SNOW CLASSIFICATION ALGORITHM FOR ENVISAT ASAR

Thomas Nagler[(1)] **and Helmut Rott** [(2)]

[(1)] *Institute for Meteorology and Geophysics, University of Innsbruck, Innrain 52, A-6020 Innsbruck,* thomas.nagler@uibk.ac.at

[(2)] *ENVEO – Environmental Earth Observation GmbH., Exlgasse 39, A-6020 Innsbruck,* helmut.rott@enveo.at

ABSTRACT

Capabilities and methods for snow mapping in mountainous areas using the Advanced Synthetic Aperture Radar (ASAR) on board of ENVISAT were investigated. For algorithm development the backscattering signatures of snow covered and snow free surfaces in Alpine valleys and on mountain slopes were studied with ASAR data of different look angles and polarizations in comparison with field measurements of snow properties and meteorological data. The algorithm for automatic generation of snow maps during the melting period with ASAR applies multi-temporal change detection, the same principle as the method developed for ERS SAR. Impacts of various look angles (swathes), polarisations and image modes of ASAR for snow classification have been studied. The investigations demonstrate the suitability of ASAR Image Mode, Alternating Polarisation Mode and Wide Swath Mode for snow mapping in mountain areas, and the preference for steep incidence angle modes (IS6 and IS7) to minimize the loss of information due to layover and foreshortening. Time series of ASAR derived snow maps were produced for Alpine watersheds, confirming the high potential of this product for runoff modelling and forecasting.

1. INTRODUCTION

Spatially distributed information on snow extent and its temporal changes are required as basic input for snowmelt runoff modelling and forecasting. In particular for operational runoff forecasting the capability of Synthetic Aperture Radar (SAR) to provide regular repeat observations, irrespective of clouds and darkness, is a significant advantage over optical sensors.

Signature research [1], [2] and airborne experiments [3] in the 1980s clearly revealed the capability of X- and C-band SAR to detect wet snow. The wet snow mapping algorithm, developed with airborne data, applied simulated radar images to eliminate topographic effects on backscattering [3]. After the launch of the European Remote Sensing Satellite ERS-1 in 1991 repeat passes SAR images became available, enabling a new approach for snow mapping based on change-detection using multi-temporal data [4], [5]. This snow mapping algorithm was further refined by Nagler [6] and Nagler and Rott [7] to improve the accuracy for steep topography. The algorithm was also applied for snow mapping with ERS SAR in northern Scotland and northern Sweden [8] and in the mountainous regions of Norway [9], and with slight modifications for agricultural areas in south-eastern Québec, Canada [10]. A slightly different algorithm, also using multi-temporal SAR data, was applied by Koskinen *et al.* [11] to map snow cover in areas with different forest density in Finland. Investigations with polarimetric AIRSAR and SIR-C/X-SAR revealed improved capabilities for detecting wet snow, in particular on fore-slopes [12], [13], [14], and the possibility of deriving the liquid water content if the snow surface is smooth [15]. The usefulness of ERS SAR based snow maps generated in near real time for daily runoff forecasting was demonstrated in the project HYDALP of the 4th RTD framework programme of the European Commission [16], [17],[18], [19], [20].

ENVISAT ASAR provides higher temporal observation frequency than ERS SAR due to its electronic beam steering capability. This is particularly important in periods of intensive snowmelt. We investigated the impact of various ASAR observation geometries and polarizations for snow classification in Alpine regions in order to prepare for optimum use of ASAR data in snow hydrology.

2. STUDY AREAS AND DATA

We studied backscattering signatures and snow classification algorithms based on ASAR data from various parts of the Austrian Alps. Fig. 1 shows the coverage of ASAR images of our database, which includes the swaths IS-2, IS-6 and IS-7, with a nominal incidence angle range of 19.2 - 26.7 deg, 39.1 - 42.8 deg, and 42.5 - 45.2 deg, respectively. The scenes were acquired in Image Mode, HH or VV polarisation, or in Alternating Polarisation Mode with co– and/or cross-polarized channels (HH/VV, VV/VH, HH/HV). All data were ordered as single look complex products (IMS and APS) because they are also used for interferometric studies. In addition, a few wide swath (WSM) images at VV polarization are available.

