# SNOW COVER INVESTIGATIONS BY MEANS OF GROUND TRUTH, MODELLING AND ERS-SAR IMAGERY

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## ABSTRACT

Investigations into snow cover dynamics can greatly benefit from the utilisation of spaceborne SAR imagery. SAR images provide insight into the snow cover not only locally but as spatially distributed data. SAR data are characterised by the all weather capability of the system and its ability to receive information from deeper layers of the snow pack. Especially approaches that relate SAR data to actual meteorological situations are of great interest where direct measurements in remote environments are rare. Only profound knowledge of the terms which dominate the backscatter signal allows to extract relevant information. Therefore ground truth measurements need to be defined according to the dominant processes involved. On snow surfaces with predominant surface scattering the signal strongly varies with exposition, slope and surface roughness. Conclusions drawn for undulating terrain can therefore be highly ambiguous without the usage of a high precision digital terrain model. Volume scattering is mainly influenced by grain size and by liquid water content in the snow cover reflecting recent and actual meteorological conditions. Hence meteorological measurements to estimate the state of the snow cover in terms of temperature and energy budget can help to interpret the SAR image to a great extent. Crystal size, ice lenses and snow density also substantially change the backscatter signal under certain conditions. Therefore snow cover properties such as liquid water content, snow temperature, crystal size, snow density and snow stratigraphy have to be evaluated from snow pits at several locations in the considered area. The outlined ground truth concepts are illustrated with examples from theoretical backscatter modelling and snow cover studies on the Antarctic Peninsula with ERS-1 / ERS-2 data.

**KEY WORDS:** Snow cover, meteorology, Antarctic peninsula, ERS-SAR-PRI, backscatter coefficient, backscatter modelling

## 1. INTRODUCTION

Since the signal measured by SAR systems is composed partly from surface scattering and from volume scattering from the snow pack SAR satellite data is used widely for studies on snow properties. The all-weather capability of SAR systems allows to obtain data on a reliable basis with the polar night being of no hindrance to the system. This opens excellent additional possibilities for investigations of the snow cover in respect to climatological, meteorological, hydrological or glaciological applications besides from optical data and thermal remote sensing data. Since a part of the backscatter signal comes from the snow volume, properties such as liquid water content, snow grain size, snow density and ice lenses influence the backscatter signal greatly. In respect to surface scattering surface roughness and local incidence angle have to be considered. The underlying ground may contribute to the signal once the radiation penetrates the snow pack completely. The snow properties listed above define structure and appearance of the snow cover. This however is a consequence from precipitation, radiation, temperature, humidity and wind speed. Hence the meteorological conditions at the moment of image acquisition and during the season or the years transform the snow or firn in such a way that a specific combination of properties leads to characteristic backscatter behaviour. Nevertheless different combinations of factors may result in similar backscatter values. The ground truth campaign focuses on sampling information on the key parameters for the interpretation of the SAR images. With limited financial resources and tight time schedules key parameters must be selected on the basis of knowledge on meteorological and climatological conditions prior to the campaign. In the following we concentrate on backscatter from multi-year snow surfaces in the accumulation zone of glaciers. In this context the knowledge on relevant ground truth parameters serves to identify methods and approaches for ERS-SAR data usage in the field of glaciology and climatology of glaciated areas. Applications demonstrated in this paper are related to locations on the Antarctic Peninsula. In this area global change is anticipated to result in pronounced changes of the glacial systems. Since the response time of glaciers is long information from the snow cover can help to investigate climate variability in the area during shorter periods of time. For this purpose we combine knowledge of the key parameters in the snow with the spatial information as obtained from the SAR image interpretation.

