TOMOGRAPHIC PROFILING WITH SNOWSCAT WITHIN THE ESA SNOWLAB CAMPAIGN: TIME SERIES OF SNOW PROFILES OVER THREE SNOW SEASONS

Othmar Frey
Gamma Remote Sensing /
Earth Observation & Remote Sensing, ETH Zurich
Switzerland
Email: frey@gamma-rs.ch

Charles L. Werner, Rafael Caduff, Andreas Wiesmann
Gamma Remote Sensing
Switzerland
Email: {cw, caduff, wiesmann}@gamma-rs.ch

***Abstract*—As part of the ESA SnowLab campaign the SnowScat device, a terrestrial stepped-frequency continuous-wave (SFCW) scatterometer which supports fully-polarimetric measurements within a frequency band from 9.2 to 17.8 GHz, was operated in tomographic profiling mode. In this tomographic profiling mode the SnowScat device is subsequently displaced in elevation direction to obtain a high-resolution not only in range direction but also along elevation. This leads to two-dimensional vertical profiles of a snowpack, which means that radar backscatter, co-polar phase difference, interferometric phase and coherence can be distinguished also along the vertical dimension of the snowpack. In this paper, we provide a summary and a few examples of a time series of tomographic measurements of snow obtained within the ESA SnowLab campaign at two different locations in the Swiss Alps during three snow seasons.**

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

I. Introduction

As part of the ESA SnowLab campaign the SnowScat device, a terrestrial stepped-frequency continuous-wave (SFCW) scatterometer which supports fully-polarimetric measurements within a frequency band from 9.2 to 17.8 GHz [1] [2], was operated in tomographic profiling mode. In this tomographic profiling mode the SnowScat device is subsequently displaced in elevation direction to obtain a high-resolution not only in range direction but also along elevation. This leads to two-dimensional vertical profiles of a snowpack, which means that radar backscatter, co-polar phase difference, interferometric phase and coherence can be distinguished also along the vertical dimension of the snowpack. These characteristics, obtained non-destructively using remote sensing techniques, are of importance to investigate and monitor snow properties such as snow stratification, microstructure, and snow water equivalent. We provide a brief summary and a number of examples of these time series of tomographic snow profile measurements acquired within the ESA SnowLab campaign at two different locations in the Swiss Alps during the last three snow seasons.

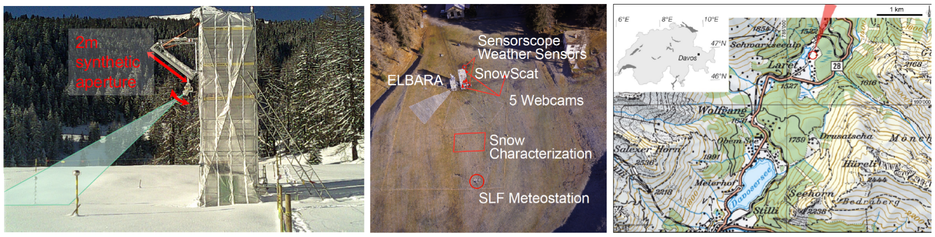
II. Experimental Setup & Data

A first campaign at a test site hosted by the WSL Institute for Snow and Avalanche Research (SLF), in Davos, Switzerland was started in 2014/2015 yielding a successful proof of the tomographic measurement concept. First comparisons of tomographic profiles with in-situ snow profiles indicated that melt-freeze crusts/ice layers present within the snowpack could be identified [7]. Other multi-baseline radar measurements with similar findings have been shown by [8]–[11].

