OPERATIONAL REMOTE SENSING METHODS TO DERIVE SNOW PROPERTIES FOR HYDROLOGICAL MODELLING

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ABSTRACT

Remote sensing methods to derive snow properties using both optical and SAR data are presented. They are for implementation in flood forecast centres responsible for the operational runoff forecast of the Neckar and Mosel in the South West of Germany.

A fully automatic algorithm to derive snow-covered area from optical data is described. Snow-cover information is processed and provided within a few minutes after online reception of NOAA-AVHRR data. Processing consists of calibration, geometric correction and classification including automatic cloud detection. For high geometric accuracy an iterative procedure using satellite orbit information and parametric geocoding including a DEM based terrain correction was integrated. The snow classification uses multispectral indices within a sensor dependent decision tree. To avoid misclassifications due to dense forests the classification procedure was adapted to consider land use influences.

In order to derive snow properties from SAR, radiometric and geometric correction tools for ERS were improved and adapted. Datasets from winter season 1998/99 of the Neckar catchment (14.000 km^2) in Baden-Württemberg were combined with modelled snow-cover and GIS information to demonstrate the innovation of multisensoral analyses of snow properties for operational hydrological modelling. The operational potential of the methodology will be decisively enforced with the availability of ENVISAT data. The presented work is part of the INFERNO+ project (Integration of remote sensing data in operational water balance and flood prediction modelling), funded by the German Aerospace Centre (DLR).

INTRODUCTION

For operational flood forecasting the application of rainfall-runoff models can be considered as the state of art. In order to reduce damages and economic loss, a high accuracy of runoff simulation is mandatory. Flood model theory is satisfactorily understood and can hardly be improved. Improvements of the forecast are however possible through a better determination of spatial input parameters to the models. In addition to rainfall distribution, especially temporally and spatially highly variable information of snow properties and soil moisture are most relevant for the description of runoff formation. Nevertheless this information is often missing or of low quality. To fill this gap remote sensing has a strong potential, as proven in a series of scientific studies and pilot projects (3), (4).

In order to transfer the scientific progress to operational applications, the INFERNO+ (Integration of remote sensing data in operational water balance and flood prediction modelling) project was started at the end of 2000. The project is coordinated by the HVZ and funded by the German Aerospace Centre DLR (No. 50EE0053). The 'Hochwasservorhersagezentrale' (flood forecast centre) HVZ is part of the 'Landesanstalt für Umweltschutz Baden-Württemberg' and is responsible for the operational flood forecast in Baden-Württemberg (e.g. Upper Rhine and Neckar). Within this project the potential for using multisensoral ENVISAT data for operational flood forecasting is analysed using test cases and demonstration runs (5). The project team consists of four partners. The HVZ defines the required products from an operational hydrological perspective. For demonstration and operational use, the remote sensing products will be integrated in the water balance model LARSIM (Large Area Runoff Simulation Model) at the HVZ (Karlsruhe) for the Neckar, and the LfW (Landesanstalt für Wasserwirtschaft) Rheinland-Pfalz (Mainz) for the Mosel catchment, respectively. The scientific research of new algorithms for information retrieval from different ENVISAT–sensors (microwave and optical) is done by the Institute for Geography of the University of Munich. The value adding company VISTA serves as the integrating link between research and hydrologists through the transfer and extension of the research results into operational procedures and stable tools. Until ENVISAT data are available, software tools are developed and products generated using existing sensors with similar specifications (ERS, RADARSAT and NOAA-AVHRR). With the availability of ENVISAT the methods will be adapted to the use of ASAR, MERIS and AATSR.

OPTICAL REMOTE SENSING METHODS

In the past several methods have been developed and published for the classification of snow cover and to distinguish snow from clouds by their respective spectral signatures (1),(2). They are based on the fact that in contrast to clouds, snow covered surfaces show a low reflectivity in the short-wave-infrared section of the electromagnetic spectrum, while both surfaces have high reflectances in the visible. Problems during operational application arise due to the low temporal frequency of high resolution optical information and the frequent appearance of cloud cover.

Operational NOAA-AVHRR processing chain

An operational processing chain has been developed for INFERNO+ to provide nearly real-time snow cover information for Southern Germany. Since winter 2001 snow cover maps are created within a few minutes after online reception of NOAA-AVHRR HRPT (High Resolution Picture Transmission) data. Reception and archiving of the AVHRR data is done at the University of Munich. Actual orbit information (two-line elements) for the reception is taken from the weekly updated CELESTRAK service (URL 1). Images from NOAA 12, 14 and since early 2001, from NOAA 16 were analysed. The improved AVHRR/3 sensor (also onboard NOAA 15 and 17) supports improved snow and cloud discrimination using mid-infrared reflectance information (1.58-1.64µm) from channel 3a.

After the reception of a NOAA flight-path the processing chain illustrated in Figure 2 is automatically activated. First navigation is performed using a 1 km grid of the investigated area. This is done for a 500x500 km region centred on the Neckar catchment (Figure 1). For each ground element the corresponding pixel in the NOAA file is determined using satellite track information from the header data. Additionally solar and sensor zenith and azimuth angles are stored for each grid point. This information is required in the following snow and cloud detection algorithm.

The second step of the processing consists in the calibration of the data using coefficients published by NOAA/NESDIS. Calibration is performed using pre-flight calibration considering published degradation (NOAA 14) of AVHRR visible channels and actual coefficients (in-flight calibration) for the thermal channels contained in the header data. (URL 2) results are the calibrated measurements of the 'top of the atmosphere' albedo of channel 1 and 2 (NOAA 16 also mid-infrared channel 3) and thermal radiation, represented by channel (3), 4 and 5 (5 channels).