## 2. BACKSCATTER BEHAVIOUR OF SNOW

In order to identify the most important snow cover properties the physics of backscatter behaviour from the surface has to be considered. The power received by the SAR is given by (Ulaby, 1982):

$$P_r = \frac{\lambda^2}{(4\Pi)^3}\int_A \frac{P_t G^2 \sigma^0}{R^4} dA \tag{1}$$

with $P_r$ the received power, $\lambda$ the wave length, $P_t$ the transmitted power, G the antenna gain, A the illuminated surface area, R the distance from the antenna to the ground and $\sigma^0$ the back-scattering coefficient. The property $\sigma^0$ integrates all the effects from geometry and dielectric characteristics that define surface scattering and volume scattering from the target area. The portioning between surface and volume scattering is given by the reflectivity coefficient $\Gamma$ which is dominated by the incidence angle and the complex dielectric constant $\varepsilon$. Its imaginary part depends on the resonance frequency of the media. Since the resonance frequency of ice or snow crystals is very different from the 5.3 GHz of the ERS-SAR the imaginary part of its dielectric constant at 5.3 GHz is negligible. As can be seen from Figure 1 $\Gamma$ is small for dry snow due to the fact that the dielectric constant is similar to the air above the surface. Therefore surface scattering from single surfaces can be omitted as long as backscatter from dry snow covers only is calculated.

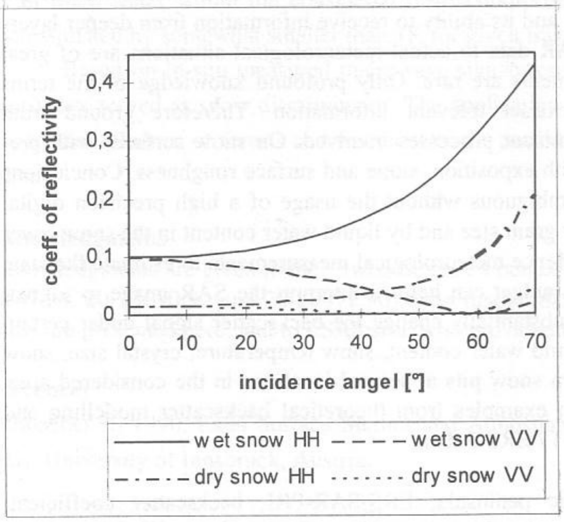

Fig. 1: Coefficient of reflectivity ($\Gamma$) at 5.3 GHz as modelled for dry snow with a snow density of 0.35 g/cm$^3$ and wet snow with 12% liquid water content and a snow density of 0.45 g/cm$^3$ for vertical and horizontal polarisation.

In contrary the imaginary part of $\varepsilon$ has to be considered for the liquid water content of the snow pack. Further to this the real part of $\varepsilon$ of water differs considerably from the dielectric constant of air. This means that $\Gamma$ is rising. Surface scattering may even dominate the backscatter behaviour in this case. Since surface scattering depends on surface roughness and incidence angle surface roughness must be evaluated in the field. Only with a high precision digital elevation model we can hope to extract the effect of incidence angle from SAR images with wet snow conditions. To model volume backscatter we may assume Rayleigh scattering in the media. The backscatter coefficient from the snow pack then depends from the cube of the snow grain size and the real part of $\varepsilon$ which can be calculated as a function of snow density. The volume that has to be considered can be calculated from the penetration depth of the radiation defined by the reciprocal of the extinction coefficient $\kappa_e$ with:

$$\kappa_e = \kappa_a + \kappa_s. \tag{2}$$

$\kappa_a$ describes the part of the radiation to be transformed into other kinds of energy whereas $\kappa_s$ refers to the part of the radiation that is scattered away from the targets. As can be seen from Figure 2 $\kappa_s$ depends greatly on grain size underlining the importance of this parameter for the backscatter behaviour of dry snow covers. While absorption is constant with grain size it changes rapidly with the liquid water content in the snow since $\kappa_a$ depends on the imaginary part of $\varepsilon$ which can not be neglected for liquid water (Fig. 3). A detailed description of the mathematical formulation of the physics of backscatter from snow and ice can be obtained from Ulaby (1986) and Hallikainen (1996).