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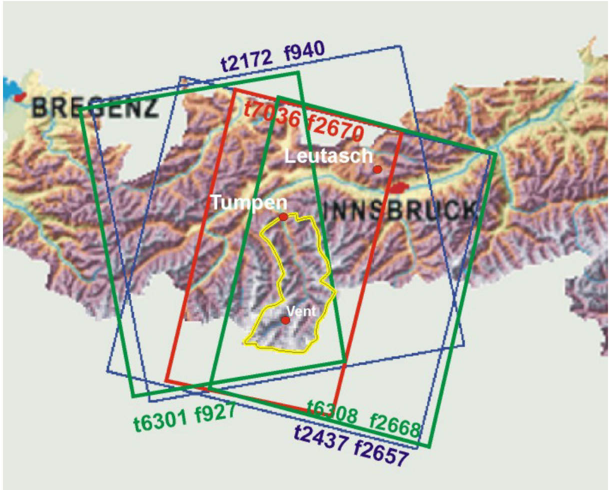

Fig. 1: Coverage of available ASAR IS-2 (blue), IS-6 (green), IS-7 (red) scenes over the Alpine study areas. The yellow line outlines the Ötztal watershed.

The main test site for signature analysis was the Leutasch valley located about 30 km northwest of Innsbruck, Austria. The bottom of the valley is flat, about 1.5 km wide and 15 km long, and mainly covered by cultivated grassland. The lower mountain slopes are covered by coniferous trees.

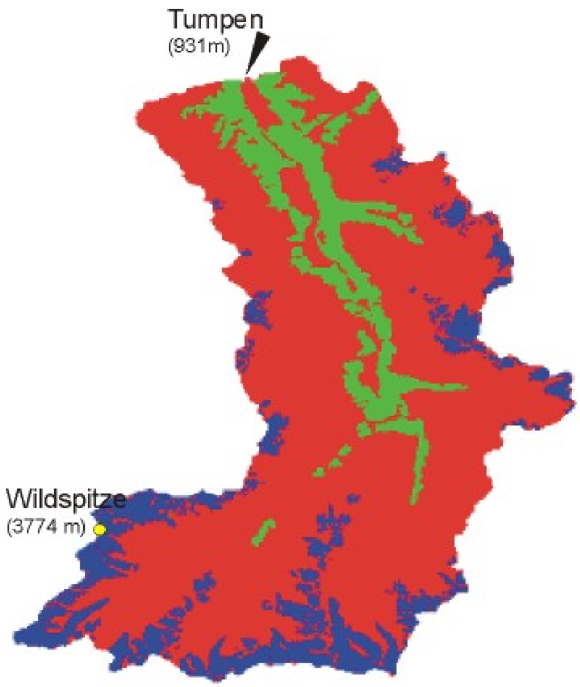

Fig. 2: The main land cover classes of the Ötztal watershed, red – low vegetation, bare soil and rock, green forests, blue – glaciers.

The Ötztal watershed, located north of the main ridge of the Eastern Alps, is our main study site for improvement and testing of the snow classification algorithm. The snow cover products are used as input for hydrological runoff modelling. The watershed covers an area of 759 km^2 and extends over elevations from 931 m at the runoff gauge Tumpen to the highest peak, Wildspitze, at 3774 m. The land cover is made up by cultivated meadows and a few agricultural fields in the valley floor, and coniferous forests on the lower slopes up to the timberline at about 2200 m. Low alpine vegetation, rocks, moraines and glaciers are the dominating land surface classes at high elevations (Fig. 2). For runoff modelling we divided the Ötztal basin above the river gauge Tumpen into four subbasins.

3. SIGNATURE ANALYSIS WITH ASAR DATA

Field measurements were carried out in the Leutasch valley to support the backscattering signature analysis and algorithm development. The temporal change of backscattering from snow-covered and snow-free surfaces was studied based on a time series of ASAR data acquired in Image (IM) and Alternating Polarisation (AP) Mode. During winter 2002/03 an automatic meteorological station operated measuring air temperature, solar radiation, wind, snow temperature at various depths, and soil temperature (Fig. 3). Vertical profiles of snow pack physical properties were measured on days of ASAR acquisitions.

Fig. 3: Test site Leutasch, 1100 m, with automatic meteorological station providing measuring air temperature, wind, solar radiation, snow temperature at 3 levels, and soil temperature.

