ALPSAR 2012-13, A FIELD EXPERIMENT ON SNOW OBSERVATIONS AND PARAMETER RETRIEVALS WITH KU- AND X-BAND RADAR

Helmut Rott [(1)], Thomas Nagler[(1)], RainerPrinz [(1)], Karl Voglmeier[(1)], Reinhard Fromm [(2)], Marc S. Adams[(2)], Simon Yueh [(3)], Kelly Elder [(4)], Hans-Peter Marshall [(5)], Alex Coccia [(6)], Ernesto Imbembo [(6)], Dirk Schüttemeyer[(7)], Michael Kern [(7)]

[(1)] *ENVEO IT, Technikerstrasse 21a, A-6020 Innsbruck, Austria, Email: helmut.rott@enveo.at; thomas.nagler@enveo.at; rainer.prinz@enveo.at; karl.voglmeier@enveo.at*
[(2)] *BFW, Department of Natural Hazards, Innsbruck, Austria, Email: reinhard.fromm@uibk.ac.at marc.adams@uibk.ac.at*
[(3)] *JPL-CalTech, Pasadena, CA, USA, Email: simon.yueh@nasa.gov*
[(4)] *Rocky Mountain Research Station, US Forest Service, Fort Collins, CO, USA, Email: kelder@fs.fed.us*
[(5)] *Department of Geosciences, Boise State Univ., Boise, ID, USA,* Email: *hpmarshall@boisestate.edu*
[(6)] *METASENSING, Noordwijk, NL, Email: alex.coccia@metasensing.com; ernesto.imbembo@metasensing.com*
[(7)] *ESA-ESTEC, Noordwijk, NL, Email: dirk.schuettemeyer@esa.int; michael.kern@esa.int*

ABSTRACT

In winter 2012-13 the AlpSAR field experiment was performed in the Austrian Alps, with the objective to acquire an experimental data base on Ku- and X-band radar backscatter of snow by means of airborne SAR, together with detailed co-located field measurements. Comprehensive data sets on physical properties of snow were acquired in three different alpine snow zones during campaigns spanning from early to late winter season. The data sets include detailed measurements of stratigraphy and physical properties of snow, and measurements of snow depth along transects in order to obtain spatially detailed patterns of snow accumulation, using conventional techniques and portable radar sounders. These data sets, together with the acquired SnowSAR backscatter images, offer excellent possibilities for development and validation of forward and inversion models on radar interaction with snow.

1. INTRODUCTION

In winter 2012-13 three field campaigns on radar observations of snow and glaciers were performed in the Austrian Alps within the AlpSAR experiment, supported by the European Space Agency (ESA), the Austrian Space Application Programme (ASAP), and the National Aeronautics Space Administration (NASA). The field experiment was aimed at enhancing the experimental data base on radar backscatter of snow by covering snow regimes in different elevation zones. A main objective for the campaign was the acquisition of data for testing and validating algorithms for Synthetic Aperture Radar (SAR) retrievals of the water equivalent (SWE) of winter snow in Alpine regions.

The activities contributed to feasibility studies for the satellite CoReH$_2$O (Cold Regions Hydrology High-resolution Observatory) which was a Candidate Mission within the ESA Earth Explorer Programme [1]. The CoReH$_2$O sensor is a dual frequency SAR, operating at 17.2 GHz and 9.6 GHz, VV and VH polarizations [1] [2]. In the AlpSAR experiment backscatter data were collected with an airborne polarimetric SAR sensor (SnowSAR), which operates at the same frequencies as the CoReH$_2$O SAR [3]. SAR data were acquired during three flight campaigns, in November 2012, January 2013 and February 2013. In addition, during the February campaign tomographic SAR data were measured over two snow sites by a ground-based SAR system operated by University of Rennes and Politecnico Milano. This is reported in a separate paper.

