent scattering properties result in the near-field effect when the wavelength is larger than the distance between scatters. Otherwise, the volume scattering albedo increases as the scatter size or size variation increases because Raleigh scattering theory explains that the scattering coefficient is proportional to the third power of the scatter radii for a given volume fraction. The studies [7][8] also showed that volume scattering albedo is directly correlated to particle size variation, since large particles play a more important role than smaller ones in the Raleigh scattering region even though large particles only constitute a very small fraction of the scatters.

When radar signal passes through a snowpack, there are several changes playing important roles in comparison to the interaction with a bare surface. First, it will result in a change of wave propagation constant because snowpack is a dense media. In other words, depending on snow density the wave length will shifted shorter so that the snow-ground interface becomes rougher. Secondly, it will also cause a change in incidence angle according to Snell’s law. Thirdly, the dielectric contrast at snow-ground interface will be different with even the same ground without snow cover. The first factor is especially important at low frequency, such as L-band. At high frequency, however, the first factor becomes less important since the surface backscattering at snow-ground interface become independent of frequency according to Geometric Optics Model [9].

Based on the scattering mechanisms described above, we have developed a physical based inversion model for estimation of snow density and ground dielectric and surface roughness parameters using L-band co-polarization measurements. Figure 3 shows a L-band VV polarization image obtained from the data-take 67.1 on April 13, 1994 on top and an estimated snow density map at bottom. The brightness is proportion to the backscattering coefficient and snow density, respectively.

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REFERENCES


Figure 1. SIR-C's C-band $\sigma^0$ image on left and the derived snow wetness map on right. The image brightness is proportion to the backscattering coefficients and snow wetness, respectively.

Figure 2. Comparison of ground measurements with SAR-derived snow wetness. The line indicates 1:1 correspondence.

Figure 3. SIR-C's L-band derived snow density map from data-take 67.1 on April 13, 1994. The black region is non-snow-covered regions. The image brightness is proportion to snow density.