### 2.1. Snow cover properties

According to the different zones in the accumulation areas of glaciers as given by Paterson 1994, dry snow zone, percolation zone and wet snow zone must be considered separately. In the percolation zone and the wet snow

| Snow zone | Example of location | Backscatter intensity on ERS-SAR scene | Dominant parameter |
|---|---|---|---|
| Dry snow zone | Plateau of Antarctic peninsula | -18 dB | Grain size, density |
| Percolation zone - frozen | McClary glacier | -2 dB | Grain size, ice lenses |
| Wet snow zone - frozen | Northeast glacier | -2 dB | Grain size ice lenses |
| Wet snow zone - melting | Northeast glacier | -19 dB | Liquid water content |

Table 1: Mean backscatter as derived from ERS-SAR scenes of the Antarctic Peninsula at 68° south. Northeast and McClary glacier are located on the west coast of the Antarctic Peninsula in Marguerite Bay. For details on topography and meteorological conditions see Wunderle (1996a, 1996b) or Schneider et al. 1997.

zone we have to distinguish between situations with a completely frozen snow pack as usually found in winter and situations with some liquid water content during melting.

*2.1.1. **Dry snow zone.*** In the dry snow zone where metamorphism is dominated by densification of the firn by overlying snow layers only small grain sizes develop without any additional ice lenses structuring the snow pack. Therefore in absence of liquid water in this zone the profile of snow densities and the grain size are most dominating parameters to be ascertained with good accuracy. Due to the refraction along varying density this is not only important for the derivation of the real part of $\varepsilon$ but also influences greatly the penetration depth. Because penetration depth may be in the range of several meters snow depth has to be known. With some of the radiation penetrating down to the glacier ice this also contributes to the backscatter behaviour.

*2.1.2. **Frozen percolation zone.*** Situations with a frozen snow pack in the percolation zone as predominant during winter still differ from what we know from the dry snow zone. Multi-year snow packs with occasional melting at the surface during the summer season show extensive metamorphosis in the snow cover due to the available melt energy. Large rounded crystals and ice lenses resulting from melting and depth hoar from situations when water vapour gradient is directed upwards may be found in the snow pack. In this case the many ice lenses lead to contribution from surface scattering although the contribution from a single ice lens may be small. Penetration depth also decreases with more refraction taking place along the path through a snow pack structured by ice lenses or wind crusts. Relative contribution from surfaces on or in the snow pack increases with decreasing snow grain size because then the part due to volume scattering decreases. This is the same mechanism as found for dry snow.

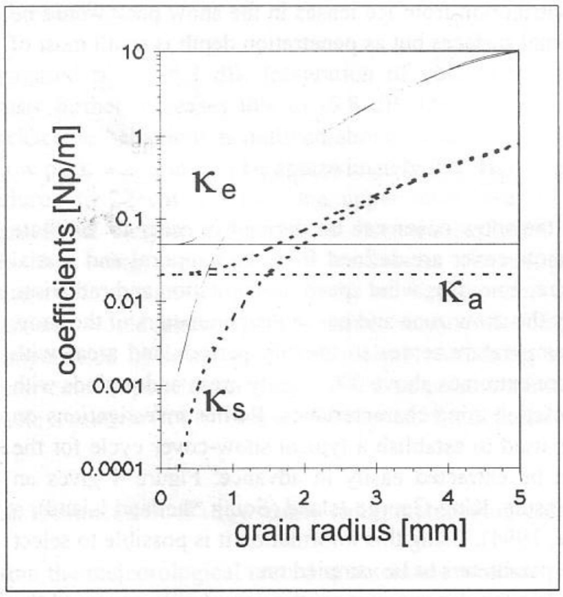

Fig. 2: Coefficients of extinction ($\kappa_e$), absorption ($\kappa_a$) and scattering ($\kappa_s$) at 5.3 GHz for dry snow with a snow density of 0.25 g/cm$^3$ (dotted line) and 0.65 g/cm$^3$ (solid line) as a function of grain radius.