During the first snow season (2015/2016) of the ESA SnowLab campaign, situated at the test site "Gerstenegg" in the central Alps in Switzerland, the tomographic hardware and the automated data acquisition of multi-temporal, polarimetric, high-resolution tomographic profiles was tested and consolidated. The measurement setup and first results were presented in [3]. In the snow seasons 2016/2017 and 2017/2018, the ESA SnowLab campaign was then carried out at the newly established SLF snow test site "Laret", Davos, Switzerland (see: Fig. 1). SLF carried out in-situ measurements during the SnowScat campaigns. In particular, in the last snow season (2017/2018) extensive in-situ measurements with more than 30 snow profiles (snow pit profiles—with snow density per 3cm, temperature per 10cm, specific surface area (SSA) per 3cm, and snow water equivalent—or snow micro pen (SMP) profiles) were taken by SLF. The test site is also equipped with a weather station. In addition, occasional micro-CT-based measurements of correlation lengths and snow density were also performed by SLF.

III. Results

The three snow seasons provided different weather regimes in terms of time of the first snow fall, distribution of snow fall and temperature over time, as well as the total snow accumulation with a maximum of more than 2m snow depth at the test site Laret in Davos, in January 2018 (see also Fig. 5).



Frequency	SFCW from 9.2 to 17.8GHz	Polarization	HH, HV, VV, VH
Incidence angle	-40^o to 110^o	Receiver dynamic range	> 80dB
Azimuth angle	-180^o to 180^o		with the 16bit ADC
Sampling spacing	0.04 m	Signal bias	< 0.5dB
Number of samples	50	Gain characterization	Internal calibr. & calib.
Synth. aperture length	1.96 m		sphere (Ø = 254mm)
3dB res. (stripmap m.)	0.15 m	RFI	Frequency blacklist
Antennas	Dual pol, < 10^o (3dB)	Antenna cross-pol	< -25dB

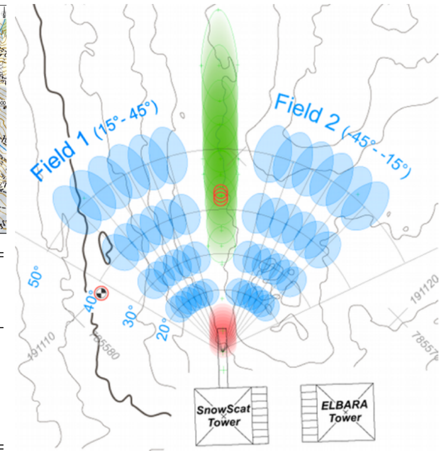


Fig. 1. From left to right: 1) The SnowScat device for tomographic data acquisitions mounted on a rail attached to a scaffolding during the ESA SnowLab campaign at the test site Davos Laret, Switzerland. SnowScat is pointing at a tomographic test target: a vertical array of eight aluminium spheres mounted on a carbon rod. 2) An aerial photo of the test site indicating the location of the various sensors deployed during the campaign and the location of the field for *in-situ* snow characterisation (UAS image by Y. Bühler and M. Jaggi, SLF). 3) Map overview of the test site. In addition, the specifications of the SnowScat system are given. On the right: a schematic top view of the ESA SnowLab test site. The surface patch coloured in green gives a rough indication of the field of view of the SnowScat device during the tomographic profiling measurements.

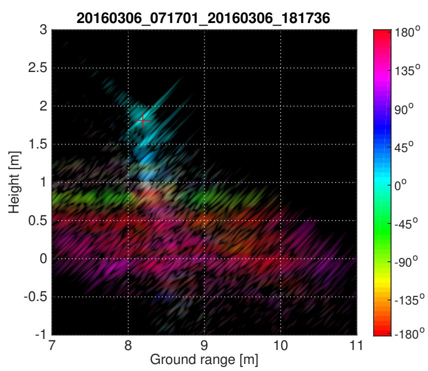


Fig. 2. Example of a differential interferogram obtained from two tomographic profiles (HH-pol) taken at different times during one day (see [3] for more details). The reference point (specular point of an aluminium sphere), is marked with a red cross. The interferometric phase is displayed in a HSV colour scheme. Hue: DInSAR phase. Saturation: coherence. Value: intensity in decibel. In this example, the interferometric phases are consistent along the horizontal direction, but show a distinct variation in the vertical direction between the uppermost melt-freeze-crust layer and the snowpack below.