2. TEST SITES

Field measurements and SnowSAR data acquisitions were performed in three test sites (Fig. 1). The aircraft operation base was at Innsbruck airport. The test sites were located within comparatively short flight range: 20 km to Leutasch (LT), 60 km to Rotmoos (RM) and to Mittelbergferner (MF).

Figure 1. Location of test sites of the AlpSAR campaign, plotted on Google Earth image.

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The Leutasch test site is located in a valley north-west of Innsbruck. The bottom of the valley along the flight lines is rather smooth, gradually rising from 1100 m to 1160 m above sea level. The dominant land cover type is cultivated meadow. There are also some coniferous forests and dispersed settlements. As in the other test sites, field measurements were performed mainly over comparatively level terrain. Fig. 2 shows the calibration site for SnowSAR where dihedral corner reflectors were deployed. In the background is the peak Hohe Munde (2662 m a.s.l.).

Figure 2. Set up of reflector at test site Leutasch, 8 January 2013.

Figure 3. Test site Rotmoos, 20 November 2012.

The Rotmoos test site (near the village Obergurgl) extends along a small secondary valley of the Ötztal valley, which is a tributary valley to the river Inn. The field measurements were carried out in the valley floor over an area of about 4 km x 1 km, at elevations ranging from 2250 m to 2400 m a.s.l. The lower section of this area is covered by alpine grass land and bogs. In the upper part the surfaces are rougher, covered by rubble and moraines. Fig. 3 shows a photo taken from a site near the automated station Rotmoos looking upstream towards the main ridge of the Alps.

Mittelbergferner (MF) is a glacier in the Ötztal Alps which has a northern aspect. It covers about 9 km² in area and extends over the elevation range from about 2500 m to 3550 m a.s.l. The western branch of the glacier is accessible by means of ski lifts. This facilitates the approach to the test site which extends over an area of about 2 km x 5 km on the eastern, undeveloped branch of the glacier (Fig. 4). The field measurements were performed on the central part of this section over the elevation range from 2800 m up to 3250 m a.s.l.

Figure 4. Test site Mittelbergferner. Oblique air photo looking towards south-west. The high peak in the background is Wildspitze (3770 m).

As the other glaciers in the region, Mittelbergferner has featured negative mass balance since the 1980s. Therefore the main part of the glacier corresponds to the ablation area with bare ice surfaces exposed in summer. End of summer 2012 firn (metamorphic snow from previous years) was present only on the upper glacier plateau at elevations above ~3100 m a.s.l. The structure of the firn volume at these sites is very coarse grained and stratigraphy is interspersed with many ice layers. The campaign objective for the glacier test site is the validation of SAR retrievals for accumulation of winter snow (snow mass, SWE) deposited on ice and firn surfaces.

3. CAMPAIGN SCHEDULE

The algorithm for retrieval of SWE from Ku- and X-band SAR data exploits the backscatter signal of the snow pack in the four SAR channels (17.2 GHz, 9.6 GHz, VV and VH-polarizations) [1] [2]. In order to obtain the backscatter signal of the snow volume for retrieval input, it is necessary to subtract the signal of the background medium from the total measured backscatter values. This is achieved by acquiring radar images over snow-free background before the start of the snow cover period. On glaciers the reference signals refer to ice and firn below winter snow.

For the AlpSAR experiment one SnowSAR campaign had been scheduled for the pre-snowfall period and/or early snow season. Because of the different altitudes of the test sites, it was not possible to capture snow-free surfaces at all three sites with the November flight. Leutasch was snow-free during the first flight campaign. The Rotmoos site was covered by dry snow of 20 to 30 cm depth (Fig. 3). On Mittelbergferner glacier ice and firn were covered by dry seasonal snow of 60 cm to 100 cm depth. Therefore retrievals of SWE for these two sites are performed for the differences in snow mass that accumulated between 20 November 2012 and the date of the 2nd (24 Jan. 2013) and 3rd (23 Feb. 2013) flight campaign, respectively.