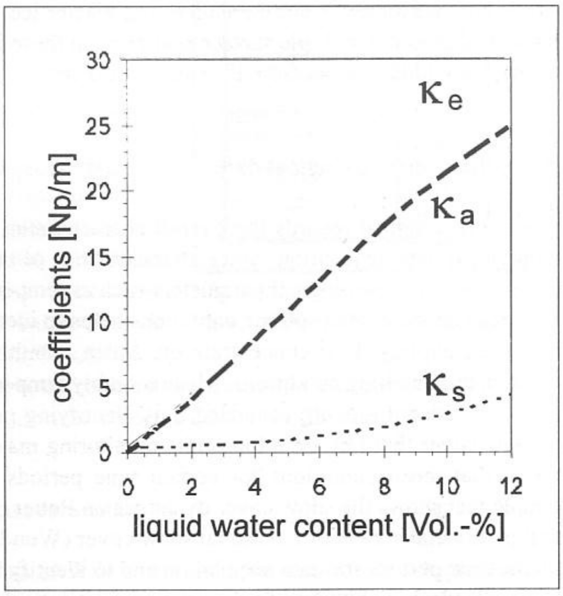

Fig. 3: Coefficients of extinction ($\kappa_e$), absorption ($\kappa_a$) and scattering ($\kappa_s$) at 5.3 GHz for wet snow with a grain radius of 2 mm and a snow density of 0.55 g/cm$^3$ as a function of the liquid water content

***2.1.3. Melting in the percolation zone and the wet snow zone.*** Under melting conditions the situation changes drastically because the liquid water content in the pack gives rise to considerable absorption and strong reduction of penetration depth. Less volume scattering but more contribution from surface scattering is the consequence of this change. Hence measuring liquid water equivalent in the pack and estimating surface roughness is of great importance. If we want to access variations in liquid water content spatially or temporally we need devices to measure liquid water content accurately. Besides volumetric measurements liquid water content can be calculated from the dielectric constant as measured between electrodes that are embedded to a flate-plate (Denoth 1989) or with a time-domain-reflectometer (TDR) buried in the snow (Huebner et al. 1997). Both methods measure changes in the electric field due to changes of the dielectric constant as a function of liquid water content and snow density. For this reason measurements of snow density must accomplish sampling of data on liquid water content. Employing the plate it is possible to sample point measurements at various depths and locations within snow pits. The TDR consists of approximately 20 m of flat band cable, which are arranged at several heights and enclosed by snow. The electromagnetic pulse sent through the cable is modified according to the dielectric properties of the surrounding snow. From this an integrated value for liquid water content from a surface area of several tenth of square meters can be obtained as a continuos measurement.

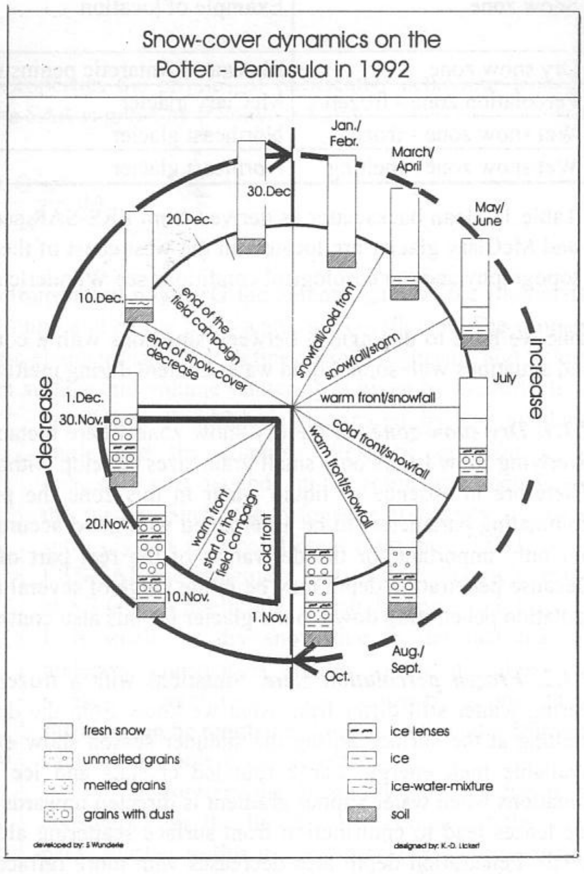

Fig. 4: Snow cover cycle of Potter peninsula, King George Island, South Shetland Islands.

The residual volume scattering still is dominated by snow grain size which also must be measured. With increasing liquid water content penetration depth is decreasing rapidly to values much lower than 1 m so that there is no contribution from the underlying glacier ice. Contribution from ice lenses in the snow pack would be important due to the multiple surface scattering at these internal surfaces but as penetration depth is small most of the layers are hidden away from the satellite's 'eye'.