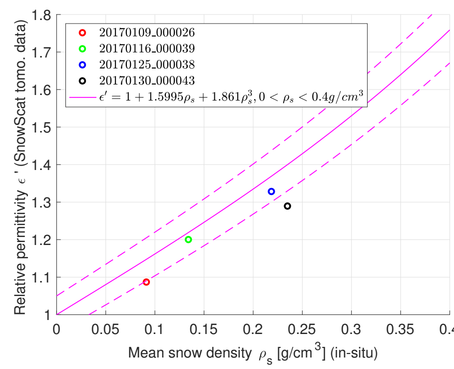


Fig. 3. Autofocus-based retrieval of relative permittivities from SnowScat tomography data versus mean snow density (reproduced from [4]; cf. for more details). An empirical model [5], [6] is plotted (magenta line) for comparison. The data pairs of mean snow density and the retrieved relative permittivities are found to be in reasonable agreement with the empirical model: three of four data points lie within the 5% intervals and one slightly outside.

Here, we give a few examples from the previous campaigns (2015/2016) and (2016/2017), and in particular from the most recent campaign (2017/2018), that illustrate the capabilities of this tomographic mode of SnowScat in terms of measuring time series of:

- 2-D vertical profiles of interferometric phase differences, see: Fig. 2 and [3],
- auto-focus-based retrieval of the relative permittivity (to derive the snow water equivalent), see: Fig. 3 and [4],
- snow stratification (development of melt-freeze crusts over time), see: Fig. 4 & 5, and
- layer-wise separation of co-polar phase differences, which are also shown in Fig. 4 & 5.

These examples illustrate that various phenomena can be investigated based on time series of tomographic profiles, such as using 1) the variation of radar backscatter to locate melt-freeze crusts/horizontal layers within the snow pack, 2) using the co-polar (HH-VV) phase difference to characterize potential anisotropy or changes in anisotropy, and 3) using differential (temporal) coherence between tomographic profiles along the time series to measure changes in the propagation delay, spatially resolved in the 2-D vertical profile. The tomographic profiles were processed using a time-domain back-projection approach (for more details see also: [12] [13]).

