Abstract—The SnowScat device, a fully-polarimetric scatterometer originally designed to measure the radar cross-section of snow at a frequency range from 9.2 to 17.8 GHz (X-band to Ku-band), has recently been extended towards a high-resolution tomographic measurement mode. Such tomographic profiling observations provide further insights into the complex electromagnetic interaction within snowpacks, e.g., by revealing different layers, such as melt-freeze crusts, inside the snowpack.

In this contribution, we report first results from an initial tomographic measurement campaign carried out at a test site in Davos, Switzerland, in winter 2014/2015.

Index Terms—SnowScat, microwave remote sensing, snow, tomography, tomographic profiling, SAR tomography, scatterometer, X-band, Ku-band, European Space Agency, ESA.

I. INTRODUCTION

The SnowScat device is a fully-polarimetric scatterometer that has originally been designed to measure the radar cross-section of snow at a frequency range from 9.2 to 17.8 GHz (X-band to Ku-band) [1]–[4] (similar measurements using a GB-SAR at X-band and Ku-band were also reported in [5]).

Recently, a modification of the measurement setup extending the capabilities of the SnowScat device towards tomographic profiling of snowpacks was implemented and tested. This extension aims at enhancing the SnowScat device in order to better respond to the ESAC recommendations which were made on the deseleced CoReH2O candidate following the user consultation meeting in March 2013 for the 7th Earth Explorer mission. Such new capability allows for performing high-resolution tomographic profiling observations that may provide further insights into the complex electromagnetic interaction within snowpacks.

When operated in the tomographic profiling mode, the SnowScat device is subsequently moved along a rail in the direction orthogonal to the mean look direction of the antennas. Thus, a synthetic aperture is formed in elevation direction, which leads to the tomographic profiling capability. The resolution in azimuth direction is determined by the (frequency-dependent) beamwidth of the SnowScat antenna. Consequently, the azimuth resolution also decreases as a function of the range distance. The new hardware setup, as shown in Fig. 1, supports both modes, the original scatterometer mode, and the new tomographic profiling mode. Thus, the tomographic measurement concept of SnowScat is somewhat different from a similar ground-based tomographic experiment, reported in [6], [7], in the sense that no synthetic aperture is formed in azimuth direction. Another tomographic profiling approach akin to the SnowScat setup was presented in [8].

In this paper, we (1) describe the tomographic mode of the SnowScat device including the experimental setup at the test site in Davos, Switzerland, as well as the tomographic processing approach. (2) First results are shown that validate the tomographic measurement concept in snow-free conditions, using a tomographic test target, as well as in presence of a snowpack.

II. METHODS

A. Experimental setup at the test site Davos

The experimental setup implemented at the test site in Davos, Switzerland, is shown in Fig. 1. The SnowScat device is attached to a rail on a triangular truss, which again is mounted onto a scaffold (see Fig. 1(a)). The SnowScat device
Fig. 1. Experimental setup for initial tests of the tomographic profiling mode at the SLF-hosted test site in Davos Gadenstatt, Switzerland, in January, 2015.

When operated in tomographic profiling mode, the SnowScat device is subsequently shifted along the rail, spanning a maximal synthetic aperture of 2220 mm (1940 mm in this experiment). The rail, tilted by 45 degree, is attached to a triangular truss, which again, is mounted onto a scaffold, such that the upper edge of the truss is approximately 10m above ground. The pointing direction of the SnowScat antennas is adjustable in elevation and azimuth. Three artificial targets were placed on the ground: A slightly tilted (15 deg) target for vertical profiling on the left, a tomographic target with its vertical array of spheres in the middle, as well as an additional calibration sphere on the right.

(a) Close-up of the SnowScat device while acquiring data in the tomographic profiling mode. (b) Overview of the entire measurement setup. (c) Close-up of the SnowScat tomographic test target.

B. Tomographic test target

A tomographic test target—an array of eight spheres vertically aligned on a carbon tube—has been placed in the field of view of the SnowScat device. The tomographic test target has been used to characterise the focusing performance of the aperture synthesis. In addition, it also serves as a reference for the data acquisition under snow conditions. Fig. 1(b) gives an overview of the measurement setup under snow conditions. Fig. 1(c) shows a close-up view of the tomographic test target.

