An Airborne Experiment on Snow Parameter Retrieval by Means of Multi-Channel SAR Data

Thomas Nagler and Helmut Rott, ENVEO IT GmbH, Innsbruck, Austria
Kostas Papathanassiou, Irena Hajnsek, Rolf Scheiber, DLR-HR, Wessling, Germany

Abstract

An airborne SAR experiment was carried out in order to investigate the L-Band and X-Band interaction with alpine snow and to study the capabilities for retrieving physical snow parameters. The investigations, including polarimetry and multi-baseline interferometry, were carried out at the high alpine area Kühtai, located in the Eastern Alps of Austria. New insights into the radar signal interaction with snow are presented showing significant effects of small dielectric changes at the snow surface layer on the interferometric phase at L-band and on backscatter intensity at X-band. First results of the analysis of the multi-baseline L-Band data set applying the Pol-InSAR technique are presented.

1 Measurement Campaigns

An airborne experiment was carried out to study the radar interaction at L-and X-band with snow cover in alpine regions under different target conditions and to develop procedures for retrieval of physical properties of the snow pack. The experiment was carried out at Kühtai, a high alpine area covered by undisturbed natural snow and ski pistes with partly artificial snow, located at about 2300 m elevation near Innsbruck, Austria. The test site was imaged by the airborne E-SAR, operated by DLR, in interferometric and polarimetric mode from two opposite flight tracks and under different look angles.

On 30 March 2004 two missions were flown, with dry snow in the morning (5:00 to 6:20 UTC) and melting snow surfaces at noon (11:10 to 11:50 UTC). The snow depths varied significantly, with maximum values of 3.5 m. On 26 May 2004 the test site was covered largely by wet snow. X-band data were acquired on 30 March, 11:10 UTC, in cross track single pass interferometric mode to determine the topographic phase. At L-band interferograms were derived with baselines of 0m, 20m and 40 m from repeat-pass data acquired on 30 March at different times and for the time span 30 March to 26 May.

The field measurements included: - deployment and geodetic survey of corner reflectors, - vertical profiles of physical snow properties at several sites, - surface roughness, - profiles of snow depth, measured at about 5 m intervals over several long lines [2]. On 30 March the snow pack was dry in the morning, and the snow surface temperature was several degrees below zero. At sites with deep snow pack the soil below the snow pack was at zero degree and wet, and also the lower part of the snow pack was at zero degree.

2 Snow Backscatter Modelling

In order to estimate the various contributions to the backscatter signal of snow-covered ground at X- and L-band, we applied a one-layer radiative transfer model with Rayleigh scattering for calculating the volume contribution. For surface scattering we used the IEM model at the snow/air interface. At the rough snow/ground interface IEM was used for L-band and the geometric optics model for X-band [3].

The calculations were carried out for dry snow pack, corresponding to the morning conditions on 30 March, and for a thin layer of melting snow, to estimate effects of melting of the top snow layer at noon. The main model input parameters for the dry snow case were: snow depth 3 m, density 400 kg/m^2, grain size 0.4 mm, snow surface roughness h = 5 mm, l = 114 mm; ground surface roughness h = 20 mm, l = 77 mm. Wet snow layer: depth 0.1 m, liquid water content 1.5% by volume.

Figure 1 shows the individual backscatter contributions over the incidence angle range 10 to 70 deg. In the centre of the test site the local incidence angles vary from 45 to 65 degrees, depending whether a pixel is located on flat terrain or on a back-slope. For L-band the backscatter contributions are very similar for the completely dry snow case and for dry snow with thin melting layer at the top. In Fig. 1 the dry snow case is shown. The by far dominating contribution comes from surface scattering at the snow/ground interface. For X-band in the dry snow case [2] backscatter at the snow/ground interface clearly dominates at incidence angles below 40 deg., whereas at higher incidence angles volume scattering becomes increasingly important. A thin wet snow layer obscures almost completely X-band signals from below, and scattering at the air/snow interface dominates.

