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ESA SnowLab

D7_v3 Final Report

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1. EXECUTIVE SUMMARY

The aim of the ESA SnowLab project was to provide a comprehensive multi-frequency, multi-polarisation, multi-temporal dataset of active microwave measurements over snow-covered grounds to investigate the relationship between effective snow- and ground parameters and the resultant signals detected by microwave radar. An important part for the development of micro-wave models is the microstructural characterisation. This characterisation can only be done by repeated measurements by SnowMicroPen and more completely, but also much more expensive, by X-ray micro-tomography. Within this project we complemented the microwave measurements of Alpine snow in Switzerland with extensive effective snow- and ground parameters and meteorological data.

During the first winter 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 Frey et al. 2016. An important task in the first part of the project was to develop and code a Tomographic Analysis Tool.

In the 3 winter seasons 2016-2019, the ESA SnowLab campaign was then carried out at the newly established SLF snow test site “Laret”, Davos, Switzerland. SLF carried out in-situ measurements during the SnowScat campaigns. It was possible to acquire three complete sets of multi-frequency and -polarisation data at 6h interval covering the full snow season from onset of snow until complete melt. Extensive in-situ measurements with more than 30 snow profiles only in 2017/18 (snow pit profiles — with snow density per 3cm, temperature per 10cm, specific surface area (SSA) per 3cm, and snow water equivalent — and SnowMicroPen (SMP) profiles) were taken by SLF. In addition, occasional micro-CT-based measurements of correlation lengths and snow density were also performed by SLF. Furthermore the test site was equipped with a weather station collecting all relevant meteorological parameters.

From previous campaigns we learned the importance of near realtime (NRT) processing of the acquired data and remote connection to detect irregularities or special conditions early on. At all sites a local area network was established that connected the SnowScat instrument, local network cameras and a network attached storage through a VPN tunnel and a GSM gateway with the GAMMA company network. Processed data, as well as current camera images, together with instrument and meteorological information was accessible on the ESA SnowLab Redmine portal. The portal hosted also all project related documents and the digital campaign logbook. This logbook was the central information point for all test site related activities.

The campaigns were conducted in close collaboration with the MicroVegSnow campaign led by Dr. Mike Schwank of WSL and other partners working on our sites. In the last winter the microwave measurements were conducted as part of the CCN2 of this project alongside the ESA WBScat instrument.

2. INTRODUCTION

The aim of the ESA SnowLab project was to provide a comprehensive multi-frequency, multi-polarisation, multi-temporal dataset of active microwave measurements over snow-covered grounds to investigate the relationship between effective snow- and ground parameters and the resultant signals detected by microwave radar.
This documents gives an overview on the 3 campaigns that were conducted in the frame of ESA SnowLab. In Section 3 the different sites and the project organisation is presented. Section 4 shows the microwave, snow characterisation and meteorological sensors that were used. Section 5 shows some of the microwave measurements, particularly the seasonal behaviour of the backscattering coefficient. Section 6 documents the dissemination activities. Finally, in Section 7 the conclusions are given and potential future actions are listed.

3. CAMPAIGNS

3.1. Organisation

3.1.1. Team and Roles

The project team consisted of GAMMA Remote Sensing AG and WSL-SLF. GAMMA was the prime and responsible, for the project management, setup of the SnowScat, measurements, setup of the communications network, interface to ESA and the science partners on the test site. SLF was subcontractor and responsible for all aspects concerning snow physics, in particular the snow characterisation.
On the test site Gerstenegg the team was complemented by the site owner Kraftwerke Oberhasli AG (KWO) and ETH Zurich. KWO made the test site available and helped with the snow characterisation. ETH Zurich provided GNSS sensors.

The test site Laret was installed primarily for hosting ESA SnowLab and is operated by WSL-SLF. The site is located on communal property of the municipality of Davos, dedicated to installations of public interest.
The free use of the test site Laret for scientific activities is granted to SLF until summer 2021 by the municipal authorities. Permanent installations such as scaffolding towers and the permanent Meteo-Station are regulated and restricted by the building permission. Major changes on the silhouette do require a new application. The current permission is valid as long as the contract with the municipal authorities will last.
Since the Laret test site now hosts different activities, the SLF is managing the organisational and infrastructural issues on the site (Figure 1).
Within the test-site, specific sections dedicated to the experiments were defined and as management tool and site-log, the ESA SnowLab Redmine tool was used by all involved parties. Every activity on the site was announced and documented there.

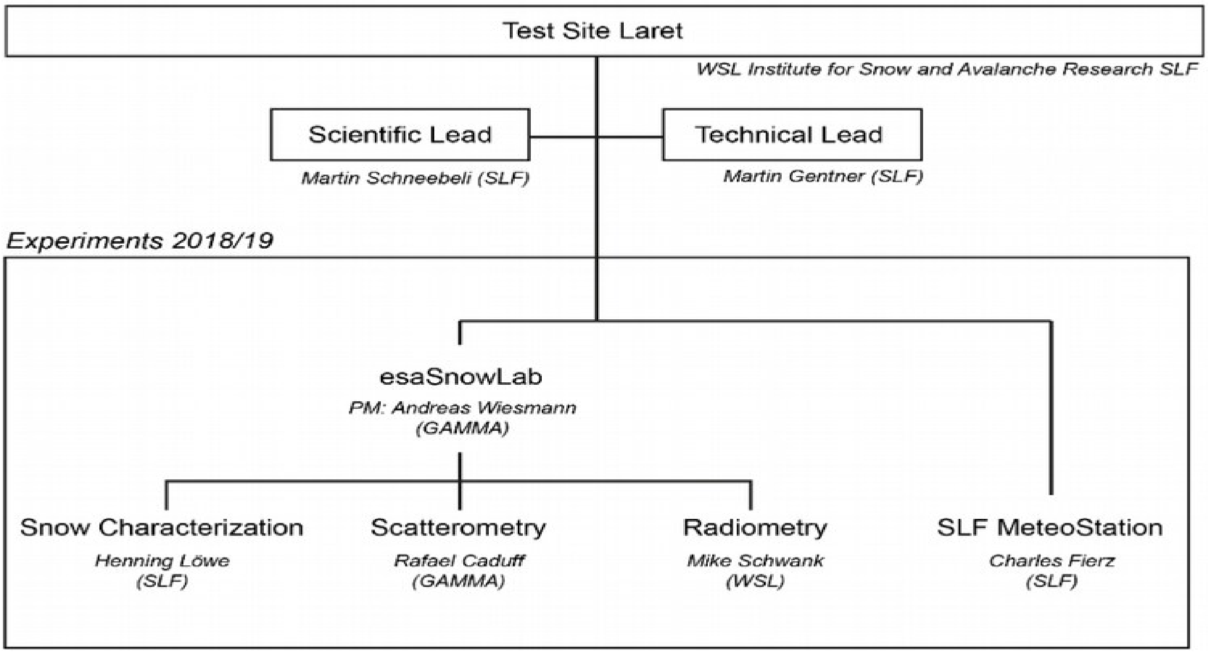

Figure 1 Organisation chart of the test site Laret with lead personnel

3.1.2. Power and Communication

All instruments except the “Sensorscope” and SLF weather stations, which are solar powered, are powered with 220V/AC. A power supply was available from the power distribution cabinet. The cabinet was in the inside of the SnowScat tower. The power line for the distribution was drawn along the scaffold up to the third platform. The power distribution outlet was secured by ELCB and over-voltage protection. The earthing was done via electrical cabinet and additionally the metal towers were connected to the ground.
As power-distribution, a network switchable power-socket (“energenie”) was used, that allows remotely triggered power-cycles at 4 single power strains (SnowScat Instrument, Synology Network Attached Storage (NAS), GAMMA Router, group of 6 Network cameras together with GammaPi).
On the test-sites an ad-hoc network was installed. As shown in Figure 2, components in the network were using either LAN or WLAN to connect to the Router (GAMMA Router). The router acts as well as internet-gateway via mobile connection (4G). The provider was “Wingo”, that uses the Swisscom grid and allows unlimited data connection. All instruments were accessible via VPN-connection from the GAMMA office network. In order to minimise sources for RFI for the passive measurements and in general to reduce radio-emissions, all devices were connected to LAN.
An alternative connection was implemented through a Raspberry Pi computer with an USB mobile dongle (Huawei) hosting a SMS gateway, that reacts pull requests and provides the instrument status. In addition, further functions (e.g. reboot, power-cycle) can be triggered, to investigate and potentially resolve issues during a router failure that results in a loss of remote access via VPN.

The SLF and Sensorscope weather stations have their own communication modules that transfer the data directly to the SLF and Sensorscope servers (www.climaps.com), respectively, via GSM connection. Control and data access for the latter is available through the climaps.com website, as well as in the campaign dataset.

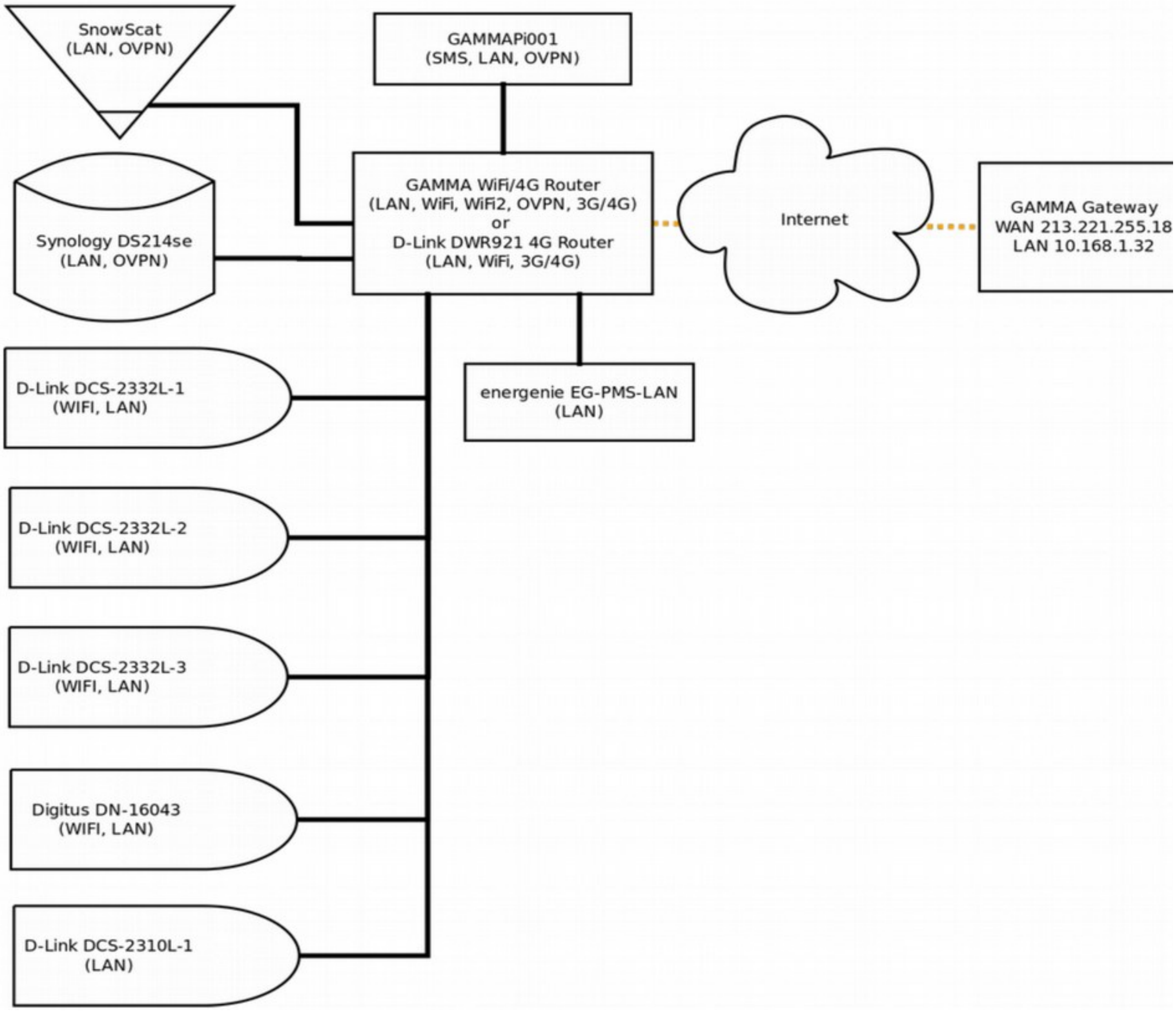

Figure 2: Network Diagram of esaSnowLab LAN.

3.1.3. Monitoring, quality control

The acquisition of the different measurements was the responsibility of the corresponding Workpackage (WP) Manager. Changes in the data acquisition plan and anomalies were documented in the electronic campaign log (hosted on the ESA SnowLab Redmine site https://redmine.gamma-rs.ch/projects/esa_snowlab/boards/4). The ESA SnowLab Project Manager (PM) reported the campaign progress monthly to the ESA Project Officer via the Redmine system. Anomalies that impact the campaign goals and planned actions are reported immediately by the WP manager to the PM and from the PM to the ESA Project Officer.

A monitoring concept was installed to identify anomalies early on. It included automated backup of the acquired data not only to the NAS co-located at the test site, but also to a storage at GAMMA. At GAMMA a near real-time processing was implemented. Processed data was then made available through E-mail and on the Redmine website. Table 1 below shows the details.

Table 1: System monitoring concept

Action	*Who*	*Schedule*	*Remarks*
SnowScat Backup to NAS	SnowScat	After each measurement	
NAS mirror to GAMMA	GAMMA14	Daily	E-mail notification if backup fails of data is missing
Reference Target Analysis	SnowScat	Before and after each Nominal Scan Cycle (8-12 times a day)	Compute reference target scatter coefficient and compare with theoretical value. Distribute results on Redmine. → SnowScat radiometric stability → Observation Geometry
Tomo Target Analysis	GAMMA14	Daily	Compute first order tomographic profile. Distribute results as PDF by mail and on Redmine. → SnowScat rail system → special snow conditions
Nominal Scan Analysis	GAMMA14	4-6 times a day	Average backscatter signal Distribute results on Redmine. → SnowScat overall performance → Nominal measurements are carried out
WBScat Range Plots	GAMMA14	4-6 times a day	Time domain plot of signal Distribute results on Redmine. → WBScat overall performance → Measurements are carried out
LAN check	GAMMAPI	Every 5 Min	Check all nodes in the local network Check Internet connectivity If anomaly is detected send a SMS Alarm → Sensors operational → Power supply/connection → Communications link
Webcam check	GAMMA14	Real time via Redmine campaign monitor	Make snapshot of a single image of all cameras → Camera operationally → Free field of view

3.2. Gerstenegg, winter 2015/2016

The test site for the winter 2015/2016 campaign was located in the Grimsel area on the municipal territory of Guttannen (Canton of Bern). The test site, named “Gerstenegg”, is located on the property of the "Kraftwerke Oberhasli AG" (KWO), close to the entrance to the turbine site entrance of the Plant Grimsel 2 (Figure 3).

The site has an elevation of 1706 m a.s.l. and is not accessible by road during the winter-closure of the pass road between Guttannen and Gletsch. However, due to an agreement with the KWO, access to the site was granted, via maintained road to Handeck and from Handeck with the cable-car to Gerstenegg. Access was possible only in accordance to the KWO safety protocol, maintained by the KWO avalanche service group.

Although the elevation of the site is relatively low, according to the KWO service, an average snow depth of max. approx. 1.2-1.5 m can be expected. For the duration of the campaign, the measured snow-depth at the observer weather station at Grimsel Hospiz (1970 m a.s.l.) recorded sub-average snow-depths (Figure 4). However, the maximum snow-depth recorded on 6. March 2016 on the SnowScat test-field reached 1.25 m measured at the tomographic calibration target.

Figure 3 Overview map with the location of the test site Gerstenegg in the Grimsel region (left). Snow-free (right top) and winter situation with snow-cover (right bottom) of the test site

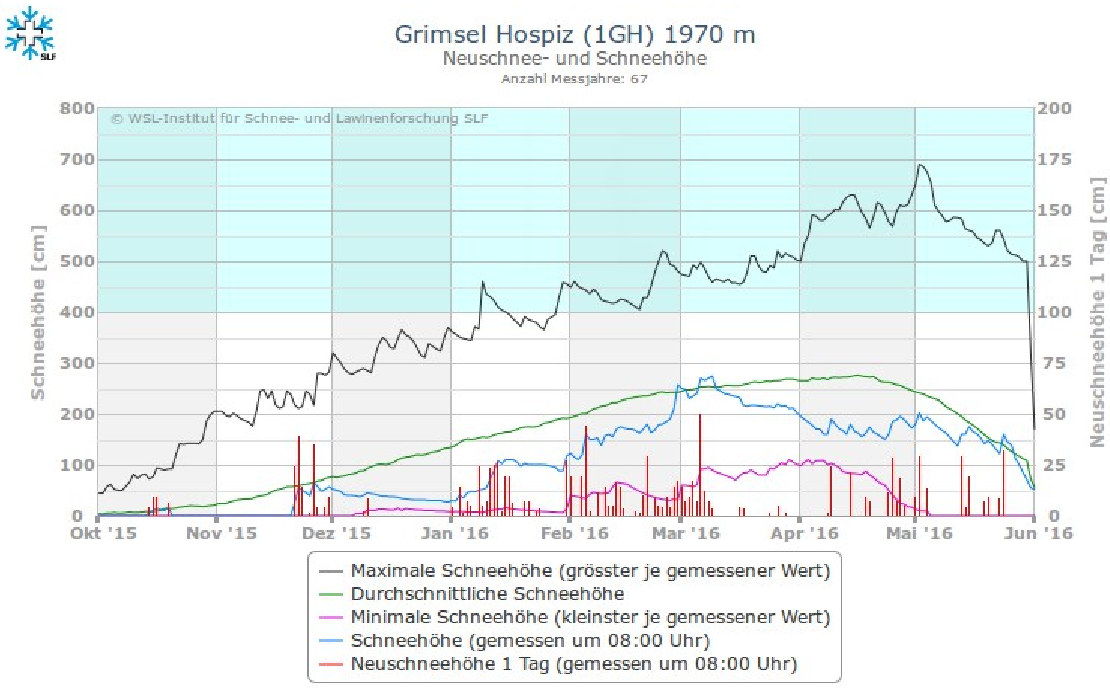

Figure 4 Measured snow depth at the Grimsel Hospiz (1970 m a.s.l.) together with maximum, minimum and average snow depth during the last 67 years.

3.2.1. Installation Details

The size of the test field was 35x30 m and was surrounded by a temporary fence (wood poles and nylon rope). The fencing was necessary to prevent any persons of disturbing the snow-cover within the area. Although, the access was limited, it is a popular starting point for ski-tourers. In addition, some of the poles were marked with a measuring colour scale of 20 cm each segment. This gives additional information on the snow-height around the test-site.

The tower was located on the north-western side of the rectangular test-field. It was built out of a metal scaffolding and had a height of 10 m above ground (top platform level). The tower was installed on 19. October 2015 and was removed on 10. June 2016. The SnowScat instrument, the communication devices, the web-cams and one GNSS receiver as well as the GNSS data boxes were installed on the scaffolding.

In front of the tower, three radiometric calibration targets for the SnowScat instrument were installed. Their locations are indicated in Figure 5 (magenta circles).