SnowSAR data were acquired during aircraft (A) deployments on the following dates:

- Campaign Nr. 1A: 21 Nov. 2012
- Campaign Nr. 2A: 24 Jan. 2013
- Campaign Nr. 3A: 21 & 23 Feb. 2013

The nominal flight altitude was 1200 m above ground, varying to some extent with topography. This resulted in a swath width of 400 m to 500 m. Over each test site several parallel, partly overlapping swathes were acquired. In the Leutasch test site corner reflectors had been deployed for radiometric calibration.

Field measurements were made during three main campaigns, associated with the three aircraft deployments. In addition, preparatory activities were carried out in October 2012, in order to set up various devices: automated stations for measurement of meteorological, snow and soil parameters at the test sites LT and RM, and installation of temperature sensors in a borehole on the glacier MF to measure a firn temperature profile.

The main campaigns for field measurements (F) extended over several days:

- Campaign Nr. 1F: 19-25 Nov. 2012
- Campaign Nr. 2/1F: 08-14 Jan. 2013
- Campaign Nr. 2/2F: 21-25 Jan. 2013
- Campaign Nr. 3F: 17-26 Feb. 2013

The January campaign was split into two parts. Deployment of the aircraft had been planned for the period 08-14 January 2013. During this period the aircraft had been stationed at an airport in 400 km distance. The approach flight could not be managed due to adverse meteorological conditions. Major field activities were already performed during the period 08-14 January 2013. Many of these measurements were then repeated during 21-25 January 2013 when the aircraft was based at Innsbruck airport.

4. SETUP AND EQUIPMENT FOR FIELD MEASUREMENTS

Field measurements were performed with conventional devices and also with advanced instrumentation. The acquisition strategy was designed to acquire basic snow parameters (snow depth, density) in a comparatively dense spatial network, in order to map the spatial distribution, as well as to measure vertical profiles of snow parameters at several points within each test site. In order to support the development and validation of backscatter forward models, particular attention was paid to parameters characterizing the microstructure of snow. In the following an overview of the field measurements and the observation techniques is presented.

4.1 Snow Depth Transects

In each test site snow depth was measured along transects, applying different techniques. Transects were aligned approximately along and across the flight lines. On Mittelbergferner the transects were arranged in a way to avoid major crevasse zones (Fig. 5).

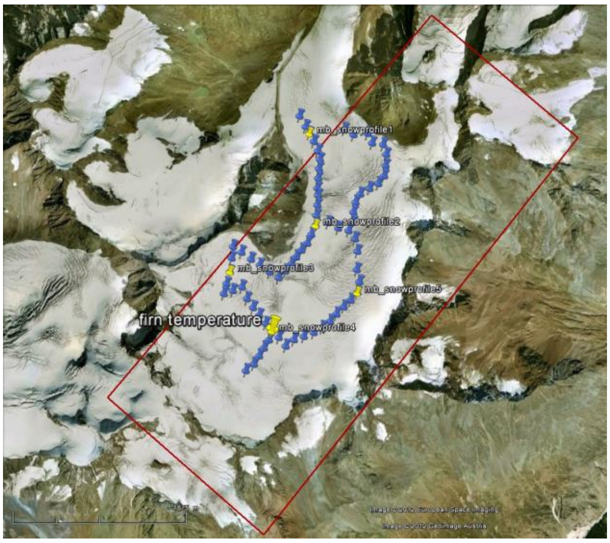

Figure 5. Test site Mittelbergferner on Google Earth image. The red box outlines the approximate area for SnowSAR acquisition. Blue pins: snow depth transects. Yellow pins: snow pits.

The basic method used for snow depth measurement was sounding with an avalanche probe. The measurements were made in steps of about 50 m in the test sites LT and RM, and about every 100 m on MF.

Each snow depth value along a transect represents the mean value of five soundings within a 3 m x 3 m area. Depth measurements we made to the nearest centimetre.

Fig. 6 shows the snow depth measured along a transect in the valley of the RM test site. The variations of snow depth are related to micro-topography and are caused by wind-effects during and after snow fall. In the LT test site, where the terrain is rather smooth, the snow depth shows little spatial variability.