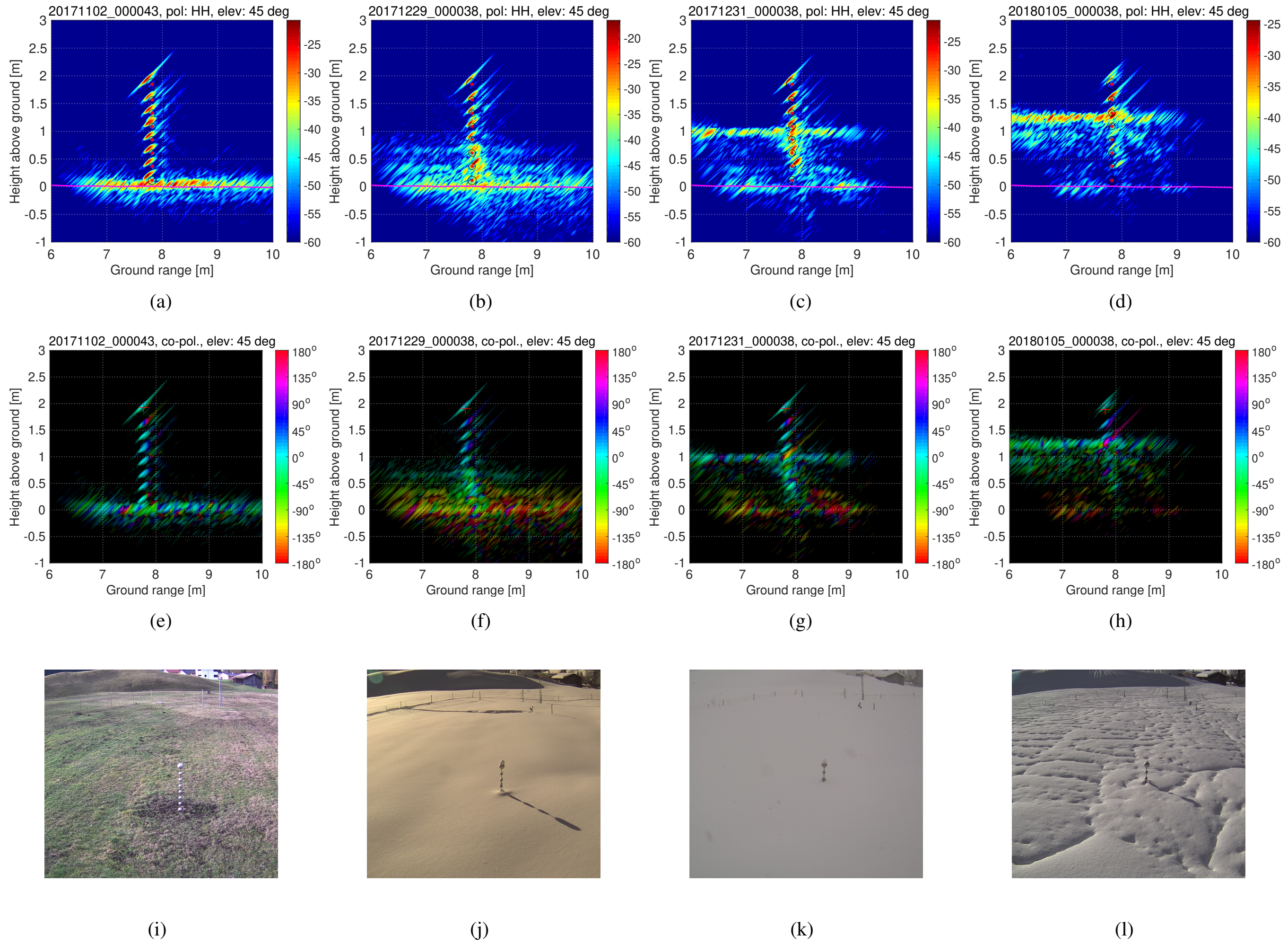


Fig. 4. Excerpts from the 2017/2018 daily time series acquired within the ESA SnowLab campaign at the test site Davos Laret, Switzerland. SnowScat tomographic profiles are shown in snow-free condition as well as under different snow conditions accompanied by photographs of the situation as seen in the viewing direction of the SnowScat device. Top row: HH-pol rel. intensity profiles. Middle row: copolar phase difference. The view direction of SnowScat is from top left to bottom right (45^o off-nadir viewing angle). The limited, skewed extent of the tomographic profile is due to the limited elevation beamwidth of the SnowScat device.

IV. Discussion

A summary of a time series of daily tomographic measurements of snow obtained within the ESA SnowLab campaign in the Swiss Alps in the snow seasons 2015/16, 2016/17, and 2017/2018 has been presented. Several new data exploitation schemes offered by such tomographic profiling measurements have been demonstrated including: measurement and tracking of temporal variation of the snow stratification, 2-D vertical profiles of interferometric phase differences and copolar phase differences (variation of snow microstructure), and auto-focus-based retrieval of the relative permittivity (to derive the snow water equivalent). While, so far, the focus of the ESA SnowLab has been laid on optimising the tomographic data acquisition and identifying potential retrieval schemes (as mentioned above), a detailed investigation and comparison of the tomographic data and the in-situ snow characterisations by SLF is now being undertaken. Last but not least, such close-range non-destructive tomographic measurements of snow structure have also the potential to be useful as complementary measurements to temporally bridge the more laborious snow-pit-based and SMP-based characterisations of snow.