### 2.2 Auxiliary meteorological data.

From meteorological records the overall characteristics of the snow cover can be derived in order to facilitate ground truth data acquisition. Since characteristics of the snow cover are defined from the temporal and spatial distribution of meteorological parameters such as temperature, humidity, wind speed, precipitation and radiation, knowledge on mean atmospheric conditions helps to identify the snow zone and hence the parameters of the snow cover the sampling must concentrate on. Mean monthly temperature serves to identify periods and areas with predominantly melting conditions. Mean monthly temperature extremes above 0°C signify areas and periods with at least occasional melting occurring thus identifying percolation zone characteristics. Earlier investigations on the snow cover that rely on a long-time monitoring may be used to establish a typical snow-cover cycle for the area so that mean conditions for certain time periods can be extracted easily in advance. Figure 4 gives an example that shows the snow cover dynamics on Potter peninsula, King-George-Island (South Shetland Island), a small periglacial area with a seasonal snow cover (Wunderle, 1994). Using this information it is possible to select suitable time periods for data acquisition and to identify key parameters to be sampled on.

Table 1 summarises backscatter intensities as found in the dry snow zone, the percolation zone and the wet snow zone on areas of the Antarctic peninsula at approximately 68° south. For more details on the SAR itself the reader is referred to Wunderle et al. 1994 and Wunderle 1996a.

## 3. APPLICATIONS OF SAR IMAGE INTERPRETATION FROM THE ANTARCTIC PENINSULA

Representation of climate behaviour along the Antarctic Peninsula located between 62° and 75° south as given by GCMs is very limited due to its small extension from east to west of only about 150 km. Nevertheless the region is of great interest for climate monitoring: Large gradients of mean annual temperature and precipitation rate both from west to east and from north to south along the peninsula will lead to strong climatological effects as a reaction to a changing climate. Local sea ice extent greatly influences climate conditions in the region because of the different energy balance of sea ice and open water. While most meteorological time series from the Antarctic Peninsula show a warming trend the data is still not statistically significant because of the short time series available (Sanson, 1989). However ice shelves along the peninsula have reduced considerably recently (Vaughan & Doake, 1996) backing climate change predictions. On the other hand the net of meteorological observations is coarse with only about 10 stations or AWS running permanently on the Antarctic Peninsula. Hence a method to support climate monitoring by means of remote sensing is of great interest. Remote sensing contributes spatially distributed information to the point meteorological time series. Two examples from King-George-Island (South Shetland Islands) and from Marguerite Bay are presented to illustrate this concept. Resolving the key parameters in the snow pack that define backscatter intensity as found in multitemporal SAR imagery offers the possibility to monitor changes in the snow pack respectively the climatological conditions both on a seasonal and on an interannual basis.

### 3.1. Backscatter modelling with ground truth measurements from King-George-Island

A snow profile (Fig. 5) from February 6th 1996 at 62°11' South and 58°33' West was selected to model the backscatter intensity the satellite would receive. At grain sizes of 2 to 4 mm the accumulative backscatter from all layers was computed to -6.6 dB assuming a dry snow cover. This is approximately the same as can be found in wintertime ERS images from the area. Contribution of surface scattering at ice lenses in the pack increased $\sigma^0$ to -6.3 dB. Integration of volume scattering from the ice crusts further increases this to -5.8 dB. Obviously grain size dominates backscatter behaviour as outlined above. Actual liquid water content in the snow pack was found to be approximately 2%. Hence penetration depth is reduced to 22 cm and only the upper most layer of 22 cm has to be considered. Despite a contribution from the surface $\sigma^0$ is deduced to -21 dB, this being consistent with backscatter intensities found on ERS-1 imagery from summer. With 5 % of liquid water content backscatter intensity would almost be the same because the higher value of $\varepsilon$ is compensated by lower penetration depth. Assuming only 0.5% of liquid water content penetration depth would be at 80 cm and the total backscatter intensity is computed to -10.5 dB. Table 2 summarises $\sigma^0$ values as computed for different liquid water contents for the profile discussed.

| Liquid water content | 0 % | 0.5 % | 2.0 % | 5.0 % |
|---|---|---|---|---|
| Volume scattering | -6 dB | -10 dB | -22 dB | -22 dB |
| Surface scattering | -32 dB | -27 dB | -25 dB | -24 dB |
| Total backscatter intensity | -6 dB | -10 dB | -20 dB | -20 dB |

Table 2: Backscatter intensity for different liquid water contents as computed for a profile from February 6th 1996. Profile parameters are given in Fig. 5.