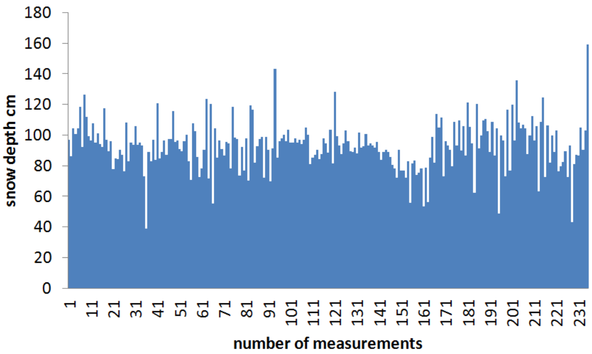

Figure 6. Snow depth of a transect along Rotmoos valley, 8 January 2013.

Additionally, during the January campaign (Nr. 2/1F) and February campaign (Nr. 3/F) soundings of snow depth and internal layers were performed along continuous lines with a ground penetrating radar (GPR). The sensor employs a 1 GHz antenna impulse system (~500 MHz - 1.5 GHz), shielded dipole antennas, and software pulseEKKO PRO. Output is voltage in the time domain. The sensor was carried on a pole between two skiers, the recording device in a backpack (Fig. 7).

Figure 7. GPR measurement of winter snow depth and internal snow layers on Mittelbergferner, 9 January 2013.

Fig. 8 shows GPR data measured on a transect along Rotmoos valley. The high spatial variability of snow depth is obvious. In addition, signals related to internal interfaces (between snow layers) are evident. Knowledge on snow layers, in addition to snow depth, is of interest for interpretation and modelling of SAR backscatter data.

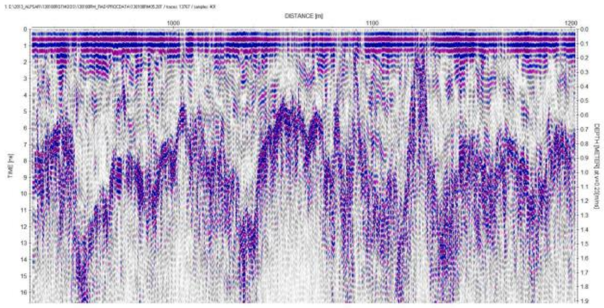

Figure 8. Section (1200 m long) of GPR transect along Rotmoos valley, 8 January 2013. Left scale: two-way travel time. Right scale: inferred snow depth.

During the February campaign (Nr. 3/F) an additional GPR system was used to measure the snow depth and layers: a frequency modulated continuous wave (FMCW) radar operating at 12-18 GHz, co- and cross-polarization with standard gain horn antennas. Output is I/Q voltage from a mixed Tx and Rx signal for each polarization, with a frequency content that can be converted to travel time.

4.2 Snow Pit Measurements

At several points of the snow depth transects vertical profiles of the following snow parameters were measured in snow pits:

- Snow layers (stratigraphy)
- Snow density
- Snow temperature
- Snow hardness
- Grain size (mean and variance), grain shape, photographic documentation

Conventional techniques were applied for these measurements. For snow hardness, additional measurements were performed with the SnowMicroPen sensor.

Fig. 9 shows an example of a protocol of snow pit measurements. The graph on the left side shows the hardness for the individual layers assessed with the hand test (blue boxes, scale at bottom), and the snow temperature in steps of 10 cm. The second column (F) shows symbols for the grain shape according to the International Classification for Seasonal Snow [7]. The third column (E) indicates the visually observed grain size (range). In the column ρ the mean density of each layer is specified in kg m^{-3} (2nd number).