Fig. 4 shows a time series of backscattering for a horizontal meadow at the Leutasch site. For the signature analysis the data were averaged over at least

81 pixels of ASAR single look complex products in Image or Alternating Polarisation mode (IM and AP) of different swaths. For deriving the backscattering coefficient the annotated calibration constants were used.

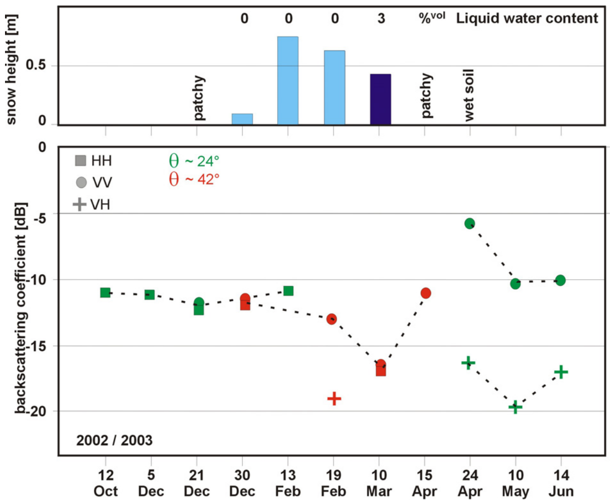

Fig. 4: Backscatter signatures (multi-looked) of meadow with and without snow at the Leutasch test site (lower diagram). The upper graph shows corresponding measurements of snow height and liquid water content.

Backscattering values are shown for IS2-images, with a local incidence angle of about 24°, and images from IS6 and IS7 scenes with higher local incidence angles of 40° to 45°. In general, σ° of VV and HH are very similar, whereas the cross-polarized backscattering coefficients are lower by several dBs. Backscattering at co- and cross polarization is very sensitive to the melting condition of snow. Thus the backscattering at cross polarisation on 19 February 2003 shows a very low value for smooth, wet snow, which is close to the noise level of the system.

4. SNOW MAPPING ALGORITHM

The main processing steps of the ASAR snow mapping procedure are shown in Fig. 5. It can be divided into three parts. The first part includes the generation of a geocoded ratio image using repeat pass images to detect changes of backscattering. At first the snow (slave) and reference (master) image are co-registered in full resolution to about one pixel accuracy. Then multi-looking and speckle filtering are applied sequentially. We found that the Frost Filter [21] is well suited for the snow mapping procedure, the filter size depends on the previously applied level of multi-looking. The ratio of the backscattering coefficient of the wet snow image (σ°_{ws}) versus the backscattering coefficient of the reference image (σ°_{ref}) is calculated, and the ratio image is geocoded using a digital elevation model and orbit parameters. By forming the ratio ($\sigma^\circ_{ws}/\sigma^\circ_{ref}$) the incidence angle dependence is strongly reduced. Masks of layover and radar shadow, and local incidence angle maps are generated from orbit parameters and the digital elevation model (DEM).

In the second part of the procedure the binary snow map is generated by applying a classification rule. For detecting wet snow on a pixel-by-pixel basis a threshold, TR, is applied to the geocoded ratio image:

if (L = True or S = True or I = True) then
No Information can be derived
else if ($\sigma^\circ_{ws} / \sigma^\circ_{ref} < TR$) then (1)
wet snow
else
snow free

where L, S, and I specify pixels, which are inappropriate for snow classification, affected by layover (L), radar shadow (S), and areas with low local incidence angle (< 17° for co-polarized data) or grazing incidence angle (>78°) (I). Based on signature studies, field observations and comparison with optical data, a threshold of TR = -3 dB was found appropriate for ERS SAR and Radarsat SAR data over alpine terrain using VV or HH polarisation [6], [19]. The ASAR data set available shows that this threshold is also suitable for ENVISAT ASAR co-polarized data acquired in Image, Alternating Polarisation and Wide Swath Mode.

For cross-polarized data we so far have only a very limited data set available, showing that the same algorithm can be used for snow classification as for co-polarized data if both the snow image and reference image are of cross-polarized mode. On the other hand, in case of co-polarized data HH- and VV-polarizations can be combined for ratioing without any problems in Alpine areas, because there is little polarization difference.

