Microwave scattering signature of snowpack – 5 years of snowscat observation experiments

Chung-Chi Lin[1], Björn Rommen[1], Nicolas Floury[1], Dirk Schuettemeyer[1], Malcolm W.J. Davidson[1], Michael Kern[1], Anna Kontu[2], Juha Lemmetyinen[2], Jouni Pulliainen[2], Andreas Wiesmann[3], Charles L. Werner[3], Christian Mätzler[3], Martin Schneebeli[4], Martin Proksch[4], Thomas Nagler[5] and Helmut Rott[5]

[1] *ESTEC, Keplerlaan1, 2200 AG Noordwijk, The Netherlands; Chung-Chi.Lin@esa.int*
[2] *Finish Meteorological Institute, Tähteläntie 62, 99600 Sodankylä, Finland*
[3] *Gamma Remote Sensing AG, Worbstr. 225, 3073 Gümligen, Switzerland*
[4] *WSL Inst. for Snow and Avalanche Research (SLF), Flüelastr. 11, 7260 Davos Dorf, Switzerland*
[5] *ENVEO IT GmbH, 6020 Innsbruck, Austria*

Abstract. ESA's SnowScat instrument is a real aperture scatterometer which was developed by Gamma Remote Sensing AG (CH). It operates in a continuous wave mode, covers a frequency range of 9.15 (X-band) to 17.9 GHz (Ku-band) in a user-defined frequency-step and have a polarimetric capability. The measurement campaigns were started first in Feb. 2009 at Weissfluhjoch, Davos, Switzerland, as an initial test of the instrument. Physical characterisations of the snowpack as well as meteorological instrumentation provide detailed in-situ data for the interpretation of the SnowScat data. SnowScat was then moved to Sodankylä in Finland, a site of the Finnish Meteorological Institute in Lapland. In addition to the in-situ snowpack characterisations and meteorological observations, continuous passive microwave observations and direct measurements of the snow water equivalent using a Gamma Wave Instrument were also performed. During the 2012-2013 winter period, a vertical time-domain snow profiling experiment was carried out in addition for resolving the scattering contributions from the snow layers of different physical properties.
The SnowScat data set represents one of the most complete, detailed and accurate active microwave observation time-series of specific snowpacks at a local scale. This paper summarises the result of the SnowScat observations and their preliminary analysis against the in-situ snowpack data. The campaign data show that snowpack is a highly variable radar target at the SnowScat frequencies, showing strong dependency on continuous snow metamorphism of its microscopic structure which are further affected by meteorological events and their inter-annual variability. There appears to be no simple one-to-one relationship between the scattering radar cross-section and the snow depth, or its snow water equivalent.

Keywords. Radar remote sensing, snowpack, snow-water-equivalent, scatterometer, microwave scattering, time-domain profiling.

1. Introduction

Snow-Water-Equivalent (SWE) of snowpack is a critical parameter for the quantitative characterisation of land hydrological cycle, but is not retrieved by existing satellite remote sensing techniques which only provide information on snow cover extent. Existing knowledge of SWE comes from passive microwave radiometers, but these measurements are challenging to interpret, are very limited in their spatial resolution (≥ a few tens of kilometres) and do not allow retrieval over deep snowpack. A satellite synthetic aperture radar (SAR) mission could potentially deliver global coverage of snow-covered regions at an unprecedented high spatial resolution if operated at frequencies which are sensitive to snowpack.

A precise knowledge of the radar signature of snowpack is a pre-requisite towards quantitative retrieval of their physical parameters using SAR imagery from space. In view of the limited availability in the literature of radar scattering information of snowpack at X-band and above, the European Space Agency (ESA) has initiated experiments using a mast-mounted scatterometer. The objective of the measurements is to establish accurate data of snowpack scattering from X- to Ku-band together with relevant snowpack and meteorological parameters, continuously over complete snow seasons with a high temporal resolution.

2. SnowScat Instrument Description

The SnowScat instrument [1] was developed by Gamma Remote Sensing AG (CH) under ESA funding. It is a fully polarimetric, coherent stepped-frequency CW radar that covers a frequency range of 9.15 – 17.9 GHz, and was designed to be operated on a mast/tower of at least 7 meters above the snow surface (see Fig. 1), capable of acquiring and storing measurement data autonomously over an extended period with pre-defined settings. In particular, it has to withstand harsh freezing environment of arctic and alpine regions over winter periods. The main instrument parameters are summarised in Table 1. Both angular and frequency diversity are used to obtain sufficient independent "looks" to reduce speckle noise and to reduce the uncertainty in the estimate of the radar backscatter. Locating the scatterometer higher above the ground permits observing a larger area achieving an increased number of looks and minimizing the complexity of interpretation when the snow depth is a significant fraction of the instrument height. The expected range of operation is less than 50 m, though the SNR is sufficiently high such that useful data could be collected up to 1 km.

Table 1. SnowScat instrument parameters.

Operating temperature Range	-40° C to 40° C; synthesizer must be above 0° C to start
Antenna	Dual H, V pol; 9 - 18 GHz; beamwidth < 10° (3 dB)
Antenna cross-polarisation	< -20 dB
Frequency range	Stepped CW from 9.15 to 17.9 GHz, 4 kHz steps minimum
Incidence angle scan range	-40° to 110°
Azimuth angle scan range	-180° to 180°
Polarizations	HH, HV, VV, VH
Dynamic range	> 80 dB with the 16 bit ADC
Radiometric bias error	< 0.5 dB
Gain characterization	Internal calibration loop; external reference target (8" sphere)
Instrument control	Remote Control through Ethernet; stand alone
Data storage	Internal; external through Ethernet

3. Davos (Weissfluhjoch) Campaign 2009

The Weissfluhjoch research field of the SLF [2] is located on a flat area of the Dorftälli, approximately 150 m below the Weissfluhjoch towards Davos, at an altitude of 2540 m. The ground is covered with stones and rocks composed of serpentine. A re-deployment of SnowScat in early summer 2009, after the snowpack had disappeared, revealed a high backscatter of this underlying surface, which may impact the snowpack observation. Fig. 2 depicts the snow accumulation over the winter period 2008 – 2009 (red), together with the minimum (cyan) and maximum (blue) accumulations ever recorded on the site in the last 70 years. The figure shows also that the snow height evolution in that winter was representative of the average accumulation (green) over those years.

SnowScat was operated from 12 Feb. to 28 April 2009 upon completion of its development. The baseline measurement cycle included calibration target measurements before and after the azimuth and incidence angle scans covering two test sites and a clutter measurement towards the sky. These cycles took about 2 hours and were repeated every three hours. The data are calibrated at 3 distinct frequencies 10.2, 13.3 and 16.7 GHz with 2 GHz bandwidth. The aggregated signature files are averaged over the azimuth measurements.

