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Development of a snow wetness inversion algorithm using polarimetric scattering power decomposition model

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ABSTRACT

In this paper, a new snow wetness estimation model is proposed for full-polarimetric Synthetic Aperture Radar (SAR) data. Surface and volume are the dominant scattering components in wet-snow conditions. The generalized four component polarimetric decomposition with unitary transformation (G4U) based generalized surface and volume parameters are utilized to invert snow surface and volume dielectric constants using the Bragg coefficients and Fresnel transmission coefficients respectively. The snow surface and volume wetness are then estimated using an empirical relationship. The effective snow wetness is derived from the weighted averaged surface and volume snow wetness. The weights are derived from the normalized surface and volume scattering powers obtained from the generalized full-polarimetric SAR decomposition method. Six Radarsat-2 fine resolution full-polarimetric datasets acquired over Himachal Pradesh, India along with the near-real time in situ measurements were used to validate the proposed model. The snow wetness derived from the SAR data by the proposed model with in situ measurements indicated that the absolute error at 95% confidence interval is 1.3% by volume.

1. Introduction

High topographic mountain regions have great physical diversity with the environment. Particularly, the snow cover and its seasonal changes play an important role. The snow wetness in the Himalayan snowpack is an important parameter for snow-melt runoff modeling, snow avalanche risk assessment, climatology, hydro-power industry and weather forecasting. Satellite remote sensing is a key tool in monitoring the snow pack parameters over a large area. Microwave remote sensing measurements can be efficiently used to infer bulk properties of snowpack. In comparison to conventional single-channel Synthetic Aperture Radar (SAR), the introduction of SAR polarimetry can significantly improve the quality of the results. These improvements are due to the quantitative ability of polarimetric SAR to scattering mechanisms. Hence, remote sensing using polarimetric SAR data has great potential in determining the extent and the properties of snow. There are many snow and glacier studies done over the Indian Himalayan region using fully polarimetric SAR data (Singh et al., 2011, 2012, 2014a, 2014; Singh and Venkataraman, 2012). The wet snow cover can be mapped by SAR in areas with low vegetation cover but the snow cover detection in dense vegetated areas is still a challenging problem.

The electromagnetic (EM) response of any material is defined in terms of its magnetic permeability (μ) and its relative complex dielectric constant (ε) (Von Hippel, 1954). The μ of snow is equal to that of free space, $\mu = \mu_0$ and therefore, the propagation of EM wave in snow is only a function of $\varepsilon = \varepsilon' - j\varepsilon''$, ($j = \sqrt{-1}$). In order to characterize snow, which is a heterogeneous mixture of air, ice and liquid water, we need to understand the dielectric properties of the mixture. The dielectric behavior of water and ice is described by a Debye type relaxation spectrum (Stiles and Ulaby, 1980). Snow is classified as wet or dry depending upon the amount of liquid water content. Dry snow consists of ice particles and air, whereas wet snow contains liquid water as a third component. Microwaves strongly respond to this change due to the liquid water content in snow (Hallikainen et al., 1986, 1987; Tiuri et al., 1984). The estimation of snow wetness requires a good understanding of the scattering mechanisms from wet snow. Scattering from the air-snow surface and the uppermost layers are effective for wet snow estimation. The attenuation of a propagating EM wave is given in terms of the volume extinction coefficient (κ_e) and the penetration depth is defined as, $\delta_p = 1/\kappa_e$.

For dry snowpack, the backscatter contribution from the air-snow surface is small and thus can be neglected. The total backscatter contribution is a combination of snow volume and

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snow-ground surface (Shi and Dozier, 2000). For dry snow, the penetration depth, $\delta_p \approx 10$ m at 10 GHz and decreases to 1 m at 40 GHz (Rott et al., 1985). Volume scattering in snow is due to dielectric discontinuities. Volume scattering from thin dry snow cover is undetectable at wavelengths longer than 10 or 15 cm, however, the level of scattering is dependent on the amount of snow on the ground (more snow implies more dielectric discontinuities for scattering) (Bernier et al., 1987). The extinction coefficient, κ_e which is inversely related to δ_p is equal to the sum of the absorption coefficient (κ_a) and scattering coefficient (κ_s). For wet snow, $\kappa_e \approx \kappa_a$, at microwave frequencies as the absorption losses are much larger than the scattering losses. Due to this, δ_p is of the order of 1 or 2 wavelengths and hence, the snow-ground scattering may be neglected. For C-band SAR, the backscattering signal from wet snow is dominated by the scattering from air-snow interface and snow volume medium (Shi and Dozier, 1995).

The radar backscatter coefficient has been shown to be very useful for quantitative estimation of snow pack parameters. Ground-based experiments were conducted to study the effect of dry and wet snow to backscattering coefficient of terrain (Stiles and Ulaby, 1980). The measured backscattering coefficient is a function of several snow and soil parameters: snow layer, thickness, snow temperature, snow wetness, snow density, surface roughness (air-snow interface as well as snow-ground interface) (Ulaby et al., 1986). Radar backscattering effects on geographical areas, relief, aspect angle, layover and shadow has also been studied (Koskinen et al., 1997; Nagler and Rott, 2000; Small, 2011). The snow volume scattering has been modeled by a discrete particle model which was experimentally justified at C-band (Kendra et al., 1998; Koskinen et al., 2000). A semi-empirical model for radar backscattering coefficient of snow covered ground was developed at 35 GHz and 95 GHz frequencies (Ulaby et al., 1995). This model relate the backscatter coefficient to the incidence angle and the snow-pack parameters (snow depth, crystal size and liquid water content) for each linear polarization.