On a separate pole to the south west of the scaffolding tower, an automatic weather station was set up. One GNSS receiver antenna was mounted on top of the Pole (at ~3.5 m height above ground) and one was placed on the ground so that it got covered by snowfall and buried within the snow pack.

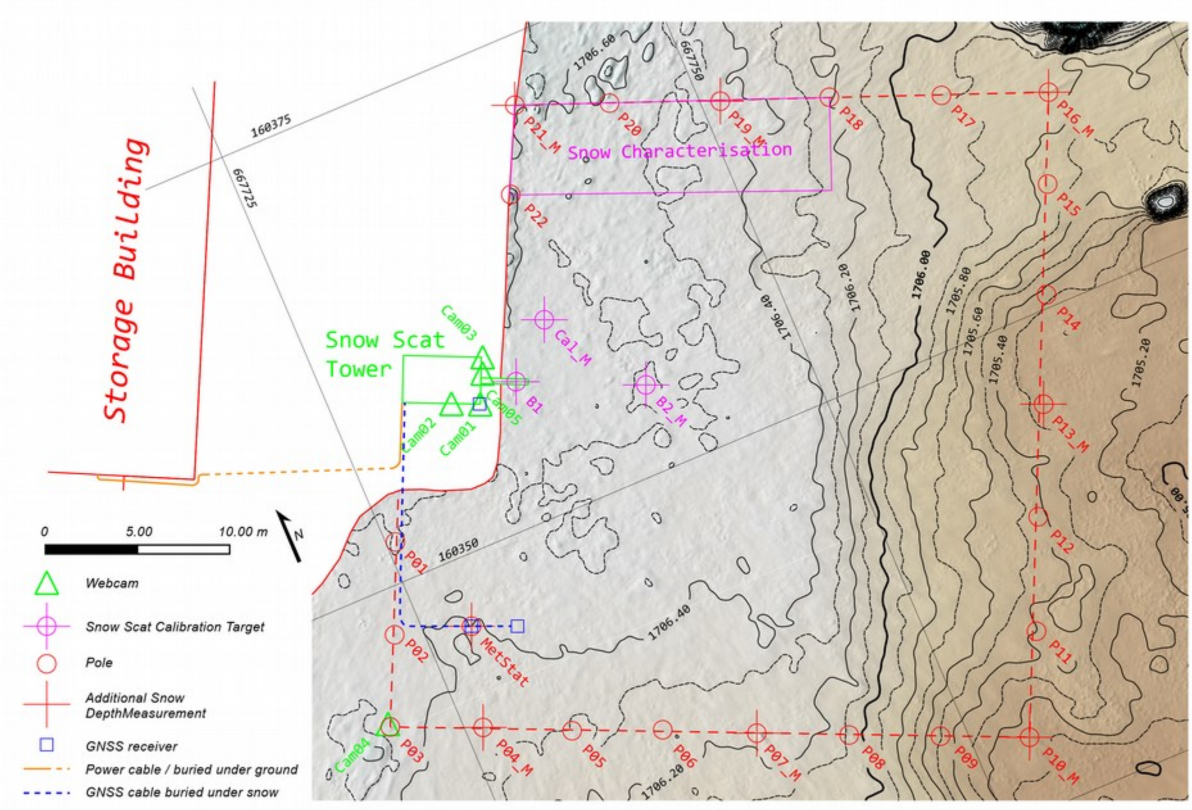

Figure 5: Detail map of the location of the Installations at the test-site Gerstenegg.

3.3. Laret, winters 2016-2019

The test site for the winters 2016-2019 campaigns were located close to the village Laret on the municipal territory of Davos (Canton of Grison) (Figure 6). The test site, named “Laret”, is located on communal property, dedicated to installations of public interest. The elevation is 1514 m a.s.l. The site itself sits on top of an old landfill that was in use from 1914-1949. Its content is mostly incineration slag. The surface is covered by a thin topsoil cover. The area is under agricultural use (meadow). Towards east, the site is shielded by the tree-line of the nearby forest.

Although, no long-term weather and snow data is available for this site, observations show that, in general, snow depth is greater than at the nearby wind observation station at the southern border of Lake Davos in Davos Dorf (Personal communication of Charles Fierz, SLF). The average snow depth for the long-term observation station at “Davos Flüelastrasse” is shown in Figure 7 in comparison to the recorded actual snow-cover situation taken during the two campaigns. The data support the assumption, that there is a comparable precipitation regime with slightly higher net-snow-accumulation. The snow situation during the 2017/18 and 2018/19 campaigns was above-average and in January 2018, the absolute maximum snow depth at the station Davos Stilli was observed since beginning of the recordings. At the Laret test site, the maximum recorded snow-depth was 193 cm on 16. March 2019.

A map view with the detailed topography is shown in Figure 8. The area of the test-field is not completely flat. Elevation differences of 2.5 m are present. The location of the two towers with the SnowScat/WBScat and radiometer instruments was selected to be in the bottom of the small valley-like structure. The orientation was set to be along this structure to measure in relatively flat terrain.

The site is accessible during the entire year by car. The nearby unpaved road is in a distance of 30 m from the location of the target. Neither the test site itself nor the land access is located in a zone prone to snow avalanche hazard. The closest permanently inhabited houses are in distances of 50 m to the left respectively 150 m in the centre line of the SnowScat tower.

The area, especially the small lake named “Schwarzsee”, that is located in the north-west of the test-site is frequented by promenaders and dog-owners during summer and winter season.

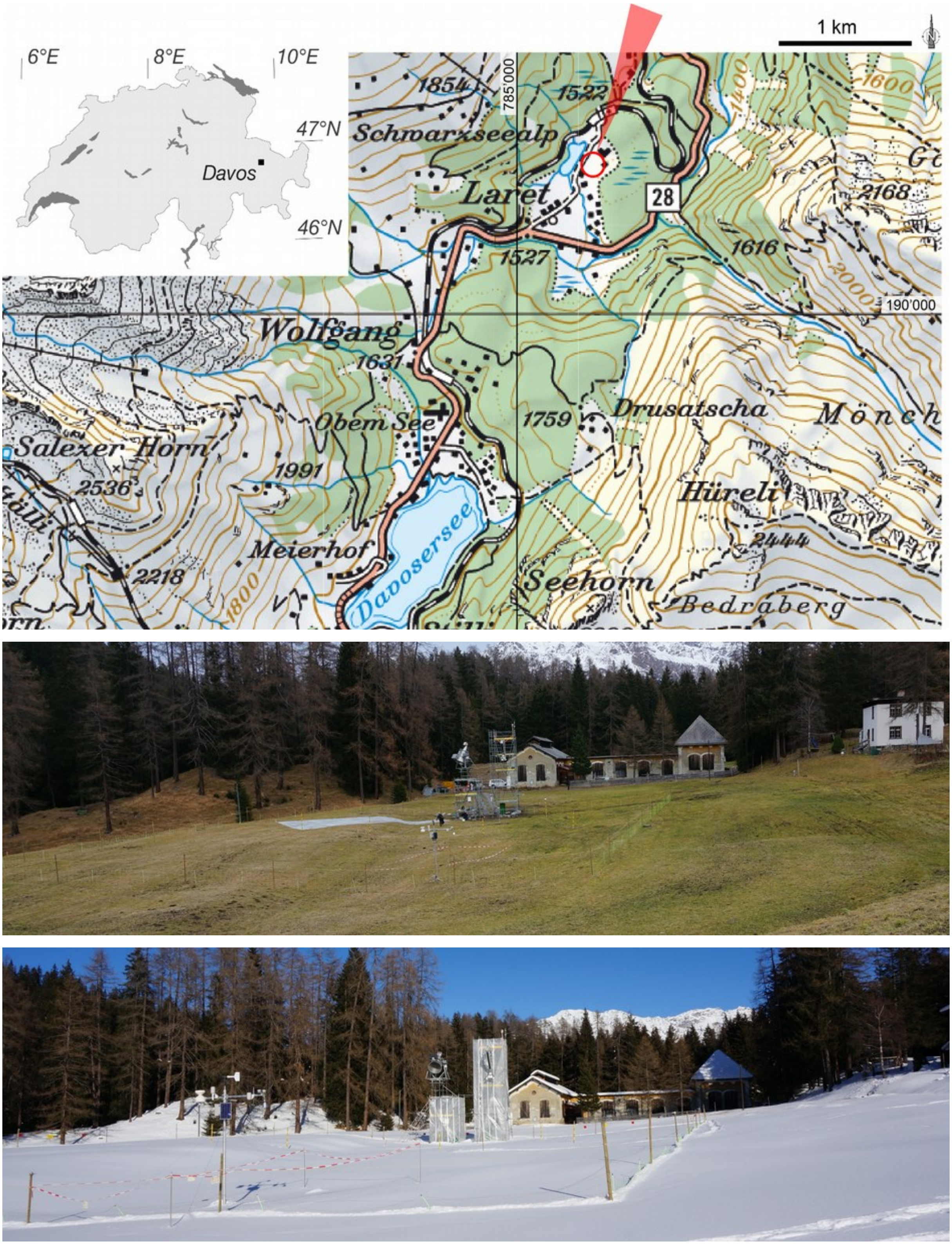

Figure 6 Overview map with the location of the test site Laret in the Davos region (top). Snow-free (middle) and winter situation with snow-cover (bottom) of the test site. Direction of the photographs is towards north-east.

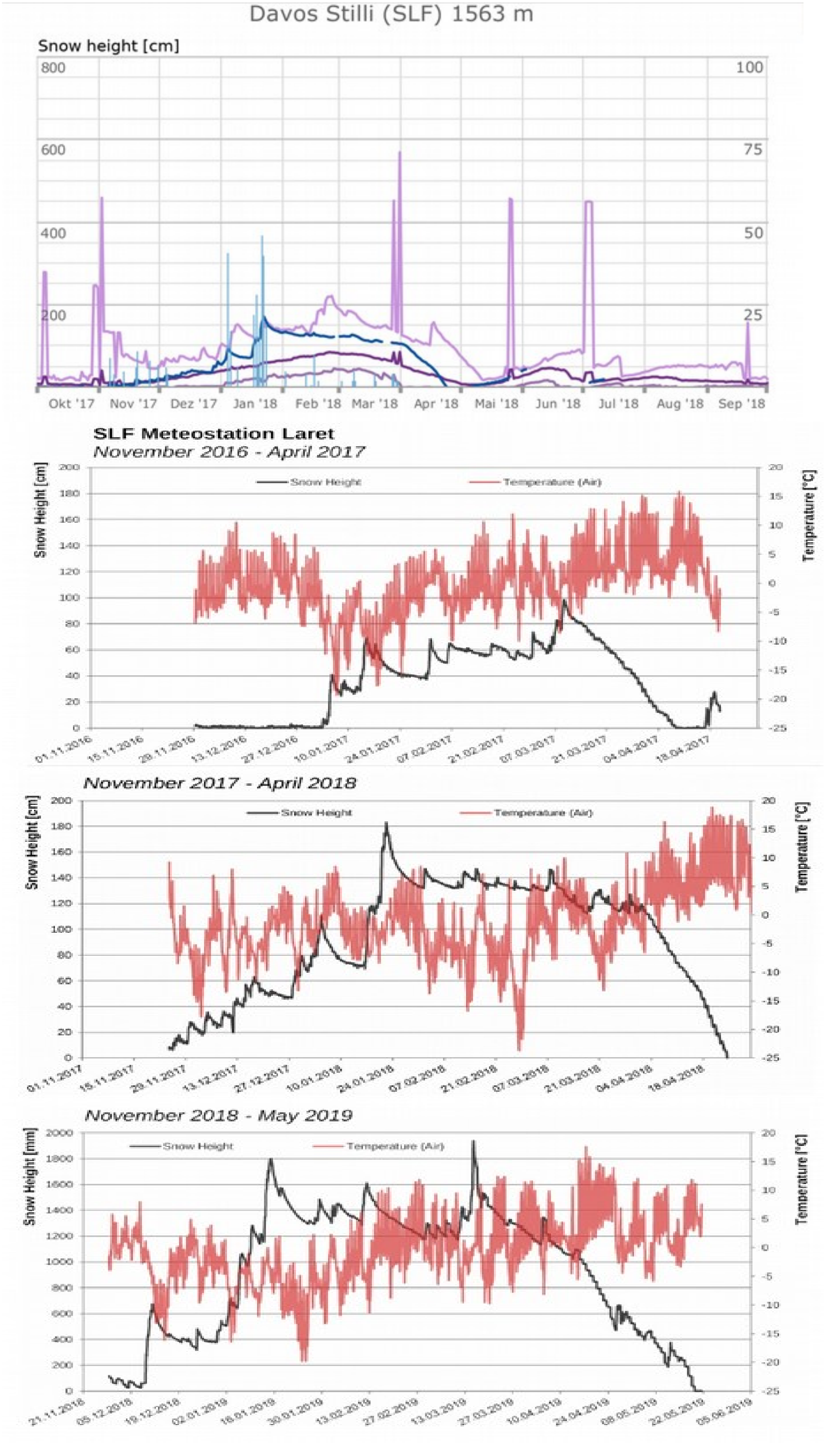

Figure 7

Top: Measured snow height at the long-term weather observation station "Davos Flüelastrasse" (1560 m a.s.l.) for Oct. 2017 to Sep. 2018 (in dark blue) together with maximum, minimum and average snow depth during the last 72 years.(Data from www.slf.ch)

Bottom: Recorded snow height and air-temperatures measured directly on the test-site Laret during the campaigns 2016/17, 2017/18, and 2018/19.

Installation Details

The general site-setup was the same for all campaigns at Laret. Only minor changes in the location of the temporary fencing of the test-site, the location of the soil sensors (MicroVegSnow) and the instrumentation of the SLF Weather station on the site were made (see Figure 8). In winter 2018/19 an adapted Julbara replaced ELBARA and WBScat was used rather than SnowScat.

The total size of the test-site was 55x50 m. It was protected against trespassing by a temporary fence (wood-pole, rope and sheep-netting fence below) and signalisation around the area. The eastern half of the test-site was reserved for active and passive microwave observations.

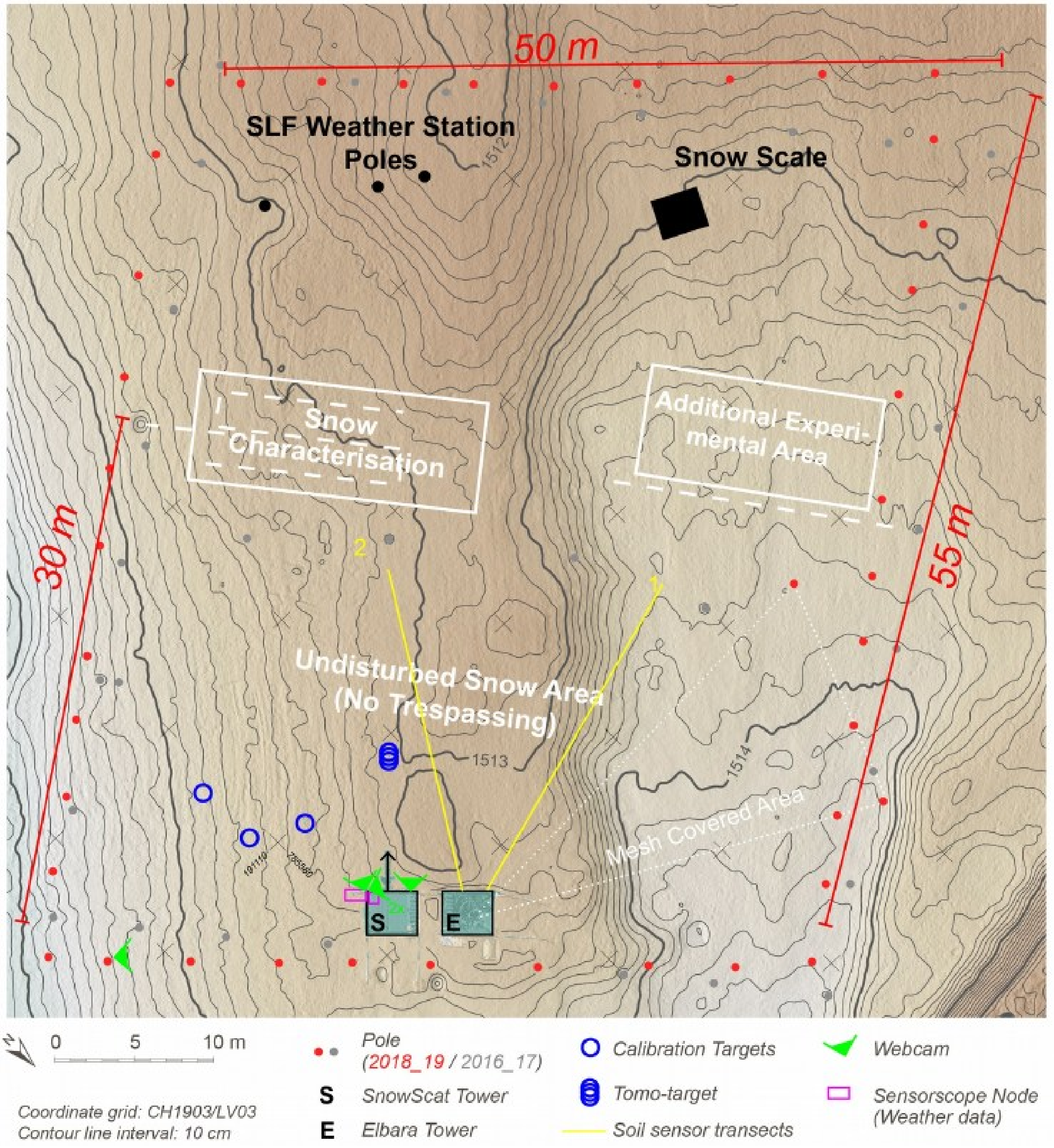

Figure 8 Detailed map view of the test-site Laret. The high-resolution topography was reconstructed using UAV Structure-from-motion photogrammetry recorded on 30.11.2016.

4. SENSORS, MEASUREMENTS

4.1. SnowScat

SnowScat was developed and built within the ESA ESTEC project KuScat contract No. 42000 20716/07/NL/EL. It is a continuous-wave stepped-frequency radar covering the frequency range from 9 to 18 GHz. The instrument is fully polarimetric and coherent. Within ESA ESTEC contract No. 200020716/07/NL/EL CCN3 the instrument was enhanced by a levelling sensor to measure the absolute levelling of the antenna. Furthermore, a rail (linear scanner) was designed and implemented that allows measuring at precise displacement steps so that tomographic acquisitions can be made. The rail system can be attached to a tower. For the ease of instrument access a removable balcony is implemented at the tower.

SnowScat acquired in 3 different operation modes: the signature scanning mode, the vertical sounding mode (altimeter mode) and the tomographic mode. As the measurements are coherent it is possible to investigate the interferometric phase and the corresponding interferometric coherence over time but also in range. To avoid conflicts among the modes and requirements on acquisition time and site equipment for each campaign a prioritisation list is made. In the first season the focus was on tomography, also to be able to develop the tomography analysis tools early on. To monitor the performance of the system a reference target (sphere) is regularly illuminated. Auxiliary targets (2 multi-sphere and 1 single sphere for absolute radiometric calibration) are also used for tomography and sounding mode to have an absolute reference in range.

Figure 10 shows the illuminated areas by the different modes. In the first winter campaign at Gerstenegg, the tomographic mode had the highest priority. At Laret the nominal scan mode was prioritized to have a full season dataset of signature measurements at a 6h interval.