Figure 1. SnowScat mounted on a mast at 10 m height from the ground surface at the Weissfluhjoch research field (2540 m altitude) of the SLF over Davos: M. Schneebeli of SLF checking the instrument.

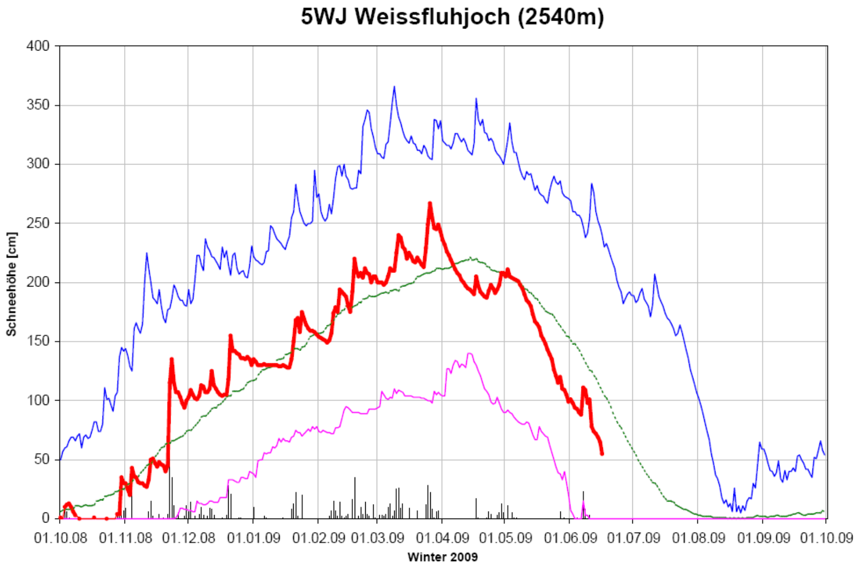

Figure 2. Snow cover development at the test site Weissfluhjoch Davos: The maximum (blue), minimum (cyan), and average snow height (green) at the test site are shown. The red line shows the snow height for the season 2008 - 2009. The black bars indicate the snow precipitation heights.

Fig. 3 depicts the backscatter coefficient time-series at 40° incidence for the VV, HH and HV polarisations at 10, 13 and 17 GHz over the measurement period. Although not shown, a smooth decrease of the backscatter coefficients with increasing incidence angle was observed in all cases. During the same period, the snow height increased from 180 cm to a maximum of 270 cm, and subsequently decreased to 200 cm at the end of the observation period. However, no significant variation of the backscattering coefficients or their trend during the snow accumulation period is observed. The radar backscatter remains stable until nearly the end of March, after which it jumps between very low and high values which correspond to the melt and refreeze events towards the end of the winter season. A comparison with Fig. 2 confirms that this period of melt and refreeze events corresponds to that of the gradual snowpack decrease. A remarkable behaviour of the backscatter during this period is the gradual amplitude increase of the jumps, which suggest some snow metamorphism associated with the melt and refreeze processes (e.g. gradual grain size growth).

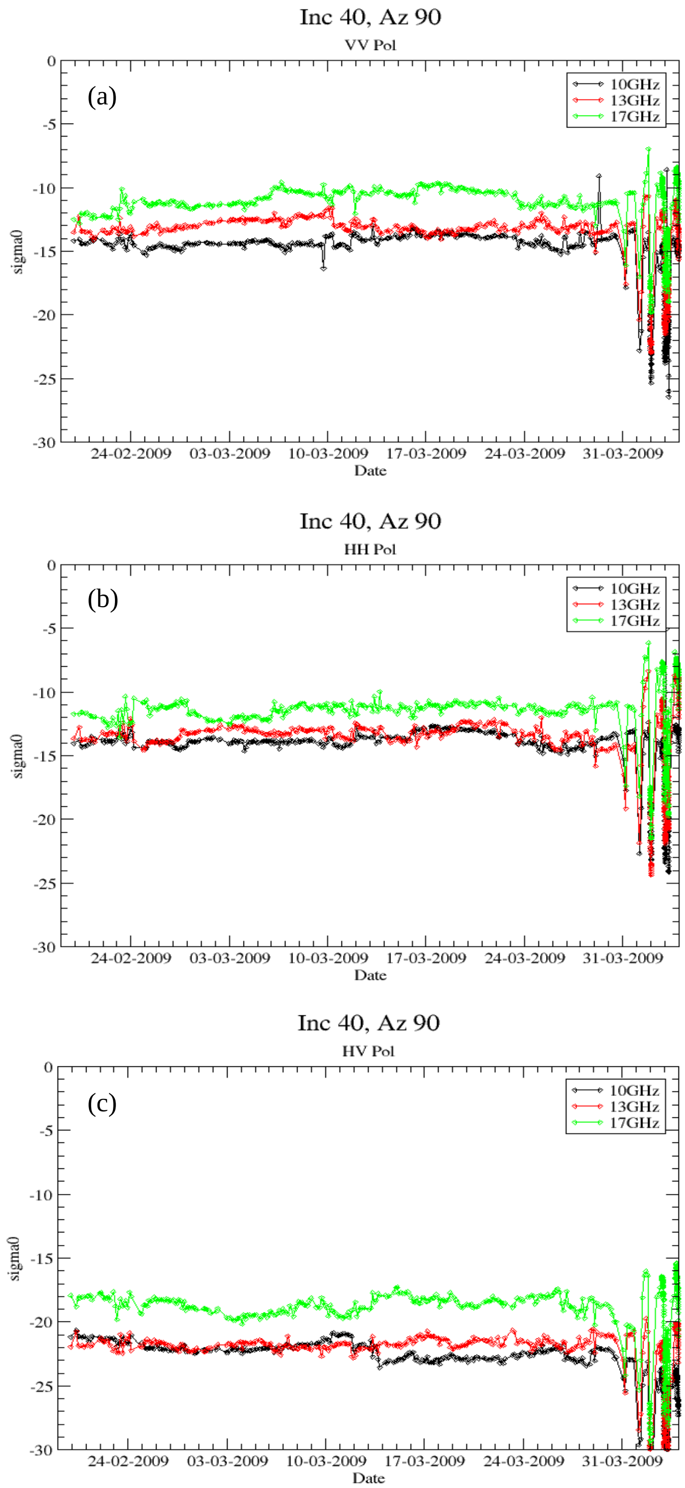

Figure 3. Backscatter coefficient time-series at 10 (black), 13 (red) and 17 GHz (green): (a) VV; (b) HH; (c) HV.

