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A B S T R A C T
This work deals with 3D structure characterization and permittivity profile retrieval of snowpacks by tomographic SAR data processing. The acquisition system is a very high resolution ground based SAR system, developed and operated by the SAPHIR team, of IETR, University of Rennes-1 (France). It consists mainly of a vector network analyser and a multi-static antenna system, moving along two orthogonal directions, so as to obtain a two-dimensional synthetic array. Data were acquired during the AlpSAR campaign carried by the European Space Agency and led by ENVEO. In this study, tomographic imaging is performed using Time Domain Back Projection and consists in coherently combining the different recorded backscatter contributions. The assumption of free-space propagation during the focusing process is discussed and illustrated by focusing experimental data. An iterative method for estimating true refractive indices of the snow layers is presented. The antenna pattern is also compensated for. The obtained tomograms after refractive index correction are compared to the stratigraphy of the observed snowpack.

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1. Introduction

SAR imaging systems provide large-scale and high-resolution imaging capabilities, independently of day–night and weather conditions. A conventional SAR projects a 3D reflectivity map on a 2D plane. This projection from 3D to 2D space induces some effects like layover and foreshortening [1]. For some applications like urban area and natural environment monitoring, 2D SAR imaging comes to be of a limited interest by omitting the description of the vertical structure of the observed scene. This limitation is a serious shortcoming for the special case of snow cover monitoring applications, like hazard forecasting, water resource management, and climate change monitoring. Indeed, for these applications, an accurate description of the vertical structure of the snow cover is of great interest [2]. Many works have addressed the problem of

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assessing the physical properties of snow covers using SAR data. Mainly, SAR data are used to estimate snow wetness [3–6], snow water equivalent [7–10], snow depth [11–13], snow density [14,15] or snow covered areas [16,17]. For the above cited works, one or more parameters of snow covers are investigated without addressing directly the vertical structure of the observed scenes which may relate into ambiguous interpretations or ill-conditioned estimation. In this context, SAR tomography (TomSAR) represents a promising tool for monitoring snow and ice due to its ability of resolving 3D scatterer contributions and therefore overcoming layover and foreshortening effects [18,19]. In this work, the description of the vertical structure of a snowpack using TomSAR data is addressed by retrieving the vertical permittivity profile that represents a key information for estimating the physical parameters. The processed data were acquired using a Ground Based SAR (GB-SAR) system developed and operated by the SAPHIR team, of the IETR of the University of Rennes-1 in the framework of the European Space Agency (ESA) AlpSAR campaign led by ENVEO in the Austrian Alps. The GB-SAR system was operated at both X and Ku bands, allowing for resolutions within a few centimeters. The processing of the acquired data is done using the Time Domain Back Projection Algorithm (TDBPA). The resulting tomograms show an overestimation of snowpack height and geometrical distortions. These distortions are caused by the implicit assumption of free space propagation during the focusing process. In order to have a correct interpretation of the obtained tomograms, the focusing algorithm must take into account the correct permittivities, unknown a priori. An iterative procedure is proposed to estimate the correct permittivity for each snow layer and the corresponding thickness. Results are discussed and compared to in-situ stratigraphic measurements made available by ENVEO.

2. GB-SAR system and data volume description

The acquisition system is a Stepped Frequency Continuous Waves (SFCW) GB-SAR, developed, implemented, and operated by the SAPHIR team of the University of Rennes-1 (France). It comprises four rectangular horn antennas fixed at different elevation positions and connected to a Vector Network Analyser (VNA, see Fig. 1). The four antennas and the VNA hold on a metallic box mounted on a 3 m-long rail equipped with a linear stepper motor. Each antenna can operate either as a transmitter or a receiver resulting in six equivalent monostatic antenna positions with constant spacing in the elevation direction. More elevation positions can be obtained by changing the position of the antenna array on the metallic box or by changing the elevation of the rail. The ground coverage of the GB-SAR is limited by the rail height and the antennas’ radiation pattern. The system and data storage are controlled by a laptop computer. The parameters describing each data acquisition are the transmitted frequency, the combination of the transmitting and receiving antennas as well as their azimuth position. Acquisitions are performed in the X and Ku frequency bands with a bandwidth $B_f = 4$ GHz. The corresponding range resolution is given by Eq. (1):

$$\delta_r = \frac{c}{2B_f} = 3.75 \text{ [cm]}$$

(1)

The GB-SAR is a high resolution 3D imaging system with a few centimeters resolution in elevation, ground range and azimuth directions. Its main characteristics are summarized in Table 1.