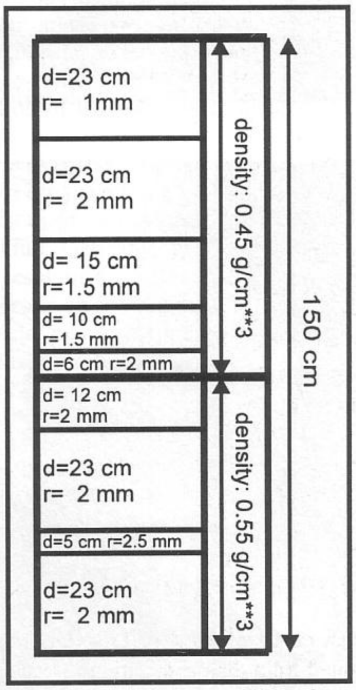

Fig. 5: Snow profile from 06.02.1996, King-George-Island.

### 3.2. Delimitation of snow zones using meteorological measurements

From the meteorological record at automatic weather stations (AWS) in the field we can extract information on the snow cover. From strong or gusty winds or from precipitation it can be concluded that there has been a change in surface conditions resulting in different values for the surface roughness. Temperature measurements serve for estimating the state of the snow cover in terms of the velocity of snow metamorphism respectively the change in snow grain size and type. Further to this the wetness of the snow can be classified from temperature, humidity and radiation recordings. Since any change in the atmospheric conditions takes time to be propagated