Depending on the ASAR image swath and the steepness of the terrain, either images from one look direction are used for snow mapping, or geocoded ratio images of crossing orbits are combined to reduce the loss of information due to layover and inappropriate incidence angles. In order to obtain suitable coverage in steep terrain such as in the Alps, two look directions are required for swaths with low incidence angle, as for example ASAR swath IS2. At swaths with higher look angle (such as ASAR swath IS6, or IS7) the loss of information due to layover and foreshortening is small and this step can be omitted (see section 5).

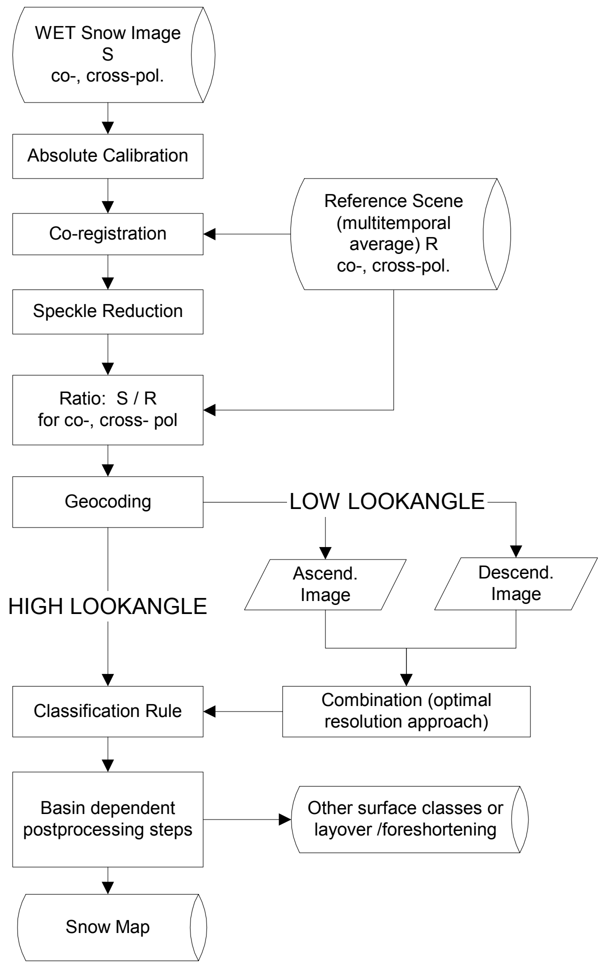

Fig. 5: Processing steps of SAR based wet snow mapping procedure (using ASAR Image mode and/or Alternating Polarisation Mode Products).

For ASAR swaths at low look angle (e.g. IS2) the following rules are applied pixel by pixel (multi-looked) for combining crossing passes:

- Exclude all pixels, which are situated in areas of layover, shadow or inappropriate local incidence angles both in the image of the ascending and of the descending pass. These pixels are included in the mask of areas where no information can be derived.

- If a pixel is excluded due to these effects in only one of the passes, the snow classification is carried out with the other pass.

- If a pixel is accepted in the image of the ascending and of the descending pass, the pixel from the pass with the higher local incidence angle is selected.

The third part of the snow mapping algorithm includes post processing steps to account for dry snow and to eliminate misclassifications due to backscatter changes that are not related to snowmelt. We apply the following rules:

- The agricultural areas are classified with optical imagery and are flagged out in the SAR images. It is assumed that these areas are snow free after the snow line has retreated to higher elevations. In alpine basins agricultural areas are located mainly at low altitudes and become snow free earlier in spring than the mountain slopes.

- In order to account for dry snow we use either the decision rule that surfaces above the upper boundary of wet snow areas are covered by dry snow, or we use archived snow maps, preferably from optical images, with similar snowline altitude. This rule is based on the observation that in mountainous regions melting is strongly influenced by topography. In general, snowmelt starts at low altitudes while the snow is still dry at higher elevations.

For regions in different climatic conditions or environment the post processing steps may have to be modified.

5. EFFECTS OF THE IMAGING GEOMETRY

Due to the steep topography the Ötztal watershed offers the possibility of investigating effects of the SAR imaging geometry. We investigated ASAR images in IM and AP mode of swath IS-2 (nominal incidence angle range between 19.2 - 26.7 deg) and swath IS-6 (nominal incidence angle range between 39.1 - 42.8 deg) (see Fig. 1 for coverage).