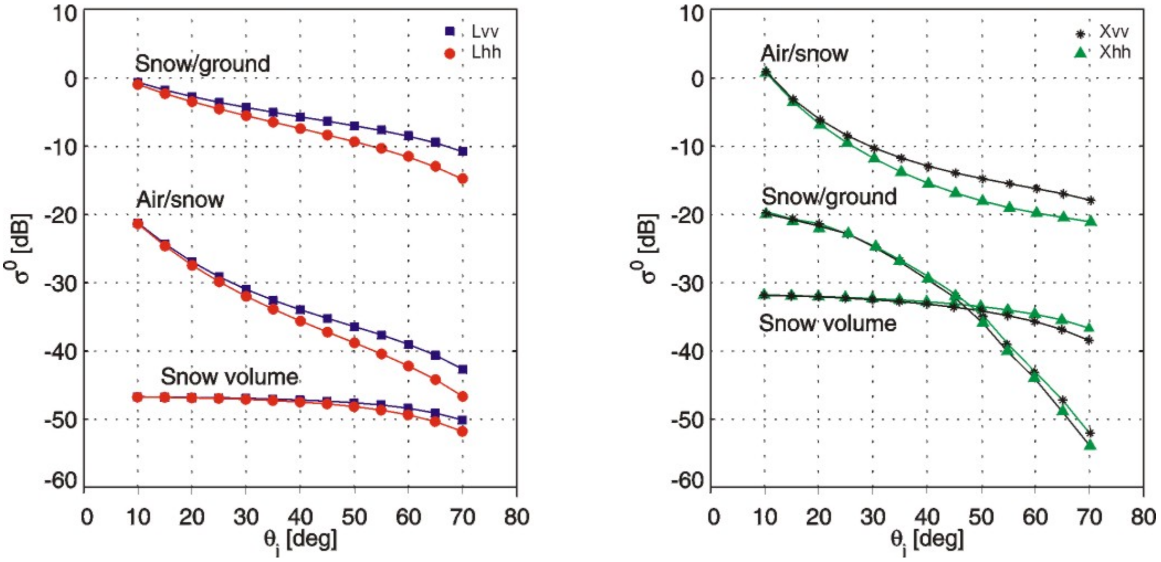

Figure 1: Model calculations of backscatter at L-band for dry snow pack (left), and at X-band for a thin layer of melting snow (right). For input specifications see text.