The processed data were acquired during the ESA AlpSAR campaign led by ENVEO in the Austrian Alps. The snowpack measured at the Rotmoos test site is composed of a stack of horizontal snow slabs, with a total height of about 137 cm. Its structure is depicted by the profile given in the panel on the right in Fig. 10, which provides the different physical parameters (see Table 2) as a function of snow depth.
3. Data processing

3.1. 3D focusing

SAR Tomography exploits multiple passes operated over the elevation direction to achieve a focusing capability along the elevation direction [20] (see Fig. 2). The response of a point target at position \( \vec{r} \) seen by the GB-SAR is expressed by:

\[
s(\vec{r} - \vec{p}, k) = \frac{\exp(-i k \|\vec{r} - \vec{p}\|)}{\|\vec{r} - \vec{p}\|} \bar{\sigma}(\vec{r} - \vec{p}, k) U(\vec{r} - \vec{p}, k)
\]  

(2)

Here \( k = \frac{4\pi}{\lambda} \) is the wavenumber, \( \vec{p} \) is the transmitting–receiving antennas position and \( U(\vec{r} - \vec{p}) \) is the transmitting–receiving antenna gain, \( \bar{\sigma}(\vec{r} - \vec{p}, k) \) is the complex response of the target.

Assuming a constant medium response over the frequency bandwidth and over the antenna positions, Eq. (2) can be written as:

\[
s(\vec{r} - \vec{p}, k) = \frac{\exp(-i k \|\vec{r} - \vec{p}\|)}{\|\vec{r} - \vec{p}\|} \bar{\sigma}(\vec{r} - \vec{p}, k) U(\vec{r} - \vec{p})
\]  

(3)

The total response recorded by an antenna couple at position \( \vec{p} \) is given by Eq. (4):

\[
S(\vec{p}, k) = \int_{\Omega} s(\vec{r} - \vec{p}, k) d\vec{r}
\]  

(4)

GB-SAR data are focused using Time Domain Back Projection (TDBP). The echoes recorded by a transmitting–receiving antenna couple are correlated with the ideal response of a target at a given position \( \vec{r}_0 \) to get the range-focused signal expressed by Eq. (5):

\[
S_r(\vec{r}_0, \vec{p}) = \int_{\Omega} S(\vec{p}, k) \exp(-i k \|\vec{r}_0 - \vec{p}\|) dk
\]  

(5)

Here \( S(\vec{p}, k) \) is the response recorded by a transmitting–receiving antenna couple at position \( \vec{p} \), \( k \) is the wavenumber, and \( \|\vec{r}_0 - \vec{p}\| \) is the geometric distance between the investigated point and the emitting–receiving antenna couple.

### Table 2

Definition of the physical parameters used to describe snow stratigraphy.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H \ [\text{cm}] )</td>
<td>Height from the base</td>
</tr>
<tr>
<td>( F )</td>
<td>Shape description</td>
</tr>
<tr>
<td>( E \ [\text{cm}] )</td>
<td>Average grain size</td>
</tr>
<tr>
<td>( E_{\text{max}} \ [\text{cm}] )</td>
<td>Average maximum grain size</td>
</tr>
<tr>
<td>( R )</td>
<td>Snow hardness description</td>
</tr>
<tr>
<td>( HW \ [\text{kg} \cdot \text{m}^{-2}] )</td>
<td>Snow water equivalent</td>
</tr>
<tr>
<td>( \rho \ [\text{kg} \cdot \text{m}^{-3}] )</td>
<td>Snow density</td>
</tr>
</tbody>
</table>
The requested resolution in the ground range and elevation is then achieved by combining coherently the range focused signals at different elevation positions and different azimuth positions as follows:

\[
I(\mathbf{r}_0) = \left| \sum_{n_z=1}^{N_{el}} \sum_{n_k=1}^{N_{az}} S_r(\mathbf{r}_0, \mathbf{p}(n_z, n_k)) \right|^2
\]