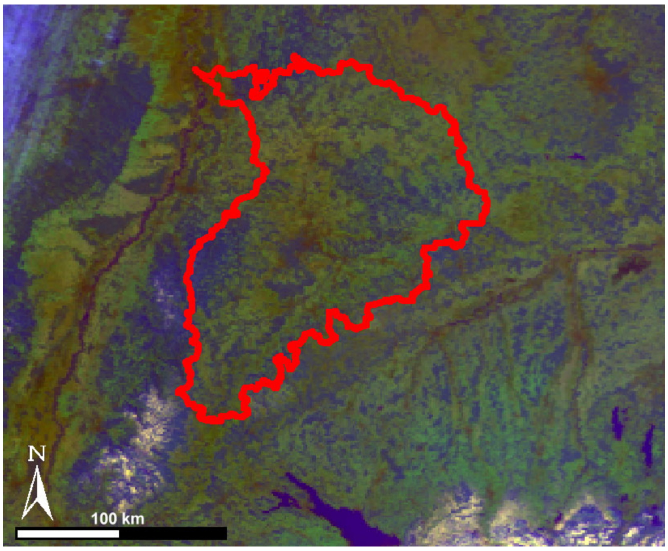

Figure 1: Investigation Area Neckar catchment in the South-West of Germany

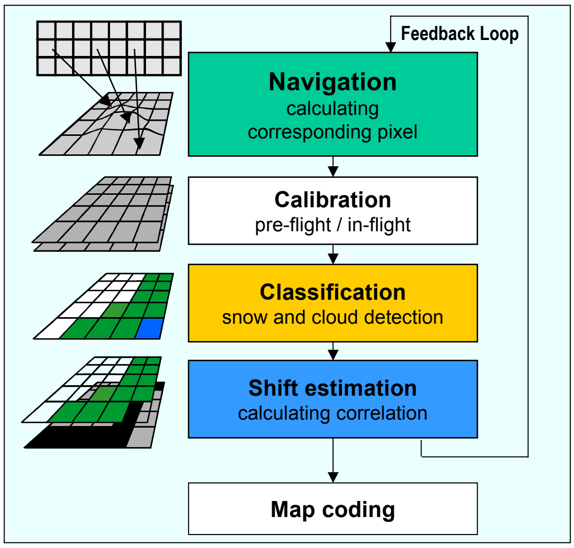

Figure 2: NOAAprocessing chain for snow classification

Operational Snow and Cloud Detection

Using the resulting 9-channel dataset (5 spectral, 4 geometric bands) a first run of the developed snow and cloud detection routine (Figure 3) is performed. Each pixel is classified using empirically determined, temporal invariable thresholds, resulting in a classification distinguishing snow, clouds and snow-free areas. Using a hierarchical decision tree firstly snow is detected using the ratio (index) between visible and mid-infrared reflectance. Depending on the applied sensor this index is derived using the Derrien method (1) in case of AVHRR/2 data (NOAA-9 to 14), or the Dozier method (2) for AVHRR/3 data (NOAA-16 / 17). For AVHRR/2 it is assumed that mid-infrared reflectance is represented by the difference of ch3 (3.55 µm) and ch4 (10.5 µm) radiation.

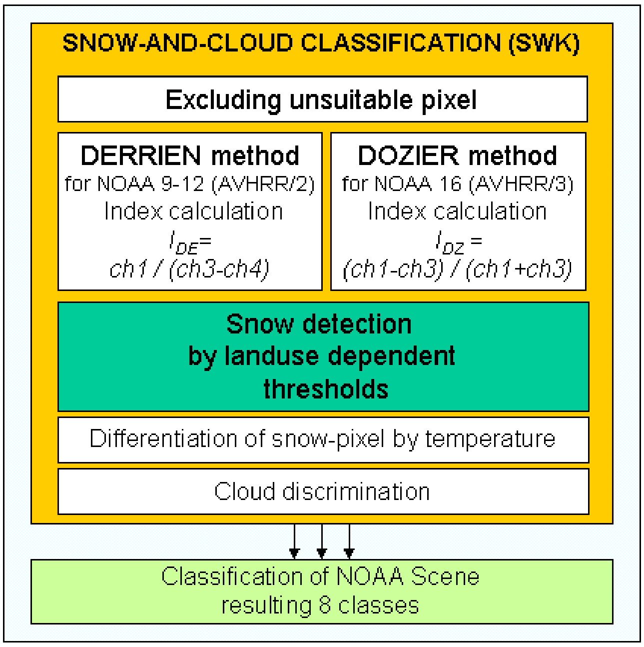

Figure 3: Snow detection algorithm

Classification is performed by thresholding the index and the reflectance values of ch1, ch2, (ch3) (corrected by solar zenith angle) and ch4 thermal radiation. For all pixels with high visible and low mid-infrared reflectance, represented by the index, snow cover is classified. For pixels with similar spectral properties a second snow class (= probably snow), mainly representing cloud-covered snow, is used.