Figure 9: SnowScat is mounted on the tomographic rail that allows a displacement along the rail of about 2.5m. In addition a Quickset pan- tilt-positioner allows to rotate to dedicated angles in elevation and azimuth.

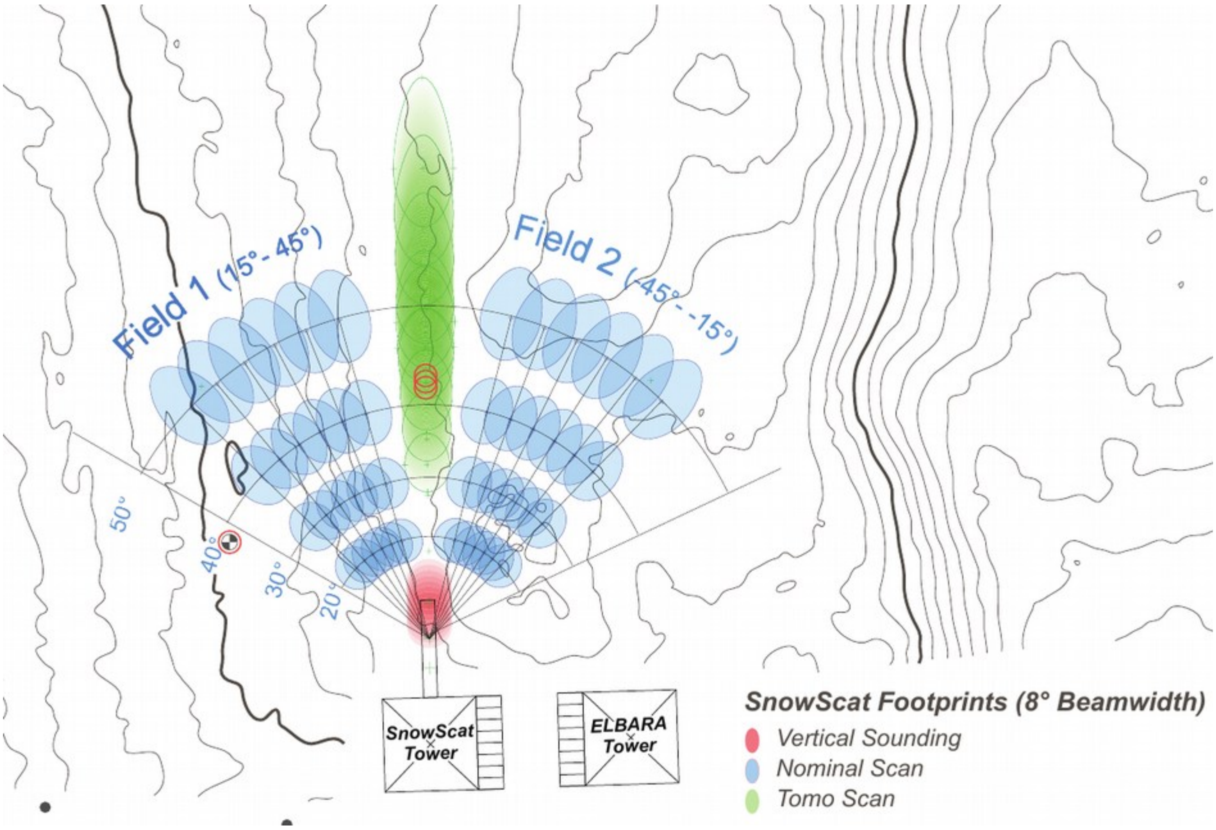

Figure 10: Experimental Setup of the different SnowScat and WBScat Measurement Modes at Davos Laret. At Gerstenegg a similar pattern was used but the reference sphere was located at a different location.Red circles indicate locations of reference targets.

4.2. WBScat

Figure 11: WBScat mounted on the SnowScat tomorail.

The wide-band scatterometer (WBScat) was developed under ESA contract (Contract No. 4000121522/17/NL/FF/mg) and was ready for testing and acquisition for the esaSnowLab campaign mid December 2018.

WBSCAT acquires fully polarimetric data in practically all-weather situations and temperatures (-40 to +50C). Based on our experience with SnowScat with respect to temperature control and construction to operate under severe environmental conditions, the WBSCAT microwave assembly has a temperature-controlled and insulated enclosure. The microwave electronics and computer that controls WBSCAT use separate enclosures to minimize temperature variations and avoid possible RFI. A Vector Network Analyzer (Keysight FieldFox N9951A) covering frequencies up to 44 GHz is used for signal generation and coherent measurement of the backscattered signal. An external calibration network with Short, Open, Load, Thru (SOLT) standards is used to calibrate the VNA and accurately measure the broad-band, low-noise amplifiers used in the receiver and transmitter. These amplifiers provide enough gain to overcome the high noise level of the VNA receiver. Quad-ridge horn antennas cover 1-6, 2-18, and 10-40 GHz with polarization isolation > 30 dB

4.3. Radiometers

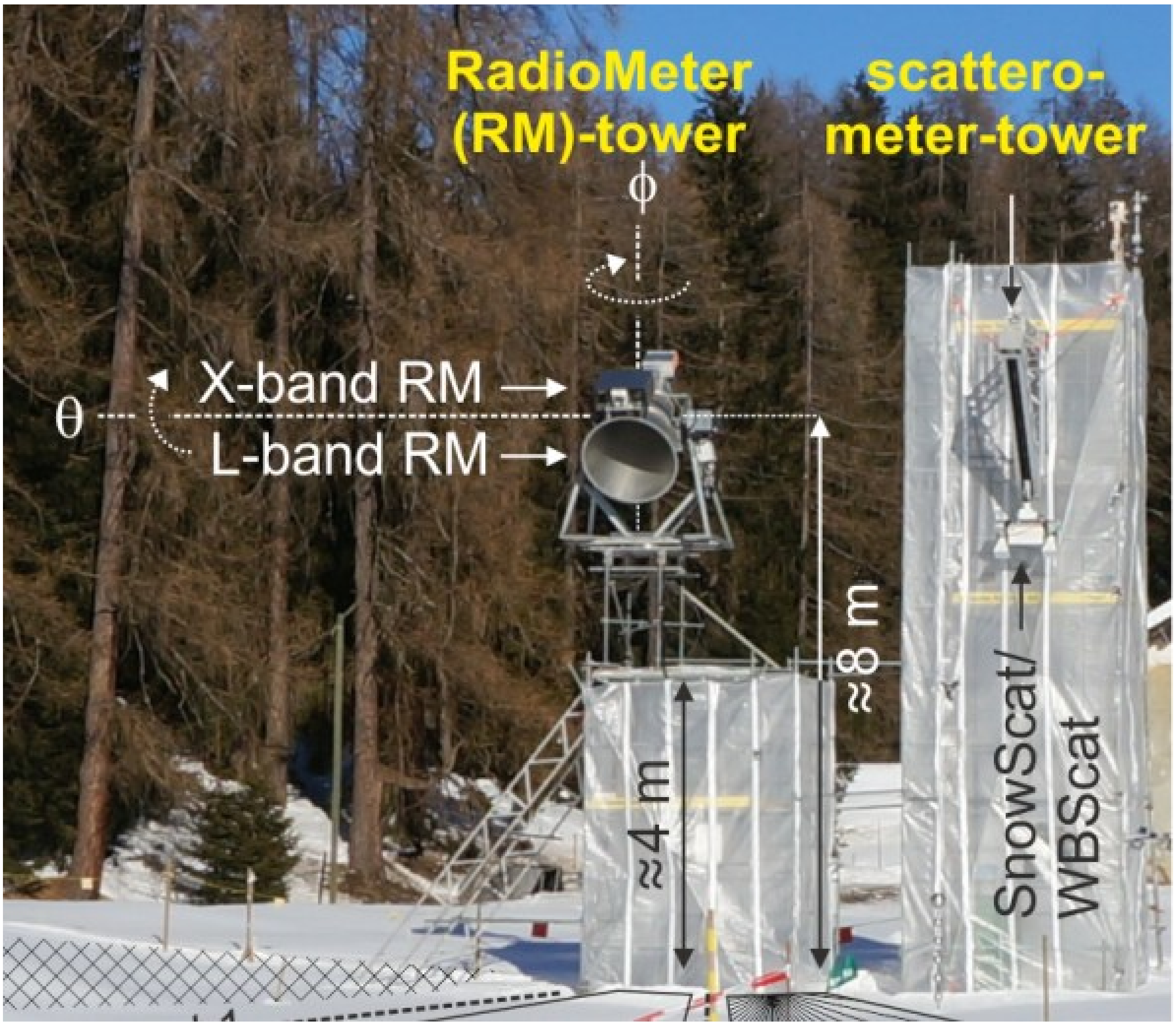

Figure 12: View of the radiometer and scatterometer from the measurement field.

The radiometer tower setup was installed in Davos-Laret, (Switzerland) in the second half of 2016 in the frame of the SNF lead agency project “Active/Passive Microwave Remote Sensing in Application to ”Vegetation & Soil” and “Snow & Soil” (MicroVegSnow). A detailed description of the site, and the passive microwave measurements performed during its first-year operation is presented in (Naderpour et al. 2017).

The passive close-range measurements conducted within the two MicroVegSnow winter campaigns (2016/2017 and 2017/2018) have been scientifically evaluated within the Ph.D. of Reza Naderpour. Within the SnowLab campaign 2018/19 the setup was repeated and the same measurement protocol was implemented. Instead of the ELBARA-II L-band radiometer, used during MicroVegSnow, the Winter campaign 2018/2019 was conducted with the “Office-Made-RAdiometer (OMRA). This radiometer was built within this CCN from a number of used RF components complemented with a new control and data-acquisition system. It has the same specifications as the ELBARA instrument.

4.4. Snow Characterisation

Snow characterisation information other than continuous snow height measurements of the weather station was gathered on a weekly basis and after larger snowfall events. The internal structure of the snow-pack was sampled with semi-destructive methods such as Snow-Micro-Pen (SMP) measurements (~2x/week) or destructive profiling with manually dug snow pit profiles (~1x/week). A detailed analysis of the micro-structure was done twice with micro-computed tomography (Micro-CT) in the SLF Laboratory.

Overall, the snowpack on the Laret site during winter 2017/2018 and 2018/2019 can be considered as extreme in view of vertical and lateral variability. This variability was mainly caused by several rain-on-snow events during the winter that caused preferential flow channels all over the site and obvious difficulties for measurements in the profile.

4.4.1. Snow Profiles

Once to twice a week, a complete snow pit profile was sampled at the test site. Parameters that were recorded include temperature profile, a density cutter profile and a near-infrared image (NIR) of the complete profile (Figure 13). For the processing of the NIR image, the original image (*.JPEG) was split into the colour channels R, G and B. The channel with the best histogram was selected for further processing. The one colour image was then filtered with an unsharpened mask filter 128x128. The resulting image gives a better qualitative impression of the snow stratigraphy. The file name of the resulting image contains which color channel was taken. NIR Photography was done using a Canon G10 (modified for NIR 850-1000 nm) with Filter X-Nite 850.

Additionally, a specific surface area (SSA) profile measurement using the IceCube Instrument (http://www.a2photonicsensors.com/medias/A2PS_IceCube_EN.pdf) was done to be able to compare the two methods.

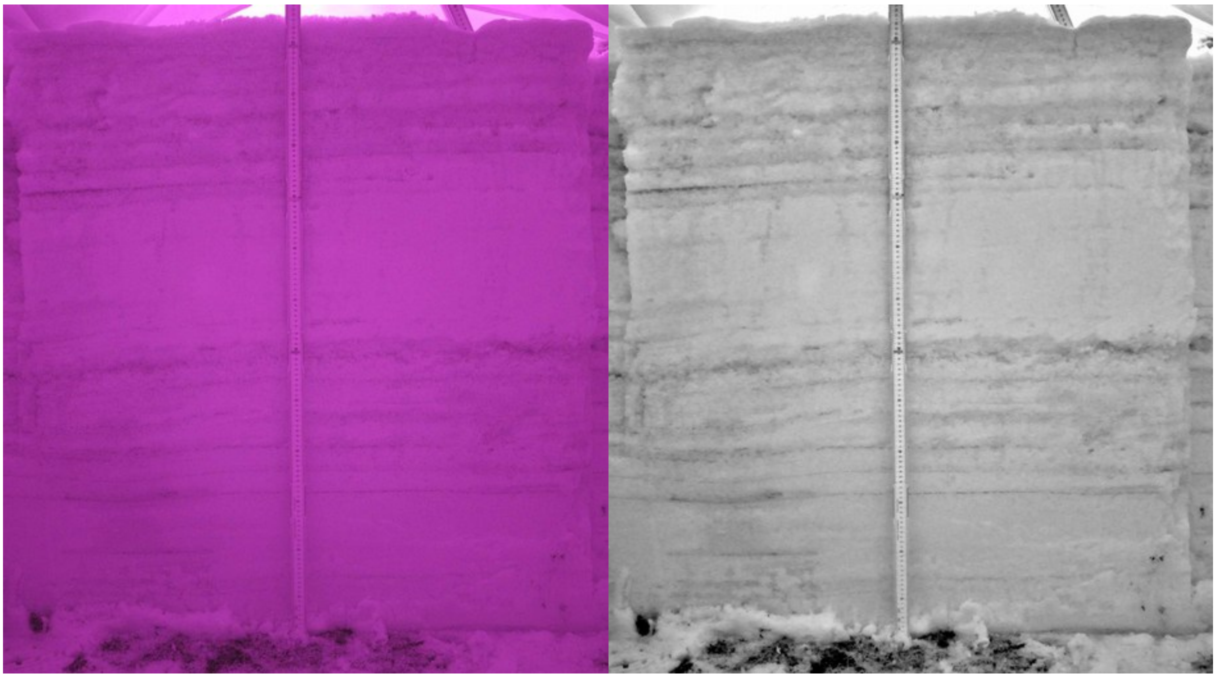

Figure 13 Raw NIR image on the left side and processed image on the right side. The picture shows the snow stratigraphy of the 13. March 2018 on the Davos Laret test site.

4.4.2. Snow Micro Pen (SMP)

The Snow Micro Pen is a variety of a Cone Penetration Test (CPT) and is developed by the SLF for the characterisation of the snow pack. In general, the penetration resistance is measured, while the measurement cone is inserted from the top of the snow column. The resolution of the SMP is better than 1 mm (sampling interval: 0.004 mm) to detect significant changes in resistance, thus allowing characterisation of different snow types (Schneebeli et al. 1999, Proksch et al. 2015).

In order to take account of the spatial inhomogeneity of the snowpack, each SMP sample consists of at least 5 individual profiles taken along a section with ~20 cm distance between sampling spots. SMP-Samples can be processed to density profiles as shown in Figure 14.

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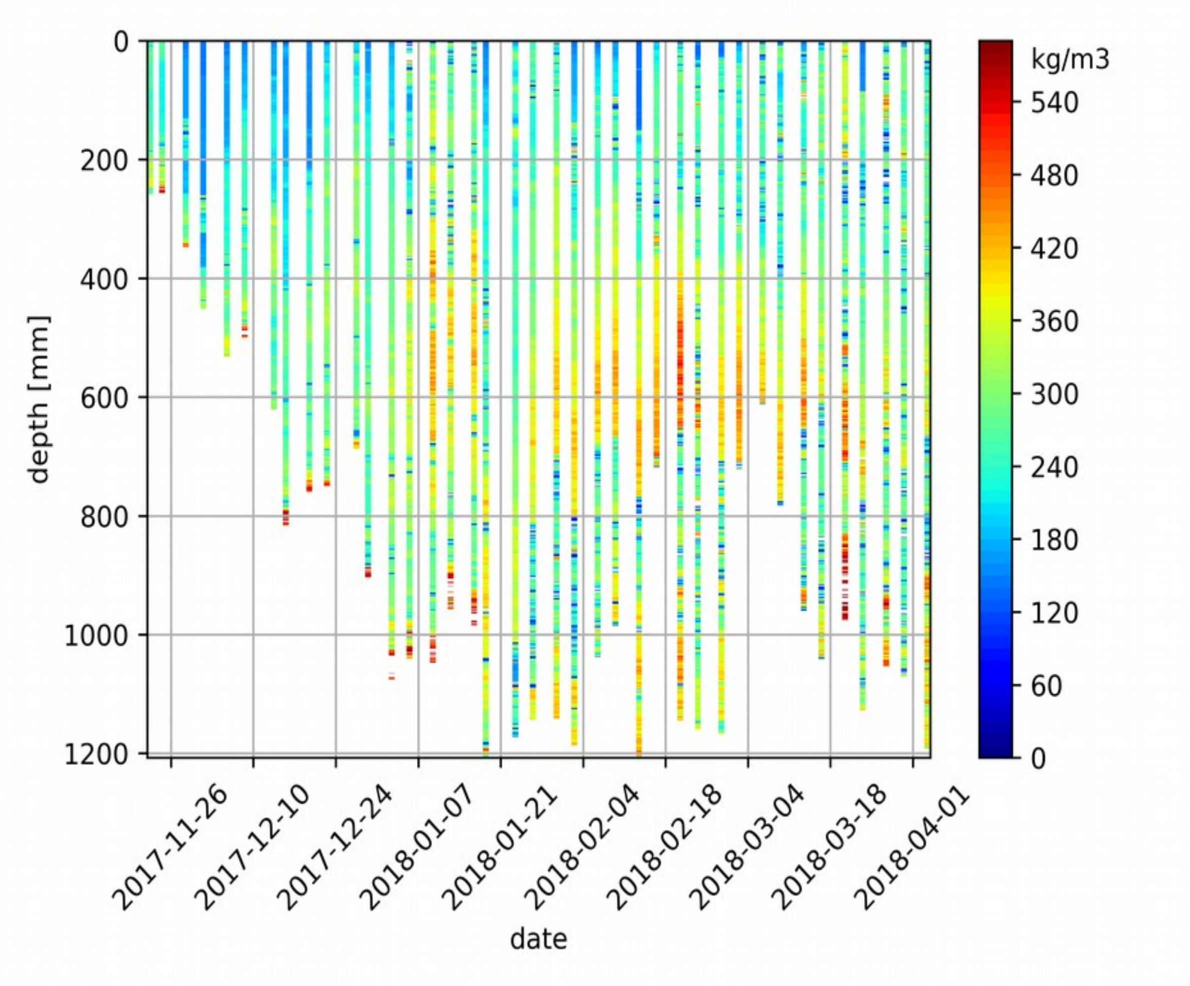


Figure 14 Color-coded density profiles of the last processed files of each SMP measurement day. The density ranges from 0 to 600 kg/m^3 with a step of 10 kg/m^3. Data was processed using snowmicropen (version v1.0.1).

4.4.3. Micro-CT

The three dimensional microstructure of snow was imaged with X-ray micro-computed tomography (micro-CT). Samples were taken on 28. November 2017, 20. February 2018 and 5. February 2019. Snow Blocks with dimensions of ~30x30x30 cm were cut-out. The samples were taken in an undisturbed part of the snow-profile wall, where temperature and density were measured before and near-infrared images were taken. On each day, blocks of snow were taken, which covered the whole snow column. The blocks of snow were transported with dry-ice to the cold laboratory (-20°C) of the SLF. There, samples with a height of 7.5 cm and a diameter of 2.7 cm were taken out of the snow block such that they were overlapping. These samples were scanned in the Micro-CT 40 of Scanco. The resolution of the resulting 3D images is 15 to 18 µm.