Several models have been developed to predict backscattering from rough surfaces: (1). the physical optics model, (2). the geometric optics model, (3). the small perturbation models (SPMs) and (4) the integral equation model (IEM) which is valid for a wide range of surfaces (Fung et al., 1992; Fung, 1994). Possibly due to surface roughness, several studies have shown both positive and negative correlation between the backscatter coefficient and snow wetness (Stiles and Ulaby, 1980; Shi and Dozier, 1992). Several algorithms for snow covered area retrieval have observed a negative correlation between the backscatter coefficient and wetness values for reasonable snow wetness and depth (Koskinen et al., 1997; Nagler and Rott, 2000; Guneriussen et al., 2001). Shi et al. developed an inversion model to estimate snow wetness based on the first-order scattering model considering both surface and volume scattering (Shi et al., 1993). The NASA/JPL airborne AIRSAR imaging polarimetric data was used in this study. However, the first-order scattering model do not apply for most natural surfaces as they are very rough on the radar wavelength scale. The Integral Equation Model (IEM) which is valid over a wider range of surface roughness is used for the inversion model to estimate snow wetness (Shi and Dozier, 1995). The polarimetric space-borne Shuttle Imaging Radar Mission C-band (SIR-C) data was used for this study. The above method was modified to estimate snow wetness from conventional dual-polarization ENVISAT-ASAR data (Singh and Venkataraman, 2010). A statistical inversion model was also developed to retrieve snow wetness using ENVISAT-ASAR alternating polarization data (Niang et al., 2007). Recently, a new snow wetness estimation model has been proposed which utilize the full-polarimetric SAR decomposition technique (Surendar et al., 2013).

In this work we have proposed a novel inversion model for snow wetness estimation from full-polarimetric SAR data based on G4U scattering power decomposition. In wet snow, the surface and the volume are the dominant scattering mechanisms, therefore the generalized surface and the volume parameters are adopted. These parameters were then directly used to estimate the surface and the volume snow wetness. The effective snow wetness map is derived from the weighted average of both the wetness maps. The weights are derived from the normalized surface and volume scattering powers. The results obtained from the proposed model are validated with in situ measurements which were obtained in near-real time along with the satellite pass.

Table 1
Data acquisition table.

No.	Date	Acquisition time (UTC+5:30h)	Pass	Incidence angle (°)
1	07 Feb 2012	6:18 AM	Descending	41.9–43.3
2	14 Feb 2012	6:14 AM	Descending	46.8–48.0
3	06 Feb 2013	6:25 PM	Ascending	39.2–40.7
4	08 Feb 2013	6:14 AM	Descending	46.0–47.2
5	18 Feb 2014	6:29 PM	Ascending	44.4–45.7
6	20 Feb 2014	6:18 AM	Descending	41.0–42.4

2. Study area and datasets

The study area comprised of snow cover over a bare flat terrain with sparse vegetation. This area is a part of the Beas and the Chandra Bhaga catchment which lies in the Kullu district of Himachal Pradesh, India. It is geographically located between the latitudes of 32°15′ N and 32°30′ N, and between the longitudes of 77° E and 77°15′ E. The Snow and Avalanche Study Establishment (SASE) under Ministry of Defense, Government of India, maintains three manual observatories at Solang, Dhundhi and Bhang which are located at an altitude of 2006 m, 2446 m and 2896 m respectively. According to the Forest Survey of India (FSI) report in 2011 (FSI, 2011), less than 17% areas in the state of Himachal Pradesh are covered with a dense vegetation.

Field campaigns were conducted to collect near-real time in situ measurements with the Radarsat-2 fine resolution quad polarimetric (FQ) data acquisitions for consecutive three winter seasons from 2012 to 2014 is shown in Table 1. The study area is outlined in blue and the three observatories where the field campaigns were conducted are marked (green star) in Fig. 1. The 3 × 3 coherency matrix was generated from the single-look complex Radarsat-2 full-polarimetric SAR data. A multi looking factor of 3 in the range direction and 4 in the azimuth direction were used to make the square pixel and the Lee-Refined filter is applied to remove the speckle noise. The local incidence angle map is generated while performing the Range–Doppler terrain correction using the ASTER GDEM and the Layover/Shadow areas were also masked before applying the methodologies.

The snow fork instrument was used in the field to measure the snow wetness in this study as shown in Fig. 2(a)–(d). The snow fork is a portable instrument which measures the resonant frequency, attenuation and the 3-db bandwidth (Sihvola and Tiuri, 1986). These measurements are then used to calculate the complex dielectric constant of snow. The snow density and the wetness are calculated using semi-empirical equations. The measurements from this instrument are reliable as it does not compress the snowpack and the measurements are easily repeatable and the results can be checked by calibration measurement in the air.

Each snow pits were dug around 30–40 cm in depth. The fork was completely inserted in every 5 cm depth interval of the snowpack and the snow wetness measurements were recorded. As per literatures, microwave C-band signal normally penetrate through the snowpack to a maximum by 15–20 cm in low to moderate