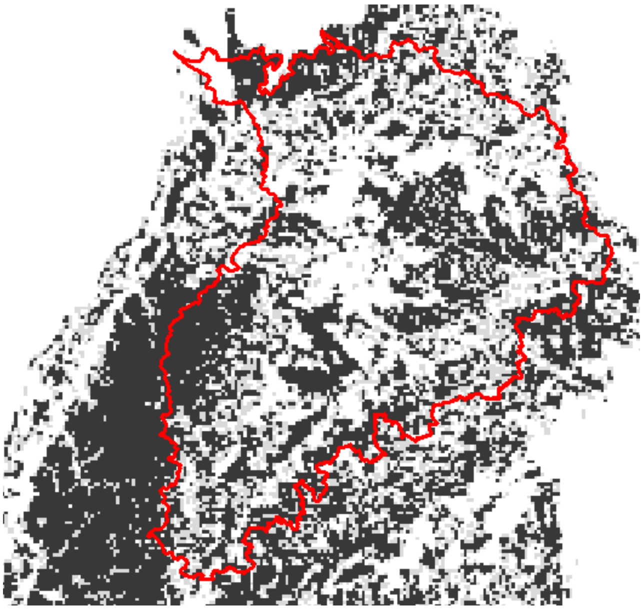

Figure 4a: Forested areas in the Neckar basin

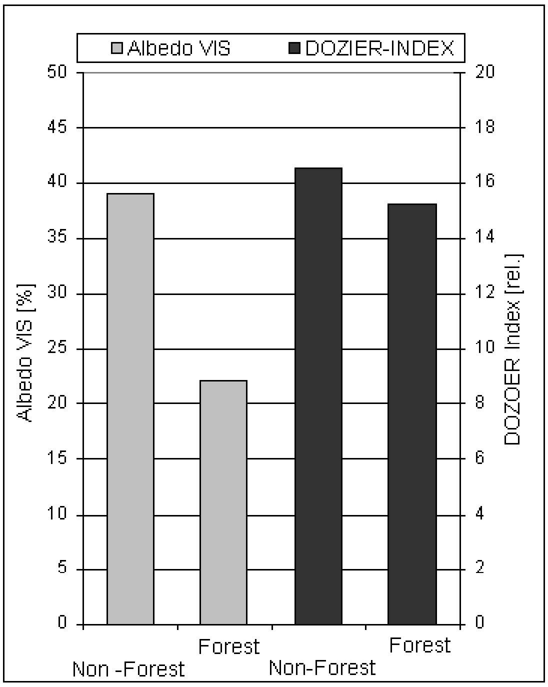

Figure 4b: Influence of forest on snow pixels

In regions with dense forests (forest covers more than 30 % of the 1 km pixel) (Figure 4a), snow classification is affected (Figure 4b). Since the reflectance in the visible is significantly reduced in dense forests, the index is slightly influenced. For compensation, land use dependent thresholds are integrated for the feedback loop. For pixels with more than one third of forested area the thresholds are optimised to compensate the reduced VIS reflectance values (Figure 5a/5b). Only during the second processing loop, after a precise automatic geocoding is achieved, land use information provided in a GIS is considered in the classification. Thus misclassified pixels due to poor co-registration are avoided.

The identified snow pixels were further differentiated. 'Cold' pixels are re-classified as "probably cloud", 'warm' pixels are classified as "tempered/melting snow". The applied classification thresholds were empirically fitted to the conditions observed during past winter periods in Southern Germany and the Northern Alps. Some of the threshold values were dynamically adapted from actual conditions by analysing local thermal radiance.

The remaining 'non-snow pixels' were tested for cloud conditions by short-wave reflectance and thermal radiance. Finally a first snow and cloud map (8 classes) is built up. All persisting pixels represent snow- and cloud-free ground reflectance. This information is used to review the geometric accuracy of the processed image.

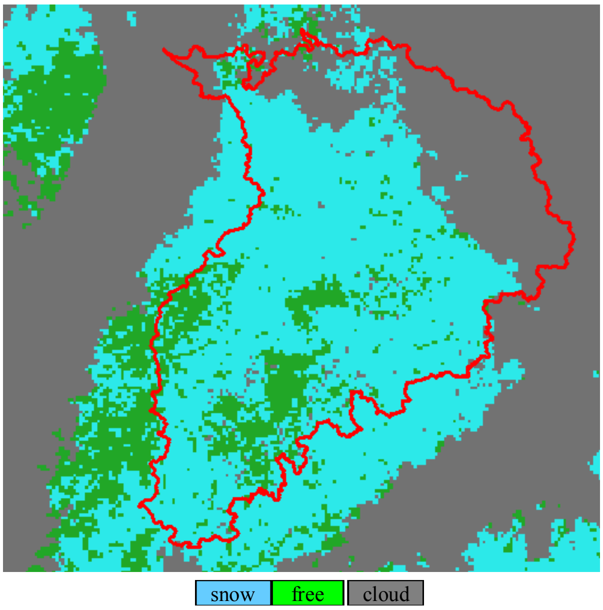

Figure 5a: Classification result without regard to forest areas (N16 13.1.2002)

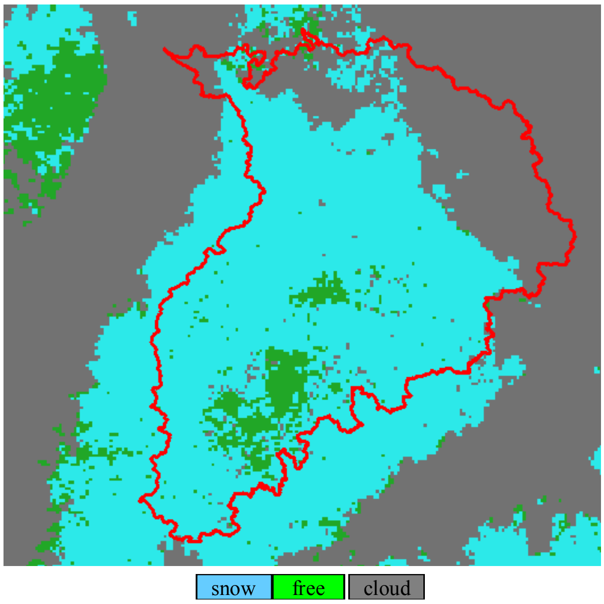

Figure 5b: Classification result considering regard forest areas (N16 13.1.2002)

Shift estimation and compensation

The evaluation of historic NOAA scenes showed that parametric geocoding alone is not sufficiently accurate. Considering the investigated area (Neckar and Mosel basin) individual linear shifts were observed of up to 15 pixels. To correct the remaining geometric error, an automatic iterative procedure for the estimation of geometric shift between actual NOAA scene and geometric reference was developed (Figure 6). Within this module the correlation between ground reflectance of cloud and snow free areas (depending on appearance) and a synthetic reference image is calculated for VIS and NIR channel. By an iterative search, the best agreement and the resulting shift factors are figured out and passed on to be integrated in a second run of the complete processing chain.

Considering the investigated shift factors, a repeated navigation run is carried out (Figure 7). Geolocation is performed using terrain information of a DEM. This corrects most of the terrain influence effects. Depending on the local incidence angle and terrain elevation a relief displacement of up to 5 pixel (5 km!) was observed and corrected in the investigated area. The remaining geometric shift amounts to less than one pixel.