The tomography raw data was further processed through several analysis steps which lie in between the snow block extracted in the field and the final parameter profiles. The main Parameters are: density (Figure 15 and Figure 16), specific surface area (SSA) (Figure 16) and correlation lengths profiles (Figure 17).

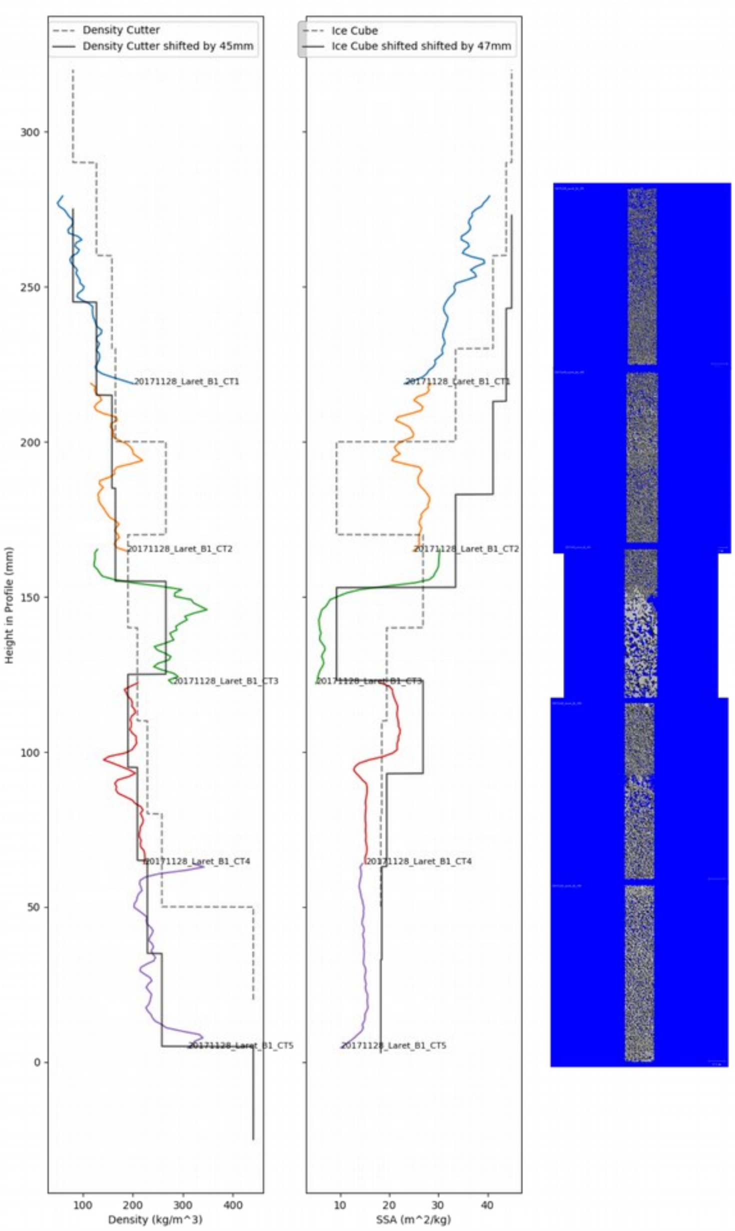


Figure 15 shows density and specific surface area derived from the 5 individual CT samples (different colours) together with a qualitative alignment of the 3D rendering of the microstructure. A satisfying alignment with IceCube Data requires a vertical shift due to spatial variability. Sample Date: 28.11.2017

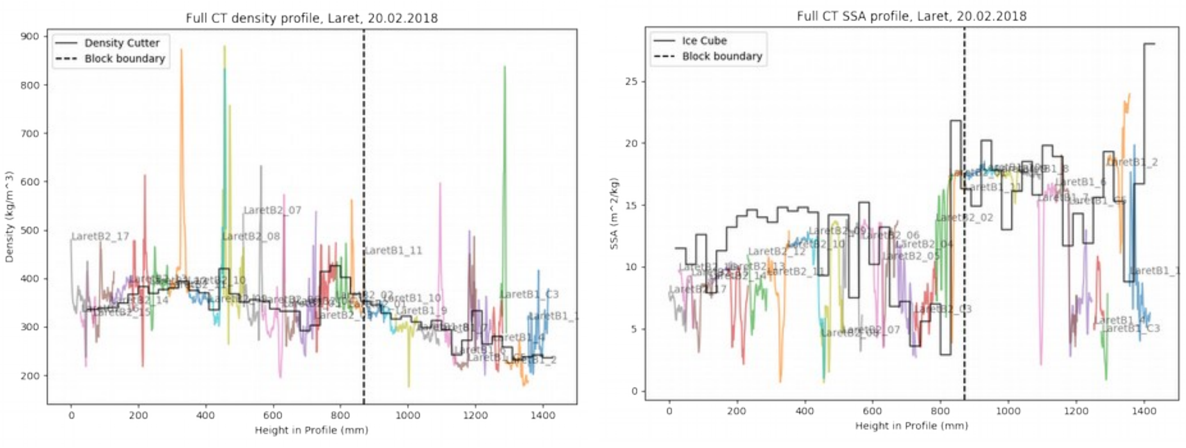


Figure 16 shows density and specific surface area derived from the 28 individual CT samples (different colours) which are manually stitched together to a full profile and compared to the data from Ice cube and density cutter from the snowprofile on the respective day. These profiles demonstrate the extreme variability of the snowpack after the several rain-on-snow events.

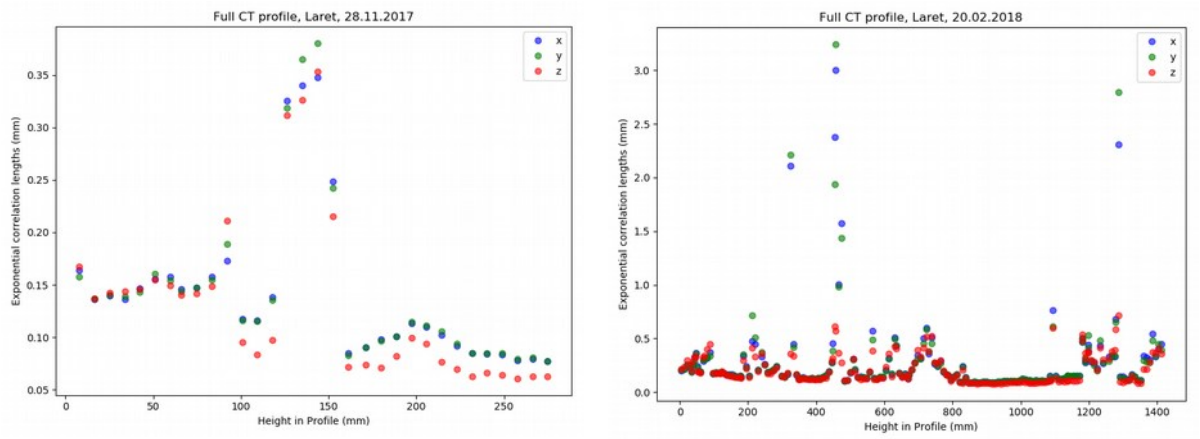


Figure 17 shows the profiles of the exponential correlation lengths in x, y, z for both CT days.(left: 28.11.2017; right: 20.2.2018)

4.4.4. UAV-Photogrammetry

On selected days, snow-height measurements were conducted with UAV photogrammetry without disturbing the snow cover. For the UAV measurements the "AscTec Falcon 8" drone and the "Sony Nex7" camera with a resolution of 24 Megapixel was used. The flight elevation above the ground was 15 to 20 m, which resulted in a ground sampling distance of 3 mm, an orthophoto-resolution of 5 mm and a DSM resolution of 1 cm. To avoid doming effects oblique imagery was done. 9 permanently installed reference points were measured with dGNSS (accuracy < 1 cm).

4.4.5. Photographic Site Documentation

The conditions of the instrumentation and the site were recorded visually with up to 6 automatic cameras. Three different camera models were used. All 6 cameras were automated network cameras, that automatically connected to the local network and provided a password protected management interface via https. Acquired images were transferred via LAN directly onto the NAS. Additional photos from the installation were taken each time the site was visited.

4.5. Auxiliary measurements

4.5.1. SLF Meteo Station

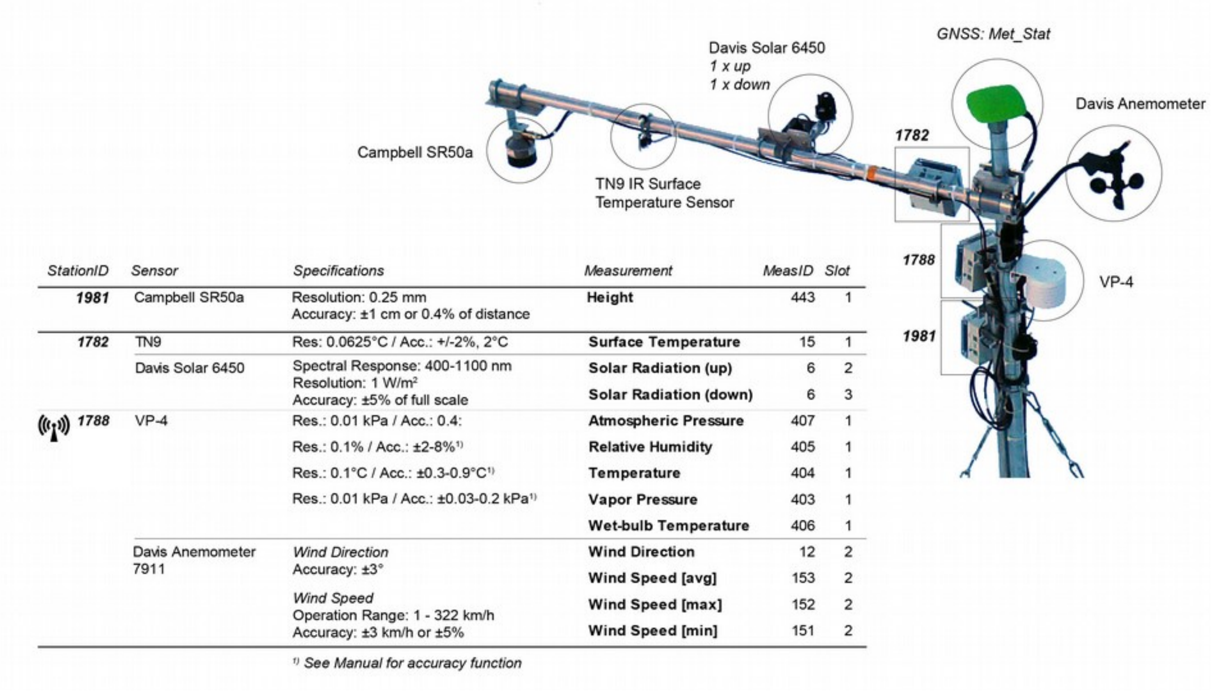
An automated weather station was installed on the site at Swiss coordinates (ch1903: 785'533 / 191'096). Installation and maintenance was done by SLF. Since the final tower for the weather station was not yet constructed, a temporary weather station was set-up at the western corner of the test-field (Figure 18). The temporal resolution of the data is 30 minutes (averaged).

Figure 18 SLF Weather station at the western corner of the test-site (Foto: 2.2.2018).

4.5.2. Sensorscope Meteo Station

For the real-time access of the data and for the supervision of the conditions at the SnowScat Tower, the automated weather station from Sensorscope was installed on site. A database with instant remote access to the data is as well maintained by Sensorscope via the climaps-portal (www.climaps.com). The following credentials can be used to access the data to the private station as read-only: (esaSnowLab/esaSnowLab). A detailed list of the sensors and the measured values is given in Figure 19.

For the Laret 2017/18 campaign, the sensor-nodes were placed at two different locations. Node 1788 (W, TA, H, P) was installed at the top of the scaffolding tower at a height of 12 m above ground. Nodes 1981 and 1782 were installed at the south-western corner of the tower at a height of 2.5 m above ground. At this position, snow height, snow surface temperature and short wave radiation were measured. Due to the vicinity of the tower, no undisturbed situation was present (reflections from plastic sheeting of the tower!). Data from the Sensorscope nodes are intended only for control purposes and should not be used for modelling.



StationID	Sensor	Specifications	Measurement	MeasID	Slot
1981	Campbell SR50a	Resolution: 0.25 mm Accuracy: ±1 cm or 0.4% of distance	**Height**	443	1
1782	TN9	Res: 0.0625°C / Acc.: +/-2%, 2°C	**Surface Temperature**	15	1
	Davis Solar 6450	Spectral Response: 400-1100 nm Resolution: 1 W/m^2 Accuracy: ±5% of full scale	**Solar Radiation (up)**	6	2
			Solar Radiation (down)	6	3
1788	VP-4	Res.: 0.01 kPa / Acc.: 0.4:	**Atmospheric Pressure**	407	1
		Res.: 0.1% / Acc.: ±2-8%$^{1)}$	**Relative Humidity**	405	1
		Res.: 0.1°C / Acc.: ±0.3-0.9°C$^{1)}$	**Temperature**	404	1
		Res.: 0.01 kPa / Acc.: ±0.03-0.2 kPa$^{1)}$	**Vapor Pressure**	403	1
			Wet-bulb Temperature	406	1
	Davis Anemometer 7911	*Wind Direction* Accuracy: ±3°	**Wind Direction**	12	2
			Wind Speed [avg]	153	2
		Wind Speed Operation Range: 1 - 322 km/h Accuracy: ±3 km/h or ±5%	**Wind Speed [max]**	152	2
			Wind Speed [min]	151	2

$^{1)}$ *See Manual for accuracy function*

Figure 19

Top: Sensor node description of the Sensorscope weather station (situation of Gerstenegg installation / No GNSS present during the Laret campaigns.

Bottom:Actual installation situation with separated sensor nodes at Laret during the campaign 2017/18: Sensor node 1788 at the top ot the tower (left). Sensor nodes 1781 and 1782 at the south-western corner of the tower (right).

5. RESULTS

5.1. Acquired Radar Data

The Tables 2 - 4 show the total numbers of SnowScat data acquisitions of the different measurement modes for the 3 winters. Figures 20 - 22 show the time-line of all acquisitions made during the 3 winters. While in the first winter the data acquisition was interrupted for a few days due to a failure of SnowScat, no gaps are present in the acquisitions during the two following winters.

Table 2: List of acquired SnowScat Data 2015/16.

	Total	*N° of Days*	*Nominal Acquisition rate [Acq/Day]*
Sphere Scans	837	149	6
Vertical Scans	250	89	3
Nominal Scans	834	149	6
Tomographic Scans	205	116	2-3

Table 3: List of acquired SnowScat Data 2016/17.

	Total	*Nominal Acquisition rate [Acq/Day]*
Vertical Scans	449	4
Nominal Scans	449 on each field	4 on each field
Tomographic Scans	115	1

Table 4: List of acquired SnowScat Data 2017/18.

	Total	*Nominal Acquisition rate [Acq/Day]*
Vertical Scans	620	4
Nominal Scans	620 on each field	4 on each field
Tomographic Scans	262 + 37 left looking	1 (4 during cold conditions)
2d Sphere Scans	20	1 per week

Table 5: List of acquired SnowScat Data 2018/19.

	Total	*Nominal Acquisition rate [Acq/Day]*
Vertical Scans	161	4
Nominal Scans	161 on each field	4 on each field
Tomographic Scans	12	1
2d Sphere Scans	~10	1 per week

Table 6: List of acquired WBScat Data 2018/19.

	Total	*Nominal Acquisition rate [Acq/Day]*
Vertical Scans	439	4
Nominal Scans	441 on each field/per band	4 on each field
Tomographic Scans	123	1 (4 during cold conditions)
2d Sphere Scans	~10	occasionally

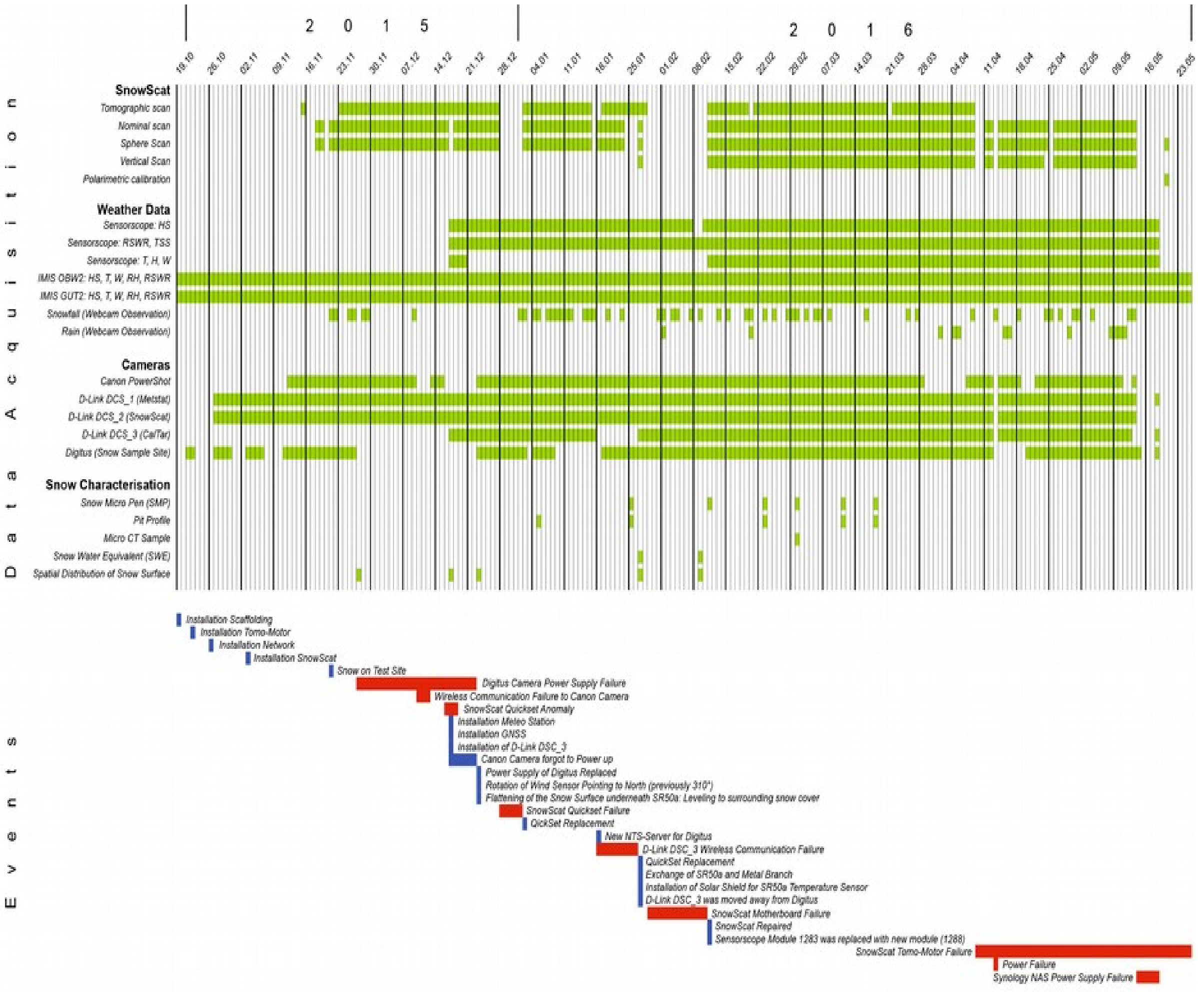


Figure 20: Data availability plot for the Winter 2015/16 campaign at Gerstenegg, Grimsel.