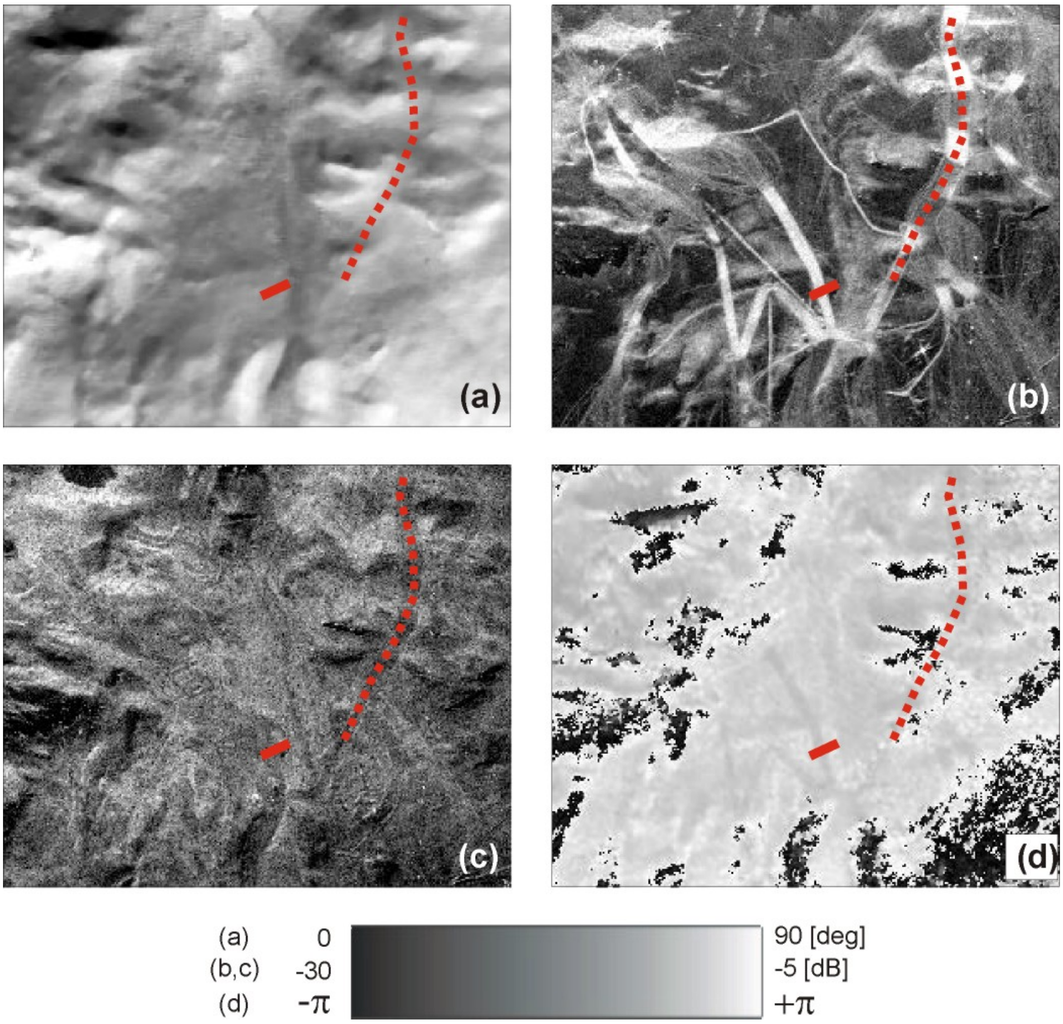

Figure 2: Section of E-SAR acquisition of the central Kühtai test site on 30 March 2004, covering about 1.5 x 1.5 km^2 in area; radar illumination from top. (a) map of local incidence angle; (b) σ° X_{VV}, image at 11:04 UTC; (c) σ° L_{VV}, 11:27 UTC; (d) L-band interferogram, based on L_{VV} 5:08 UTC and 11:27 UTC. The grey bar shows the dynamic scale of the 4 figures.

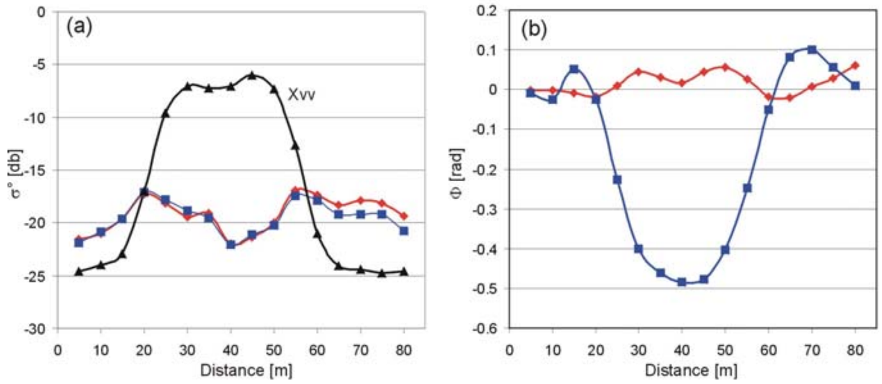

Figure 3: Profile across a ski piste (full line in Fig. 2): (a) σ° at X_{VV} 11:04 UTC, L_{VV} 5:08 UTC (red), L_{VV} 11:24 UTC (blue boxes) (b) L_{VV} phase for 5:08 UTC - 6:12 UTC (red) and 5:08 - 11:27 UTC (blue).

3 Interferometric and Backscatter Signatures

The study of the interferometric signatures focused so far on the 30 March L-band repeat pass data sets, morning to morning (with different baselines) and morning to noon. The 30 March to 26 May interferograms show only small parts with suitable coherence, the main part of the test site decorrelated because it was covered by wet snow on 26 May.

Figure 2 shows the central part of the test site. In the X-band VV image acquired at noon (Fig. 2b) the backscatter coefficient σ° of undisturbed snow is quite low (< –20 dB). This is because of high dielectric losses in the thin (about 5 cm) melting snow surface layer, caused by intense solar illumination. The main part of the snow pack was cold, but at X-band the signal does not penetrate the thin melting layer (Figure 1).

Striking is the X-band backscatter difference between undisturbed snow and ski pistes (the bright linear features in the SAR image). σ° of most ski pistes is more than 10 dB higher than in the surroundings. Only on south-facing slopes, where surface melt is more efficient, the σ° differences are smaller. The high σ° of the ski pistes is similar to that of dry snow, where backscatter from the volume and snow/ground interface dominates. Obviously, the higher thermal conductivity of compacted snow at the pistes delayed the onset of melting on the flat parts of the pistes, whereas on south-facing slopes σ° decreased due to melting also on ski pistes (dotted line in **Figure 2**). Undisturbed snow has lower density and consequently better thermal insulation.

The thin melting layer does not have an impact on L-band backscatter. The σ°-values of the morning and noon images are almost identical, without any clear temporal trend. However, in the morning-to-noon interferograms (Fig. 2d) phase shifts between ski pistes and undisturbed snow are evident that can be attributed to changes of the surface snow layer.

A detailed analysis of this effect is shown in a short profile across one of the ski pistes (**Figure 3**). X-band σ° at the piste is almost 20 dB higher than in the surroundings. This coincides with an L-band phase shift of about 0.5 rad. Taking into account the various scattering mechanisms, this shift can be attributed to the slightly increased backscatter contribution of the air-snow interface, when the thin top layer of the snow pack is wet [3]. Theory shows that the change in phase in L-band under the given conditions cannot be explained by increase of phase delay through the snow pack, because the amount of liquid water was very small. However, the slight increase of backscatter at the snow surface, not clearly evident in σ°, causes the shift of the scattering phase centre between morning and noon. This points out that the interferometric phase is more sensitive to changes of target properties than backscatter intensity.