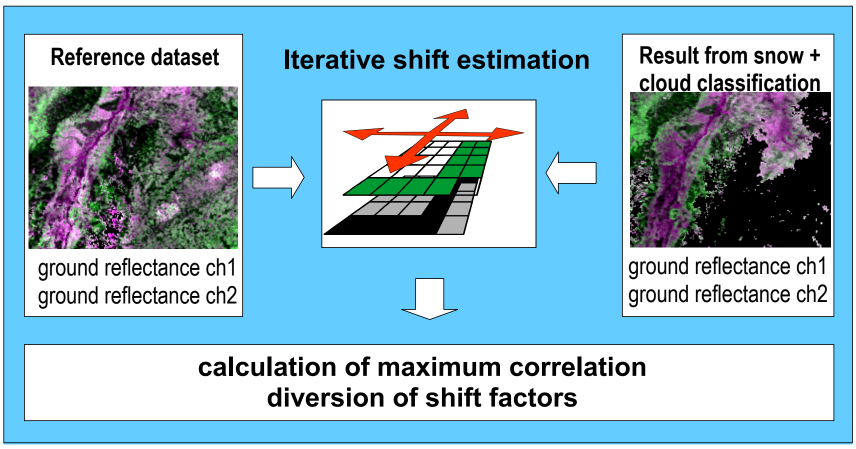

Figure 6: Iterative shift estimation

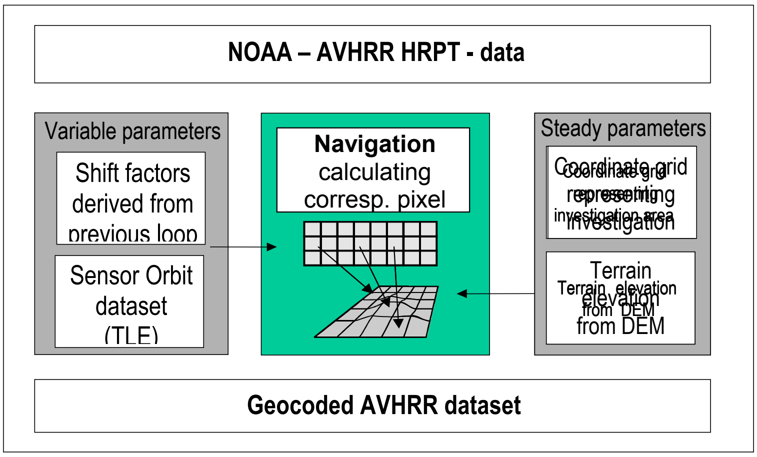

Figure 7: Geocoding and terrain correction

The following processing steps are equal to the first loop of the process. After the final snow and cloud detection (with land use dependent thresholds) and additional shift control, the resulting map and the spectral and geometric datasets were combined and finally archived. In case cloud coverage allows successful geometric correction, the snow mapping result are transformed and transmitted for integration in hydrologic modelling at the HVZ.

The Large Area Runoff Simulation Model LARSIM

The HVZ applies the water balance model LARSIM (Large Area Runoff Simulation Model) to calculate flood forecasts for several gauges in Baden-Württemberg. LARSIM enables continuous spatially distributed process simulations of the water balance terms for mesoscale catchments (6). The water balance model processes runoff generation and translation and retention in river channels, as well as interception, evapotranspiration, water storage, and accumulation, metamorphosis and melting of a snowpack. The model is operationally applied to the Neckar basin. Two of the continuously provided results in a 1km resolution grid are snow depth and water equivalent (Figure 8).

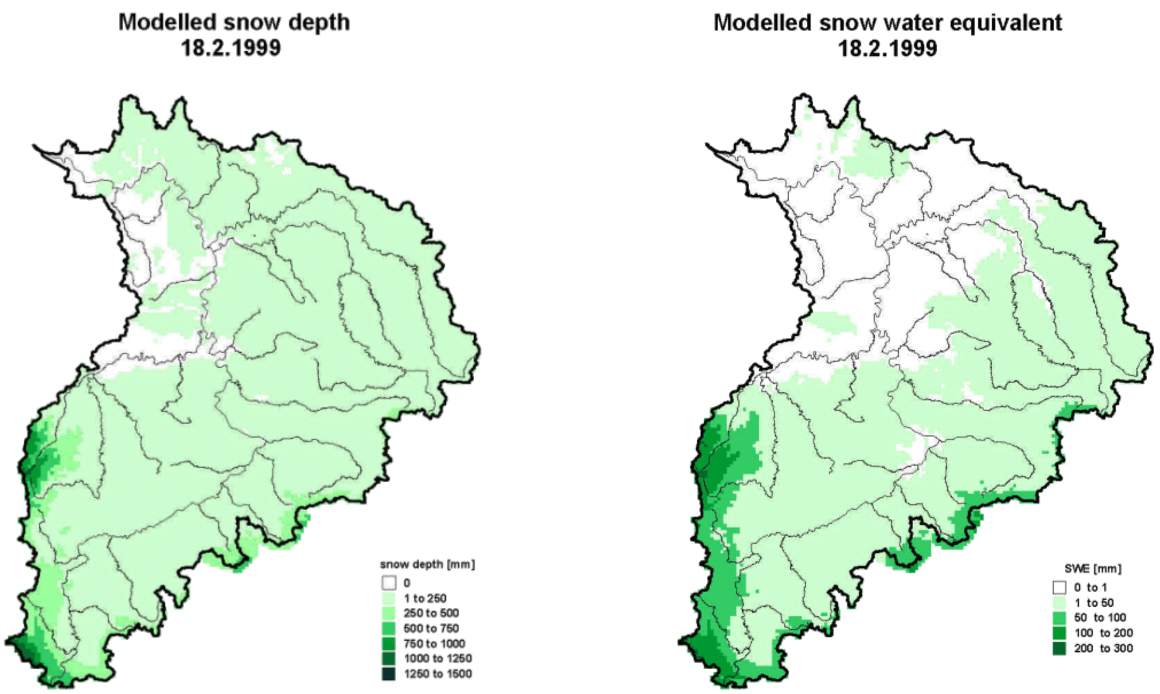

Figure 8: Snow depth and water equivalent model results from LARSIM

RESULTS OF OPTICAL ANALYSES

The automatic evaluation of NOAA-AVHRR scenes since the winter 2001 brought experiences in operational service. All received scenes from NOAA-AVHRR were operationally handled and classified in near real-time (within one hour after reception). Due to data errors (NOAA 14) and disadvantageous path times, mainly NOAA 16 recordings were evaluated so far. Problems and limitations appearing during operational use, like insufficient data, antenna failure, data errors and of course mostly cloud cover were recognized and considered automatically. The developed algorithm proved to be highly reliable, since problems were automatically detected. Results from the demonstration run during winter season 2001/2002 are shown in Table 1.

