CORRELATION BETWEEN ANTARCTIC DRY SNOW PROPERTIES AND BACKSCATTERING CHARACTERISTICS IN RADARSAT SAR IMAGERY

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ABSTRACT

To further our understanding of global paleoclimate variations, the European Project for Ice Coring in Antarctica (EPICA) has started to drill two deep ice cores in Antarctica, with one located on the Amundsenisen plateau in Dronning Maud Land. In order to determine an optimal drilling location, extensive glaciological, geophysical and remote sensing projects were started in 1995. In support of these projects, this study attempts to understand the influences of physical snow pack parameters on the signal strength in RADARSAT SAR imagery.

Twenty-six RADARSAT SAR standard beam images acquired in May 1997 are analysed. Processing steps include radiometric calibration, geometric correction and the generation of a mosaic that covers most of the study area. Field data were collected during the Dronning Maud Land traverse (1997/1998) of the Alfred Wegener Institute for Polar and Marine Research (AWI), and include accumulation rate, firn temperature, dielectric properties and the number of layers in snow pits. The field data are interpolated spatially to cover the entire study area. To determine the influence of the different snow pack parameters on the radar backscatter signal, a linear correlation is performed on the field-derived data on a point-to-point and on an area basis.

Since in the study area, the azimuthal modulation of the backscattering signal is assumed to be relatively low, variations of $\sigma°$ should also be attributable to internal characteristics of the dry snow pack. Results show that the backscattering coefficient is negatively correlated to the accumulation rate, and positively correlated to the heterogeneity of the dielectric properties. The lower the accumulation rate, and the more heterogeneous the snow pack, the stronger the backscatter signal. However, correlations are still relatively poor, and therefore neither surface characteristics nor internal properties of the snow pack alone can account totally for the observed backscattering patterns.

INTRODUCTION

The polar ice caps of Greenland and Antarctica represent some of the earth's most important climate archives. They are a primary source of evidence about both past climate and atmospheric composition, and ice cores from these regions have reached depths of several kilometres and provided information up to 500,000 years old.

Within the scope of the EPICA program (*European Project for Ice Coring in Antarctica*), two ice cores are currently being drilled in East Antarctica, one at Dome Concordia (started in 1998), and the other started in the 2000/2001 season at the Kohnen station on the Amundsenisen plateau in Dronning Maud Land (site DML05 in Fig. 1). Such drill sites have to meet several requirements:

they have to be set in a dry snow region to exclude melting, the ice cover has to be thick and undisturbed, and a high snow accumulation improves the resolution of the record (especially of the last glacial cycle). Besides, flow structures may disturb the results and render the drilling more difficult. Therefore, drill sites are usually located on an ice divide characterised by predominantly vertical ice movement and low horizontal flow velocities.

To be able to find such an optimal drill site, detailed geophysical and geochemical surveys have to be carried out. In an inaccessible and remote region such as the interior of Antarctica, the logistics and material for such surveys are extremely expensive. It is therefore of great interest if satellite remote sensing can support these pre-site surveys. In particular, radar sensors can be of significant use because their data is independent of weather, seasons, and time of day.

For this reason, this study investigates how RADARSAT SAR imagery can be used to extract information about the structure of the ice and snow cover of a dry snow zone of the Antarctic ice sheet, and how this information can be used for pre-site surveys of potential ice coring locations. Using the example of the Amundsenisen plateau in Dronning Maud Land, a determination is made of which physical parameters of a dry snow cover affect the backscattering signal in RADARSAT SAR data.