Fig. 6 shows amplitude images in slant range geometry of the investigation area. The geocoded products are shown in Fig. 7 and Fig. 8. Due to the steep look angle, foreshortening and layover are important in the IS-2 images, while areas in radar shadow can be neglected. In the Ötztal basin about 46 % of the area are situated in layover. Therefore, as for ERS SAR, the combination of images of crossing orbits is required to obtain suitable coverage. At swaths with high look angles, as the case for swath IS-6 and IS-7, much less information is lost due to the SAR image geometry, and one scene, ascending or descending, is sufficient. In the Ötztal basin the amount of layover is only 6% for IS-6. This means that in this terrain high look angle swaths (e.g. IS-6 and IS-7) are the preferred imaging mode, because they provide information on snow extent for more than 90% of the basin, which is a sufficient coverage for most applications in hydrology.

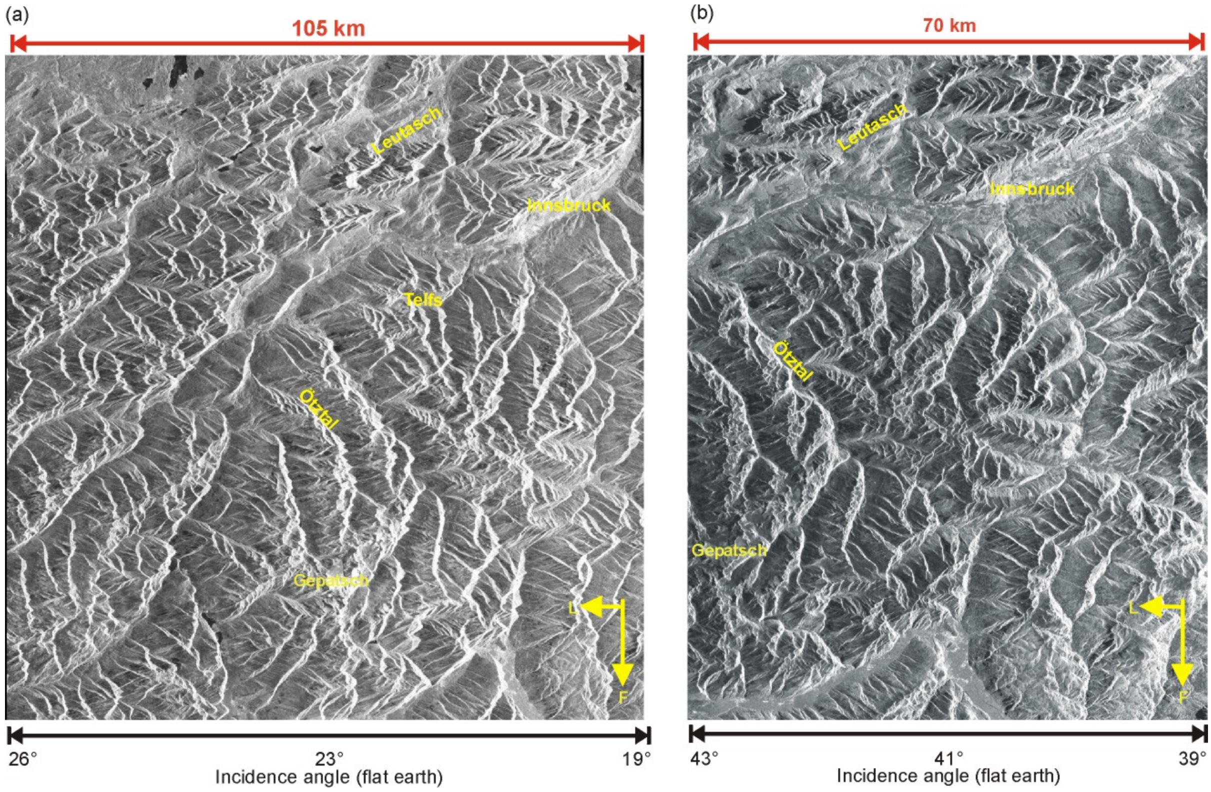

Fig. 6: Example of ASAR swath IS2, track 437 (right) and swath IS6, track 301 (left) multi-temporal average amplitude images, acquired during descending passes, covering the Ötztal and parts of the Inn valley. For orientation a few land marks are annotated in the images, including the signature test site Leutasch. (L - look direction, F - flight direction).