Table 1: Results from operational demonstration run (13.10.2001 – 28. 02. 2002) NOAA 16

	Total	Processing successful completed snow map derived	Cloud cover > 95% no processing	Technical Problems
Number of scenes	135	85	29	21
Portion	100%	63%	21%	16%

Verification of the retrieved snow classification is performed using the dense station network of the DWD (Figure 9). The DWD operates 50 snow gauges in the Neckar catchment, registering and transmitting snow depth and snow water equivalent three times a week. Measurements of about 400 further DWD stations are available offline to enable validation of historic events. Results for the winter 1998/1999 show the high potential of the selected methods for the application in the investigated midland area. During the calibration phase (winter 1998/99) snow detection in comparison with station measurement achieved high agreement. For 4 of the evaluated 12 NOAA scenes station measurements from 117 DWD stations were available on the same day (8). Results of classification in comparison with station measurements are shown in Table 2. Since the DWD data do not differentiate between 'snow free' and 'missing data', the error of wrongly classified snow pixels at stations that were snow free could not be quantified. Detailed investigations of 1998/1999 results showed that most of the wrongly unclassified snow pixels were dense forest. After integration of land use dependent thresholds a further improvement is expected. This will be tested for the winter 2001/2002 season. As soon as the ground measurements are available the statistical basis of the verification will be improved.

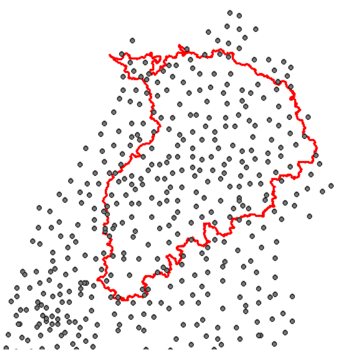

Figure 9: Station network of the DWD for Baden-Württemberg

Figure 10 shows comparisons between classified snow cover from satellite imagery (left), and LARSIM modelled snow depth (centre). For February 26th 1999 (top), only small differences in snow cover between satellite imagery and LARSIM results can be observed. For February 27th 1999 LARSIM calculated less snow than observed at DWD stations (red dots). Station measurements, however, agree well with NOAA observed snow cover. Snowmelt between 26th and 27th was obviously overestimated by LARSIM.

Table 2: Results of NOAA-14 classification (4 scenes) in comparison with station measurements (1998/99)

	NOAA classification agrees with station measurement	NOAA classification did not recognize snow
Number of observations	169	8
Percentage	*95%*	*5%*

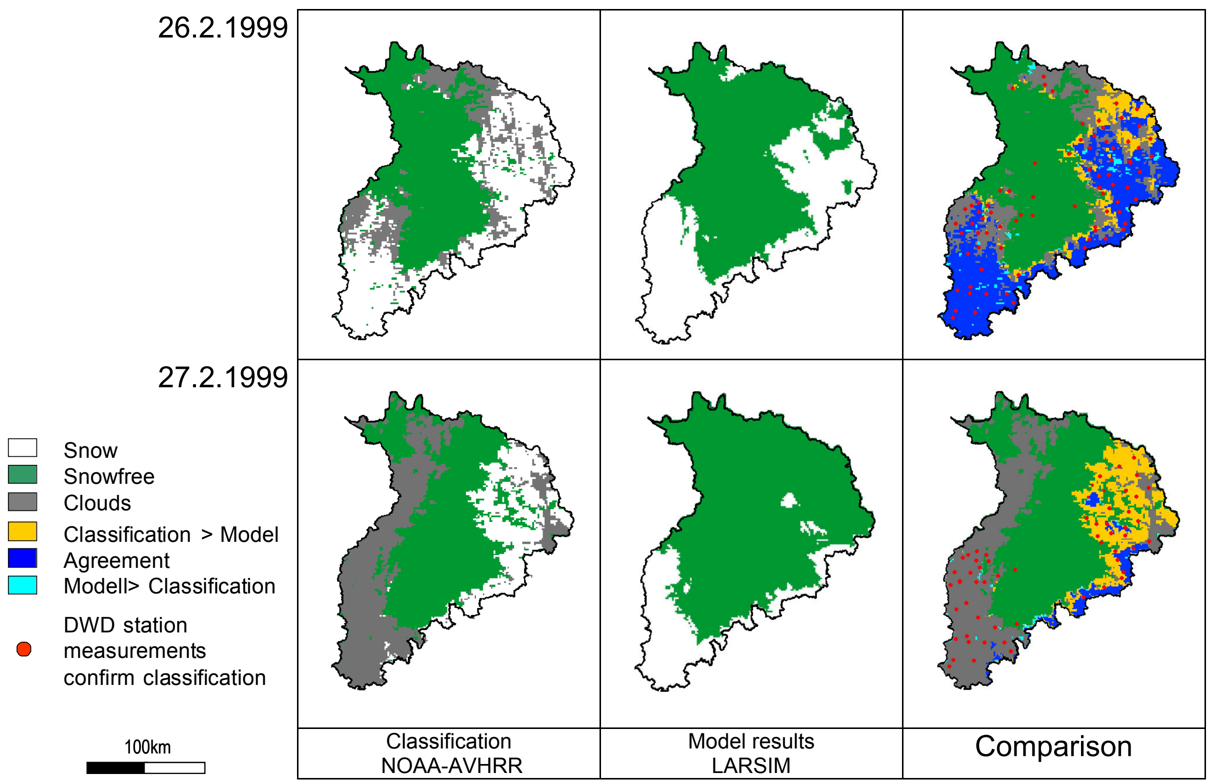

Figure 10: Comparison between NOAA snow classification, model results and station measurements

MICROWAVE REMOTE SENSING METHODS

A synergistic multisensoral approach is chosen to demonstrate the application of SAR data in hydrologic modelling, using combinations of optical and microwave data for the derivation_of snow properties.

Snow cover retrieval from SAR data

Applying Synthetic Aperture Radar (SAR), the backscatter coefficient of a snow-covered area comprises information on the air/snow, the snow/ground interface, the ground and volume scattering in the snowpack. Dry snow is nearly transparent, so backscatter is significantly dominated by the underlying soil properties. The appearance of liquid water on the upper snow layer has however an evident influence on the microwave penetration depth, since it significantly reduces the backscattered SAR signal (Figure 11). Mapping of wet snow can therefore be done by ratioing and thresholding backscatter observations from reference and actual conditions, demonstrated by (10).