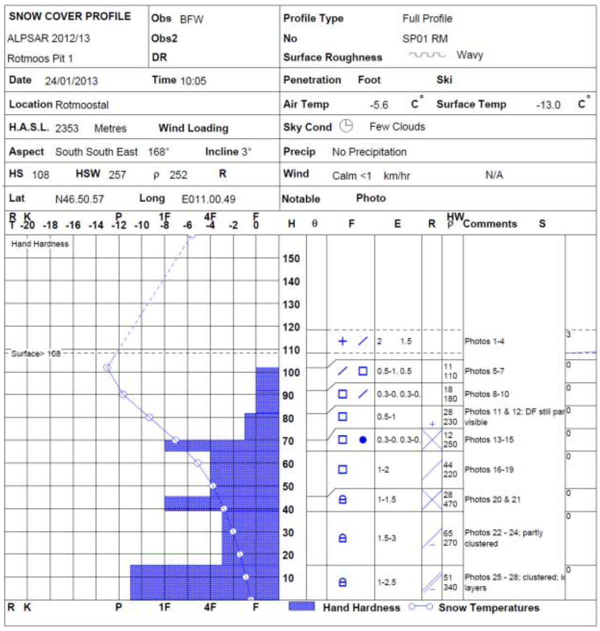

Figure 9. Example for protocol of snow pit measurements. Rotmoos, pit Nr.1, 24 January 2013.

4.3 Measurements of Snow Hardness

Snow hardness is closely related to the micro-structure of snow which has a major impact on radar backscatter. Therefore measurements of snow hardness by means of objective methods are of interest for backscatter studies. The Snow-MicroPen, a constant speed penetrometer, is a portable device for measuring the penetration hardness of a small cone driven through the snow pack [4] [5]. From these measurements micro-structural parameters of the snow volume can be derived [6].

An electric step motor is used to push a pole through the snowpack. At the tip of the pole is a cone with a diameter of 4 mm (Fig. 10). The force which is acting on the cone during the penetration procedure is measured and recorded.

Figure 10. Cone of the SnowMicroPen.

Results of SnowMicroPen acquisitions are vertical profiles of resistive forces with very high resolution and accuracy. The measurements are of relevance for investigations on snow metamorphic processes and avalanche formation, snow hydrology, and electromagnetic modelling (microwave emission and scattering). An example for a vertical profile of penetration resistance is shown in Fig. 11 for measurements made in pit 2 at the RM test site in January. High resistance is observed in the lower 20 cm of the snow pack (right-hand side on the x-axis). This layer dates back to melt-freeze events in autumn when the snow pack was shallow.

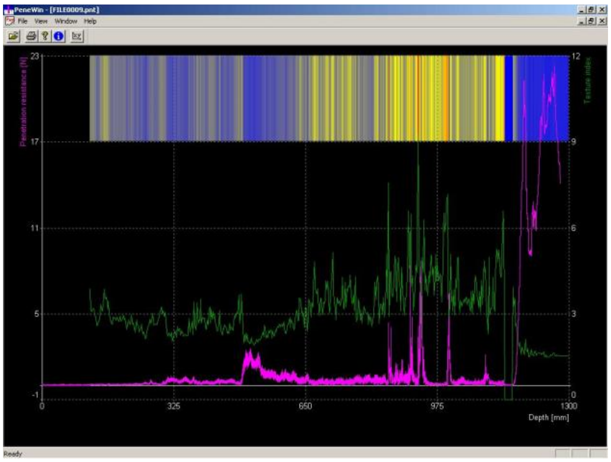

Figure 11. Display of SnowMicroPen profile near snow pit 2, Rotmoos, 8 January 2013. Purple: penetration resistance [N]. Green: texture index.