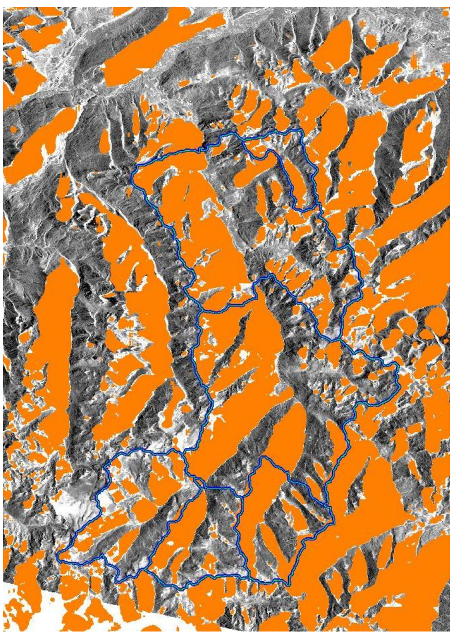

Fig. 7: Geocoded multitemporal amplitude image of ASAR swath IS-2, track 437. Layover areas are shown in orange, the blue line outlines the Ötztal basin.

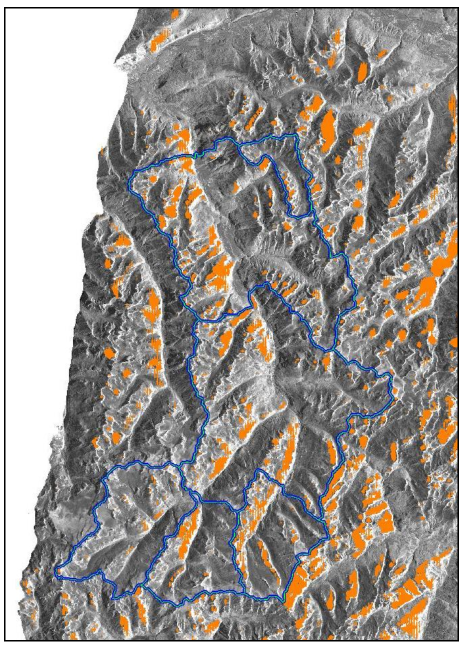

Fig. 8: As Fig. 7, but for IS-6, track 308.

6. SEGMENTATION OF WET SNOW

ENVISAT ASAR offers various acquisition modes: the Imaging mode (Stripmap SAR operation), the Alternating Polarisation mode, the Wide Swath mode (ScanSAR operation). The availability of the optimum mode for a particular application and time cannot be guaranteed because of conflicting interest of various users. Therefore it is important to study different options for snow classification.