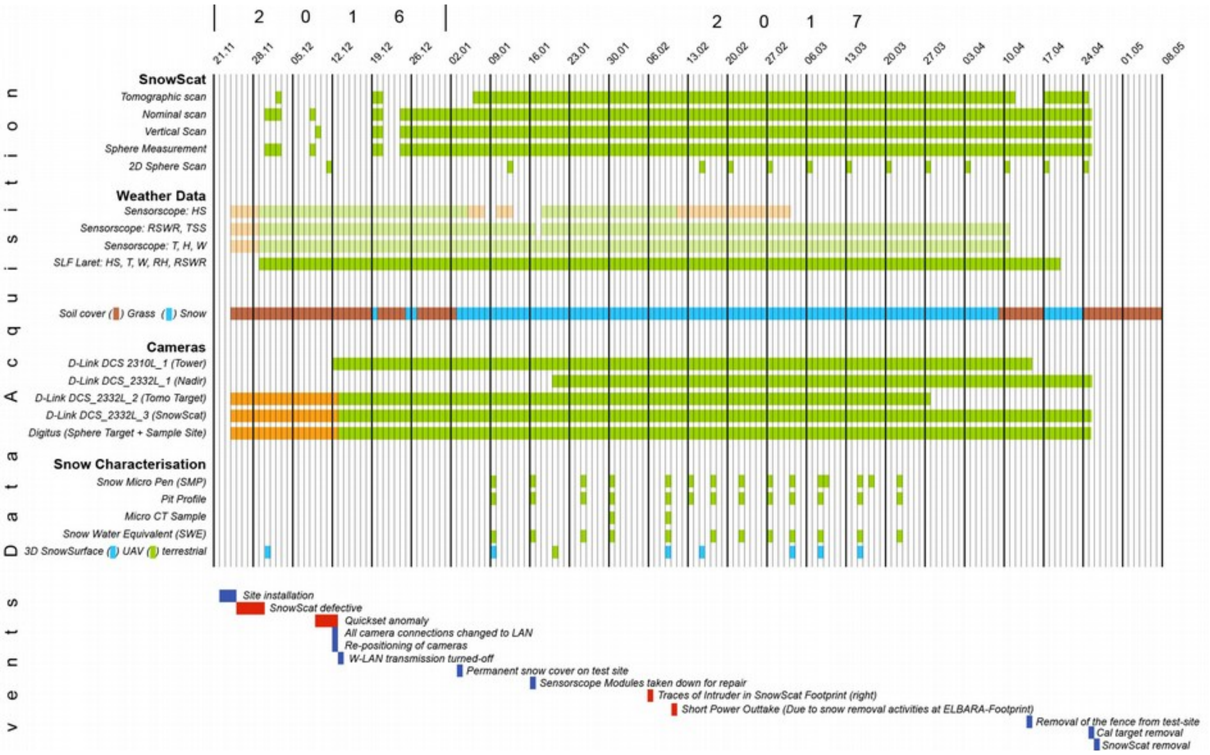


Figure 21: Data availability plot Winter campaign Laret 2016/17

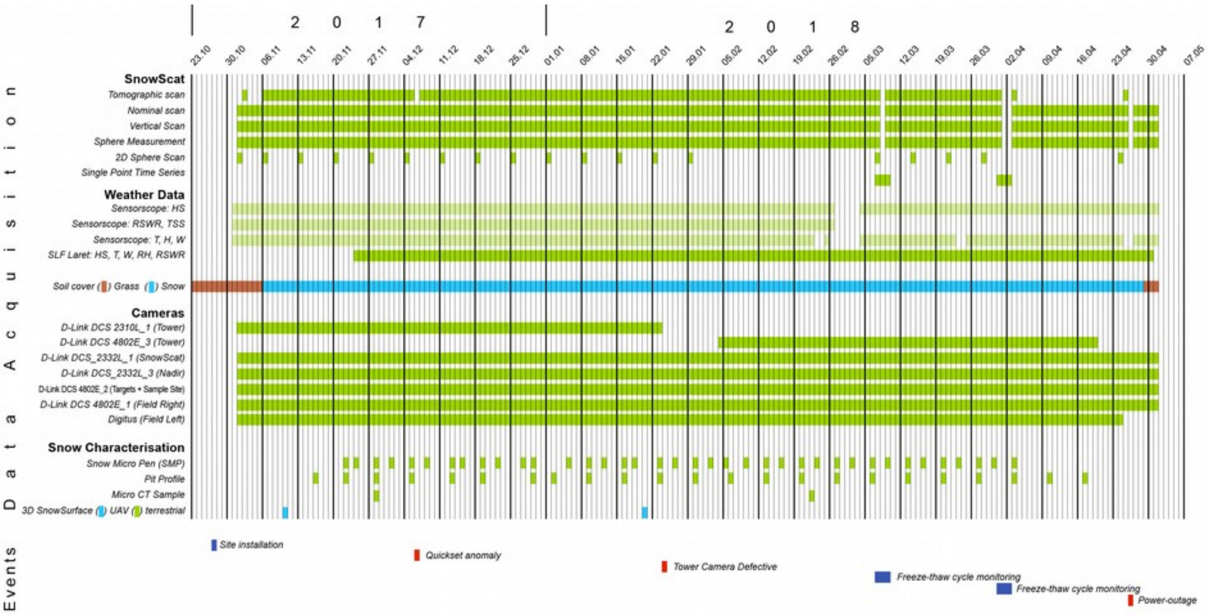


Figure 22: Summary chart showing the on-site data acquisitions and recorded incidences at daily resolution in winter 2017/18.

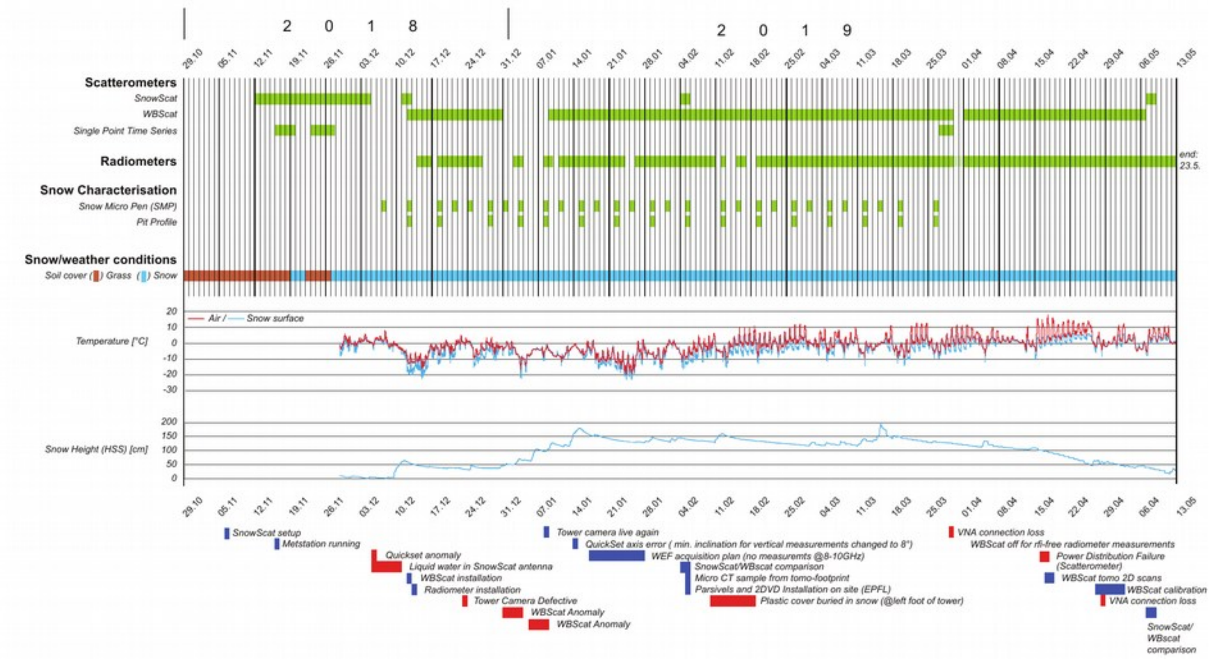


Figure 23: Summary chart showing the on-site data acquisitions and recorded incidences at daily resolution in winter 2018/19. For readability reasons the camera acquisitions are not shown explicitly. Cameras are measuring at 10 minute intervals if not stated otherwise in the issues list above.

5.1.1. Nominal Measurements

Nominal measurements were conducted on a regular schedule and at least 4 times a day. They cover the azimuth and elevation scan of 2 sections of the test site. The measurement of several azimuth angles allows to increase the number of looks for a selected incidence angle. For each season the signature time series are shown below. While stable dry winter snow shows smooth backscatter trends, periods with melt freeze events show high dynamic in the backscattering coefficient. In winter 2018/19 SnowScat was used until WBScat became available and then for intercomparison during selected occasions.

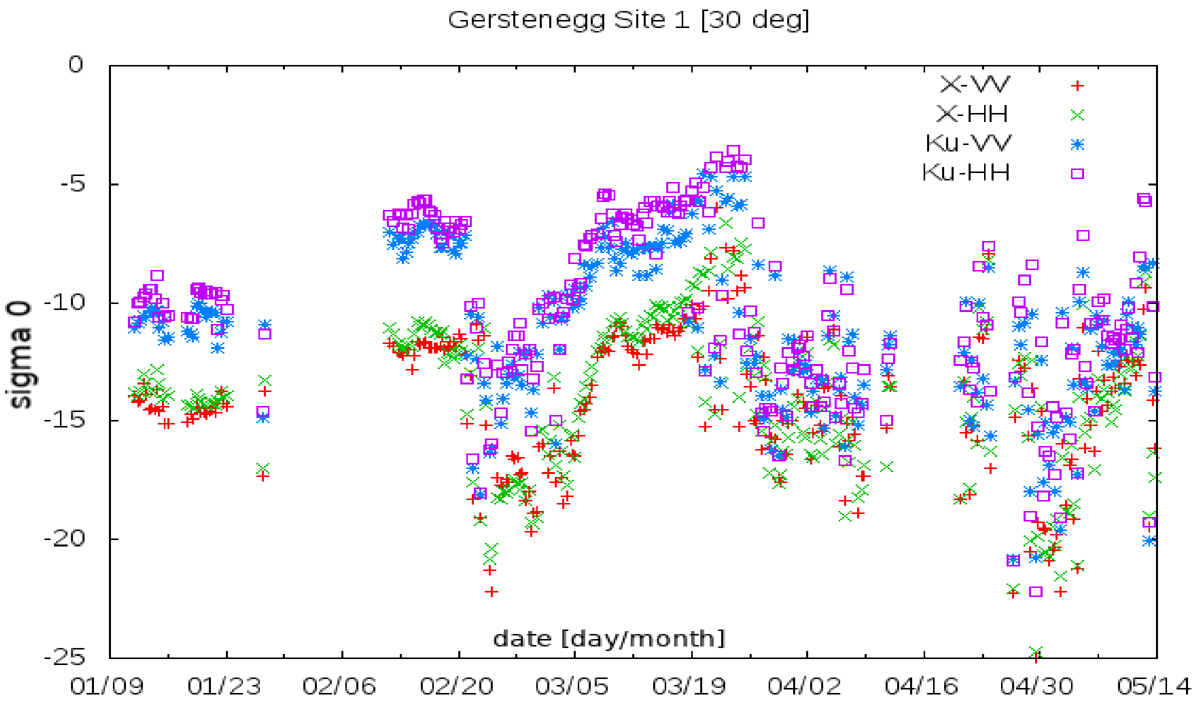


Figure 24: Example of SnowScat time series of sigma zero normalized radar cross section obtained from the nominal slant-range scans after L1b radiometric calibration of the channels HH and VV at 30 degrees incidence angle. X-band is 10.2 GHz with 2 GHz bandwidth, Ku-band is 16.7 GHz with 2 GHz bandwidth. Valid sigma zero backscatter data of the snowpack was obtained until beginning of April 2016. Testsite: Gerstenegg 2015/2016.

σ

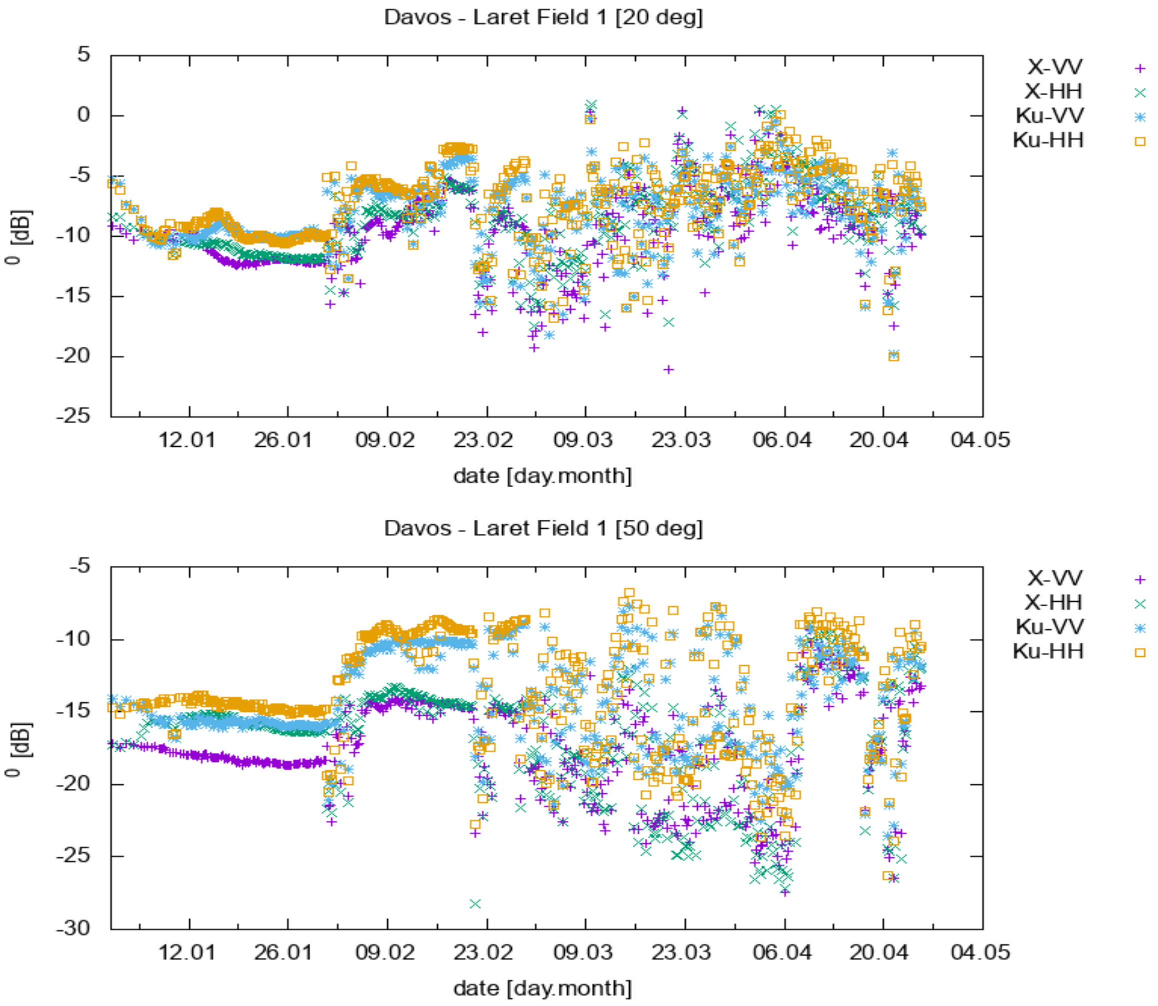


Figure 25: Example of SnowScat time series of sigma zero normalized radar cross section obtained from the nominal slant-range scans after L1b radiometric calibration of the channels HH and VV at 20 (top) and 50 (bottom) degrees incidence angle. X-band is 10.2 GHz with 2 GHz bandwidth, Ku-band is 16.7 GHz with 2 GHz bandwidth. Valid sigma zero backscatter data of the snowpack was obtained until end of April 2017. Testsite: Davos Laret 2016/2017. Field 1.

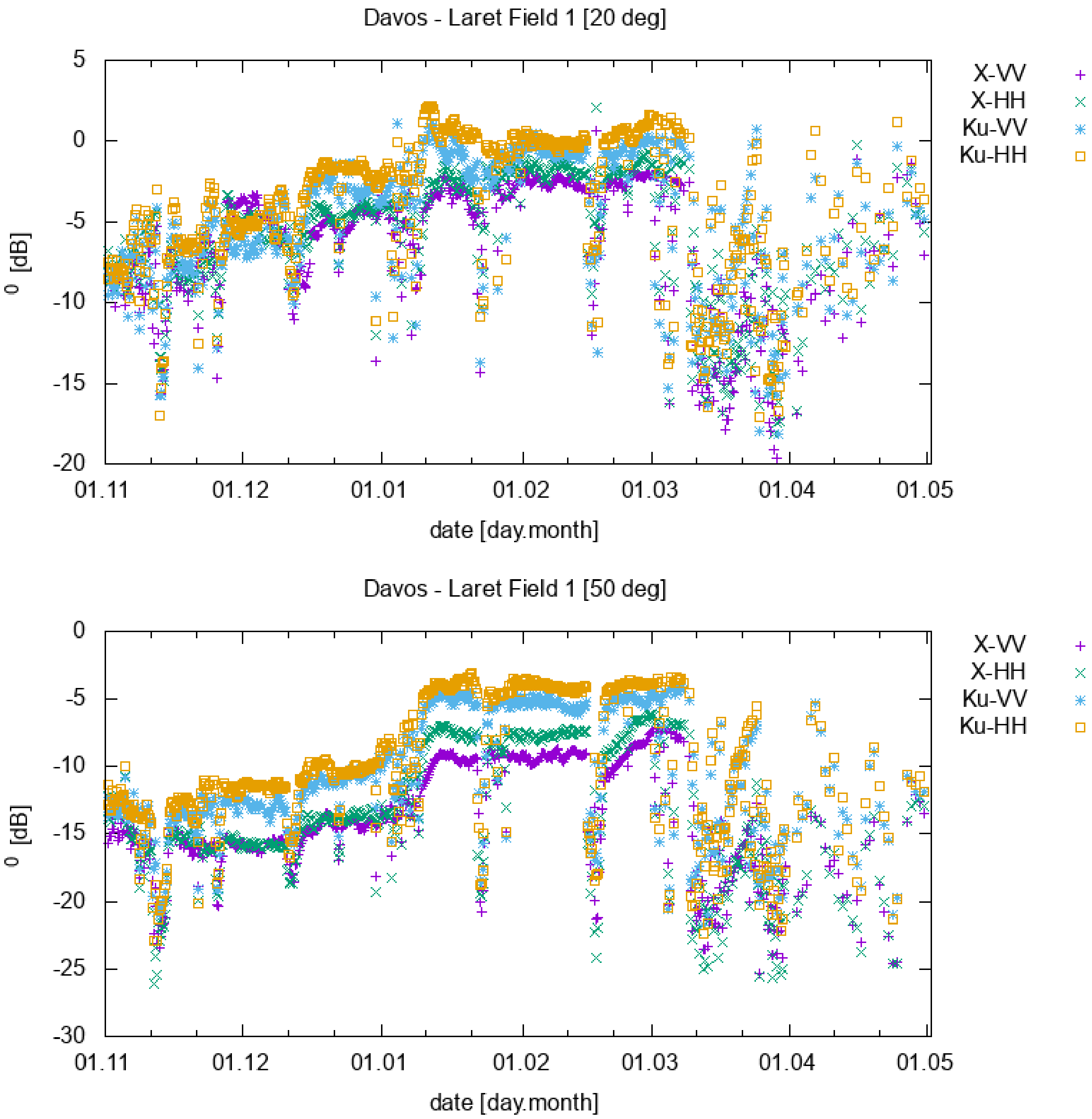


Figure 26: Example of SnowScat time series of sigma zero normalized radar cross section obtained from the nominal slant-range scans after L1b radiometric calibration of the channels HH and VV at 20 (top) and 50 degrees incidence angle (bottom). X-band is 10.2 GHz with 2 GHz bandwidth, Ku-band is 16.7 GHz with 2 GHz bandwidth. Valid sigma zero backscatter data of the snowpack was obtained until end of April 2018. Testsite: Davos Laret 2017/2018. Field 1.