C. TDBP-based tomographic profiling

The vertical snow profiles are obtained by a time-domain back-projection (TDBP) approach [9], [10], i.e. basically, through aperture synthesis along the elevation direction. The TDBP processing employed, so far, is essentially a ray-tracing approach that takes into account a simplified refraction model assuming one homogeneous snow layer with refraction occurring at the air/snow interface. The calculation of the point of entry at the air/snow interface is based on the trigonometric relationships as depicted in Fig. 2. A virtual range distance \( R_v \) is obtained iteratively based on the incidence angle \( \theta \), the angle of refraction \( \theta_S \), the refractive index \( n_s \), and the different phase velocities \( c \) (in air) and \( v_S \) (in the snow volume). The TDBP aperture synthesis along the elevation direction can then be written as:

\[
v(\bar{r}_i) = \sum_{k=1}^{M} g_k[R_v(\bar{r}_i, \bar{r}_k, n_s)] \cdot \exp[i \frac{4 \pi}{\lambda} R_v(\bar{r}_i, \bar{r}_k, n_s)],
\]

where \( \bar{r}_i \) is the 3-D pos. vector of the target location for which the tomographic inversion is performed, \( \bar{r}_k \) is the 3-D pos. vector of the antenna phase centre at position \( k \) within the synthetic aperture, \( g_k(\ldots) \) is the range-compressed signal at antenna position \( k \), \( \lambda \) is the wavelength of the carrier signal, \( R_v(\bar{r}_i, \bar{r}_k, n_s) \) is the (virtual) range distance between antenna
position \( k \) and the location \( \vec{r}_i \) using the simple refraction model, and \( \nu(\vec{r}_i) \) is the focused signal at location \( \vec{r}_i \).

### III. RESULTS

In Fig. 3, tomographic profiles obtained by TDBP-focusing of 50 SnowScat radar echoes are shown: Measurements of the tomographic test target with its 8 aluminium spheres, the ground surface, and a snowpack were taken at the test site in Davos, Switzerland.

On the left, 1-look tomographic profiles (HH channel) of the situation are shown under snow-free and snow-covered
condition. Aperture synthesis was performed by a TDBP approach as described in Section II-C. On the right, the phase of the complex polarimetric coherence of the co-polar channels HH and VV, displayed in combination with the HH intensity in a HSV colour scheme, are shown (see Fig. caption for details). A distinct (non-zero) phase difference between the co-polar channels is observed for both, back-scattering from the pasture (snow-free condition) and also for back-scattering under snow-conditions. For the data acquisition under snow condition (03. March 2015) a vertical profile of mean intensity averaged over 1 m horizontally is also given. In addition, in-situ snow profile measurements were taken on 02. March 2015 (see Fig. 3 bottom right).

In Fig. 4, a special case is shown: the data was acquired under melted snow surface condition. Virtually no penetration into the snow is observed. Instead, “ghost targets” are visible due to double bounce and triple bounce scattering. The phase values of the polarimetric coherence of the co-polar channels HH and VV at the location of the double bounce and the triple bounce ghost targets confirm this observation.

IV. DISCUSSION

The basic measurement concept for the SnowScat tomographic profiling mode was successfully verified: The 8 metal spheres are well focused and can easily be distinguished in the tomogram under snow-free conditions. In addition, substantial backscattering signal is also obtained from the base of the test target as well as from the ground. Both features appear well-focused and are well-distinguishable in the tomogram.

A comparison of the tomographic profiles under snow conditions with the in-situ snow profiles indicates that two of the three main melt-freeze crusts/ice layers, and also the ground level can be identified in the tomographic snow profile. The phase plots of the polarimetric coherence show distinct non-zero phase that reveal polarisation-dependent scattering for both the grass land and the snow-volume above grass land. This, so far rather qualitative, confirmation of anisotropic scattering is one of the major points requiring further analysis.

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