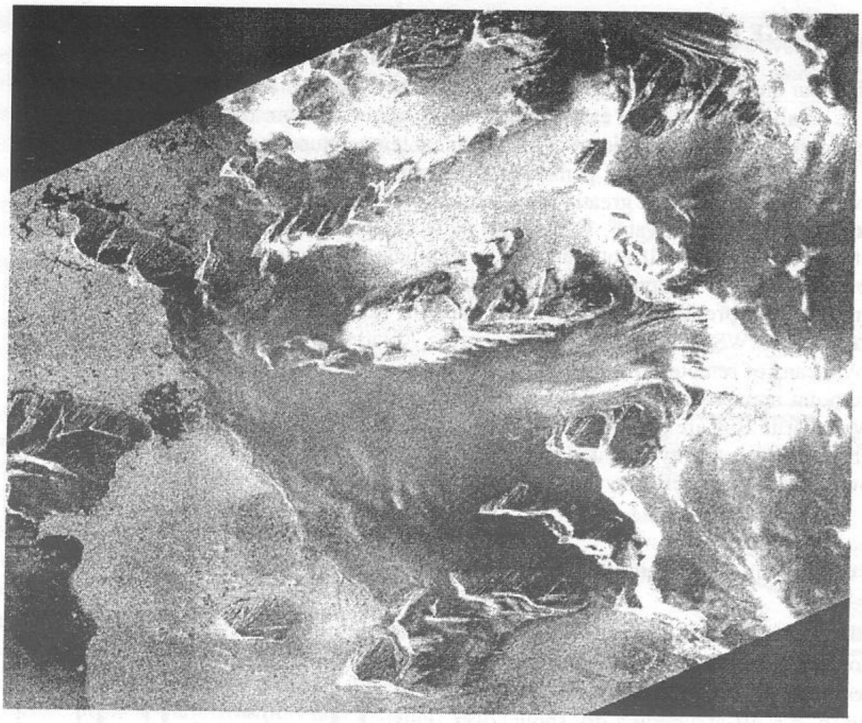

Fig. 6a

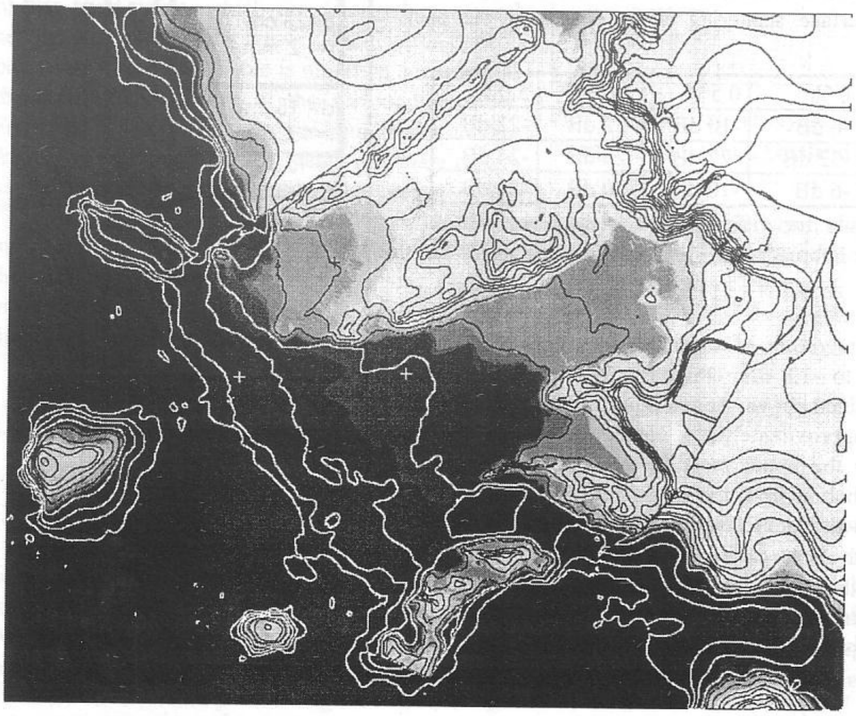

Fig. 6b.

Figure 6. ERS-1 PRI image from 18.01.1995, 2:00 local time (a) and model result for the same time (b). The ERS image depicts an area on the west coast of the Antarctic Peninsula at 68° south and 67° west. The plateau of Palmer land can partly be seen at the eastern margin of the image. The central parts of the image are comprised by McClary glacier to the north and Northeast glacier to the south. Bright areas on the north-western parts of McClary glacier are due to frozen snow interspersed with ice lenses. The low lying parts of McClary and the surface of Northeast glacier are depicted in dark tones signifying the presence of liquid water in the snow cover. Model result (b) for the time of image acquisition based on meteorological measurements and a simple snow cover model with 7 snow layers. Contour lines with 100 m intervals as derived from the DTM are overlaid. Discontinuities at contour lines result from merging DTMs with different resolution. The crosses mark the locations of automatic weather stations. All areas with shaded grey tones represent areas with some liquid water content leading to reduced backscatter intensities on the SAR image. Only the lightest grey tone stands for areas with absolutely frozen snow and with no liquid water content at all.

down into deeper layers of the snow not only the meteorological readings at the instant of the satellite's overpass have to be considered but also the time period before image acquisition.

Figure 6 gives an example of the capabilities of AWS readings for the interpretation of ERS-SAR data. The model result represented in Figure 6b is derived from spatial energy balance estimates. For this purpose AWS were operated at three locations on the glaciers marked with crosses in Fig. 5a during the summer season 1994/1995 on two glaciers on the west coast of the Antarctic Peninsula at 68° south. The data acquired was used to compute sensible heat flux and latent heat flux according to the bulk transfer equations (Brutsaert, 1982). The effect of stable stratification in the atmosphere was taken into account using the bulk Richardson number (Ri) and a formulation of the correction term given by Braithwaite (1995).

The relationship between energy balance estimates and meteorological parameters was further studied using multiple regression analysis in order to derive spatially distributed data. Regression analysis of air temperature and solar irradiance as independent variables and energy balance as dependent variable turned out to be best when performed on the basis of means of six hours or four values per day. Actual temperature gradients calculated from the AWS located at different altitudes were used to provide a data layer of air temperature for each quarter of each day. Short-wave irradiance was modelled employing the Short-Wave-Irradiance-Model (SWIM), described in detail in Parlow (1996). The effect of cloudiness was considered by computing the ratio between modelled and measured irradiance for the three locations of the AWS. Employing an interative approach this ratio was re-introduced into the modelling scheme of SWIM.