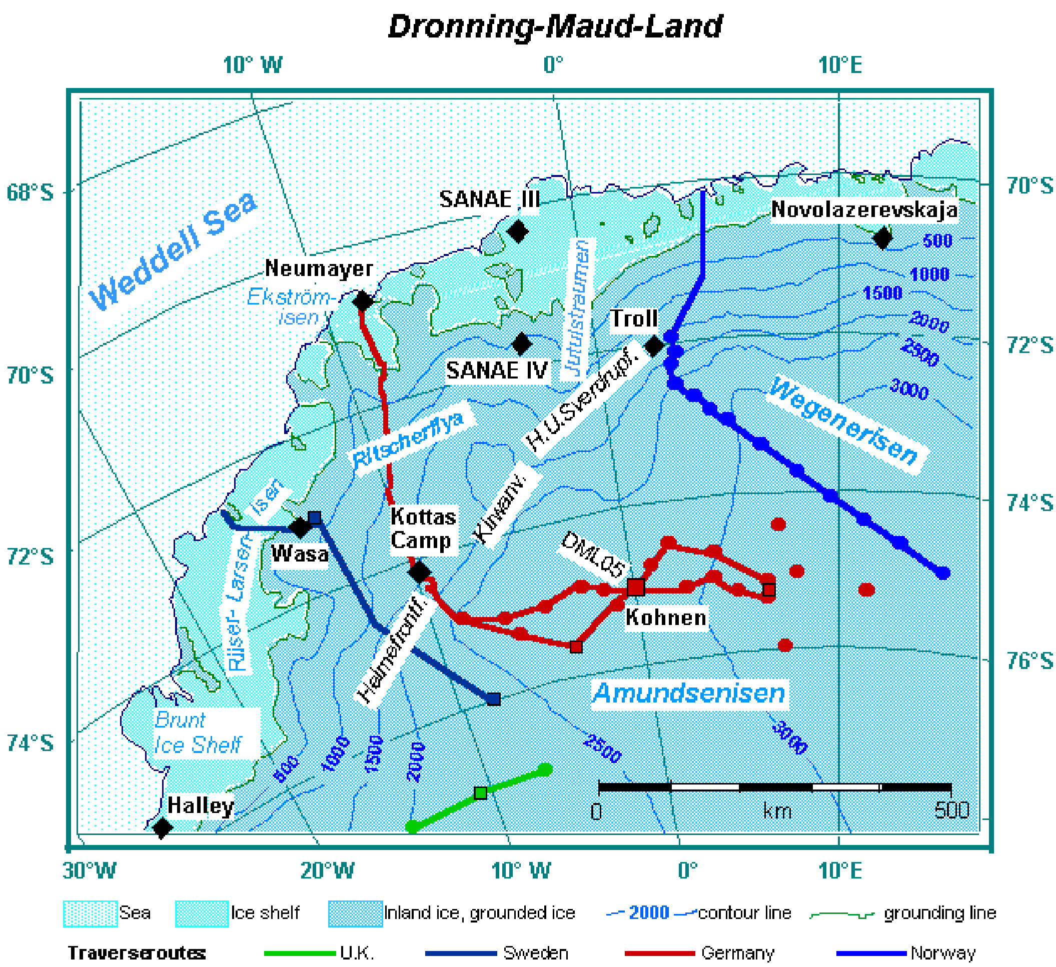

Figure 1: Map of Dronning Maud Land showing locations visited during the EPICA pre-site surveys, as well as supply routes. The EPICA drilling point is Kohnen station at 75° S, 0° E.

METHODS

Twenty-six RADARSAT Standard Beam images, recorded between 2-8 May 1997, were acquired to guarantee an as complete and simultaneous coverage of the study area as possible. The data were provided by the Alaskan SAR Facility (ASF), along with a set of software tools (STEP, now renamed APD) to carry out the necessary preprocessing. Firstly, to extract the backscattering values ($\sigma°$), all scenes were calibrated using calibration resources provided by ASF (1). To facilitate visual interpretation, speckle filtering was performed using the Enhanced Frost Filter (2), which yielded the best results amongst the most common speckle filters (3). As a first step in building a mosaic, the scenes were geocoded using orbital parameters. However, due to the considerable elevation of the study area on the Amundsenisen plateau (up to 3500 m a.s.l.), an additional terrain correction was conducted. With increasing elevation, a pixel's actual location is closer to the sensor than is given by its planimetric position with respect to the CLARKE 1866 ellipsoid (ASF's default ellipsoid). This relief or elevation displacement is given by

$$R = \tan \theta \cdot H$$

where R is the displacement in the range direction, θ is the incidence angle and H the elevation. The digital elevation information came from a radar altimetry derived model by Bamber et al. (4). Due to the flatness of the Amundsenisen plateau, this relatively simple terrain correction proved to be sufficient for the purpose of this study. Finally, all 26 images were resampled from an original resolution of 25 x 28 m to a resolution of 1 x 1 km, and merged into a mosaic with an absolute radiometric accuracy of ±2 dB and a relative accuracy of ±1 dB (Fig. 2).

