Potential and Limitations of RADARSAT SAR Data for Wet Snow Monitoring
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Abstract—Based on Canadian Satellite (RADARSAT) synthetic aperture radar (SAR) images and simulations from a radar-backscattering model, we determined that conventional wet snow-mapping algorithms should perform optimally for a snowpack with a liquid-water content \( \geq 3\% \), at low incidence angle \((\theta = 20\text{–}30^\circ)\) and for a rather smooth surface (rms height \( \leq 2.1 \text{ mm} \)).

Index Terms—RADARSAT, synthetic aperture radar (SAR), wet snow.

I. INTRODUCTION

Mapping the wet snow cover by means of synthetic aperture radar (SAR) has already been achieved using ERS-1 SAR images. Algorithms for wet snow mapping have been developed and validated in high mountain terrain [1], in agricultural areas [2], and in low-density forested areas [3]. The wet snow-mapping algorithms are based on the differences between the backscattering coefficients \( \sigma^0 \) of an image acquired in wet snow conditions and a reference image, acquired in dry snow conditions. The reference image also could have been taken under snow-free conditions, preferably when the soil is frozen. In most studies, [1]–[3], the mean difference observed between the backscattering coefficients of dry snow and wet snow areas at the beginning of the snow-melt period, is of the order of 3 dB. The wet snow algorithms are generally applied for ERS-1 SAR images acquired under the same geometry (similar satellite orbit: ascending or descending), so that a given element on the Earth’s surface is imaged under the same incidence angle and look direction. In all cases, good results were obtained for open areas.

To investigate the potential of the Canadian satellite RADARSAT for the development and validation of such wet snow mapping algorithms, RADARSAT SAR images were acquired over a study area located in northern PQ, Canada. This paper deals with the analysis of those data and the relationship between the backscattering coefficients, snow-surface wetness, incidence angle, and wet snow surface roughness. A model is used to determine the optimal snow conditions and RADARSAT SAR configuration for wet snow mapping.

II. STUDY AREA AND DATA DESCRIPTION

The study area is located in the La Grande River watershed in northern PQ, at a latitude of 54°N. It consists mainly of low density (<25%) black spruce forests, lakes, and open areas (mixture of bare rock, lichens, shrubs, and small trees). Two RADARSAT SAR (C-HH, 5.3 GHz) images were acquired in standard mode (100 km \( \times \) 100 km) S7 (incidence angle of 45°–49°) on March 30 and April 23, 1997 at 17:48 local time, from an ascending orbit. The spatial resolution is 25 m \( \times \) 28 m (range, azimuth), and the pixel dimension is 12.5 m \( \times \) 12.5 m. The image of March 30 was acquired under dry snow conditions, whereas the image of April 23 was acquired under wet snow conditions. Fig. 1 shows a segment of the April 23 image. Absolute calibration of RADARSAT standard images has been carried out by the Canada Centre for Remote Sensing jointly with the Canadian Space Agency [4]. This calibration enables the derivation of backscattering coefficients \( \sigma^0 \) using algorithms developed by those agencies [5] and available in the image-processing software of PCI, Inc., Toronto, Ont., Canada. In order to remove SAR image distortions caused by topography, a digital-elevation model was incorporated into the geometric-rectification process [6]. In addition, the geocoded images were filtered by a gamma filter (5 \( \times \) 5 window) to reduce the speckle noise related to the variability of \( \sigma^0 \).

In conjunction with RADARSAT overpasses, field campaigns were conducted in order to measure the dielectric and structural properties of the snow cover, as well as the soil characteristics, on 18 test sites distributed over an area of 100 km \( \times \) 50 km. On March 30, the snowcover depth ranges from 60 to 100 cm for open and forested areas with an average density of 240 kg/m\(^3\). The lakes were frozen with the ice thickness varying from 30 to 60 cm. This ice was covered with about 30 cm of dry snow. On April 23, at the moment of the image acquisition (17:48), the snowpack over land areas was wet throughout the profile, with a liquid-water content of 7% in the top layer. The mild temperatures of the previous days (>0°C) have also transformed the dry snowpack over lakes into a wet snowpack. Moreover, those same conditions have caused multiple fractures in the ice, resulting in a rise of water to the surface and consequently to an increase in the liquid-water content of the snow at the surface of the lakes. The liquid-water content of the snowpack over lakes was not measured, but we can fairly estimate that it was greater than the one over land areas (>7%). Snow depths on April 23 ranged from 40 to 80 cm for open and forested areas, respectively, with an average density around 450 kg/m\(^3\). Fig. 2 shows typical profiles of the snowpack in open areas for March 30 and April 23, 1997.
III. ANALYSIS OF THE RADARSAT IMAGES