4 Pol-InSAR signatures of snow

Next to the multi-temporal experiment component, a multi-baseline fully polarimetric data set has been acquired at L-band in a repeat-pass interferometric mode with temporal baselines of about 10 – 20 minutes and spatial (nominal) baselines of 10 and 20 m (corresponding to vertical wave-numbers of k_z=0.1 and k_z=0.2 respectively). The main objective of the multi-baseline Pol-InSAR data analysis is to provide a first evaluation of the polarimetric and baseline dependent behaviour of the interferometric coherence over snow at L-band. For coherence estimation the terrain induced coherence bias was corrected using the XTI derived DEM.

Two key observations that allows insights in the scattering nature of snow at L-band:

1. The interferometric coherence varies with polarisation according to the scattering properties of the underlying ground: The attenuation through the snow layer is weak so that an increase of scattering amplitude of the underlying ground reflects directly into an increase of the overall interferometric coherence so that $\gamma_{VV} \geq \gamma_{HH} \geq \gamma_{HV}$ for both baselines. The strong polarimetric behaviour of the ground reflects into a wide spec-

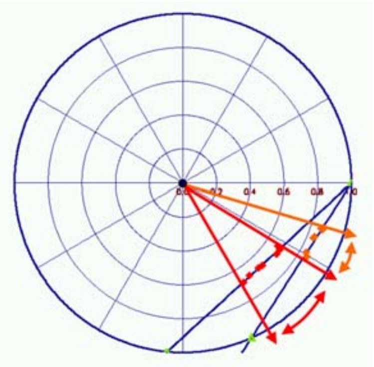

Figure 4: Pol-InSAR snow signature. The orange loci belong to complex coherences at different polarisations obtained for k_z=0.1 while the red for the corresponding loci for k_z=0.2.

trum of coherence values as function of polarisation.

2. The interferometric coherence varies with baseline because of uncompensated terrain effects and - more important - volume decorrelation that becomes more evident in flat terrain areas. This is indeed a surprising result indicating that the snow layer is characterised by a volume scattering component even at L-band. This volume scattering component is weak and becomes suppressed in the amplitude image information but becomes visible in the interferometric coherence as volume decorrelation component that varies with baseline.

In order to demonstrate both effects the Pol-InSAR snow-signature for a flat area within the scene is shown in Figure 4. The loci of the (complex) interferomeric coherences at different polarisations (HH, HV, VV, HH+VV, HH-VV, first, second and third Optimum polarisation [1,4]) multi-looked over a 10x10samples window are plotted in the unit cycle for both baselines (orange for k_z=0.1, red for k_z=0.2):

- The variation of the interferometric phase with polarisation indicates that the phase centres at different polarisations are located within the snow layer at different heights. This validates once more - and this time independently of terrain or other decorrelation effects - the volume scattering component of the snow layer and supports fully the interpretation of the multi-baseline observations.
- The alignment of the complex coherence loci along a straight line is a first indication for a polarisation independent propagation through the snow layer [1,4]. However the thin volume layer combined with the strong ground component make a definitive statement difficult.
- The maximum phase difference between the different polarisations is given by the phase centres of the optimum polarisations and is 17° and 28° for the first (k_z=0.1) and the second (k_z=0.2) baseline respectively. This corresponds to a separation of about 1.44 and 1.22 meters respectively; a realistic height difference seems regarding the given snow conditions.

5. Conclusions

The airborne SAR experiment, aimed at studying the capabilities of repeat pass InSAR to retrieve snow physical properties, revealed new insights into the scattering mechanisms and interferometric phase characteristics of snow in alpine environment. Analysis of interferograms over time spans of a few hours revealed that at L-band the phase is much more sensitive to small dielectric changes than backscatter amplitude. At X-band, on the other hand, the backscatter intensity is very sensitive to snow physical properties, as large differences between undisturbed snow and ski pistes demonstrate. The multi-baseline Pol-InSAR analysis indicates that relatively dry snow acts as weak volume scatterer at L-band. The weak volume scattering component leads to volume decorrelation effects in interferometric observation of snow. The interferometric coherence of snow covered terrain is polarisation dependent primarily due to the strong polarimetric behaviour of the underlying ground. Finally, the difference of the location of the individual phase centres within the snow layer has been evaluated. Work on analysis of the airborne data set is going on, in order to study methods for retrieval of snow parameters such as snow water equivalent.

Acknowledgements

The work was supported by ESA, Contract No. 16366/02/NL/MM. The E-SAR data acquisition was contributed to the experiment by DLR.

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