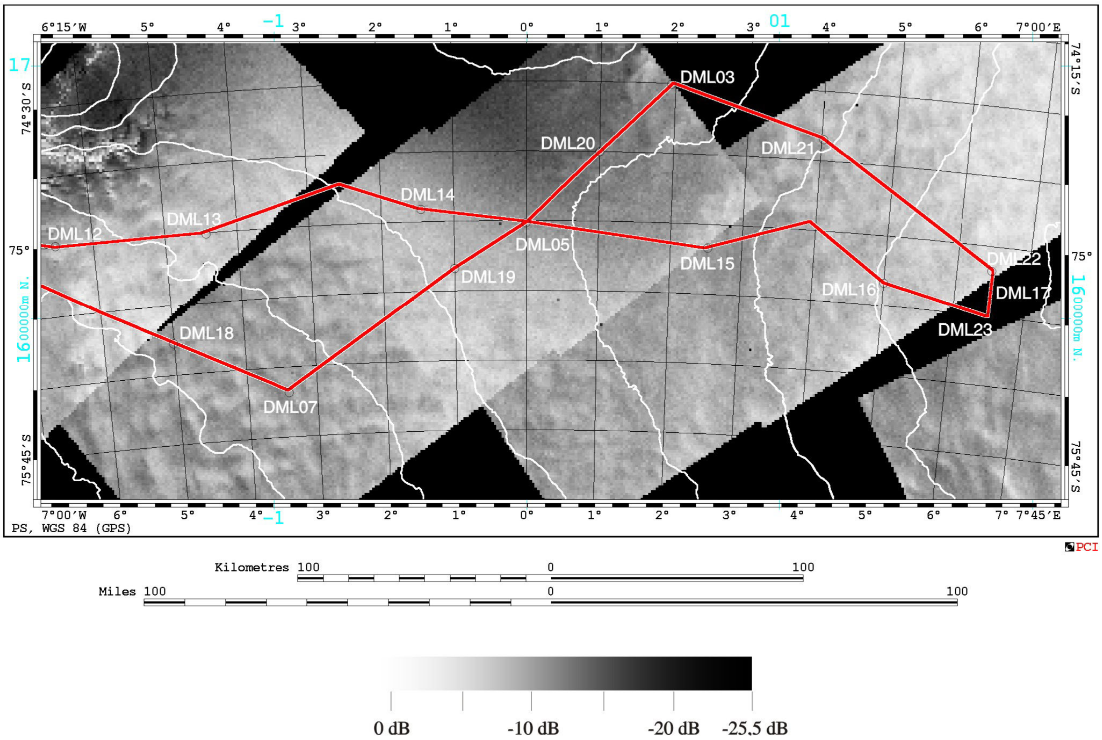

Figure 2: RADARSAT SAR mosaic covering the study area on Amundsenisen. Also shown are the route of the AWI traverse 1997/1998 and the test sites.

In RADARSAT Standard Beam images, the incidence angle does not vary significantly in order to alter the backscattering signal from the study area. Previous studies, however, have investigated the influence of azimuth variations in Antarctic firn using scatterometer data (5,6,7). Such variations can be caused by the alignment of well-developed sastrugi resulting from an intense katabatic wind regime (8,9). However, in the study area on the Amundsenisen plateau in Dronning Maud Land, the influence of azimuthal modulations is assumed to be relatively weak (7,9). Therefore, volume scattering has to be taken into account.

The backscattering signal strength reflected by a dry snow pack depends primarily on the dielectric properties, the number of internal reflectors and the grain size. In a perfectly homogeneous, dry snow pack without internal scatterers, snow reflectivity increases with the dielectric constant. However, more important than the bulk permittivity are stratification as well as the size, number density and distribution of scatterers. A large number of ice lenses, wind crusts or pronounced layer boundaries increases reflectivity. Heterogeneous snow packs should therefore appear brighter than homogeneous ones. Larger snow crystals should cause stronger backscattering than small ones. Grain size itself is influenced by accumulation rate and firn temperature. Since regions with low accumulation often show larger grain sizes, this could result in higher backscattering values. A higher firn temperature favours crystal growth and may also lead to stronger backscattering (10,11).