In conclusion, no significant variation of the radar backscatter with respect to the snowpack height could be evidenced during the period of dry snow accumulation which was covered by the campaign observation. This may be due to the saturation of the radar backscatter above 180 cm snowpack, or due to the high background reflectivity of the underlying stony surface. It would be necessary to repeat the SnowScat experiment from the beginning of a snow season in order to resolve possible reasons for this observed lack of variation.

4. Sodankylä, Finland, Campaign 2009 - 2013

The NoSREx campaign series [3] from 2009 to 2013 was conducted near the town of Sodankylä in Northern Finland, ca. 100 km north of the Arctic circle. The town hosts the Finnish Meteorological Research Centre (FMI-ARC), the main site of NoSREx activities. The site is representative of the Eurasian taiga belt, characterized by a mosaic of sparse conifer-dominated forests, open/forested bogs and small lakes. The landscape is generally flat or gently rolling although small mountain regions (fjells) are typical. The main site for NoSREx activities, the Intensive Observation area (IOA), is located at the FMI-ARC premises (67.362N, 26.633E). The area is mostly covered with sparse pine forest; the measurement area itself is located in a forest clearing as depicted in Fig. 4, protected from wind. The ground vegetation consists of low lichen, moss and heather. The soil is mostly very fine mineral soil, with a thin layer of forest litter on the surface (ca. 5 cm). The mineral soil composition is 70 % sand, 1 % clay and 29 % silt.

Figure 4. Image from a webcam installed in the NorSEN mast showing the IOA (spring 2010). The SnowScat tower and instrument can be seen in the background left. The main area of observations is in the centre, with the main manual snow observations performed in the area on the right side of the image.

SnowScat was installed on a mast at a height of approximately 9 m. The main measurement directions of SnowScat are divided in two sectors as shown in Fig. 5, approximately towards north-east-northwest (Sector 1 – upper part of Fig. 5) and alternately towards southeast (Sector 2 – lower right part of Fig. 5). The approximate locations of SnowScat footprints in the respective sectors are indicated as elliptical contours. The elevation of the surface height measured during NoSREx-II in May 2010 is also shown in the same figure. SnowScat measurements during the first campaign season of NoSREx included only measurements of Sector 1. The purpose of the second sector was to provide additional samples in the azimuth range (increase independent number of looks per elevation angle). For the last two campaign seasons, an artificially flat surface (aluminum mesh) was used to cover Sector 2. The number of azimuth look angles is 17 in Sector 1, and 5 in Sector 2. The typical measurement protocol of SnowScat included the initiation of a scan of the measurement sectors every three (for first campaign season) or four hours. Scans in the azimuth direction were made at incidence angles of 30, 40, 50 and 60°. A reference target (aluminum sphere) was measured before and after each scan for the instrument absolute calibration and for monitoring its radiometric stability.

In addition to the microwave instrumentation, operational automatic ground measurement instruments are located at the IOA. Two sites record snow depth (SD) and air temperature, one in the forest opening and one in the surrounding forest. Soil moisture and soil temperature are measured at three locations at 2 and 10 cm depth. In addition, the snow temperature profile is measured at 10 cm intervals. For the last two campaign seasons, soil moisture and temperature profiles are also available at 80, 40, 20, 10 and 5 cm depths. SWE is measured directly with an experimental device (GWI, Gamma Water Instrument), and also by means of manual snow density profile measurements. Other automated in situ observations (Automated Weather stations) are available from the FMI sounding station and Meteorological mast in the immediate vicinity of the IOA.

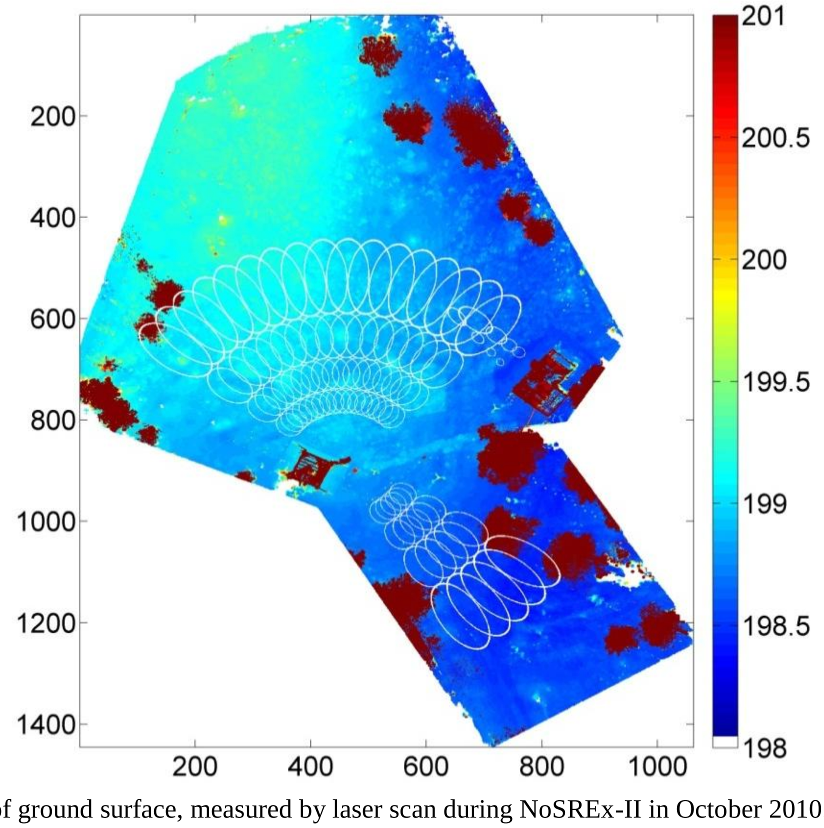

Figure 5. Elevation of ground surface, measured by laser scan during NoSREx-II in October 2010. Approximate locations of SnowScat footprints in Sectors 1 (upper part) and 2 (lower right) indicated as white ellipses. Data corresponding to the beam footprints overlapping with trees were removed after the scan.

The snowpack in Sodankylä is representative of a high latitude snow cover, characterised by low snowpack density and water content. The maximum observed snow depth ranged between 0.7 and 1.5 m during the 4 years campaign period starting from the autumn 2009. Fig. 6 below shows the snow depth and temperature time-series at different depths from the surface for the winter 2009 – 2010.