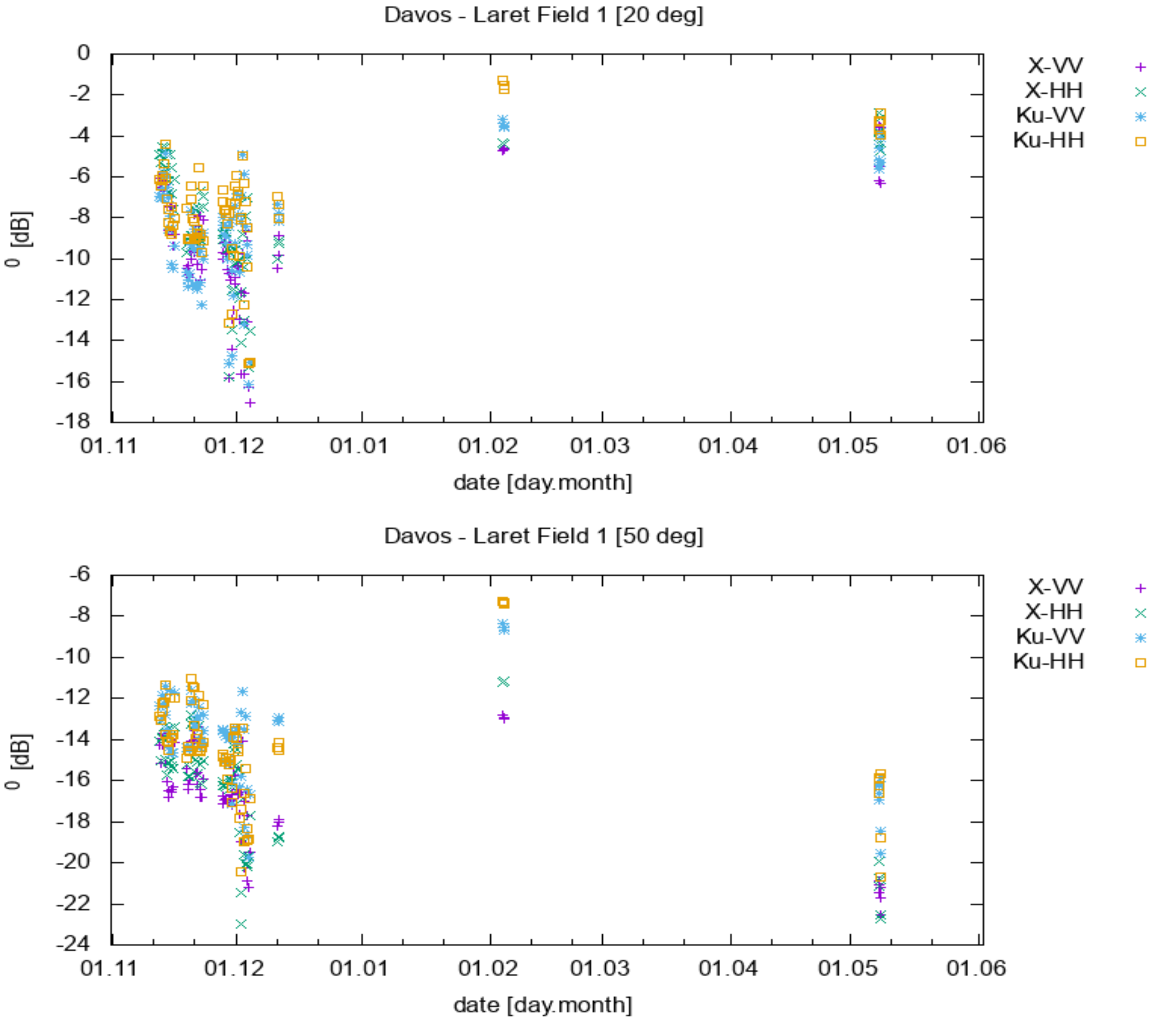


Figure 27: Example of SnowScat time series of sigma zero normalized radar cross section obtained from the nominal slant-range scans after L1b radiometric calibration of the channels HH and VV at 20 (top) and 50 degrees incidence angle (bottom). X-band is 10.2 GHz with 2 GHz bandwidth, Ku-band is 16.7 GHz with 2 GHz bandwidth. Valid sigma zero backscatter data of the snowpack was obtained until early May 2019. Testsite: Davos Laret 2018/2019. Field 1.

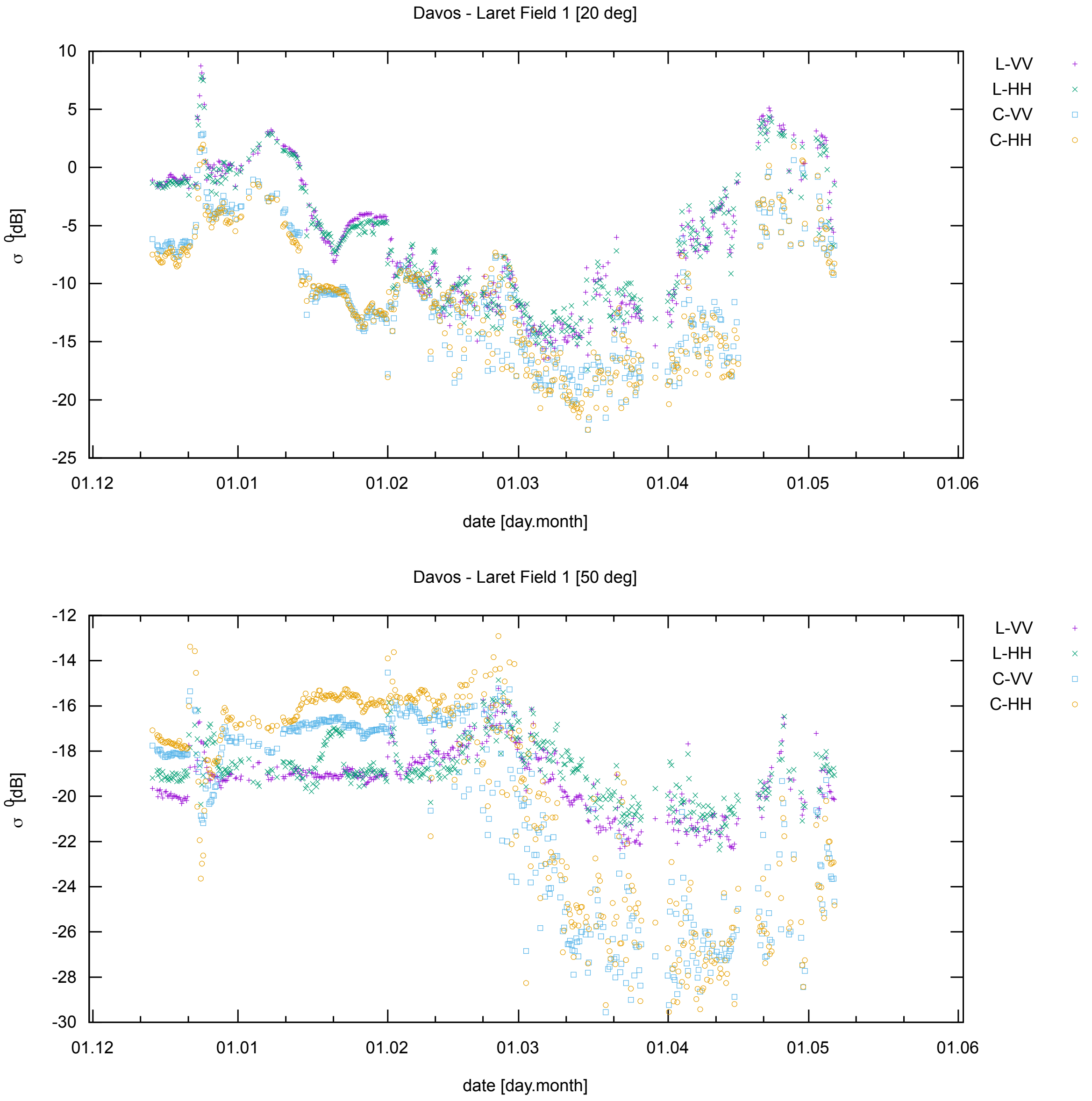
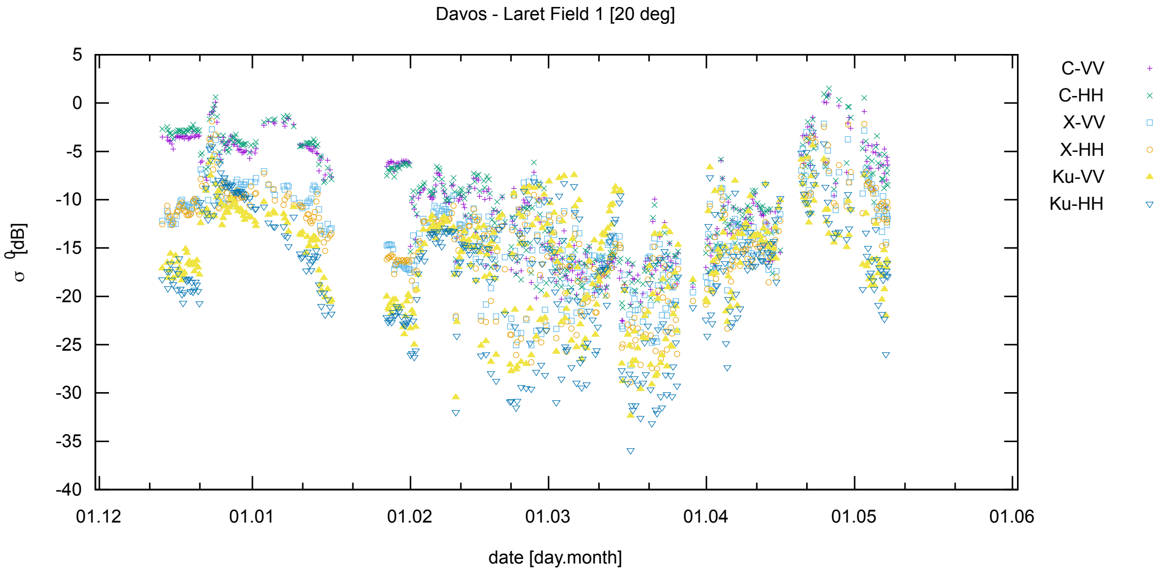


Figure 28: Example of WBScat time series of sigma zero normalized radar cross section obtained from the nominal slant-range scans after L1b radiometric calibration of the channels HH, VV at 20 (top) and 50 degrees incidence angle (bottom). Frequency 2 GHz and 5 GHz with 2 GHz bandwidth. Valid sigma zero backscatter data of the snowpack was obtained until early May 2019. Testsite: Davos Laret 2018/2019. Field 1.



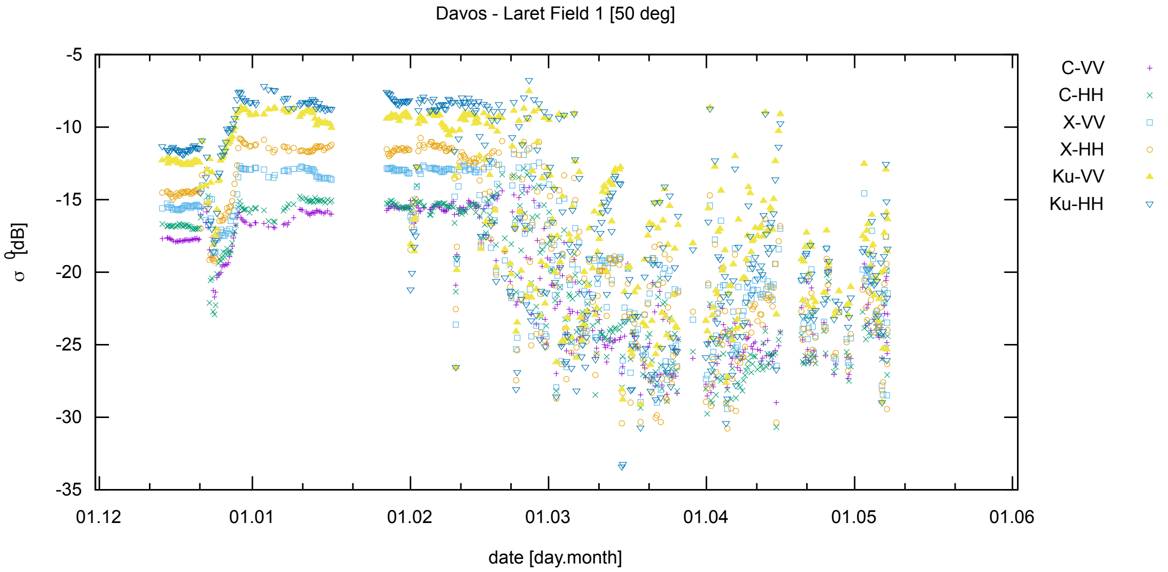


Figure 29: Example of WBScat time series of sigma zero normalized radar cross section obtained from the nominal slant-range scans after L1b radiometric calibration of the channels HH, VV. Frequency 6 GHz, 10 GHz and 16 GHz with 3 GHz bandwidth. Valid sigma zero backscatter data of the snowpack was obtained until early May 2019. Testsite: Davos Laret 2018/2019. Field 1.

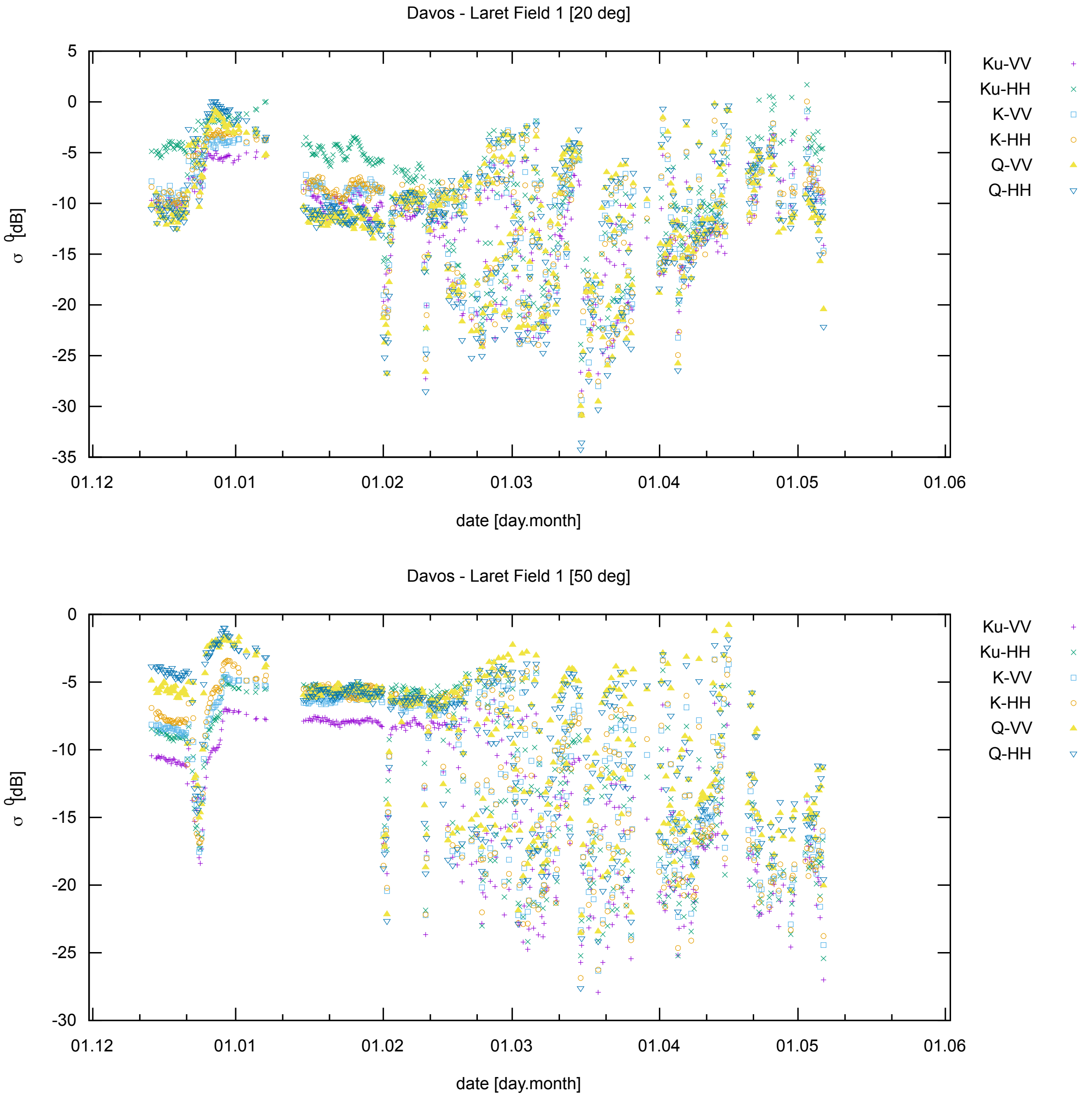


Figure 30: Example of WBScat time series of sigma zero normalized radar cross section obtained from the nominal slant-range scans after L1b radiometric calibration of the channels HH, VV at 20 (top) and 50 degrees incidence angle (bottom). Frequency 18 GHz, 24 GHz and 36 GHz with 4 GHz bandwidth. Valid sigma zero backscatter data of the snowpack was obtained until early May 2019. Testsite: Davos Laret 2018/2019. Field 1.

5.1.2. Tomography

Within the project a major task was the development of a Tomography Analysis Tool for the ESA SnowScat device. The Tomography Analysis Toolbox (TAT) was developed in Octave. Octave is free and open source software (FOSS). The Octave interpreter can be run in graphical user interface (GUI)-mode, or on the command line in a terminal window. The tomographic processing can be run as an Octave script or it can be run as part of a shell script. This allows to use the tool within a shell-script-based near-realtime processing during the campaign as well as to use it within the user-friendly open source software environment of Octave. The tools including documentation were delivered to ESA as D4 Tomography Analysis Tool.