Searching for an optimal drill site for EPICA, extensive field data were collected during the 1997/1998 Dronning Maud Land traverse led by the AWI. Among the collected and computed parameters were the accumulation rate, the variation of the dielectric constant with depth, the 10 m firn temperature and the number of layers within the first 2 m (12). The data were collected at 17 locations distributed over the Amundsenisen plateau (Fig. 2). At each location a firn core was drilled and snow pits were analysed.

Of the firn cores, fourteen had an average depth of 30 m, while at three locations a core of more than 100 m was drilled. Density and dielectric constant was measured in 5 mm steps (13). For this work, the mean complex dielectric constant was calculated for two different depth intervals: 0-4 m and 0-15 m. For the same intervals, the standard deviation of the dielectric constant was computed as a measure of the heterogeneity of the snow/firn pack. The two different intervals were chosen to accommodate for both the significance of the upper parts of the snow pack, and for the potential penetration depth of C-band microwaves in dry snow (> 20 m, (14)). To provide another measure of the heterogeneity of the snow pack, the number of layer transitions per metre was extracted from field books. The accumulation rate was determined over the period 1816 to 1998.

All field parameters were processed in the same way: a raster image was generated by interpolating image values between the sample locations using a Radial Basis Interpolation algorithm, which implements a Thin Plate Spline scheme. This algorithm leaves the original values unchanged, and tries to minimise the curvature of the surfaces between these known points.

To determine the dependency of the backscattering signal strength on the sampled field data, the degree of correlation was determined in two different ways:

(i) With a sample site in their centre, circles were drawn with a radius of 4.5 km. The average backscattering coefficient of each circular area was then calculated to provide a representative value for the backscattering conditions of each sample location. Finally, a linear Pearson correlation coefficient *r* was computed (Table 1). It should be remembered that *r* only provides a general measure of the interrelation between two variables, since correlations are just indices of possible causal connections. The significance of a correlation also depends on the sample size (e.g., for 13 to 17 samples, a correlation would be statistically significant at the 95% confidence level if the correlation coefficient exceeds 0.5).

(ii) For comparing and testing the results from (i), the second approach correlated the interpolated raster values (rather than just the limited number of test sites) with the SAR data. Only those pixels were included that were covered by the SAR mosaic and lay within a polygon spanned by the test sites. Such a correlation has to be handled with caution, since it is possible to compare incorrect values as a result of positional errors in the SAR imagery and the interpolation uncertainty. However, this procedure might help to support the results from the first approach using the test sites only.

Finally, for an additional visual interpretation, supplementary optical and ScanSAR imagery were used in addition to the Standard Beam data to investigate glaciological features such as crevasse fields and ice divides.

RESULTS

A visual interpretation of the SAR imagery indicated an excellent representation of glaciological features. In particular, crevasse fields were much more prominent than in optical imagery. Interestingly, the AWI traverse route of 1996/1997 was clearly identifiable in the imagery, as well as the landing strip near Kottas Camp and the camp itself (Fig. 3). Over the topographically homogeneous Amundsenisen plateau, the backscattering signal strength ranges between –4 and –18 dB (Fig. 2).

A plot of the interpolated accumulation rate is shown in Fig. 4, while Fig. 5 shows an example of the correlation between the field parameters and backscatter. The strength of the calculated correlation between all measured field parameters and the signal strength in the SAR imagery is illustrated in Table 1.