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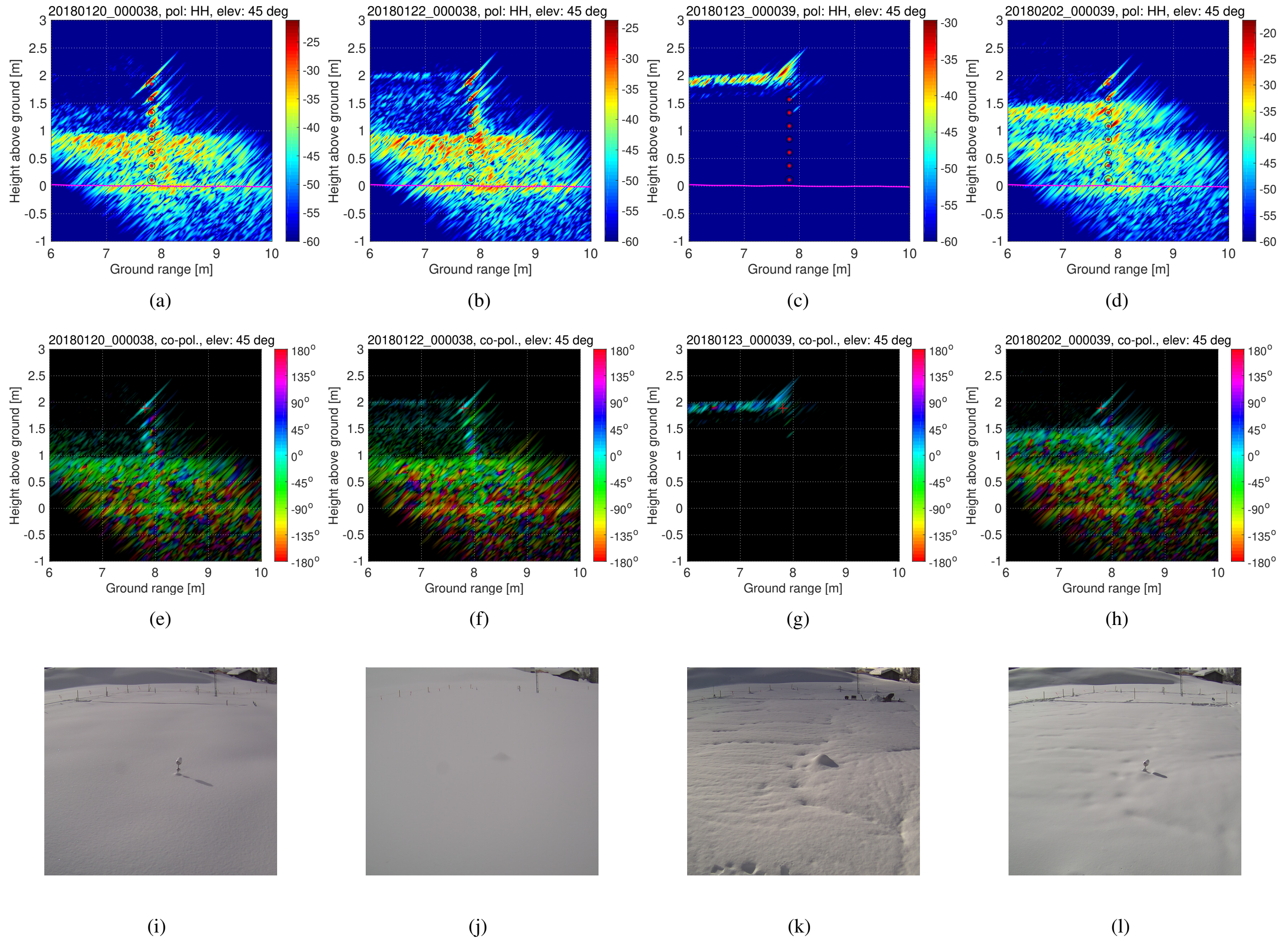

Fig. 5. Continuation of Fig. 4: Particularly note the sequence of fresh snow accumulation (1. & 2. col.), followed by a wet snow surface without microwave penetration (3. col.), and the subsequently re-frozen snowpack with full penetration of the microwave signal into the snowpack (4. col.).

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