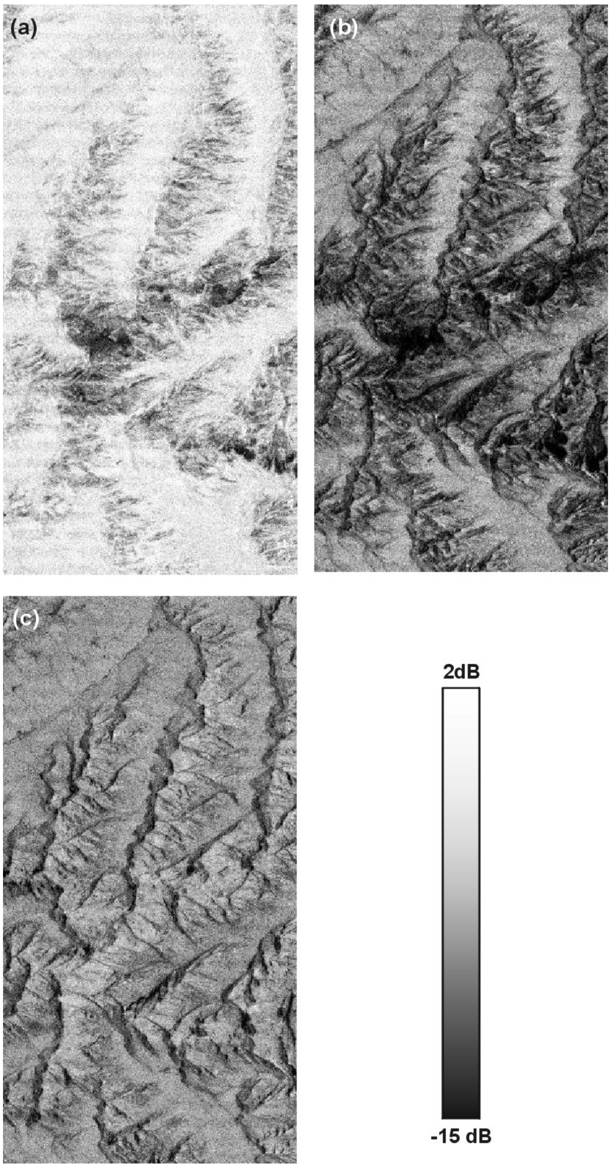

Fig. 9: Multitemporal ratio images of wet snow (10 May) versus dry snow reference (21 Dec.) and single track ratio). Multitemporal approach: (a) 10 May 2003 (AP, VV) versus 21 Dec 2002 (IM, VV), (b) 10 May 2003 (AP, VH) versus 21 Dec 2002, (IM, VV). Single track approach (c) 10 May 2003 (AP): VH versus VV.

To investigate the dynamic response of backscattering at different polarisations due to melting snow we analysed different combinations of IM and AP scenes for the segmentation of wet snow. The combination of different imaging modes can provide a better time sequence, which is of interest especially during the main melting season when the snow line may retreat significantly within a few days.

Fig. 9 shows ratio images of various polarisations covering the western part of the Ötztal Alps. Fig. 9 a and b show ratios of multi-temporal image pairs, which means that snow and reference images are acquired on different dates. In this case the wet snow image was acquired on 10 May 2003 in AP mode (VV, VH polarisation) and the reference image on 21 December 2002 (IM mode, VV polarisation). Both the combination of two co-polarised channels and of one cross- and one co polarized channel show sufficient dynamic range of backscattering to enable segmentation of wet snow. However, in the combination of co- and cross-polarized backscattering the topographic effects are not fully compensated by forming the ratio because of different incidence angle dependence.

We investigated also the option to apply polarization ratios of single tracks of an AP image for snow mapping, using the combination of two co-polarized channels (HH/VV), as well as the ratio of cross-polarized versus co-polarized channels (VH/VV, or HV/HH). In both cases the dynamic range of the backscattering ratio of snow-covered versus snow-free ground is small, not enabling the clear detection of wet snow (Fig. 9 c).

7. SNOW COVER MAPS

Fig. 10 shows a time series of composite snow maps of the melting season 2004, superimposed to a multi-temporal amplitude image. For snow mapping ASAR IS-6 scenes of 4 May, 8 June and 13 July 2004 were used, as reference image only a single scene, acquired on 7 October 2003. To improve the representativity of the backscattering properties and for speckle reduction it is preferable to use a multi-temporal average of several reference images if available. In spring 2004 the snowmelt was retarded compared to other years, as the ASAR snow maps show. The snow extent in the Ötztal basin amounted to 403.2 km^2 (55.1 % of the basin) on 4 May, 324.1 km^2 (44.3 %) on 8 June, and 153.3 km^2 (20.9 %) on 13 July 2004.

Fig. 11 shows as an example the change of melting snow areas from 10 May to 14 June 2003, derived from ASAR WSM data. Because so far we have only a small data set available, we used the image of 14 June 2003 as reference. The first results show that wide swath images are useful for snow mapping also in mountain areas, although with less detail than images acquired in AP or IM mode. When more WSM data of the melting season will become available, we plan to compare the accuracy of the WSM and high resolution snow products.