Fig. 3 shows the mean backscattering coefficients $\sigma^o$ of 34 training sites (20 x 20 pixels or greater) extracted from the two images (April 23 and March 30, 1997). These training sites include the 18 test sites and other sites of the same nature based on a Landsat-TM classification. The standard deviation (SD) of $\sigma^o$ is around 1 dB for lakes and forests and 1.3 dB for open areas. The contrast between dry snow and wet snow surfaces is only around 1 dB in open areas and burned forests, less than 0.5 dB in forested sites, and as high as 8 dB for lakes. The difference is far from the expected 3 dB [2]. Except for lakes, the wet snow-mapping algorithms discussed earlier could not be applied to those images. One explanation could be the following. In the case of the dry snow image (March 30), backscattering from snow-covered terrain consists of contributions from surface scattering at the air–snow interface (function of the snow surface roughness and dielectric properties of the snow surface), volume scattering within the snowpack, and surface scattering at the snow–ground interface (if the attenuation from the snow layers is small). In addition, the backscattering coefficient depends on the SAR configuration (frequency, incidence angle, and polarization). The dry snow cover being mostly transparent at C-band, the snow–ground interface is the significant scattering component. $\sigma^o$ is also independent of the snow surface roughness for dry snow [7]. Conversely, $\sigma^o$ is strongly dependent on the snow surface roughness for wet snow. The scattering from a low liquid-water content snowpack is a combination of surface and volume scattering, and the relative strength between the two components depends on the snow properties [8]. The contribution of the surface-scattering term decreases as incidence angle increases. At small incidence angles, surface scattering contributes more than volume scattering. At large incidence angles, the opposite is true [9]. For a high liquid-water content snowpack (like on April 23), only the surface-scattering term is important because of the very small scattering albedo and large extinction coefficient within the snowpack. Furthermore, a wet snowpack generally has a rough surface due to erosion during melting, and this surface roughness increases with the increasing liquid-water content of the snow. Consequently, most areas imaged on April 23 behaved as a very wet snowpack with a very rough surface. The backscattering coefficients were thus as high as those of March 30 (~12 to ~17 dB). In the particular case of the lakes, the water rising at the surface has a smoothing effect on the snow surface. The backscattering coefficients are then characteristic of a very wet and very smooth surface (~20 dB).

IV. RADAR-BACKSCATTERING MODELING OF WET SNOW

To confirm this analysis and determine the optimal conditions for wet snow mapping using RADARSAT SAR data, we will look at the relationships between the backscattering coefficient, wet snow surface roughness, snow-surface wetness, and incidence angle. A numerical study is carried out by using a radar-backscattering model that simulates the snowpack as a multilayer medium for various snow-cover conditions and for parameters specific to the RADARSAT SAR (C-HH). Detailed field measurements carried out in six test sites have allowed us to choose one typical snow profile for each snow condition (see Fig. 2). To calculate the backscattering coefficient ($\sigma^o$), we used a model developed by Fung [7]. To simplify the modeling process, the snowpack
Fig. 2. Typical profiles of the snow cover for open areas on March 30 and April 23. Density ($\rho$), grain diameter ($d$), liquid-water content ($m$), r.m.s. parameter (rms), correlation length ($L$), and temperature ($T$) are shown. The snow-roughness parameter and the correlation length have not been measured at the time of the radar survey but are obtained from simulations.

is considered to be made out of six homogeneous layers, and the simulated backscattering coefficient does not take the topography and the local variations of the ground surface into account. The simulations have been carried out only for open areas.

For the typical snow profiles of March 30 and April 23, 1997, we have simulated the radar-backscattering coefficient for incidence angles $\theta$ varying between $20^\circ$–$50^\circ$. At the snow–soil interface, we used the mean dielectric constant of the soil measured at three different test sites during field campaigns. The roughness parameters (correlation length $L$ and rms height) of the soil were those measured at some of the test-sites in the fall of 1997. Since scattering is essentially coming from the surface layer of the soil in dry snow conditions, we adjusted those parameters to obtain a best fit between the $\sigma^\prime$ values from the I.E.M. backscattering model and the $\sigma^\prime$ mean values extracted from calibrated RADARSAT SAR images over dry snow at $\theta = 23^\circ$ (S1) and $\theta = 41^\circ$ (S7). The S1 image of dry snow was acquired in January 1998, processed like the S7 images, and used to fit the simulation.

The initial snow-roughness values were those used by Fung [7] in his simulations. Only the values for the air–snow interface were adjusted to obtain a fit with the RADARSAT SAR images. In the case of wet snow, the first snow layer is the most sensitive, since either a strong attenuation or a strong surface scattering should be observed. Fig. 4 shows $\sigma^\prime$ (from model) and $\sigma^\prime$ (from images) for the two snow conditions (dry and wet snow) in open areas. We can see that the difference in backscattering coefficients for dry and wet snow increases when the incidence angle decreases. Wet snow mapping under snow conditions such as those of April 23 would thus be possible at low incidence angle. For RADARSAT, the S1 mode $\theta = 20$–$27^\circ$ should therefore be the most appropriate.
Fig. 5. Simulated behavior of the backscattering coefficient (C-HH) as a function of the snow liquid-water content for various surface roughnesses (rms height) at an incidence angle of: (a) 20\(^\circ\), (b) 30\(^\circ\), and (c) 50\(^\circ\).