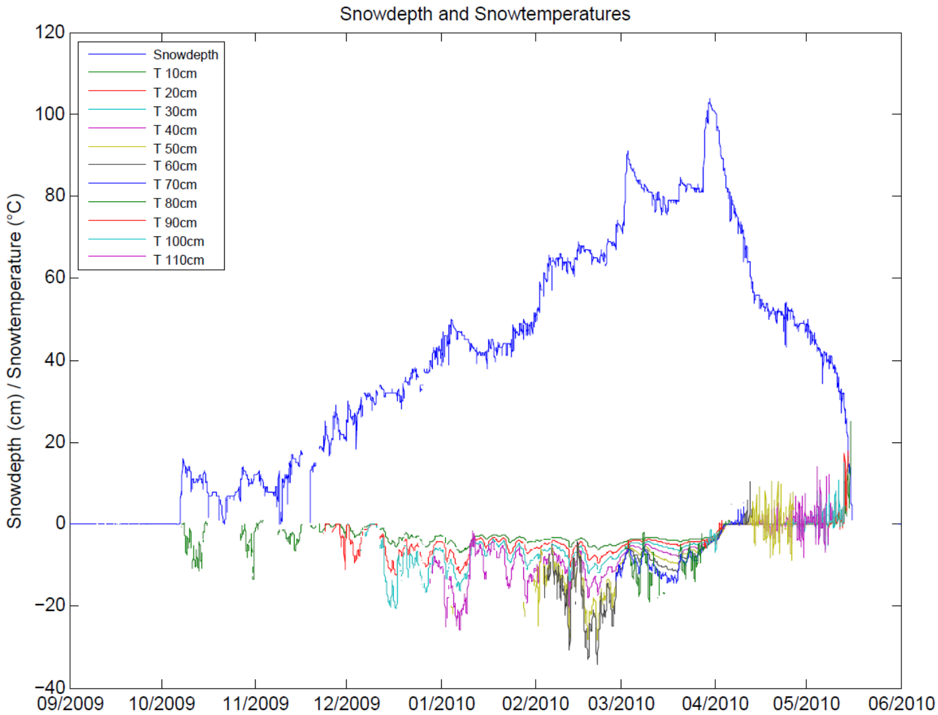

Figure 6. Snow depth (blue) and snow temperature time-series at different depth (see colour code) for winter 2009 - 2010

Fig. 7 below depicts the SWE over the two winters, 2009 – 2010 and 2010 – 2011, as estimated from the snow depth and manual snow density profile measurements. The snow accumulation in winter 2009 – 2010 was unusually high, whereas it was normal for winter 2010 – 2011.

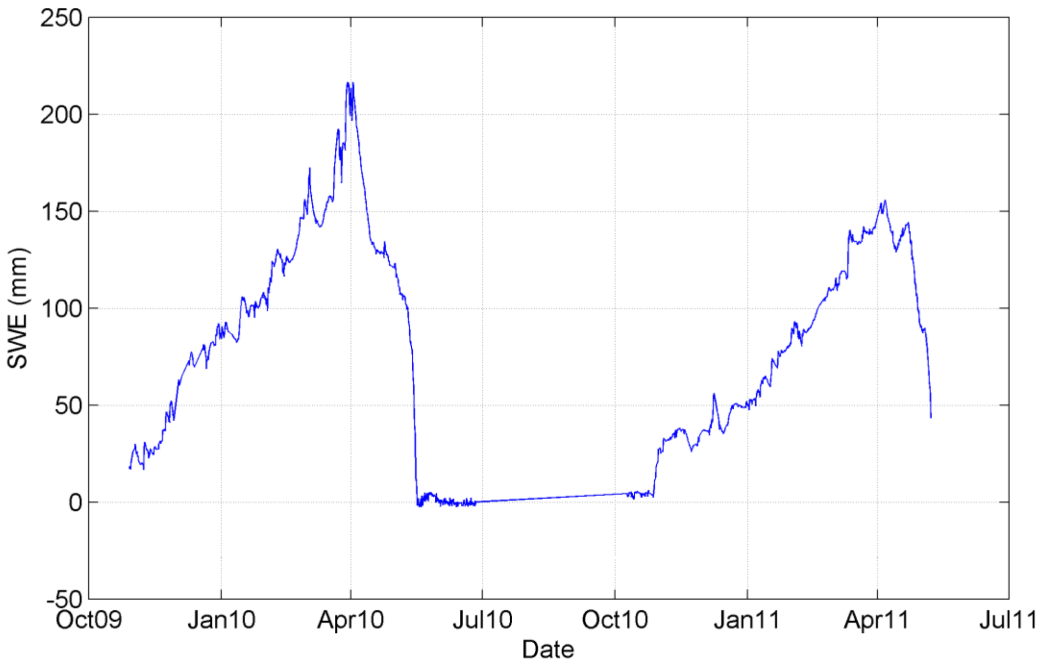

Figure 7: SWE time series for winters 2009 – 2010 and 2010 - 2011

Fig. 8 shows on the left-hand-side the corresponding (2009 – 2010) radar backscatter coefficient time-series at 10 GHz (lower) and 17 GHz (upper) for the VV polarisation in a linear scale, and those of the winter 2010 – 2011 on the right-hand-side. Those time-series well-illustrate the range of the backscatter behaviours over the 4 years period. The temporal behaviour for the other polarisations generally follows that of the VV backscatter, although the values of the cross-polarisation return (i.e. VH and HV) are substantially lower. One can typically observe three distinct periods: (1) the first period of unstable radar backscatter where the early season snowfalls alternate with rain, melt and refreeze events; (2) a period with a more stable radar backscatter during which dry snow gradually accumulates; (3) a period starting with the onset of snow melting where the radar backscatter value displays large jumps.