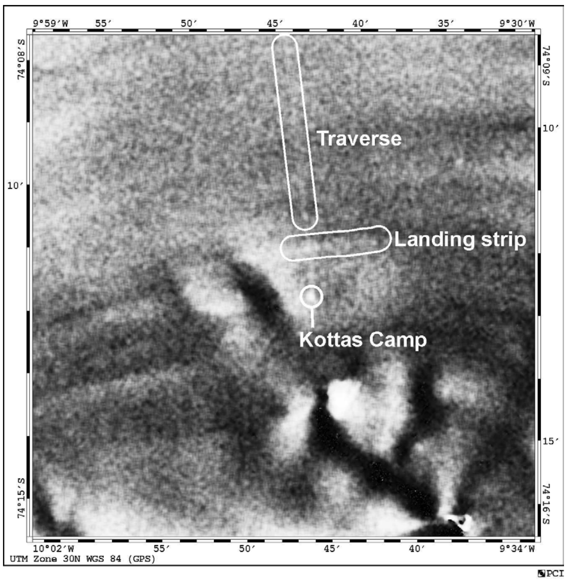

Figure 3: Radar image of the surroundings of Kottas Camp (see Fig. 1). The tracks of snow vehicles, air planes, and the camp itself are clearly identifiable. (Subset of RADARSAT scene R-7854-646, filter: Enhanced Frost 11x11 pixel, spatial resolution 25 x 28 m, illumination from southeast.)

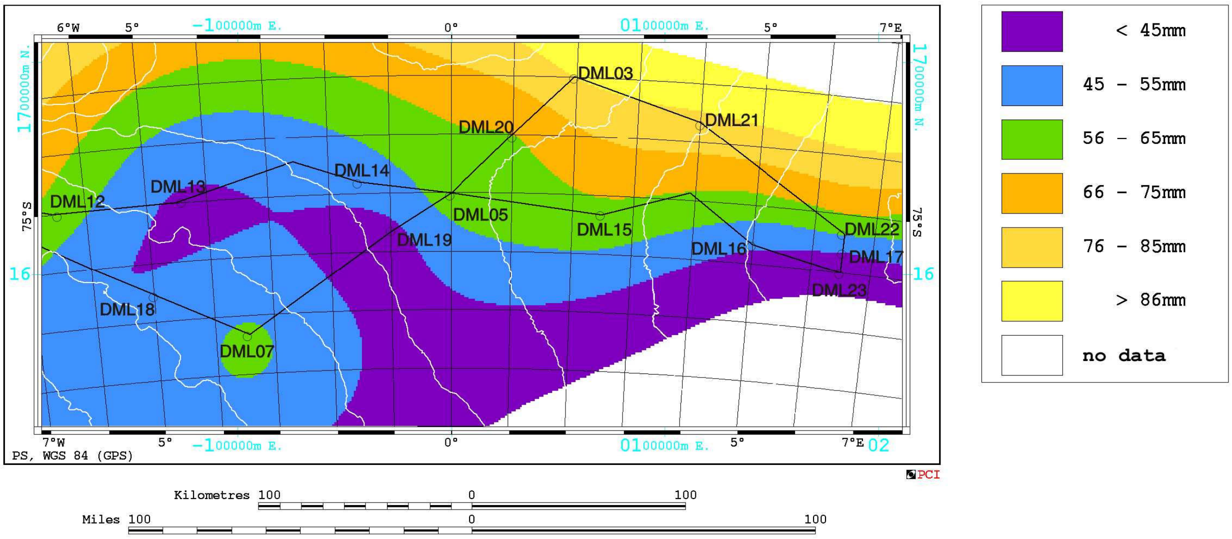

Figure 4: Spatially interpolated accumulation distribution across Amundsenisen plateau. Interpolation was conducted using a spline algorithm and the data of 15 test sites.

Table 1: Correlation coefficients r *between field data and backscattering signal strength (bold-faced values in the point-to-point column are significant at the 95% confidence level).*

field parameter	*r* (point-to-point)	*r* (areal)
mean accumulation rate (1816-1998)	**-0.55**	-0.48
firn temperature (10 m)	0.24	0.03
mean dielectric constant (0-4 m)	-0.10	-0.25
mean dielectric constant (0-15 m)	-0.28	-0.36
standard deviation of dielectric constant (0-4 m)	**0.51**	0.38
standard deviation of dielectric constant (0-15 m)	**0.50**	0.51
layers per metre (snow pits)	0.33	0.02