The tool was used within the project to process the tomographic data. Tomographic measurements were conducted on a regular base, usually around midnight to avoid decorrelation of the snowpack within the data acquisition time of 2 hours. Two sample plots are shown below.

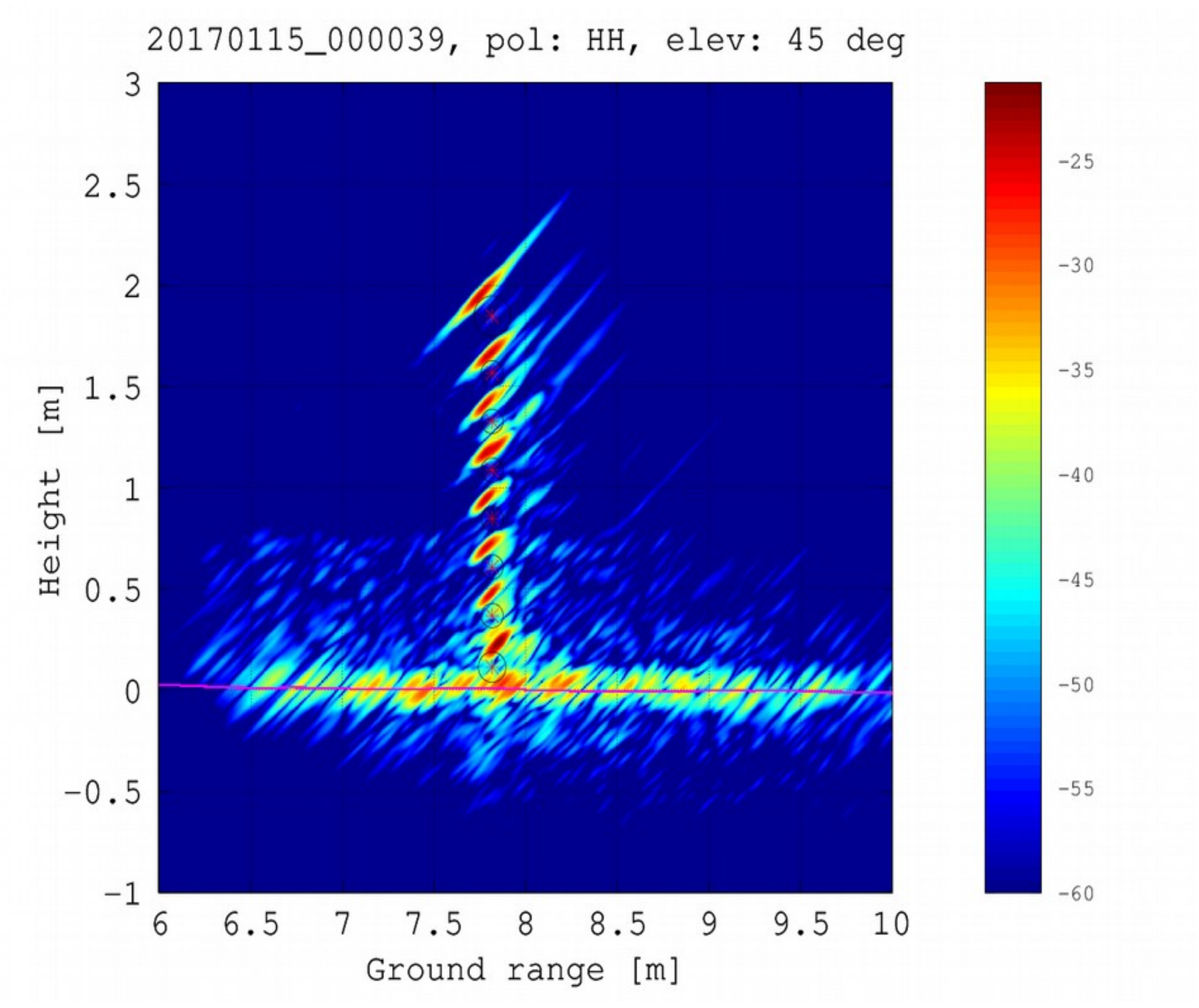


Figure 31: Situation with 80 cm of dry snow on 15.1.2015.

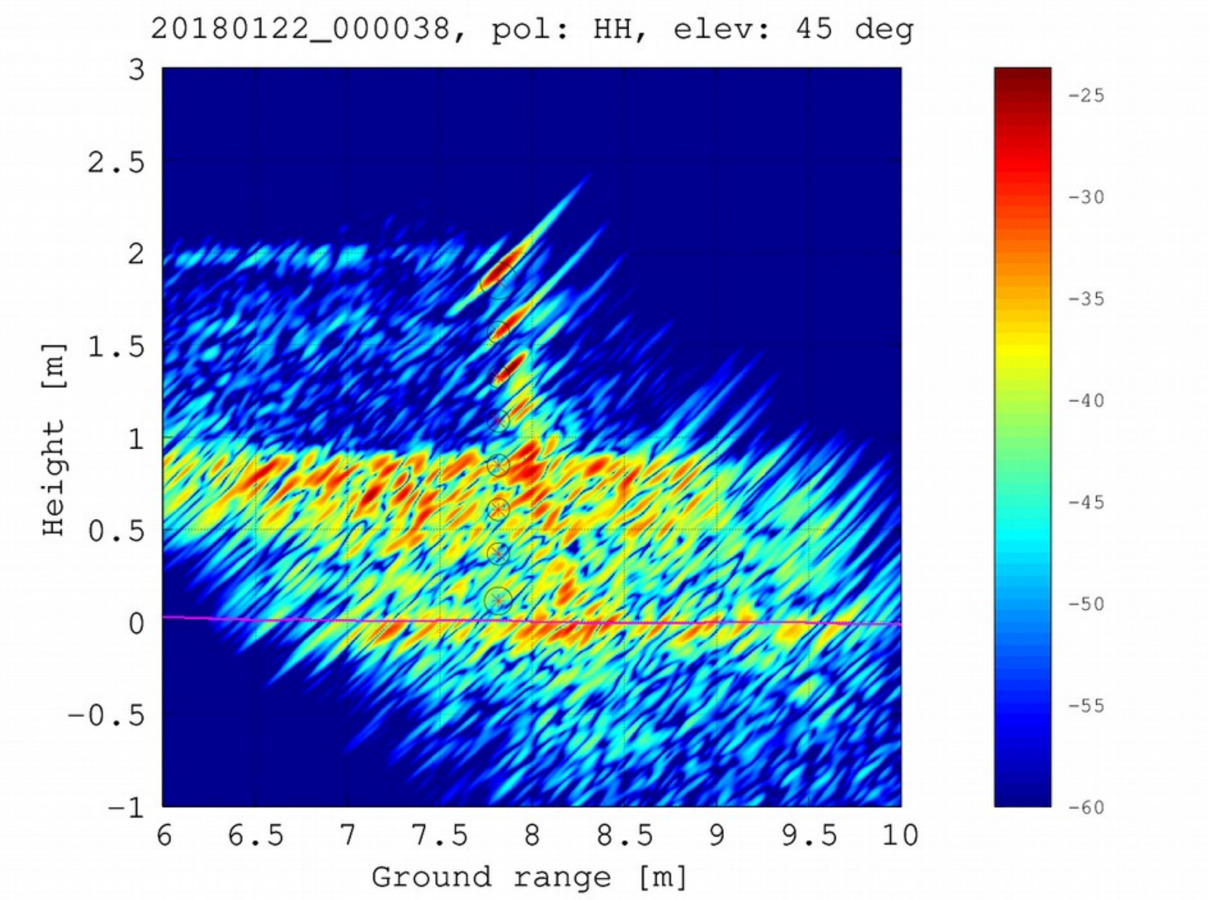


Figure 32: Maximum snow situation on 22.1.2018 with ~2m snow at the target location. The refrozen crusty snow at the lower meter of the snowpack can clearly be distinguished from the fresh dry snow on top.

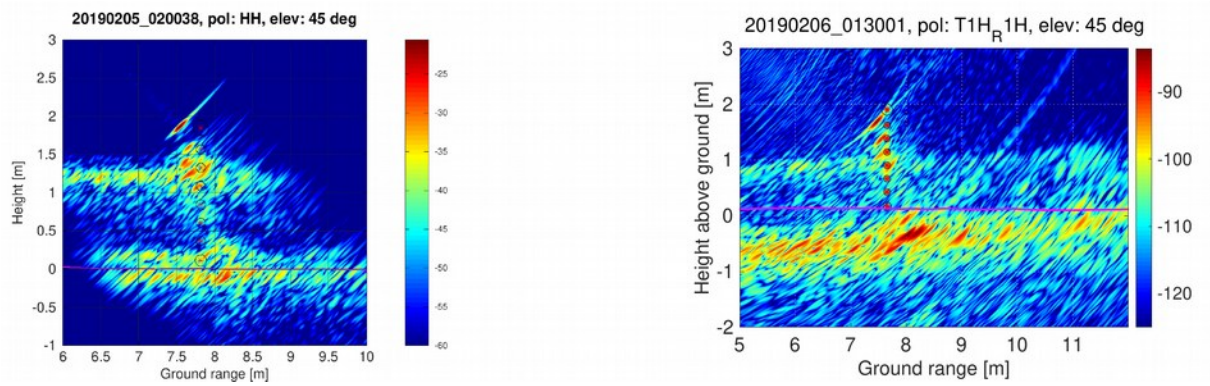


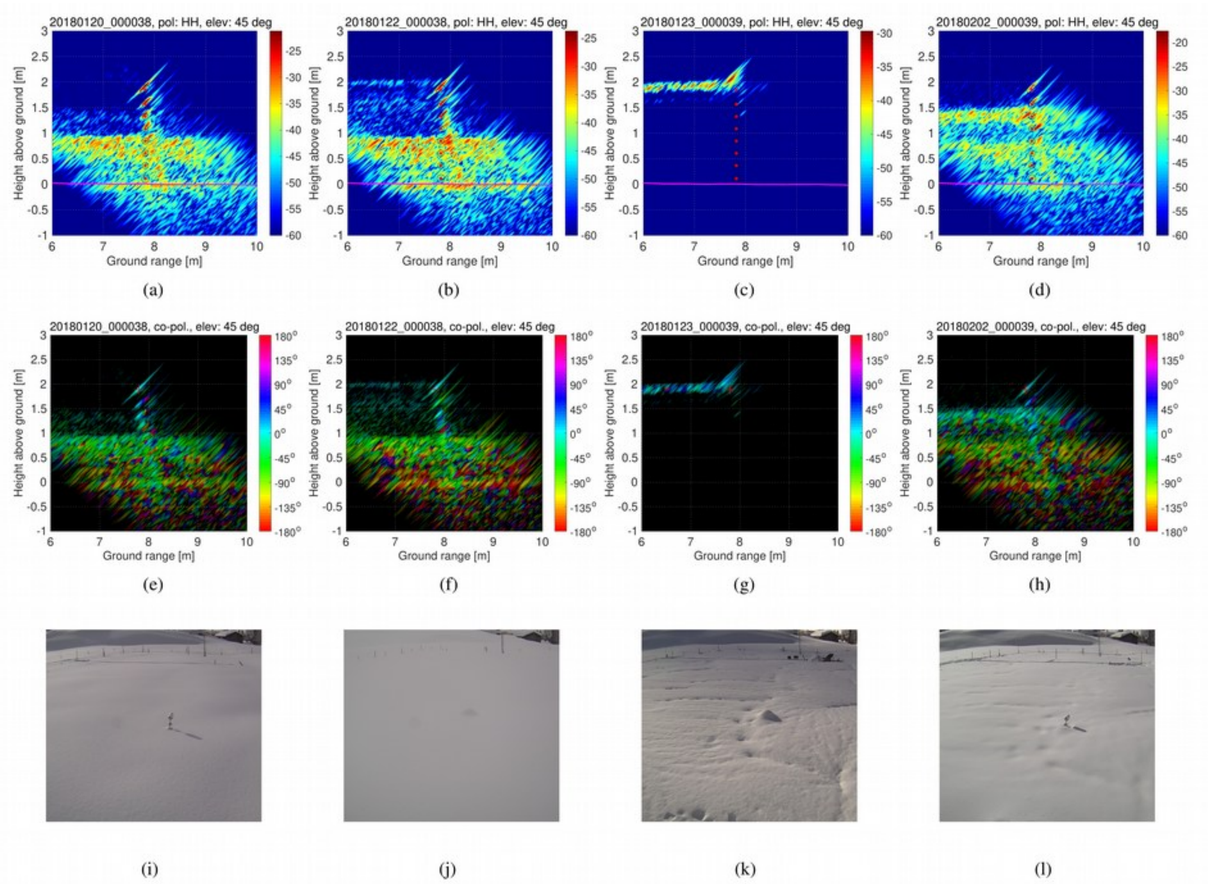
Figure 33: Comparison of SnowScat tomographic analysis with first order WBScat processing. SnowScat acquisition was made on 5 Feb 2019, WBScat on 6 Feb 2019.

For further discussion and demonstration of the technology it is referred to Frey et. al. 2018. Here we present a few examples from the the 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

- auto-focus-based retrieval of the relative permittivity (to derive the snow water equivalent)
- snow stratification (development of melt-freeze crusts over time)
- layer-wise separation of co-polar phase differences

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 Frey et al. 2011, 2016.



(a) (b) (c) (d)

(e) (f) (g) (h)

(i) (j) (k) (l)

Figure 34: Excerpts from the 2017/2018 daily time series acquired within the ESA SnowLab campaign at the test site Davos Laret, Switzerland. Top row: HH-pol rel. intensity profiles. Middle row: co-polar phase difference. From left to right figures show 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.).

5.1.3. Vertical measurements

The vertical measurements of the snowpack were conducted from the uppermost position of the tomography rail. However, it has to be noted that even at that position the snow in the footprint is affected by the tower and snow height is lower than at the snow height sensor position. Nevertheless it shows the potential for snow height and stratigraphy information retrieval. Below SnowScat time series are shown for the first two winter campaigns at Laret 2015 - 2018.

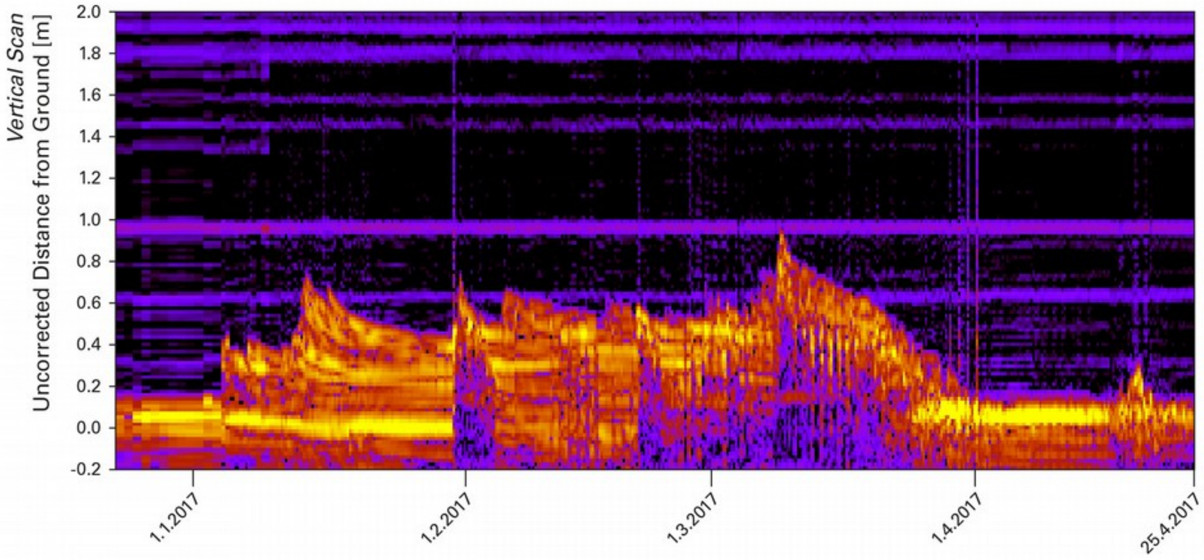


Figure 35 Result of all vertical scans taken during the campaign. Yellow means high backscatter intensity. The range distance is not yet corrected with respect to the snow pack.

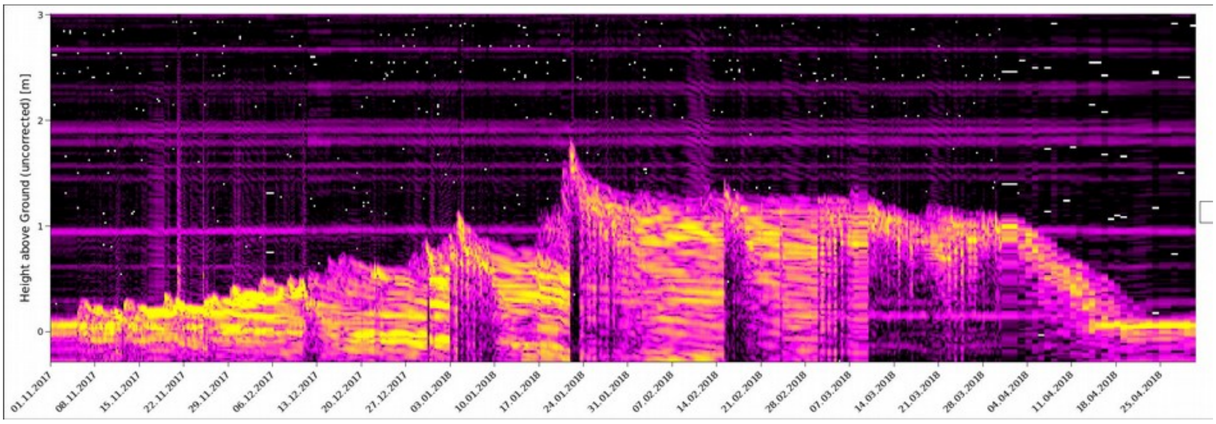


Figure 36: Result of all vertical scans taken during the campaign. Yellow means high backscatter intensity. The range distance is not yet corrected with respect to the snow pack.

5.2. Passive L-band Measurements

During the winters 2016/17 and 2017/18 passive close-range measurements at L- and X-band have been acquired using the L-band radiometer ELBARA-II (on loan from ForschungsZentrum Jülich (FZJ), Germany) and the X-band radiometer MORA (on loan from the Institute of Applied Physics (IAP), University of Bern, Switzerland). During ESA's SnowLab CCN project in Winter 2018/19, the measurements of passive close-range microwave brightness temperatures were continued using a similar experimental setup. However, for the Winter 2018/19 the ELBARA-II L-band radiometer was no-longer available from the FZJ because the lead-agency project "MicroVegSnow" (performed by WSL (snow-part) and FZJ (vegetation part)) came to an end. Therefore, WSL has implemented the alternative L-band radiometer OMRA (Office Made RAdiometer) within the ESA SnowLab CCN contract. This instrument was developed from the old L-band radiometer JÜLBARA, the antenna, and the automated staring mechanism partially denoted by FZJ. The almost 15 year old JÜLBARA was complemented with an new temperature controlled housing (Figure 37a) and JÜLBARA's original control and data-acquisition unit was replaced/complemented with RASPBERRY-PI components (Figure 37b). Finally, the entire OMRA radiometer system was successfully tested at the WSL-Birmensdorf (Figure 37c) before its deployment in Davos-Laret at 14th December 2018.