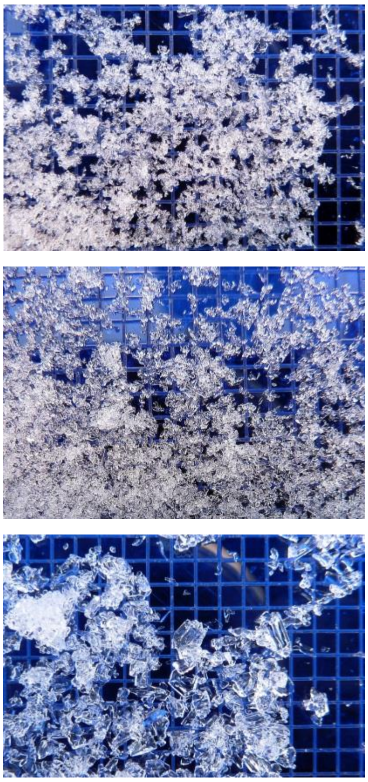

Figure 13. Photos of snow grains from three layers of snow pit 2, Rotmoos, 8 January 2013. 2 mm grid.

Photos of snow stratigraphy from snow pit 2, Rotmoos, 8 January 2013 (Fig. 12) provide hints on the link between microstructure and penetration resistance. The top photo represents the near-surface, decomposing, new snow layers on the left portion of the graph in Fig. 11. The centre image shows grains associated with the stronger, well-bonded layer located at about 500 mm depth on the x-axis of Fig. 11. The bottom photo shows the large depth hoar grains found at the very base of the snowpack.

4.3 Snow Depth by Terrestrial Laser Scanning

In the Rotmoos test site two experimental devices were used to measure the change in snow depth between different dates: a terrestrial laser scanner, and digital stereo-photography acquired from RPAS (Remotely Piloted Aircraft System).

The terrestrial laser scanner of the type Riegl LPM-321, operating at 905 nm wavelength, was set up on a control point near the summit of the peak Hohe Mut (2640 m). This point provides a good view of the northern section of the RM test site from a distance of about 1000 m. The corresponding grid resolution of the scans is 0.6 m.

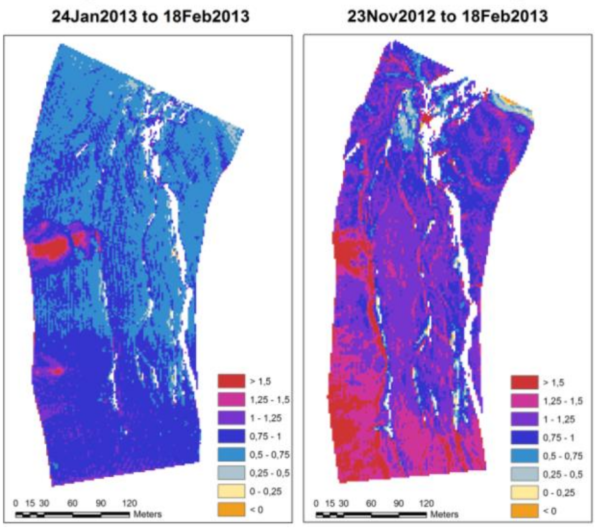

Figure 13. Change of snow depth (colour scale in metre) between individual campaigns for northern section of Rotmoos valley, derived from terrestrial laser scanner measurements.

The laser scans are processed to obtain accurate digital elevation models. Repeated scans during the winter deliver detailed maps of elevation changes related to the accumulation of snow (changes of snow depth). Fig. 13 shows examples for changes in snow depth in the northern section of Rotmoos valley between campaigns. The analysis covers the valley bottom at an average point spacing of 2 m. The accumulation increases towards south (bottom of the figure) and on the east-facing slope (left). This is caused by the dominant wind pattern. The red blot (high accumulation) in centre left corresponds to an avalanche cone deposited between 24 January and 18 February 2013.

5. TEMPORAL EVOLUTION OF SNOW COVER

In this section we show examples of meteorological and snow parameters recorded at the automated station Rotmoos during 2012/13 (Figs. 14 & 15).