The coherence of the image is defined as the ratio of the coherent sum of the contributions of the different antennas \(I(\mathbf{r}_0)\) to the non-coherent sum over elevation contributions, which is the sum of the absolute values of those contributions:

\[
CR(\mathbf{r}_0) = \frac{\sqrt{I(\mathbf{r}_0)}}{\sum_{n_z=1}^{N_{el}} \sum_{n_k=1}^{N_{az}} |S_r(\mathbf{r}_0, \mathbf{p}(n_z, n_k))|}
\]

In the case of a Stepped Frequency Continuous Wave (SFCW) SAR, \(S_r(\mathbf{r}_0, \mathbf{p})\) is formulated as a discrete sum over the available wavenumber bins. For \(N_k\) equidistant wavenumber bins ranging from \(k_{\text{min}}\) to \(k_{\text{max}}\) (with a step equal to \(\Delta k\)), the range-focused signal can be expressed as:

\[
S_r(\mathbf{r}_0, \mathbf{p}) = \sum_{n_k=0}^{N_k-1} S(n_k, \mathbf{p}) \exp(i(k_{\text{min}}+n_k \Delta k) \| \mathbf{r}_0 - \mathbf{p} \|)
\]

Equation (8) may then be slightly modified in order to account for the fact that the VNA delivers baseband signals, i.e. signals whose spectrum is demodulated around the null frequency:

\[
S_r(\mathbf{r}_0, \mathbf{p}) = \exp(ik_c \| \mathbf{r}_0 - \mathbf{p} \|) \sum_{n_k=0}^{N_k-1} S_{\text{mes}}(m_k, \mathbf{p}) \exp(im_k \Delta k \| \mathbf{r}_0 - \mathbf{p} \|)
\]

where \(S_{\text{mes}}(m_k, \mathbf{p})\) is the measured response around the null frequency and \(k_c\) the central wavenumber.

The sum expressed in Eq. (9) is the IFFT of \(S_{\text{mes}}(m_k, \mathbf{p})\). This IFFT is computed over a regular distance grid ranging from 0 to \((N_k - 1) \times \delta_k\). Then, it is interpolated at each image position defined by the range distance \(\| \mathbf{r}_0 - \mathbf{p} \|\).

For 3D focusing, the imaging grid is defined by a fixed azimuth slice in the elevation-ground range plane. The set of used antennas is chosen in such a way that all investigated points fall within the -3 dB azimuth aperture of the antenna pattern.

Fig. 3 shows a multilooked tomogram obtained by applying the TDBP algorithm over 25 azimuth slices. The observed snowpack is characterized by a multi-layered vertical structure. The strongest backscattering contributions are associated with internal and bottom snow layer interfaces, whereas contributions from surface and near-subsurface are barely visible on the intensity image but well highlighted on the coherency image. The surface and the near-subsurface snow interfaces appear to be horizontal, whereas the depths associated with internal ones appear to decrease with the range. Another interesting feature is that the total snowpack height estimated by the tomogram is about 160 cm, while the in-situ measurements give a snow height of 137 cm. This clearly brings out geometrical distortions affecting the tomogram. These distortions are caused by the assumption of free space propagation used during the focusing process and are discussed in section 3.2.