While most studies on wet snow area estimation were conducted in alpine areas, the project area of INFERNO+ lies in the low mountainous area of the Neckar and Mosel watershed, where the small scale heterogeneity of land use shows explicit backscatter variability due to the respective differences in surface roughness. In order to quantitatively improve classification results, these differences will be compensated applying land use dependent thresholds (11).

Consequently the spatial and temporal location of the transition from wet to dry snow zone can be monitored with a time series of SAR images. ENVISAT ASAR will provide images with high temporal frequency of about 3 days. This is a great step towards operational monitoring. For the demonstration of the applicability of SAR data in hydrologic modelling for the Neckar basin, first results of the multisensoral approach using combination of optical (NOAA) and microwave (ERS-2) data were produced.

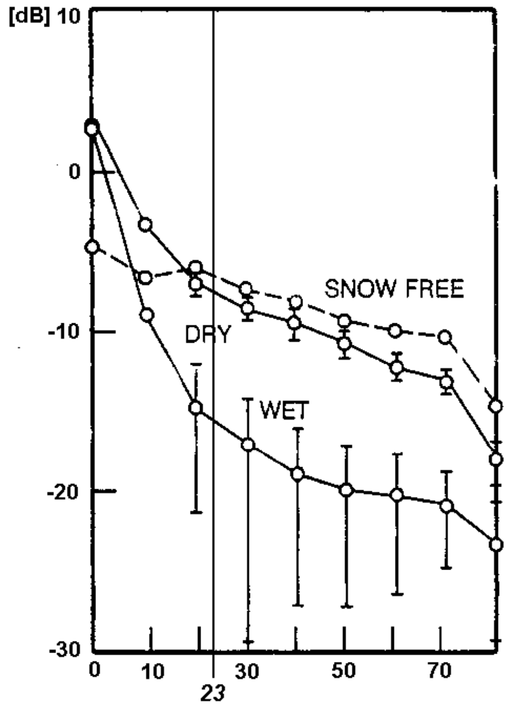

Figure 11: Backscatter behavior of snow and snow free areas (9)

SAR data processing

Processing of ERS-SLC data consists of several steps, starting with transcription and calibration of slant range images, using software-tools from ESA-ESRIN/ Telespazio (SAR-TOOLBOX).

Parametric geocoding and illumination corrections are performed using software developed at the University of Munich (12). These software tools were improved and adapted to enable nearly automatic processing. Using only one tiepoint in the image, the geometric correction terms for the scene can be derived. Applying this term together with ERS orbital information and a Digital Elevation Model (DEM), unique geometric relations between slant range data and ground surface are calculated. Together with information on local pulses and angles for each ground element the slant range image is then warped on to the DEM (see Figure 12). Illumination influences due to terrain effects are compensated by incoherent summation of multiple backscatter information covering one DEM element (12). Projection and spatial resolution is dependent on the utilised DEM. An example is shown in Figure 13 for a region near Stuttgart.