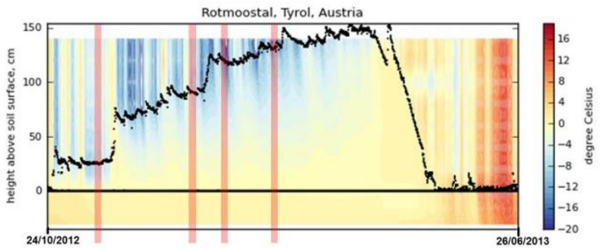

Figure 14. Snow height and temperature of snow and soil at the Rotmoos station, 24 October 2012 to 26 June 2013. Pink lines: field campaigns.

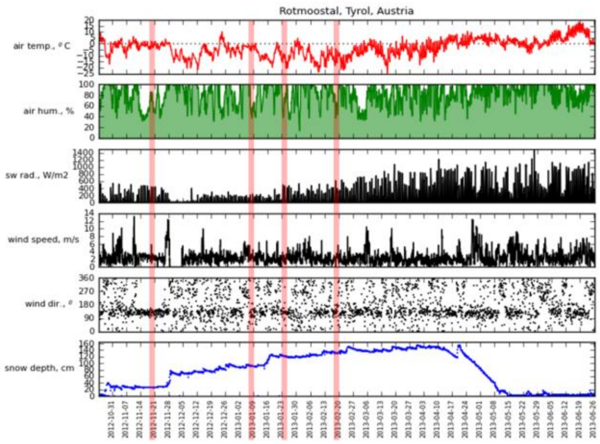

Figure 15. Meteorological parameters and snow height recorded at the Rotmoos station from 24 October 2012 to 26 June 2013.

At Rotmoos the first snow fell in late October. This snow was subject to melt/freeze events. Because of early start of the snow period, the soil below the snow pack remained un-frozen throughout winter. During the first campaign on 20/21 November the ground was covered by 20 to 30 cm of re-frozen snow. From the first campaign in November 2012 until end of February 2013 about 1.2 m of snow accumulated. The snow pack stayed dry during this period.

On Mittelbergferner snow started to accumulate in early October. Melt/freeze events during October resulted in a 20 cm layer of coarse-grained snow at the bottom of the winter snow pack. Above this layer comparatively fine-grained snow with a few thin wind crusts accumulated between the field campaigns. During the November campaign the depth of seasonal snow was already 0.7 to 1.0 m.

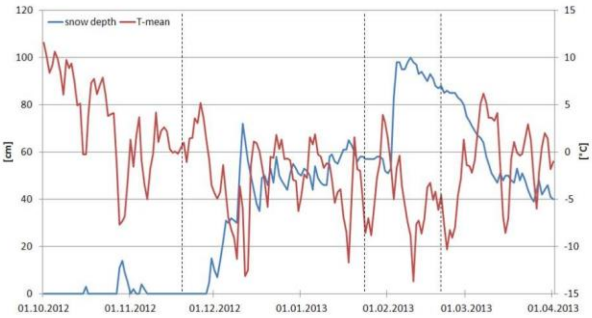

Figure 16. Snow depth and daily mean air temperature recorded at the station Leutasch-Kirchplatzl, 1 October 2012 to 1 April 2013. The dashed vertical lines indicate the dates of the three flight campaigns.

In Leutasch accumulation of winter snow cover started end of November (Fig. 16). During the 1st flight campaign the surface was snow-free. The flight campaigns on 24 January and 21 February 2013 happened to take place during cold periods so that the snow pack was dry. Due to transient melt events between the campaigns the snow pack contained coarse grained hard layers which were frozen on the dates of the flights.

6. EXAMPLES OF SNOWSAR IMAGES

Examples of SnowSAR images at Ku-band VV polarizations are shown in Figs. 17, 18 and 19, acquired over the three test sites on 24 January 2013. The colour coded data correspond to the backscatter coefficient per unit surface area (σ°), after geocoding, terrain correcting and calibrating the data, taking into account the local incidence angle.

In Leutasch over open land (meadows), the σ°-values range between -6 and -8 dB. Low σ°-values, visible in some parts of the image, are caused by geometric effects, such as radar back-slopes (slopes facing towards NW due to radar illumination from SE) and forest shadow. Also in Rotmoos low σ°-values refer to back slopes (facing here towards NE). On level terrain the σ°-values range between -7 dB and -9 dB.