3.2. Refractive index estimation for 3D focusing

When applying TDBPA under a free-space propagation assumption, the distance \(\| \mathbf{r}_0 - \mathbf{p} \|\) holds for the geometric distance between the antennas couple and the investigated point. Obviously, snow cover is a medium with refractive index \(n(z)\) higher than unity \([21,22]\) and consequently the electromagnetic distance \(d(\mathbf{r}, \mathbf{p})\) is different from the geometric one. In order to correct the focusing process, the correct electromagnetic distance \(d(\mathbf{r}_0, \mathbf{p})\) must be used instead of the geometric one. To quantify the undergone distortions under a free space propagation assumption in a medium with a permittivity
higher than unity, one may consider the configuration of Fig. 4. The medium is a stack of \(N_l\) homogeneous layers with permittivities \(\{n_l\}\). The antenna at position \(\mathbf{r}_a = (x_a, y_a, z_a = H)\) records echoes from a target at position \(\mathbf{r}_t = (x_t = 0, y_t, z_t)\). The total one-way time delay from the target to the antenna is:

\[
\tau = \frac{1}{c_0} \int_{\mathbf{r}_t}^{\mathbf{r}_a} n(z) \, dl
\]

(10)

In Eq. (10), \(c_0\) is the free-space propagation speed, and \(n(z)\) is the refractive index of the laterally layered medium. For the case of Fig. 4, Eq. (10) can be written as:

\[
\tau = \frac{1}{c_0} (d_0 + \sum_{l=1}^{N_l} n_l d_l)
\]

(11)

where \(d_0\) is the distance traveled in the free space.

Focusing the SAR data using the geometric distance to locate image points in the range domain considers a constant velocity and a constant incidence angle within the medium (see Fig. 4). In other words, the same propagation time delay is expressed as:

\[
\tau = \frac{1}{c_0} (d_0 + d'_l)
\]

(12)

Thus, the target is seen at an apparent position satisfying \(d'_l = \sum_{l=1}^{N_l} n_l d_l\) and the undergone distortions can be computed knowing the refraction angles \(\{\theta_l\}\) and the permittivity profile \(\{n_l\}\). The higher the permittivities of the medium is, the higher the distortions are. Scatterers located at far range will be affected by stronger distortions than nearer targets.

In the case of the AlpSAR campaign data, the permittivities of the observed snow covers have to be estimated. In this work, an iterative procedure for estimating refractive indices of an horizontally layered medium is introduced with application to snowpack permittivity profile retrieval. This procedure relies on the fact that the detected snow interfaces appear horizontal if the correct refractive indices are used in the focusing algorithm. This procedure iteratively estimates indices from top layers to bottom ones since the total electromagnetic distance of a target at elevation \(z_1\) depends on the refractive index profile \(n(z)\), where \(z \geq z_1\). One may consider a medium with three layers and four interfaces, as depicted in Fig. 5. The first interface is the air–medium interface. The second one separates layer 1 from layer 2. To estimate the refractive index of layer 1, the GB-SAR data is focused for different increasing values of refractive index \(n_1\). For each refractive index value, the distance taking into account \(n_1\) is computed and introduced in the TDBP algorithm. The estimated value of \(n_1\) is chosen in such a way the second interface appears horizontal in the final tomogram. Once \(n_1\) is fixed, the value of \(n_2\) is estimated by focusing GB-SAR data using \(n_1\) as refractive index for the first layer and an increasing value of \(n_2\) until the third layer appears horizontal on the final tomogram. This procedure is repeated for each layer until all interfaces are made horizontal.