Using the coefficients of the multiple regression analysis, the spatial data sets of temperature and irradiance were used to produce estimates of the spatial distribution of the energy balance for each quarter of a day. To separate dry and wet snow zone a simple snow cover model with seven layers of approximately 10 cm depth each was assumed. The idea of the model is to reduce the number of wet layers by one if air temperature and energy budget are negative at a given grid point and to do the opposite if both determining data sets show positive values at a grid point. If the snow cover is comprised by only dry layers nothing is changed in case of further cooling. After complete wetting of all seven layers of the upper snow cover this is not enhanced in case of further 'warming'. The snow cover model is optimised according to the local conditions characterised by a snow pack composed of highly metamorphosed snow grains of 1 to 3 mm diameter and interspersed ice lenses. ERS microwave radiation penetrates frozen snow with these properties to a depth of approximately 0.7 m (Friedrich, 1996). However even small amounts of liquid water reduce the backscatter intensity significantly (Fig. 3). Therefore we assume that only a model result with all seven layers being completely frozen will result in bright tones on the ERS-1 image as found on the upper parts of McClary glacier on January 18th 1995. For all grid points with at least one layer containing liquid water a considerable reduction of the backscatter intensity as found on Northeast glacier on the same frame is forecasted.

Fig. 6b) represents the status of the model for the time of the satellite's overpass. Contour lines with 100 m intervals are overlaid. The discontinuities in the digital terrain model (DTM) originate from merging to different DTMs. The inner part with 40 m ground resolution and approximately 10 m of vertical accuracy was produced from aerial photography by the Institute of Applied Geodesy in Frankfurt, Germany, whereas the frame was derived from the SCAR's 'Digital Database Antarctica' at a much lower resolution. The transition from wet to dry snow zone is modelled correctly for both glaciers. Even the wet snow zone on the outlet of to the northeast is modelled accordingly. Some discrepancy can be observed on the glacial bed to the north of McClary-Glacier. However this may be attributed to an inaccurate DTM in this area. It is promising that despite the many over-simplifications in the model there is good agreement between model result and SAR image. For more details on this approach see Schneider et al (1997).

On the right margin of the image parts of the plateau of Palmer land can be identified in dark tones signifying low backscatter values. At altitudes above 1000 m this part belongs to the dry snow zone (Wunderle, 1996b). Consequently small grain sizes result into low backscatter values as discussed in section 2.1.1. and summarised in table 1.

## 4. CONCLUSION

SAR data are the only remote sensing data to be regularly available in polar areas where limited daylight in winter and high average percentage of cloud cover hamper the usage of optical remote sensing systems. Furthermore SAR data include information not only from the surface of the snow but also the snow volume. Nevertheless interpretation of ERS-SAR-PRI images from snow covered areas is complicated because of the variety of parameters influencing the backscatter intensity. In order to limit the number of parameters that have to be considered ground truth measurements are needed. Backscatter intensities modelled on the basis of the ground truth data yield results that are in good agreement with the values that can be derived from ERS-SAR-PRI images for typical snow surfaces as found on the Antarctic peninsula. Liquid water content, snow density and grain size are the dominant parameters that must be evaluated in the field. Number and location of ice lenses and surface roughness contribute to the backscatter behaviour for dry snow snow with very small grain sizes or for wet snow. The integration of meteorological data opens up additional possibilities for the interpretation of SAR data because the state of the snow cover and its genesis can be estimated from the meteorological records. It can be shown that the transition from dry to wet snow as computed from spatially distributed energy balance estimates in a GIS on the basis of meteorological recordings can also be found in ERS-SAR images.

## 5. ACKNOWLEDGEMENTS

This research was supported by the German Secretary of Science and Research (BMBF) within the programme 'Dynamic Processes in Antarctic Geosystems' (DYPAG) (Contract Number: 03PL016A) and by the ESA pilot study 'Monitoring Of Dynamic Processes in Antarctic Geosystems' (MODPAG), (Contract Number: AO2.D149). The authors would like to thank the Instituto Antarctico Argentino (IAA), the British Antarctic Survey (BAS) and the German Alfred-Wegener-Institut für Polar- und Meeresforschung (AWI) for their support in respect to logistics and field equipment during several field campaigns. The authors are grateful for the invaluable assistance and discussions in the field by the Argentine and German collaborators.

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