On Mittelbergferner there seems to be a trend of increasing σ° with altitude, but the spatial variability of σ° is also to a significant part determined by variations of the local incidence angle. These effects need to be separated for signature studies and comparison with backscatter models.

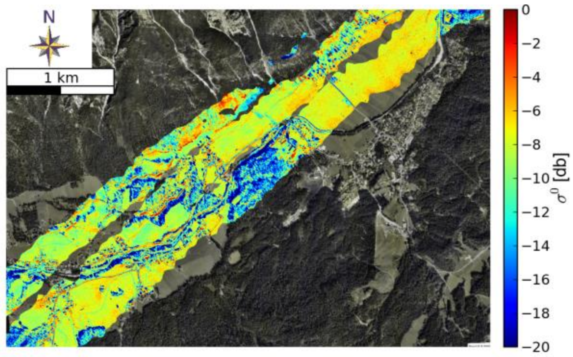

Figure 17. Geocoded SnowSAR backscatter image, Ku-band VV, three SAR swathes, Leutasch, 24 January 2013, on Google Earth image.

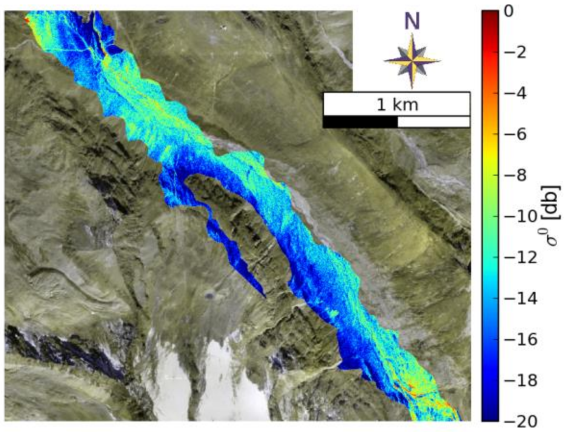

Figure 18. As Fig. 17, single swath, for Rotmoos, 24 January 2013.

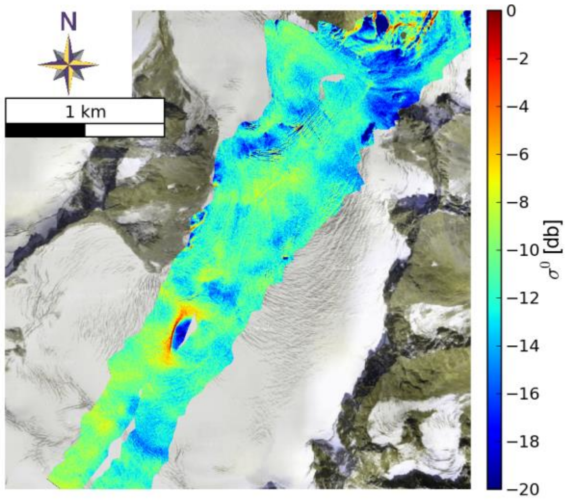

Figure 19. As Fig. 17, two swathes, Mittelbergferner, 24 January 2013.

7. CONCLUSION

Comprehensive data sets on physical properties of snow have been acquired on test sites in three different snow zones of the Alps during campaigns spanning from early to late winter season. The data sets include detailed measurements of vertical profiles of physical properties and structure in snow pits at many points, as well as measurements of snow depth along transects in order to obtain spatially detailed patterns of snow accumulation and layering, applying various measurement techniques. This data base, together with the acquired SnowSAR Ku- and X-band backscatter images, offers excellent possibilities for development and validation of forward and inversion models on radar interaction with snow. The intercomparison of the field data itself, acquired by different measurement techniques, is also of interest, in order to evaluate and assess the capabilities of the various methods.

8. ACKNOWLEDGEMENTS

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