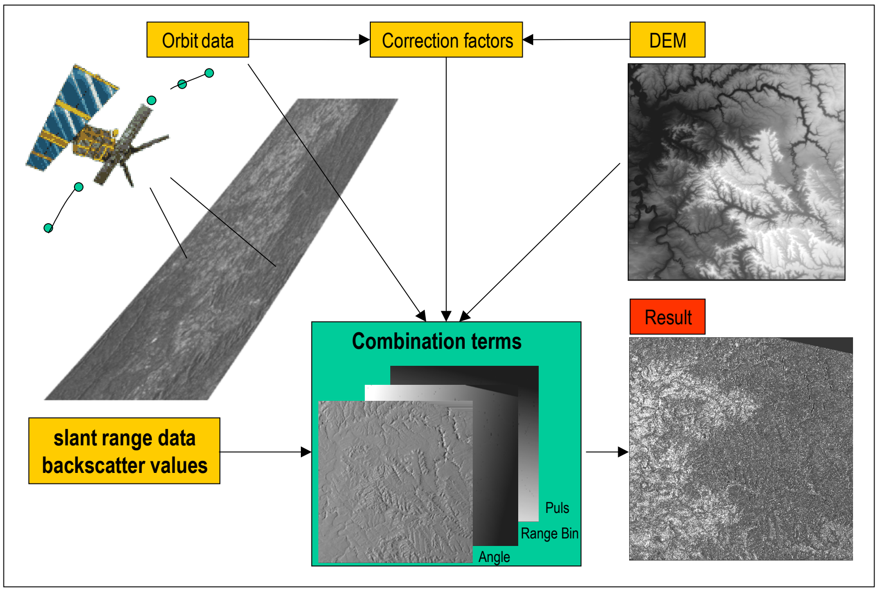

Figure 12: Geocoding of SAR data

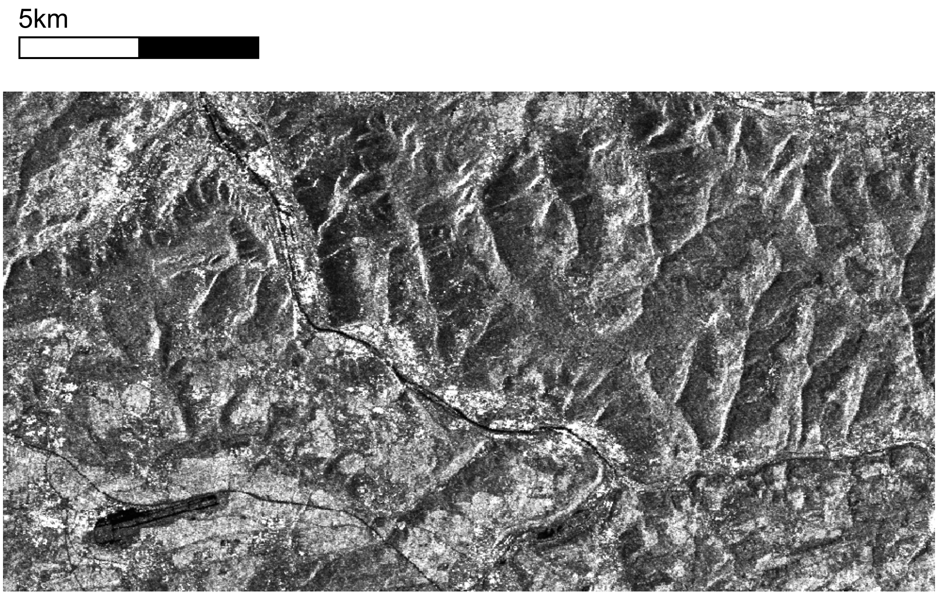

Figure 13a: Ground range SAR image showing distinct terrain influences

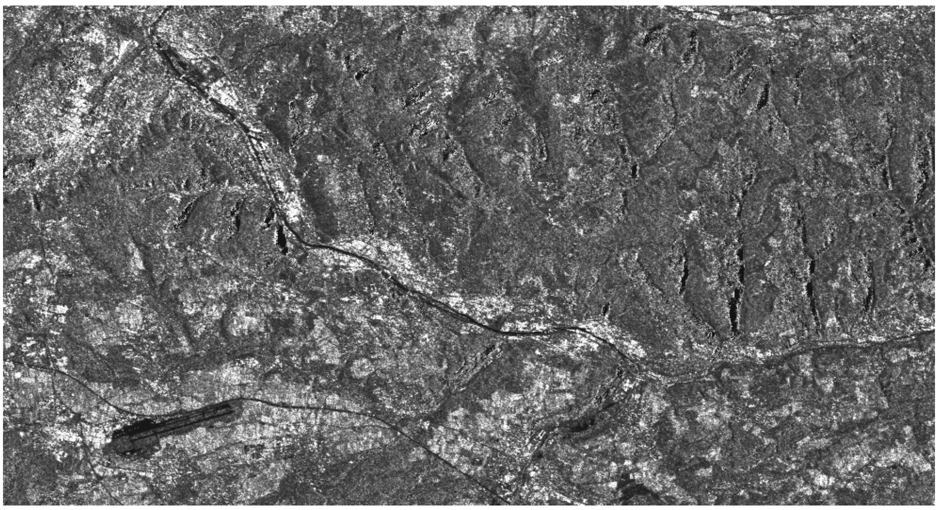

Figure 13b: Geocoded and illumination corrected SAR images

Retrieval of snow properties

Image processing, leading to calibrated and geocoded backscatter images, was applied to ERS-2 datasets of the winter 1998/99. Combining two descending path scenes, most of the Neckar basin is covered (Figure 14). By an optical combination of the backscattered signal from a reference image (snow free conditions at 13.11.1998) and supposed snow image (26.2.1999), areas with changed backscatter values can be easily identified. In Figure 14 reduced backscatter (indicating wet snow) appear in cyan colours, increased backscatter show up in red. The high backscatter values in these red areas are caused by increased soil moisture, an additional working field within Inferno+ project. For more detailed investigations, the ratio method published by (3) and (10) was successfully adapted to classify wet snow areas in the Neckar watershed (Figure 15). Using full resolution 30m datasets, the ratio between reference and snow scene was calculated. For agricutural and grassland pixels a threshold of –2.5 dB was applied to determine wet/melting snow. Forests and built up areas were masked for this evaluation.

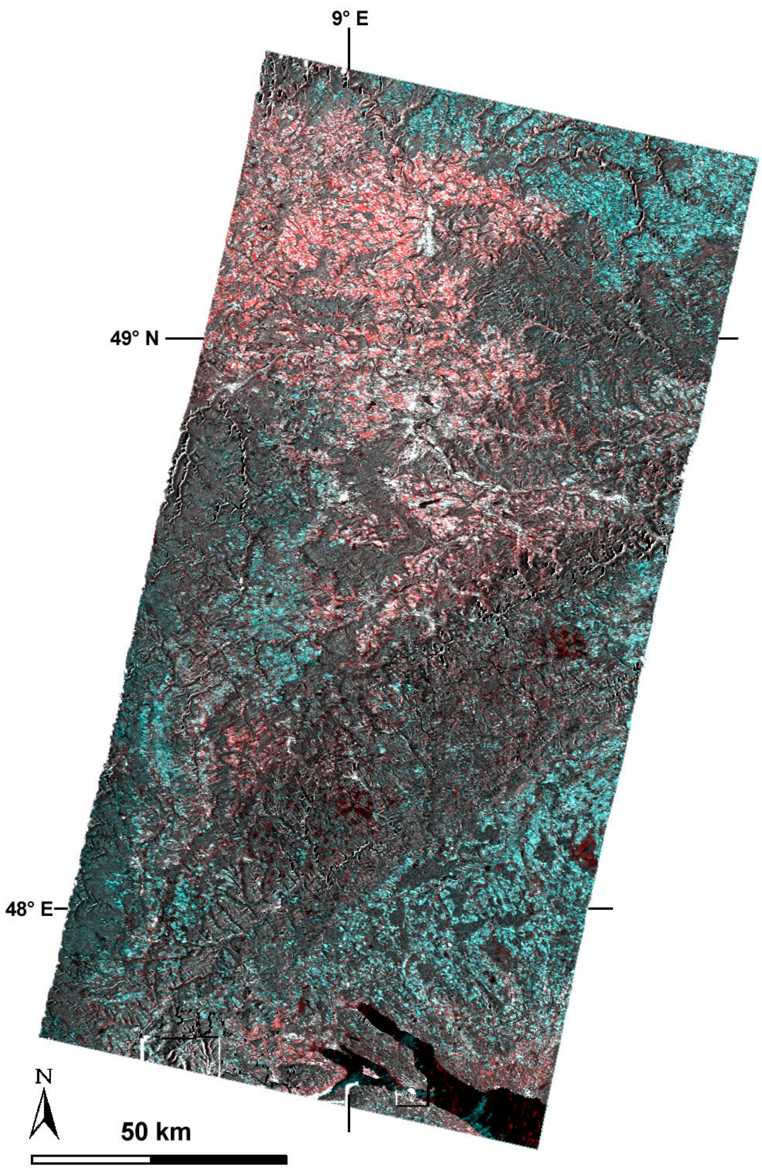

Figure 14: Change in backscatter between reference and snow scene Neckar catchment (13.11.98/26.02.1999)