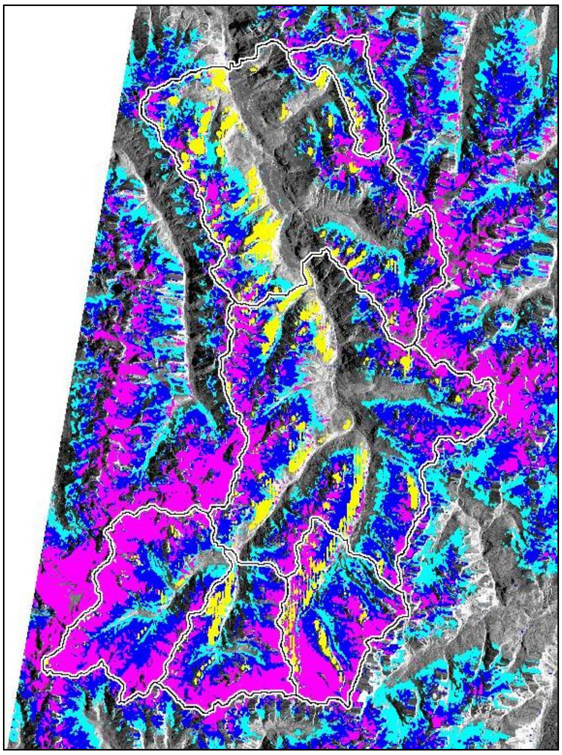

Fig. 10: Multitemporal snow map from ASAR IS-6, images, track 308 superimposed to a geocoded multitemporal amplitude image. Decrease of snow area from 4 May 2004 to 8 June 2004 (cyan), from 8 June 2004 to 13 July 2004 (blue), remaining snow extent on 13 July 2004 (magenta). Areas where no information can be retrieved are shown in yellow.

8. SUMMARY AND CONCLUSIONS

The automatic snow classification algorithm based on multi-temporal segmentation, which was developed previously for ERS and Radarsat SAR, has been successfully applied to ENVISAT ASAR with minor modifications. Data in Image Mode, Alternating Polarisation Mode, and Wide Swath Mode are well suitable for mapping melting snow in alpine areas. Snow cover maps derived from data of the different ASAR modes can be used to generate consistent snow cover time series, thus increasing the database for snowmelt monitoring and runoff modelling. Various options for image segmentation to classify wet snow areas were studied. Single term backscattering ratios of cross- versus co-polarized data of ASAR Alternating Polarisation Mode do not provide sufficient dynamic

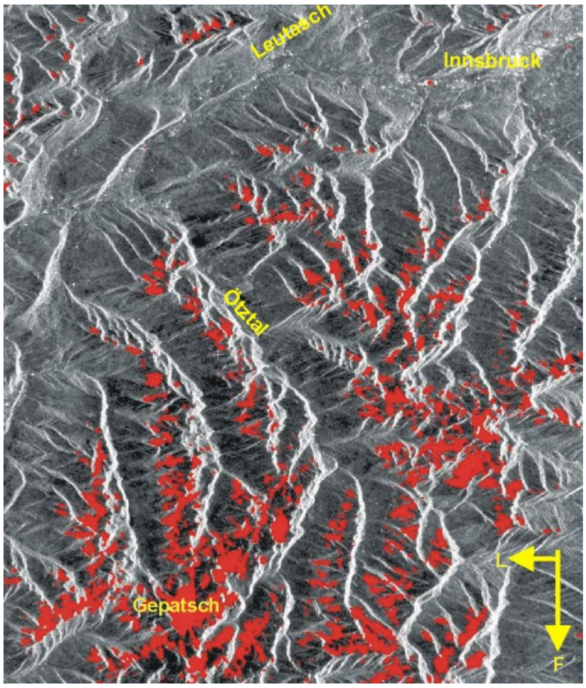

Fig 11: Change of wet snow area from 10 May to 14 June 2003 (red), from ASAR WSM data, VV polarisation. The snow map is overlaid to the amplitude image in ground range geometry.

range for clear detection of snow. For multi-temporal segmentation, using snow and reference images of different dates, various combinations of polarization are suitable. Multi-temporal ratioing is not only restricted to images of the same polarization, but HH- and VV-polarized data can be combined without any problems because of little polarisation differences in Alpine terrain. On the other hand, the combination of co- and cross-polarized backscattering is less suitable because the topographic effects are not fully compensated due to different angular dependence of backscattering.

In mountainous areas the image swaths IS-6 and IS-7 are preferred, because the loss of information due to topographic distortion is reduced significantly compared to the low incidence angle swaths, and suitable snow maps can be produced from data of a single look direction. At low look angles the loss of information is high (e.g. 46 % in the Ötztal basin for the descending pass of IS-2) and the combination of data from crossing orbits is required.

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