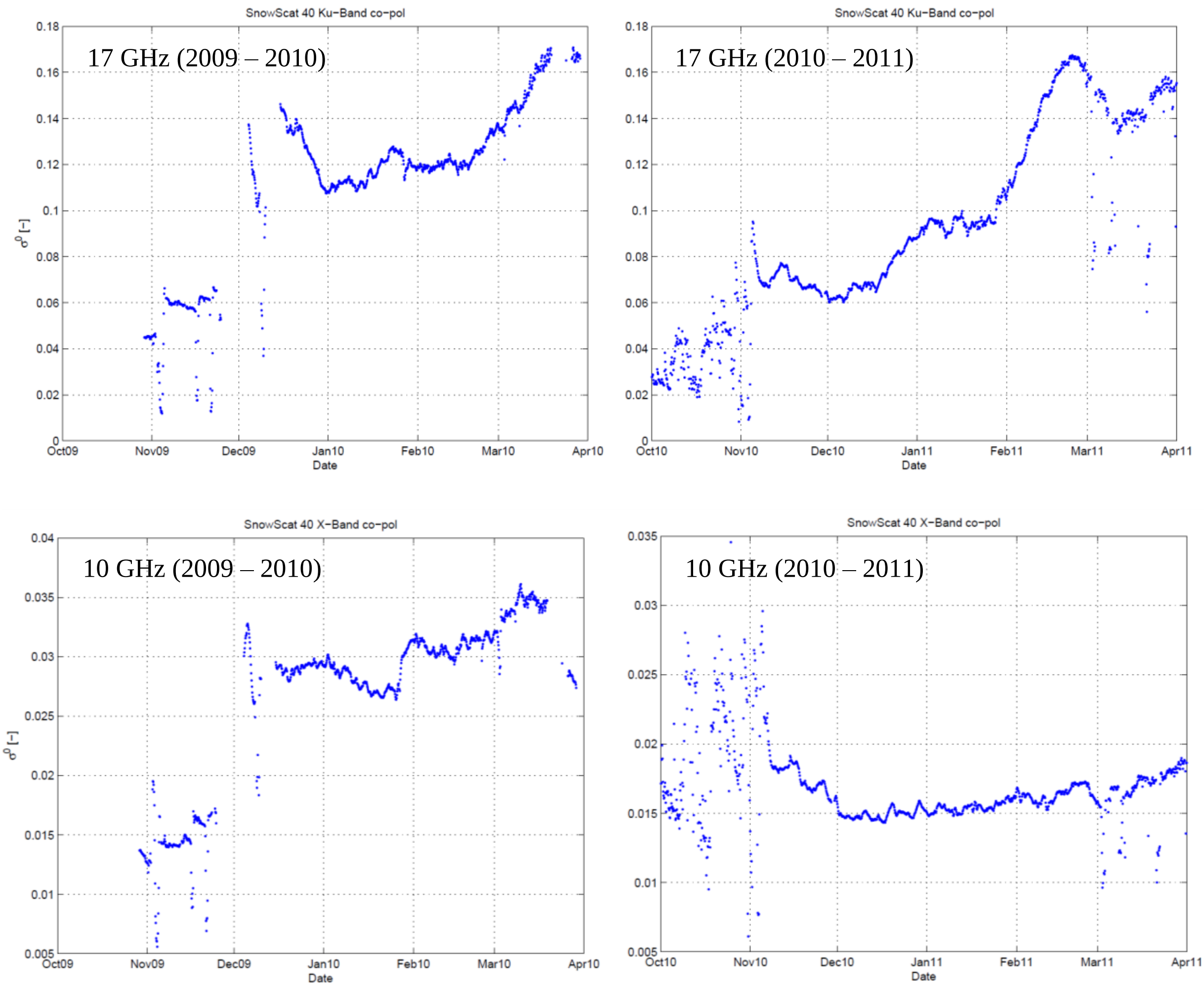

Figure 8. Backscatter time-series over winter 2009 – 2010 (left) and 2010 – 2011 (right) at 10 GHz (lower) and 17 GHz (upper) for the VV polarisation.

The corresponding SWE vs. radar backscatter is shown in Fig. 9 where the colour-coding indicates the observation dates. For the period corresponding to the dry snow accumulation and especially for the winter 2010 - 2011, some correlation between the SWE and radar backscatter is observed at 17 GHz, however it is not a monotonic function of the SWE. At 10 GHz however, no noteworthy dependence of the radar backscatter with respect to the SWE can be observed. An examination of the overall campaign result from 2009 to 2013 reveals that the SWE vs. radar backscatter relationship can largely vary from one winter to the next even if the general growth pattern of the snowpack over the respective years did not significantly differ.

A possible explanation might be found in the snow metamorphism process in the beginning of the snowpack formation where succession of snowfalls, interleaved by rainfalls, short periods of melting and refreezing naturally occur, leading to a formation of some base layers. Depending on the meteorological conditions prevailing during such initial period, the final grain size resulting from the snow metamorphism could be small or large, thus giving rise respectively to a weak or stronger radar backscatter. A comparison with the air temperature measurements indeed shows that the beginning of the winter 2009 – 2010 was associated with several cycles of melt and refreeze events lasting until mid. Dec. 2009, possibly resulting in formation of a hard snow crust at the base. The winter 2010 – 2011 on the other hand had the first snowfalls associated with a rapid drop in the air temperature, thus possibly limiting the formation of a hard crust. Unfortunately, such a hypothesis could not be verified due to a lack of sufficiently detailed physical snow parameter measurements at the beginning of the snow accumulation.

Reasons for a gradual decrease of the radar backscatter at 17 GHz, observed in the beginning of the dry snow period in Fig. 8, could be attributed to the snow metamorphism associated with the drop in the air temperature and ensuing temperature gradient relaxation within the snowpack. Such a hypothesis is supported by the fact that the observed decrease is much pronounced at 17 GHz and less so at 10 GHz. A vertically resolved radar backscatter measurements, such as the one described in Section 5 would be required in order to better understand the observed decrease.