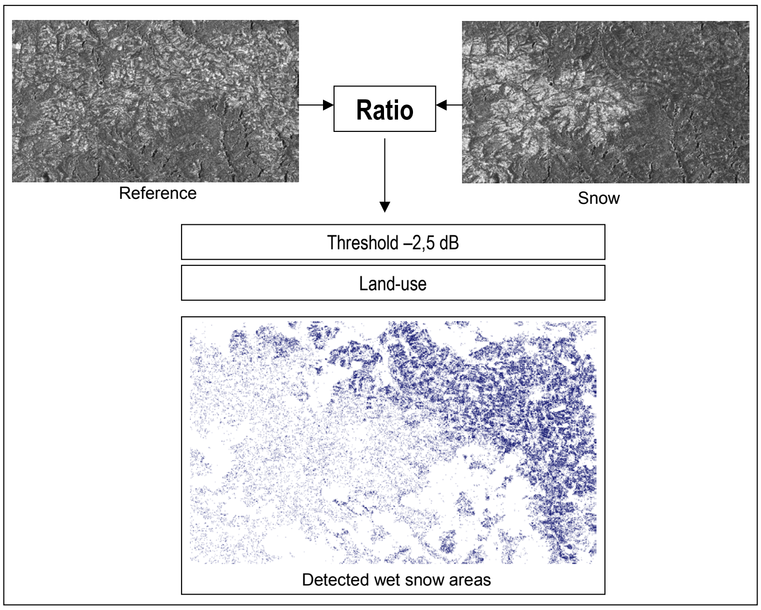

Figure 15: Application of ratio method to derive wet snow areas

RESULTS OF SYNERGISTIC DATA UTILIZATION

In combination with snow-cover information derived from NOAA-AVHRR data on the same day the first synergistic results can be presented. For the 26.2.99, the reduction of backscatter (wet snow) shows high correspondence with the snow cover map derived from optical data. In addition station measurements from DWD (at 26.2. and 27.2.) agree with the observed snowmelt at the higher areas (Figure 16). The snowmelt observed on agricultural fields increases with decreased elevation due to higher temperatures in lower regions. The information on wet snow zones based on SAR analyses will in a next step be used for a better detection of the local snow line and thus help to improve hydrological model parameterization.

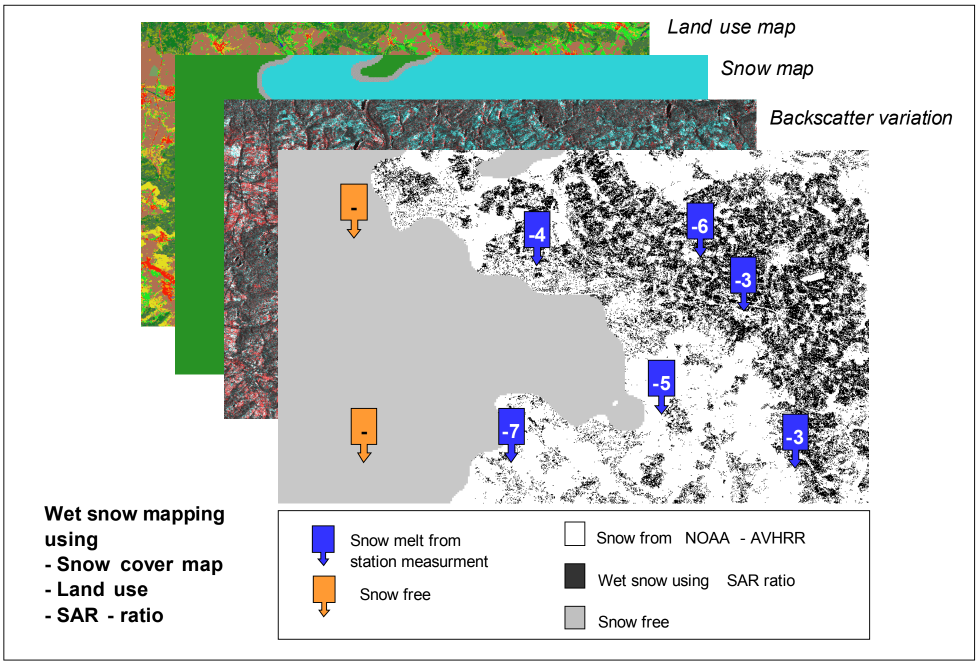

Figure 16: Wet snow mapping using snow cover map from NOAA-AVHRR, land use information and SAR ratio

CONCLUSIONS AND OUTLOOK

Optical and microwave remote sensing methods serve as a valuable information source for the spatial determination of snow cover and wet/melting snow zones. This land surface information will be used for an optimized parameterization of the LARSIM snow module. Optimization can be done in several ways. For calibration of model input data, reliable information on actual catchment conditions is necessary. Detection of the actual snow line can help to improve modelling of snow accumulation. Even though snow depth and snow water equivalent cannot yet be determined directly from remote sensing data, reliable spatial information on snow-cover / non-snow-cover can help screening model outputs. Thus the modelled snow water equivalent can be improved by remote sensing data assimilation. In certain cases areas of temperate / melting snow and partial snow cover (detected by thermal radiation) can indicate local decreasing water retention and increasing runoff of the snow cover. Time series of C-Band data allow the screening of the extent of wet snow areas. For the ablation of a snow cover also influenced by rain input, this information will be an essential parameter for updating model parameters.

The integration of the remote sensing products in the hydrological model LARSIM will be a central task in the future. Besides data assimilation, the transfer of the methodologies to the sensors of ENVISAT (ASAR, MERIS, AATSR) will be a main issue. For example, variable incidence angles and dual polarization of ASAR have to be taken into account. It is planned to analyse first benefits from derived snow properties already during the next winter season (2002/2003).

The products (snow cover distribution and snow properties) will be generated using the introduced tools. Snow cover maps will be continuously generated from daily NOAA 14, 16 and, for the winter 2002/2003, NOAA 17 datasets, recorded and processed automatically in Munich. Additional information on snow properties (wet snow extent), at the moment generated from ERS-2 scenes, will be retrieved from ENVISAR ASAR WideSwath data. The existing SAR data processing tools are adapted to semi-operational use of ERS and ENVISAT data. ASAR WideSwath data will be provided in 'near-real time' by ESA. Information derived from remote sensing data will be made available for the HVZ within half an hour for optical data (NOAA - AVHRR) and about 12 hours after reception of ENVISAT ASAR data.

ACKNOWLEDGEMENTS

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