For each iteration of the correction procedure, the electromagnetic distance \(d(\mathbf{r}, \mathbf{r}')\) is computed. For this paper, the electromagnetic distance taking into account the different refractive indexes is computed using the eikonal equation formulation which describes the wavefront propagation through a medium defined by an isotropic varying velocity distribution. A detailed derivation of the eikonal equation can be found in Ref. [23]. The eikonal equation is:

\[
\|\mathbf{V} d(\mathbf{r}, \mathbf{r}_a)\|^2 = n^2(\mathbf{r})
\]

(13)

Equation (13) is numerically solved using the fast-marching method [24]. For the AlpSAR data, the computation of the correct electromagnetic distance on the image grid is not performed for all antenna positions. Since, the observed scene
is a laterally varying medium, the z-axis is a revolution symmetry axis. Hence, the distance from an antenna position \( \mathbf{r}_a = (x_a, y_a, z_a)^T \) to a given target \( \mathbf{r}_t = (x_t, y_t, z_t)^T \) is not changed when considering an antenna at position \( \mathbf{r}_a' = (0, 0, z_a)^T \) and a target at position defined by Eq. (14):

\[
(x', y', z') = (0, \sqrt{(x_a - x_t)^2 + (y_a - y_t)^2}, z_t)
\]

This remark allows us to compute the electromagnetic distance for a track \( n_z \) once over a fine grid, then the distance computation over the \( N_x \) antenna positions belonging to the \( n_z \)-th track is done by linear interpolation over a grid representing the focusing positions.

The final result after refractive index correction is shown in Fig. 10 and compared with the snow stratigraphy. A detailed discussion is given in section 4.

3.3. Antenna pattern compensation for 3D focusing

A correct interpretation of the generated tomograms must take into account the antenna pattern effect on the recorded backscatter echoes. In our case, the antennas are wideband rectangular horn antennas with apertures of about 40° in both elevation and azimuth directions. To describe the antenna pattern effect, one may consider the complex signal amplitude for a given image position \( \mathbf{r} \) as follows:

\[
I(\mathbf{r}) = \sqrt{K_s} e^{i\phi_s} \sigma(\mathbf{r}) \otimes h(\mathbf{r}) + \sqrt{K_s} \epsilon(\mathbf{r})
\]

(15)

Here, \( K_s \) and \( \phi_s \) represent the gain and the phase of the SAR system, \( \sigma(\mathbf{r}) \) is the complex backscatter coefficient at position \( \mathbf{r} \), \( h(\mathbf{r}) \) is the impulse response of the SAR system and \( \otimes \) holds for the convolution operation. The term \( \sqrt{K_s} \epsilon(\mathbf{r}) \) accounts for additive noise. To be able to compare intensities within the same image, the effect of the system gain must be compensated for. For the AlpSAR data, \( \phi_s \) is considered as null because the system is phase corrected before acquisition by calibrating the VNA and after acquisition by geometrical calibration of antennas positions based on the idea of [25]. Hence, the system gain is expressed by Eq. (16):

\[
K_s = \frac{G_{tx}(\theta_{tx}, \phi_{tx}) G_{rx}(\theta_{rx}, \phi_{rx}) \lambda^2}{R^4} \alpha_s
\]

(16)

In Eq. (16), \( G_{tx}(\theta_{tx}, \phi_{tx}), G_{rx}(\theta_{rx}, \phi_{rx}) \) are the transmitting and receiving antenna gains, \( R \) is the target range and \( \alpha_s \) adjusts for all SAR parameters common between all targets. The factor \( \alpha_s \) is unknown a priori for processed data, hence, it does not affect the comparison between the intensities within the same image. It is worth noting that the computation of view angles for any target with respect to antenna differs in 3D focusing from 2D focusing. In 3D focusing, the elevation angles \( (\theta_{tx}, \phi_{tx}) \) to be considered are not the geometrical ones, but those defined after refractive index correction. If the air–medium interface is defined at elevation \( 2_0 \), the angles \( \theta_{tx}, \phi_{tx} \) will be the out angles of the electromagnetic rays on the surface defined by \( z_0 \) (see Fig. 6).