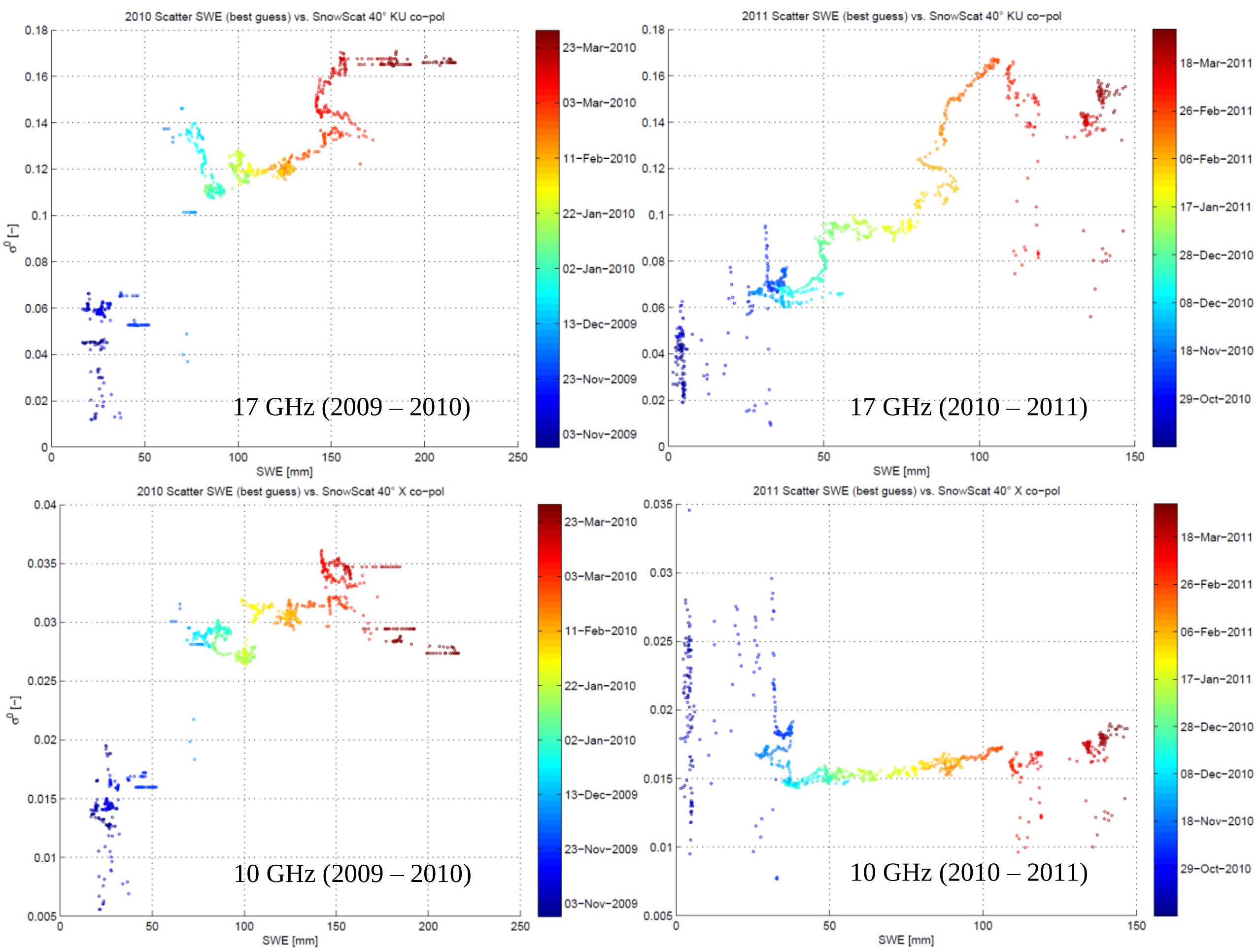

Figure 9. SWE vs. radar backscatter VV for winter 2009 – 2010 (left) and 2010 – 2011 (right) at 10 GHz (lower) and 17 GHz (upper) for the VV polarisation.

5. Sodankylä Snow Profiling Experiment 2013

In Feb. 2013, SnowScat mounting set-up was modified from the slant geometry to the nadir pointing configuration in order to perform a vertical time-domain snow profiling experiment. For avoiding spurious scattering by the tower structure, SnowScat was mounted at the tip of an extension beam which provided a horizontal clearance of 3 m from the tower (see Fig. 10). The beam was successively swung horizontally such that vertical profiles were obtained at 11 different (approximately) equidistant positions over an arc of 2 m. At each horizontal position, a complete frequency range was swept and the measurement data stored. The data were subsequently converted into a time-domain profile using a fast Fourier transform (FFT) processing. Upon completion of the data acquisitions at all horizontal positions, a snow pit was made along the measurement positions in order to study the snow stratigraphy.

Figure 10. SnowScat mounted in the nadir pointing configuration at a height of 8 m with a horizontal clearance of 3 m from the tower.

The maximum vertical resolution Δh achievable by SnowScat is given by:

$$\Delta h = c/(2\sqrt{\epsilon_r}B)$$

where c is the speed of light in free-space, ε_r the relative permittivity of the medium and B the system bandwidth. Using the maximum available frequency range, a vertical resolution of 17 mm in free-space is achieved. A window/weighting function was further used when using the FFT in order to attenuate range-sidelobes, however at the cost of a degraded range resolution. Fig. 11 shows examples of a time-domain/range echo profile processed with three different window functions where the range distance was computed assuming a free-space. Some significant impacts on the range resolution are observed depending on their choice. Both the Kaiser window with beta=4 and Hanning window appear to provide a satisfactory range resolution.

Fig. 12 depicts those profiles measured at all 11 horizontal positions along the arc of approximately 2 m. One can see a gentle slope of the snow surface, which is also reflected in the echoes from the depth, likely reproducing the ground surface slope.