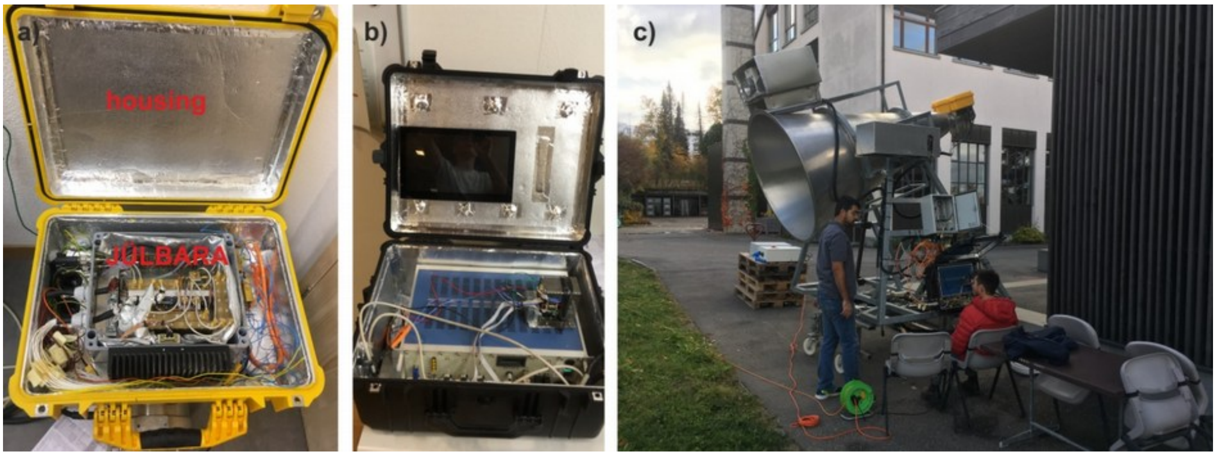


Figure 37: Development and test of the Office Made L-band Radiometer (OMRA) developed from used parts within the ESA SnowLab CCN project.

As was the case during the Winter campaigns 2016/17 and 2017/18 the passive L- and X-band radiometers were installed on the 6-m radiometer tower next to the 10-m tower hosting the scatterometer (SnowScat or WBScat). As shown with Figure 38, the radiometers were mounted on an elevation and azimuth tracker allowing to measure L- and X-band brightness temperatures at the elevation angles $\theta = \{30°, 35°, 40°, 45°, 50°, 55°, 60°\}$ and the azimuth angles $\alpha = \{35°, 90°, 145°\}$ on hourly basis. The passive measurements at $\alpha = \{35°, 90°\}$ yielded brightness temperatures of footprints consisting of the natural ground covered with the developing and thawing snowpack, whereas the footprints at $\alpha = 35°$ overlapped with areas measured with the scatterometer. The radiometer footprints at azimuth $\alpha = 145°$ were artificially prepared, meaning that a reflective metal-mesh grid was places at the ground before the first snow-fall. Accordingly, the brightness temperatures measured at $\alpha = 145°$ yielded L- and X-band emission of mostly the snowpack because emission of the below ground was shielded by the metal-mesh reflector. In addition to the passive close-range measurements, in-situ measurements of ground permittivity and temperature at 5cm depth were performed along two in-situ transects (2 x 8 SMT100 sensors).

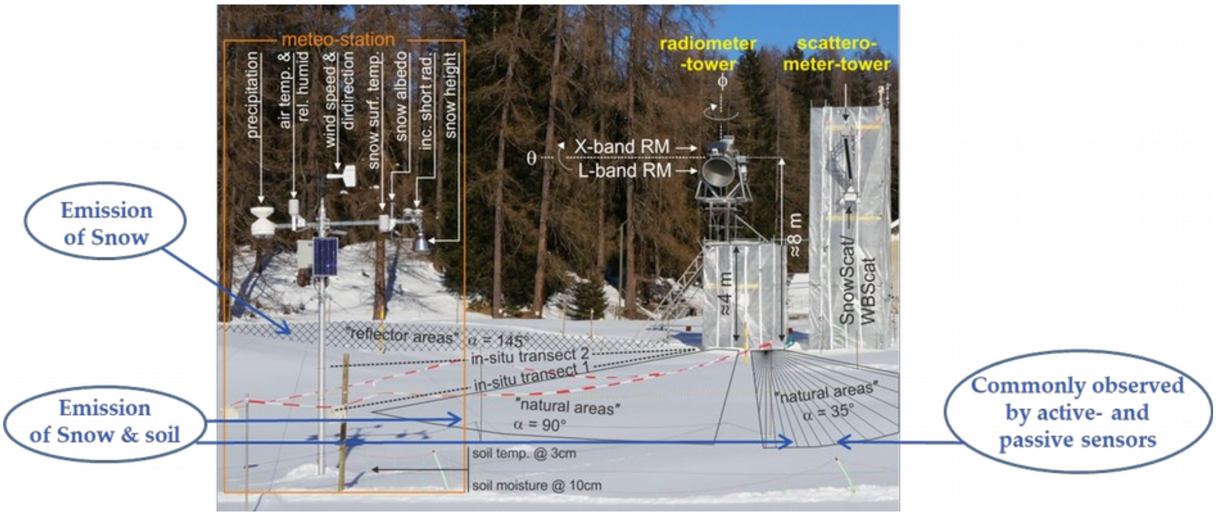


Figure 38: Setup of the passive close-range microwave measurements at Davos-Laret during the Winter 2018/19.

Albeit of the very limited time and funding available for the preparation and implementation of the OMRA L-band radiometer system, we succeeded in acquiring a comprehensive time-series of L-band brightness temperatures $T_B^{p,\theta,\alpha}$ $p=\{H,V\}$,at $\theta=$ {30°, 35°, 40°, 45°, 50°, 55°, 60°}, and α = {35°, 90°, 145°} of almost 160 days between 14th December2018 and 23th May 2019. Figure 39 shows the operative (gray) and inoperative (white) times of the passive measurements during the Winter campaign 2018/19.

An excerpt of the L-band measurements acquired at , $\theta = 45°$ and $\alpha = 145°$ ("reflector areas" in Figure 2), is shown in Figure 40. During the snow-free and dry-snow periods (indicated with orange ellipses) brightness temperatures are much lower than during wet-snow periods (indicated with green ellipses). This is due to the strong increase of absorption (self-emission) of the snowpack with increasing snow liquid water. However, $T_B^{p=\{H,V\},\theta=45°,\alpha=145°}$ during snow-free and dry-snow periods (indicated with orange ellipses) are still higher than downwelling sky radiance at L-band, which is of the order of $T_{sky} \approx 5\,K$. This is due to the limited directivity (±13° at -3dB sensitivity) of the radiometer Picket horn antenna which leads to radiative contributions originating from "natural areas" in the vicinity of the "reflector areas". As was done for the earlier two Winter campaigns, the measured $T_B^{p,\theta=45°,\alpha=145°}$shown in Figure 40 will be corrected to compensate for these radiative contributions by consideration of the antenna sensitivity pattern. This will yield L-band brightness temperatures $T_{B,\text{reflector areas}} \approx T_{sky}$ during snow-free and dry-snow periods. The accordingly corrected $T_{B,\text{reflector areas}}$ measured during wet-snow periods carry the information on the self-emission of the wettening snowpack.

Mainly as a consequence of the nearby performed active microwave measurements, measured $T_B^{p,\theta,\alpha}$ were sometimes distorted by non-thermal RFI. Heavily distorted $T_B^{p,\theta,\alpha}$ were identified via the analysis of Kurtosis and Skewness of measurement samples acquired at 800Hz, and by means of the occurrence of exaggerated differences between two frequency channels (1400-1413MHz and 1413-1427MHz) measured within the protected part of the L-band (1400 – 1427MHz). Furthermore, non-thermal RFI $\Delta T_B^{p,\theta,\alpha}$ included in slightly distorted $T_B^{p,\theta,\alpha}$ was quantified by analyzing the Probability Distribution Function (PDF) of measurement samples in comparison to the Gaussian PDF expected for perfectly undisturbed pure thermal emission. This RFI mitigation approach was developed and tested during the previous Winter campaigns 2016/17 and 2017/18.

In a nutshell, the following conclusions can be drawn from the passive microwave measurements performed in Davos-Laret within the ESA SnowLab CCN project during Winter 2018/19: The passive L- and X-band measurements were successful, and the resulting brightness temperature data have been included in the final data-package delivered to ESA. The scientific analysis of the passive measurements, in combination with the synchronous active measurements, is still outstanding. The aspired ESA science study is an important element to this! The developed L-band radiometer system OMRA will be maintained and tested for the use during the APRESS campaign in Davos-Laret during Winter 2019/2020 together with WBScat.

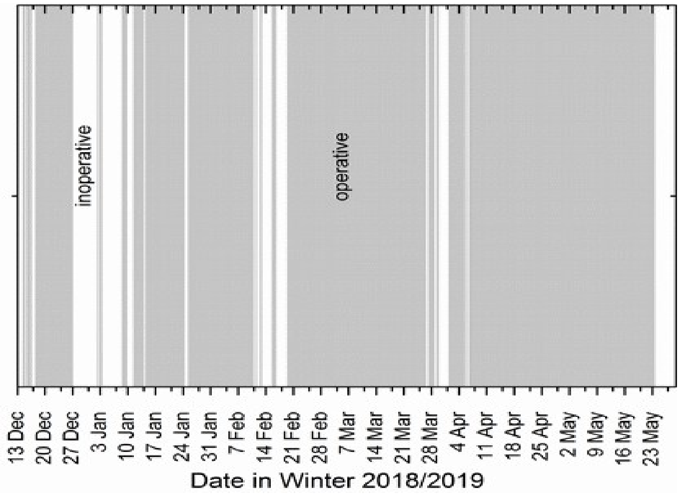


Figure 39: Operative (gray) and inoperative (white) time-periods of the passive measurements during the Winter campaign 2018/19 in Davos-Laret.

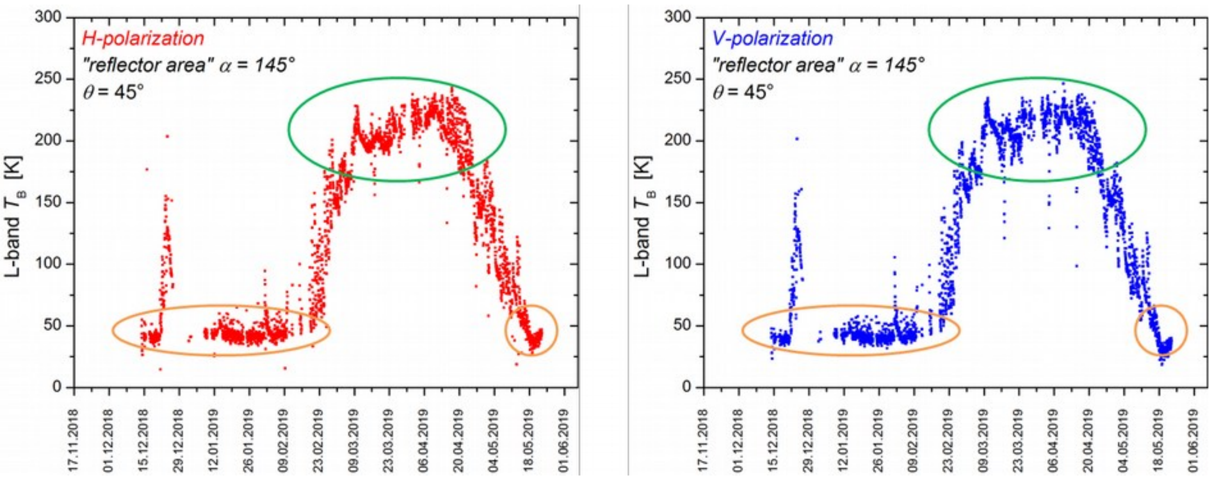


Figure 40: Excerpt of the L-band measurements performed over the "reflector areas" (Figure 38) during the ESA SnowLab CCN Winter campaign 2018/19.

6. DISSEMINATION

The project was presented on several conferences:

- EGU 2018 A multi-frequency, -polarisation and -annual microwave snow dataset — Results and lessons learned from ESA's Snowlab Projec, Andreas Wiesmann et al., 2018
- IGARSS 2018, ESA SnowLab - 3 years of microwave and structural measurements of Alpine snow, Frey et al., 2018
- EGU 2016, Andreas Wiesmann, Rafael Caduff, Othmar Frey, and Charles Werner, EGU2016-13506 ESA SnowLab project, EGU Vienna 2016.
- EUSAR 2016, Othmar Frey, Charles L. Werner, Rafael Caduff, and Andreas Wiesmann. A time series of SAR tomographic profiles of a snowpack. In Proc. of EUSAR 2016 - 11th European Conference on Synthetic Aperture Radar, pages 726-730, June 2016.
- EARSEL 2017, Martin Schneebeli, Henning Löwe, Matthias Jaggi, Margret Matzl WSL Institute for Snow and Avalanche Research SLF, Switzerland Minimal and Optimal Structural Measures to Characterize Snow for Remote Sensing at Different Wavelength, 2017.
- EARSEL 2017, Andreas Wiesmann, Rafael Caduff, Othmar Frey, Martin Schneebeli, Thorsten Fehr GAMMA Remote Sensing AG, Switzerland ESA SnowLab - Microwave and Structural Measurements of Alpine Snow, 2017.
- EARSEL 2017, Mike Schwank, Reza Naderpour, Andreas Wiesmann WSL-Birmensdorf, Switzerland "MicroVegSnow" Project at Davos-Laret Remote Sensing Test-Site as Part of the "Swiss Alp-SnowLab for Climate-Research and Remote Observations" (SASCRO), 2017.
- Fringe 2017, Frey, Othmar; Werner, Charles; Caduff, Rafael; Wiesmann, Andreas; Tomographic Profiling Of Snow: Time Series And In-Situ Measurements Within The Scope Of The ESA SnowLab Campaign 2016/2017.
- BioGeo 2018, Time series of high-res vertical snow profiles obtained from tomographic profiling using SnowScat. Frey et al. 2018.
- Living Planet Symposium 2019 (invited Session: C.2.07 Emerging Technologies: SAR Tomography of Natural Media: Current State-of-the Art and Perspectives for Future Applications) Tomographic profiling using SnowScat: radar-based time series of high-resolution 2-D vertical snow profiles Frey et al. 2019.
- IGARSS 2019, Wide band scatterometer (1 - 40 GHz) data of the seasonal snowpack in Davos, Switzerland, acquired within the ESA SnowLab project in winter 2018/19. Discussion and first results, Wiesmann et al. 2019.

Publications:

- Frey, O., Werner, C.L., Caduff, R., and Wiesmann, A.: "Tomographic profiling with SnowScat within the ESA SnowLab Campaign: Time Series of Snow Profiles Over Three Snow Seasons". In Proc. IEEE Int. Geosci. Remote Sens. Symp., pp. 6512-6515, 2018.
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7. CONCLUSIONS AND OUTLOOK

The multi-year ESA SnowLab project has been carried out at the newly established Davos-Laret test site (Switzerland) from 2016 until 2019. Before, a one season campaign at Gerstenegg was conducted.

SnowLab provides a comprehensive multi-frequency, multi-polarisation, multi-temporal data set of active microwave measurements over snow-covered grounds in an Alpine snow regime. The main instrument in ESA SnowLab was ESA's SnowScat X- to Ku-band coherent tomographic scatterometer for the 2015-2018 campaigns and WBScat for the 2018/19 campaign. The active microwave measurements are complemented by micro meteorological measurements and regular snow characterization using state-of-the-art sensors, in order to allow resolving the 3D snow microstructure necessary to investigate the origin of electromagnetic signatures associated with scattering effects. The resulting data set is needed to further investigate the relationship between effective snow and ground parameters and their specific microwave backscatter, measured by radars. In addition to traditional backscatter signature measurements, SnowScat/WBScat was used to acquired tomographic and vertical snowpack measurements. All 4 campaigns can be considered highly successful. More than 1800 signature scans were conducted and more than 500 tomographic profiles collected. Near real-time processing and data visualisation supported the monitoring and quality control of the running campaign.

A major project activity was the design and implementation of a Tomographic Toolbox to explore the tomographic data acquired with SnowScat. The toolbox was implemented in Octave that can be used within the Octave environment but also stand-alone in a shell or script as part of e.g. the automated data analysis.

In parallel to the SnowLab campaign in Davos Laret, the snow part of the lead agency project MicroVegSnow led by Dr. Mike Schwank of the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) and the Forschungszentrum Julich (FZJ) funded by the Swiss National Science Foundation (SNF) has been conducted from 2016-2018. MicroVegSnow provides collocated and time-synchronous passive microwave data measured with the L-band radiometer ELBARA-II/OMRA and an X-band radiometer MORA, both mounted on a common elevation- and azimuth scanner installed on a tower next to the tower used for SnowLab (Figure 8). The passive L- and X-band measurements are accompanied by in-situ measurements of ground permittivities and temperatures. These measurements were continued in the frame of the ESA SnowLab project in winter 2018/19. The snow part of the MicroVegSnow project aims to explore the thermal microwave emission of snow covered grounds and its relation to effective ground and snow states. The knowledge gained is used to develop novel retrieval schemes that allow to estimate snow and ground parameters (such as snow density, snow liquid water, ground permittivity) based on passive microwave data.

The concurrent implementation of the two projects SnowLab and MicroVegSnow in 206/17 and 2017/18 at the common test site in Davos-Laret has provided a unique set of active and passive microwave data including comprehensive in-situ data. These data will be available for conducting the research proposed hereafter, which is of fundamental importance to advance the scientific foundation of emerging microwave space-borne missions dedicated to the estimation of snow properties.

A first preliminary analysis of the active microwave data has been elaborated within the framework of the ESA SnowLab project, however, a detailed scientific analysis is outstanding which should be the goal of a future study. Especially the potential of the wide band data collected with the WBScat needs a deeper investigation. Furthermore, the combined scientific analysis of active- and passive microwave data has not yet been done; this issue also poses a central theme of a future study.

The following aspects should be addressed in a future activity:

- Perform a detailed scientific analysis of the active microwave backscatter data collected within the ESA SnowLab campaign together with the in-situ measurements (e.g. snow temperature / density profiles, snow micro-structure, ground states) for an alpine snow regime to study the microwave response to snow and ground parameters.
- Investigate time domain coherence and phase together with the collection of in-situ measurements for an alpine snow regime to study the microwave response to snow and ground parameters.
- Validate and calibrate the new ESA Snow Microwave Radiative Transfer (SMRT) model for an Alpine environment.
- Develop new methods to estimate snow properties, such as bottom-layer snow density and liquid snow water (snow moisture states) based on passive microwave observations at L-band (with possible application to SMOS and SMAP) and X-band.
- Explore the potential of combined use of passive- and active microwave measurements at low-frequency bands for the retrieval of snow parameters (e.g. mass density, liquid water column,…).
- Assess the potential and the limits of differential interferometry to estimate (retrieve) SWE using: a) SnowScat/WBScat data, and b) SAR data.
- Investigate the polarimetric phase differences in radar time series and its applicability to detect anisotropies in the snowpacks.
- Explore the potential of tomography and time domain techniques to observe snow stratigraphy. This includes exploring a new way to translate this snow stratigraphy information to main snow parameters.

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