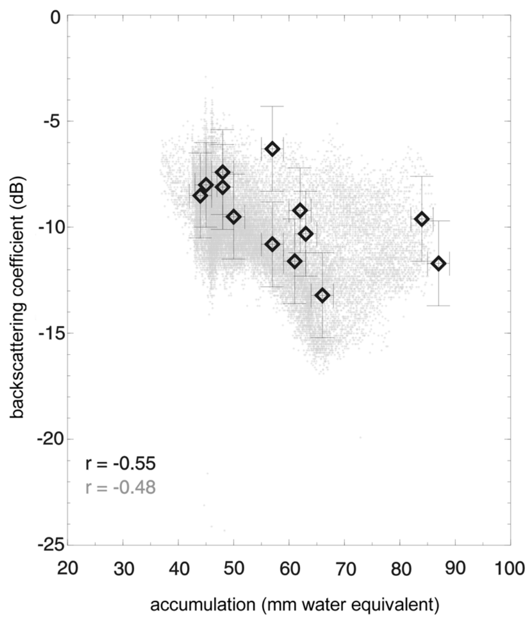

Figure 5: Accumulation versus backscattering coefficient. Point-to-point (black diamonds, with error margins) and areal (grey shaded) correlation.

CONCLUSIONS

For the backscattering characteristics of dry snow, differences in polarisation can be neglected (15). Data from other C-band SAR systems (e.g. on ERS-1, -2) should therefore give similar results as the RADARSAT data used in this study.

On the Amundsenisen plateau, the backscattering signal strength of RADARSAT SAR data is not totally controlled by volume scattering: the roughened, possibly compacted surface created by snow vehicles and airplanes is clearly identifiable in the SAR scenes. This indicates that other features such as sastrugi may also have an influence on the radar signal. However, previous studies indicate that the influence of azimuthal modulations on the Amundsenisen plateau is relatively low (7)(9). In dry snow, $\sigma°$ is also controlled by volume scattering and the microwave signatures depend on absorption and scattering losses within the snow pack.

Where large-scale and small-scale topographic variations are negligible, the grain size should be a major influence on the radar backscatter. To explain the observed variations of the backscattering coefficient in a completely homogeneous dry snow pack, the grain size would have to range from 0.3 mm (≡ -4 dB) to 0.9 mm (≡ -18 dB) (after Partington (16)). These are reasonable values for the study area, but these calculations neglect all other possible controlling factors. In addition, since no grain size data were available for this study, other measures were investigated that control grain size, such as accumulation or firn temperature.

The results of this study show that a distinct heterogeneity of the snow pack and a low accumulation rate seem to produce strong backscatter. This is in agreement with results from the interior of Greenland (17). No effects can be demonstrated from other field data. The variations of the complex dielectric constant with depth seem to be more important than its mean value. The 0-15 m mean varies from 1.90 to 1.95. Using the model of Partington (16), this would result in a backscatter variation of ca. 1 dB for a homogeneous grain size of 1 mm. This is within the uncertainty of the SAR data, and cannot account for the observed variations of more than 10 dB. Likewise, the 10 m firn temperature, which is also an approximation for the annual mean air temperature, varies too little to have a significant effect on grain size. The quality of the snow pit data may have been affected by varying measurement standards and techniques of different researchers in the field. If this is not the case, it could indicate that the investigation of 2 m snow pits is useful for the distinction of different glacier zones (dry snow, wet snow, percolation zone), but not for the distinction of different properties within a dry snow zone.

The multitude of parameters that might influence backscattering makes a quantitative analysis of each individual parameter very difficult. Using the methods presented in this study, it is therefore not possible to determine absolute values of accumulation or heterogeneity from solely analysing RADARSAT SAR imagery. A more advanced, multivariate statistical approach might help to better understand the complex interrelation between snow pack parameters and the radar signal. Additionally, one has to take into account the presence of surface features such as sastrugi, which might have an important influence on the microwave signatures.

However, for a pre-site survey within the scope of an ice core drilling project, the SAR imagery can provide the following useful information:

1. In regions where azimuthal modulations are negligible, it is possible to extract initial qualitative estimates of accumulation rate and/or heterogeneity of the snow pack in a region where no information about dry snow properties exists.
2. On the large scale, the position of ice divides is clearly identifiable in the imagery.
3. On the small scale, RADARSAT SAR imagery is extremely useful for planning and tracing a traverse due to its excellent representation of glaciological features such as crevasses.

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