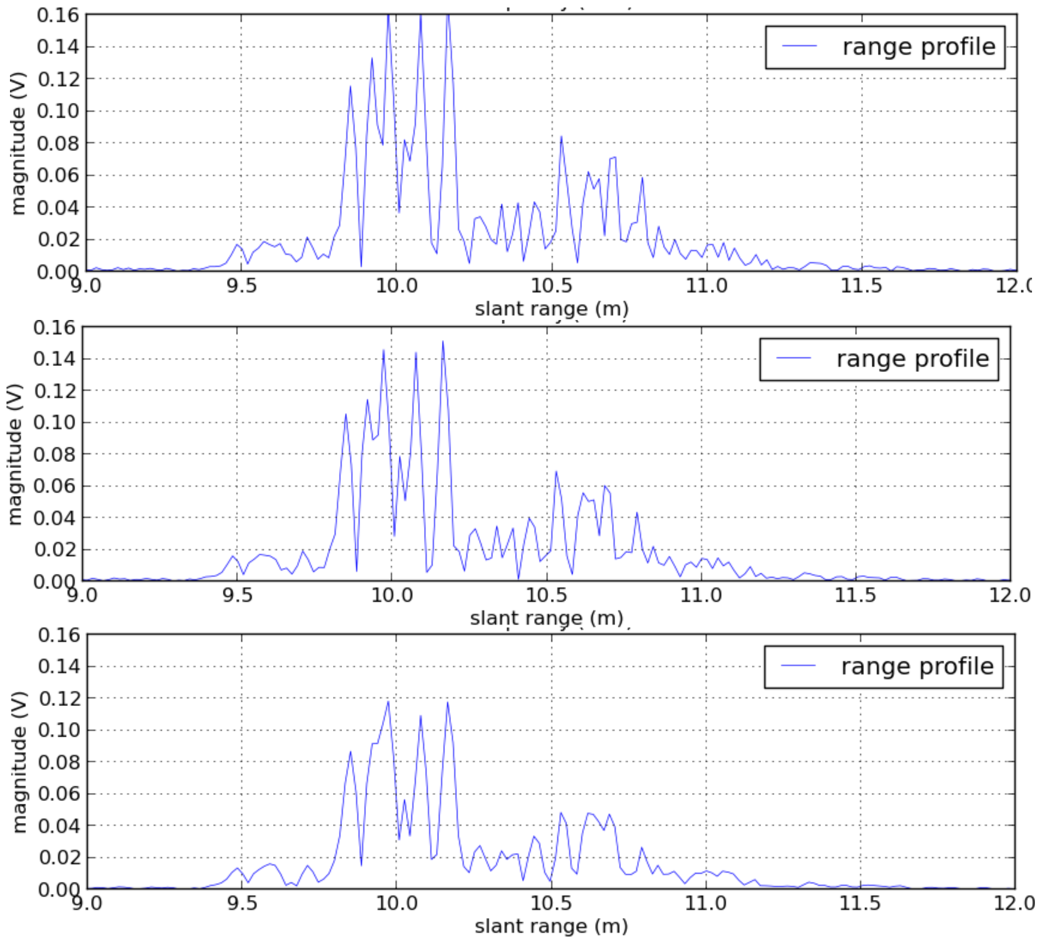

Figure 11. Examples of time-domain echo profiles using Kaiser window with beta=4 (top), Hanning (middle) and Nuttall (bottom) windows.

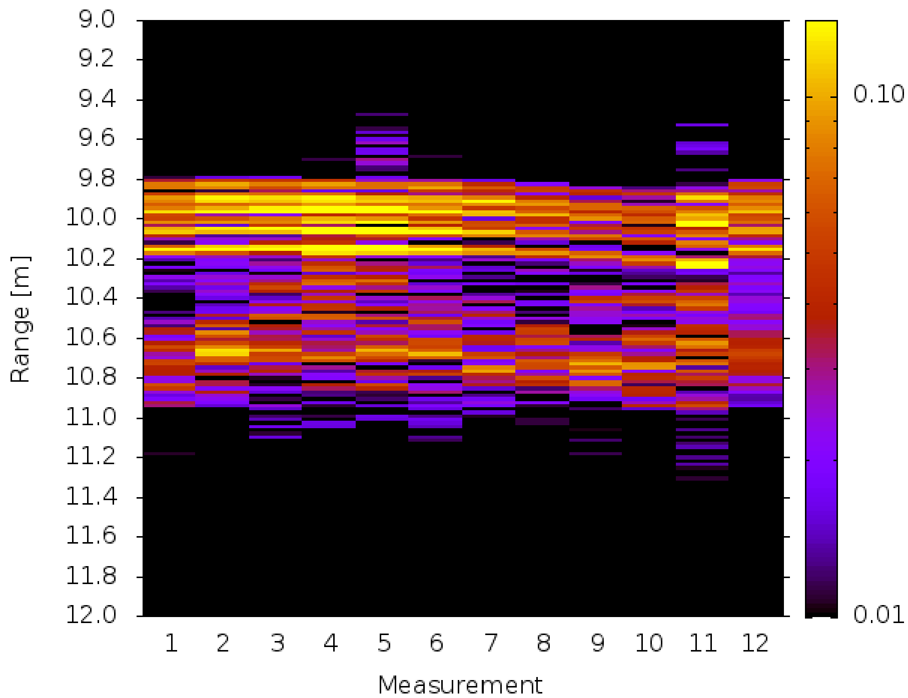

Figure 12. Range-echo profiles at all 11 horizontal positions along an arc of 2 m assuming free-space propagation (the colour code indicates the signal amplitude) - Profile No. 12 is an average of the 11 profiles.

A near infrared (NIR) photograph made from the snow-pit section along the nadir points of the vertical SnowScat measurement positions is shown in Fig. 13. From the photograph, the so-called specific surface area (SSA), which describes the micro-physical structure of the snowpack, is derived [4]. The SSA of snowpack is closely related to the correlation length or more broadly to the optical grain size [5].

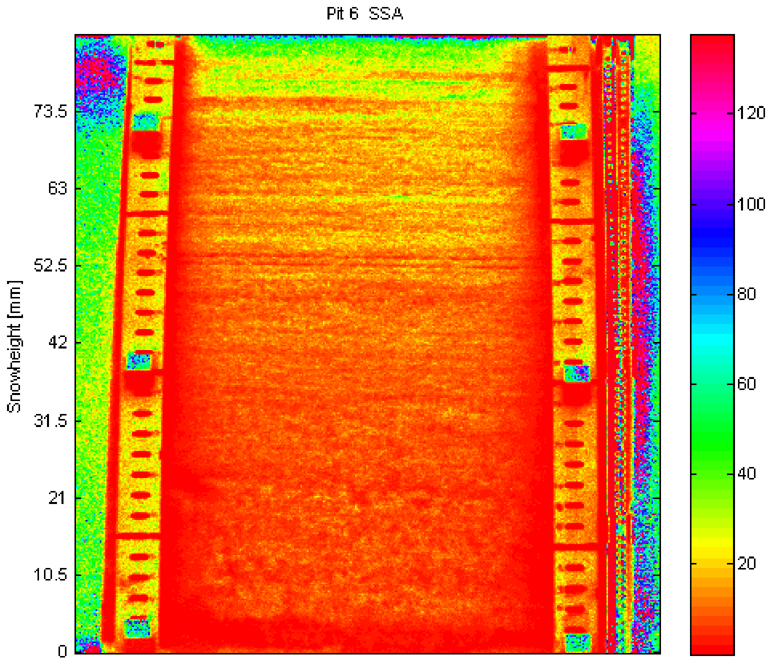

Figure 13. NIR photograph of a section of the snowpack corresponding to the positions of the vertical profiling experiment.

A comparison between the SSA profile, derived from the NIR photograph, and one of the SnowScat range profiles is shown side by side in Fig. 14. Since at the time of writing this paper, no measurement result of the snow density profile was available, a simple vertical scaling was applied in order to align the first and last significant reflections with the snow surface and ground level, respectively. Such an empirical scaling is incorrect in principle, as the snow density is not expected to be uniform with respect to the snow depth, i.e. the scaling should be 'depth-dependent'. It is generally expected that the reflections are generated by discontinuities in the electromagnetic properties of the snowpack medium, i.e. at the interfaces between the layers of distinct microphysical characteristics. However, no correlation between the locations of the reflections and SSA profile is immediately obvious from the comparison.

6. Conclusion

This paper described the results of the SnowScat campaigns over 5 winters from early 2009 to 2013. The data collected during the campaigns shows that there is no consistently repeatable relationship between the snowpack's height or SWE on one hand, and the radar backscatter as observed by SnowScat on the other hand. The radar backscatter appears to be more sensitive at a higher frequency such as 17 GHz than at lower frequency, i.e. 10 GHz. At 10 GHz, little variation of the backscatter with respect to the dry snowpack height or SWE has been observed.