For the synthetic aperture, an average antenna footprint compensation factor over the used antenna positions and frequency bins is computed, resulting in Fig. 7a. Using \( \frac{1}{\sqrt{\alpha_s}} \) as the compensation coefficient gives the tomogram of Fig. 7b. The relevant remark here is the artefact out at the limits of the \( -30 \) dB aperture of the antenna where the compensation factor is too high. It is clear that the intensity recorded for image pixels where the antenna gain is too low is more likely to be noise and not a meaningful intensity value. A modified compensation factor taking into account the noise level is therefore used to obtain Fig. 8a and 8b:

\[
\beta = \frac{\sqrt{K_s}}{K_s + \sigma_n^2}
\]

(17)
The interpretation presented next is based on the following considerations.

In order to interpret the obtained tomographic results, the coherency image is exploited since the coherency highlights even coherent backscattering with low intensity. The total snow height observed after correction is less than the total snow height given by the snow stratigraphy (see Fig. 10). The last interface, after correction, is placed at height 15 cm and thus the ground surface is not detected. The snow stratigraphy shows that the first layers are new-fallen dry snow with low densities and small rounded particles. For this kind of snow, the refractive index in the microwave region depends on the snow density and is frequency and temperature independent [21,22]. This explains the low refractive indices found for the first and the second layers (1.1 and 1.2 respectively) where densities are about 150 and 300 kg m$^{-3}$ for the first and the second layers, respectively. In [22], for dry snow densities ranging from 100 to 400 kg m$^{-3}$, refractive indices ranging from 1.10 to 1.30 are found. For deeper layers, the snow wetness, the densities and the grain sizes increase. The snow
particles are well-bonded melted forms with poly-clusters. These characteristics explain the higher refractive indices found for the deepest layer snow slabs. The estimated values of refractive indices for the third and the fourth layers are 1.4 and 1.7 respectively. In [21,22], it is shown that the snow refractive index increases with snow wetness and density and ranges from 1.41 to 1.61 at 10 GHz.

Analyzing the height of the detected interfaces and layers, it comes out that the detected interfaces and their positions after correction correspond to changes in the physical parameters of some layers reported on the snow stratigraphy. The second interface is a transition from a layer with a low density and decomposing new-fallen snow into a denser layer with spherical particles. The third interface, within the limits of the resolution of the system, can be considered as the separation between two layers with different particle shapes. The upper one contains mixed forms, while the lower one contains fairly well bonded particles with some melting. The fourth interface, located at 33 cm of snow height, separates an upper snow layer, with fairly bonded melting forms from lower layer with higher wetness, larger grain sizes and more particles aggregates. The last interface defines the last layer with increasing wetness, grain sizes up to 4 mm and depth hoar.

4.2. Backscattered intensity analysis

In Fig. 10, the effect of antenna pattern before compensation can be clearly identified in ground ranges between 1 m and 2 m corresponding to a null between the main lobe and the first side lobe of the antennas. After compensation for the antenna pattern (see Fig. 8b), low backscattered intensities are observed on the shallowest snow interfaces. This can be explained by the low changes in the refractive index as well as the high local incidence angles on these interfaces (see Fig. 9). Indeed, the monostatic backscattering coefficient from a rough surface depends on the incidence angles where higher incidence angles give lower backscattered intensities [26,27]. For deeper interfaces, the high backscattered intensities observed are more likely due to the low local incidence angles on these interfaces. The maximum of the local incidence angle is found to not exceed 42° for the last interface, while it exceeds 72° for the first one.

5. Conclusion

In this work, experimental results of TomSAR applied to snow cover characterization have been presented. The GB-SAR system was operated to characterize the vertical structure of snowpacks. The interfaces between different snow slabs were identified and the influence of free-space propagation assumption for subsurface focusing was highlighted. An iterative procedure was proposed for correcting the focusing process by estimating layer permittivities and thickness of the observed snowpack. For proper interpretation of intensity information, an antenna pattern correction was applied to the tomograms.
The obtained tomograms after index and antenna pattern correction were related to the physical properties of the observed snowpacks. The strongest contributions were found to arise from the deepest snow slabs' interfaces, where the local incidence angles are small. The results of this work show the great potential of SAR tomography for the characterization of snowpacks and for tuning physical model of electromagnetic interaction with snow.

References