To push the analysis further, we changed the snow-surface characteristics to determine optimal conditions for the application of a wet snow-detection algorithm. The snow-surface wetness \((m_w)\) is varied from 1\% to 10\%, while it remains unchanged for the lower layers,
and the incidence angle is varied from 20° to 50°. The wet snow surface-roughness parameters are set to rms height 1.5 mm with L, 7 mm, 2 mm with 10 mm, 3 mm with 20 mm, and 5 mm with 25 mm. First, it can be observed in Fig. 5 that the correlation of $\sigma^2$ with snow wetness is negative at first but tends to become positive at a certain snow liquid-water content threshold. This phenomenon is stronger for high surface-roughness values and can be explained by the scattering mechanisms involved. When the volume backscattering contributes more than the surface scattering, a negative relationship is observed. However, as the snow water liquid content further increases, the surface scattering becomes the major scattering source, and a positive relationship is then observed. Shi et al. [9] have also observed such $\sigma^2$ behaviors.

Second, Fig. 6 shows that the difference between $\sigma^2$ for dry and wet snow is strongly dependent on the wet snow surface roughness, the incidence angle, and the snow liquid-water content. Therefore, wet snow mapping with the usual algorithms should be possible for an incidence angle of 20° [Fig. 6(a)], an rms height $\leq$ 2.1 mm, and a snow liquid-water content $\geq$ 3%. Mapping should also be possible for an incidence angle of 30° [Fig. 6(b)], an rms height $\leq$ 1.9 mm, and a snow liquid-water content $\geq$ 3%. Finally, for an incidence angle as high as 50° [Fig. 6(c)], mapping should be possible for a rather smooth surface (rms height $\leq$ 1.6 mm) and a snow liquid-water content $\geq$ 3%.

V. Conclusion

Detection of wet snow has already been achieved in southern Quebec with ERS-1 SAR data [2], and we were confident that RADARSAT SAR data would give similar results. However, the analysis of two RADARSAT S7 images acquired in 1997 showed similar backscattering coefficients for either dry or wet snow conditions. A model was used to help understand this phenomenon. The model simulations and the RADARSAT SAR data analysis have shown that the backscattering coefficient of wet snow is strongly dependent on the snow-surface roughness and on the incidence angle. It also appears that a very high liquid-water content could reduce the contrast between the backscattering coefficients of wet and dry snow. On April 23, 1997, a combination of high liquid-water content (7%), high roughness (rms height = 2 mm), and a high incidence angle (47°) caused the backscattering coefficients to be very similar to those of March 30. The lakes are an exception because of their very smooth and almost specular surface. The optimal conditions for wet snow mapping are thus estimated to be: $\theta = 20°$–30°, rms height $\leq$ 2.1 mm, and 3% $\leq m_v \leq$ 10%. Finally, it is suggested that the S1 mode should be selected if RADARSAT SAR images are to be used for wet snow mapping. However, additional acquisitions in S1–S7 modes, and under variable wetness conditions, should help to adapt the wet snow-mapping algorithms to all types of RADARSAT images.

ACKNOWLEDGMENT

The RADARSAT images were provided by the Canadian Space Agency under the ADRO program (Project #29).

REFERENCES


The “Myth” of the Minimum SAR Antenna Area Constraint

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Abstract—A design constraint traceable to the early days of spaceborne synthetic aperture radar (SAR) is known as the minimum antenna area constraint for SAR. In this paper, it is confirmed that this constraint strictly applies only to the case in which both the best possible resolution and the widest possible swath are the design goals. SAR antennas with area smaller than the constraint allows are shown to be possible, have been used on spaceborne SAR missions in the past, and should permit further, lower-cost SAR missions in the future.

Index Terms—Antenna area, synthetic aperture radar (SAR).

I. INTRODUCTION

The design of antennas for synthetic aperture radar (SAR) has received a great deal of attention in the literature on the subject. Most antennas for spaceborne SAR’s are rather large in size, with a range of 9–15 m being fairly typical for the antenna length (azimuth dimension), and somewhere between 10–20 times the wavelength for the antenna height (elevation dimension). Since spaceborne SAR’s flown to date have had wavelengths in the range of 3–24 cm, this means that the antenna heights are fairly significant. Spaceborne SAR antennas are thus some of the largest sized structures flown in space. Even when the an-