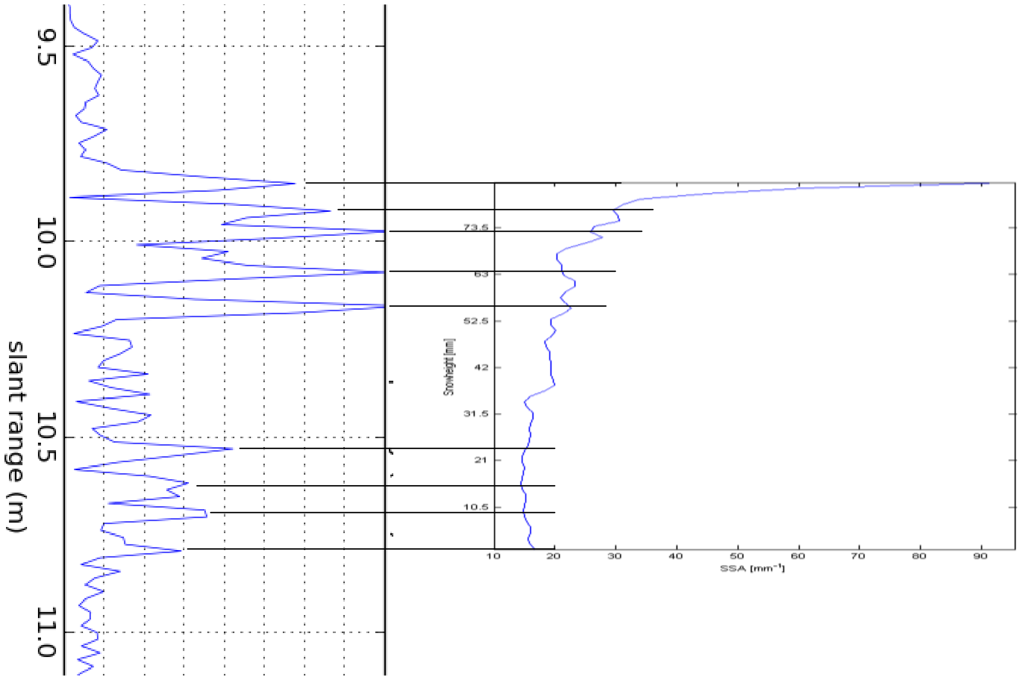

Figure 14. Side-by-side comparison of the SnowScat range-profile and SSA profile

The time-series of the radar backscatter over the entire snow seasons show that:

(1) Snowpack appears to be a highly evasive target when observed by a radar. Its scattering cross-section varies widely according to its moisture and micro-structural states which are driven by the atmospheric conditions and snow metamorphisms.

(2) The succession of snow melt and refreeze events in the early period and late season appears to drive snow metamorphisms: the melt events are characterised by a sudden decrease of the radar backscatter by more than 10 dB in general; whereas each refreeze event brings up the backscatter to a value generally higher than the one immediately before the last melt event.

(3) The snow metamorphism in the early snow season, as a result of melt and refreeze events, can lead to high radar backscatter, even if there had been low snow accumulation (e.g. < 30 cm in Dec. 2009 in Sodankylä). This high background reflectivity of the base layers appears to strongly affect the scattering signature of the growing snowpack during the dry snow period.

(4) The variation of the radar backscatter at 17 GHz over the dry snow period is generally weak, with a maximum of 4.3 dB observed from Dec. 2010 to March 2011 in Sodankylä.

(5) For the thick alpine snowpack in Weissfluhjoch, no noteworthy variation of the backscatter with respect to the snow height or SWE during the dry snow period was observed at all frequencies.

The initial result of the vertical snow profiling experiment appears inconclusive at the time of writing this paper. The lack of snow density measurement result did not permit us yet to estimate the effective permittivity of the snowpack, thus unable to convert the time-domain profile into the range profile. Nevertheless, the presence of time-resolved reflections seems to indicate a presence of distinct layers of differing electromagnetic properties in the snowpack. Further analyses of the data would be required in order to examine the relationship between the SSA and range profiles, and to attempt retrieval of physical parameters of the different layers constituting the snowpack.

Finally, the results of the campaigns and their initial analysis helped us to formulate a preliminary set of requirements to be put on the development of snowpack scattering model(s) for use in snow retrieval. Those are as follows:

i) The model needs to take into account of the snow layers of differing physical properties which constitute the snowpack, as well as a good knowledge of the underlying ground in terms of its electromagnetic properties and actual state (e.g. frozen, non-frozen, depth of freeze). In particular, the result of the snow metamorphism prior to the dry snow accumulation period, i.e. the formation of the base layers, must be well-characterised in terms of their electromagnetic properties.

ii) The temporal evolution of the micro-physical properties of the different snow layers must be known, as snow metamorphism processes continuously transform them during the season and those have direct impacts on the radar backscatter.

iii) The dominant snowpack parameters influencing the radar backscatter may be the specific surface area (SSA) or correlation length [5], and density. The SSA or correlation length can also be expressed as optical grain size.

Further analyses of the campaign data are on-going and additional campaigns are planned which draw lessons from the work performed so far. In particular, there is a definite lack of complete backscatter time-series over alpine snow with large SWE content.

Campaign reports and data availability

The reports of the SnowScat campaigns are available together with a list of the collected data on the ESA's Earthnet campaign site [6]. The data are available free of charge upon request.

References

[1] Werner, C., Wiesmann, A.., Strozzi, T., Schneebeli, M., Mätzler, C., *The SnowScat ground-based polarimetric scatterometer: Calibration and initial measurements from Davos, Switzerland*, Proc. IGARSS Symposium 2010, Honolulu, Hawaii, U.S.A., July 2010, pp. 2363-2366.

[2] http://www.slf.ch/ueber/standorte/weissfluhjoch/index_DE

[3] Lemmetyinen, J., Pulliainen, J., Arslan, A., Rautiainen, K., Vehvilainen, J., Wiesmann, A., Nagler, T., Rott, H., Davidson, M., Schuettemeyer, D., Kern, M., *Analysis of active and passive microwave observations from the NoSREx campaign*, Proc. IGARSS Symposium 2011, Vancouver, BC, Canada, July 2011, pp. 2737-2740.

[4] Matzl, M., Schneebeli, M., *Measuring specific surface area of snow by near-infrared photography*, Journal of Glaciology, Vol. 52, No. 179, 2006, pp. 558-564.

[5] Mätzler, C., *Relation between grain-size and correlation length of snow*, Journal of Glaciology, Vol. 48, No. 162, 2002, pp. 461–466.

[6] https://earth.esa.int/web/guest/campaigns