# Comparison of Microwave Backscatter Measurements with Observed Roughness of the Snow Surface in East Queen Maud Land, Antarctica


Teruo Furukawa National Institute of Polar Research
9-10, Kaga 1-chome, Itabashi-ku, Tokyo 173, Japan
Phone: +81 3 3962 5580, fax: +81 3 3962 5719
furukawa nipr.ac.jp

Neal W Young Antarctic CRC and Australian Antarctic Division
GPO Box 252-80, Hobart, Tasmania, 7001, Australia
Phone: +61-3-62262955, +61-3-62262979, fax: +61-3-62262902
Neal.Young antcrc.utas.edu.au , http://www.antcrc.utas.edu.au
http://www.antdiv.gov.au



## Abstract

**A directional anisotropy is observed in backscatter from the surface of the East Antarctic ice sheet as measured by the C-band wind scatterometer carried by the ERS-1 satellite. The anisotropy is characterised by the amplitude of the variation with azimuth of the backscatter coefficient, and an orientation given by the antenna look direction for minimum backscatter. These data are compared with field observations of surface roughness defined by the frequency of occurrence and orientation of surface microrelief in the form of snow dunes, and sastrugi of various sizes, which are produced by the surface wind. The field data were collected along the traverse route from near the coast (69.03°S, 40.06°E, 591 m a.s.l.) to Dome Fuji (77.31°S, 39.66°E, 3810 m a.s.l.) in east Queen Maud Land. In the katabatic wind region from 2000 m to 3600 m in elevation, the amplitude of the directional anisotropy along the traverse route is consistent with the total frequency of occurrence of surface microrelief and the low variability in the orientation of those features. A weaker anisotropy in the backscatter is observed about the inland dome area above 3600 m elevation (anisotropy amplitude less than 2 dB compared to values up to 4.5 dB elsewhere). This is associated with both a lower frequency of occurrence of surface microrelief and greater variability in the orientation of the microrelief. The amplitude of the directional anisotropy appears to exhibit the strongest association with the frequency of surface microrelief with larger scale and of ridged shape such as sastrugi.**



*Keywords: scatterometer, Antarctic, anisotropy, roughness*


## 1. Introduction

Microrelief on the surface of the ice sheet are formed by the action of the wind eroding and re-depositing the surface snow. The orientation of the microrelief is determined predominantly by the direction of the surface wind when the microrelief were formed. The regional characteristics of the microrelief are influenced on the broad scale by the shape of the drainage basin through its control on surface wind direction and strength, and the supply of drifting snow redistributed by that surface wind (Furukawa et al. 1996). Mesoscale topography in the form of surface undulations with a wavelength of 5 to 15 km modifies the wind speed and thus its capacity to carry drift snow. This process influences the spatial distribution of rates of erosion and deposition of snow on the surface and thus the size and form of the surface microrelief.

Measurements of the microwave backscatter coefficient of the Antarctic snow cover have been obtained with the C-band wind scatterometer instrument carried on the ERS-1 satellite. Young et al. (1996) showed that the backscatter from the snow cover exhibits a directional anisotropy such that the backscatter depends on the look direction of the instrument's antenna for each observation. The anisotropy is characterised by an amplitude and an orientation which correspond to the amplitude of the variation with azimuth of the backscatter coefficient, and the orientation or look direction for minimum backscatter, respectively. Young et al. (1996) also showed that the orientation of minimum backscatter agrees closely with the orientation of the longitudinal axis of surface microrelief in the form of sastrugi on the snow surface and also with the direction of the mean wind measured at Automatic Weather Stations (AWS) in East Antarctica. They found that the C-band microwave backscatter properties of the snow cover over most of the ice sheet area are stable with time. On the other hand, a significant decrease in the value of the backscatter coefficient can occur in conjunction with snow melt as a result of an increase in snow moisture content (Young and Hyland 1997). This usually occurs at low elevations around the coastal margins and on ice shelves, and is less common at higher latitudes.

In this paper, field observation data on surface roughness given by the frequency of occurrence of different types of surface microrelief and the orientation of the microrelief along a traverse route in East Queen Maud Land, Antarctica, are compared with the amplitude and orientation of the directional anisotropy in the satellite microwave backscatter measurements.

## 2. ERS-1 wind scatterometer measurements

The Active Microwave Instrument (AMI) on the ERS-1 satellite operates at 5.3 GHz in the C-band with vertical (VV) polarisation. In the wind scatterometer mode, backscatter measurements of the surface are obtained with three antennae pointing to the right of the spacecraft in three directions. We used measurements of the backscatter coefficient calculated from data acquired on ascending and descending passes of many separate orbits to provide multiple observations with different incidence angle and look direction for any location within the instrument's view.

Young et al. (1996) found that the backscatter coefficient exhibits an approximately linear dependence on incidence angle and that the variation with antenna beam look direction can be described by a bi-sinusoidal function of azimuth. They proposed that the variation in the backscatter coefficient (in dB) can be described by

$$s = s(q0) + A\cdot(q - q0) + B\cdot\sin[2(l + f)] + e \tag{1}$$

where

$s(q0)$ is the mean backscatter coefficient normalised to a reference incidence angle $q0$,
$q$ is the incidence angle of the observation,
$l$ is the azimuth of the observation,
$f$ is the orientation, or look direction, for minimum backscatter coefficient, and
$e$ is the residual term.

The anisotropy parameters are computed from the backscatter observations on a regular array of cells. Observations are assigned to the cell in which the centre of the antenna footprint falls. The coefficients a and b and the orientation term f are determined for each cell through the least squares solution of Equation 1 which minimises the variance of e for all observations assigned to that cell from a given time interval. We use the coefficients calculated by Young et al. (1996) for cells of 25 km square using time intervals corresponding to each calendar month.

## 3. Field observation data

Surface microrelief of the Antarctic ice sheet occurs at various scales and in a number of different forms, for instance dunes, sastrugi, and erosional (or etch) pits. The character of the microrelief is constantly changing in response to changing surface conditions of wind, temperature, snow precipitation, etc. Often more than one form of microrelief will co-exist at any location. We use data collected in December 1992 by Furukawa et al. (1996) to derive simple measures of the surface roughness along the traverse route from S16 (69.03°S, 40.06°E, 591 m a.s.l.) near the coast to the local summit of the ice sheet at Dome Fuji (77.31°S, 39.66°E, 3810 m a.s.l.) in East Queen Maud Land (Figure 1). They counted the number of occurrences of a given form of microrelief that were intersected by the track of one of the over-snow vehicles in each 2 km interval to give the frequency of occurrence of that microrelief. The vehicle track defines a convenient transect line with which to sample the microrelief characteristics.

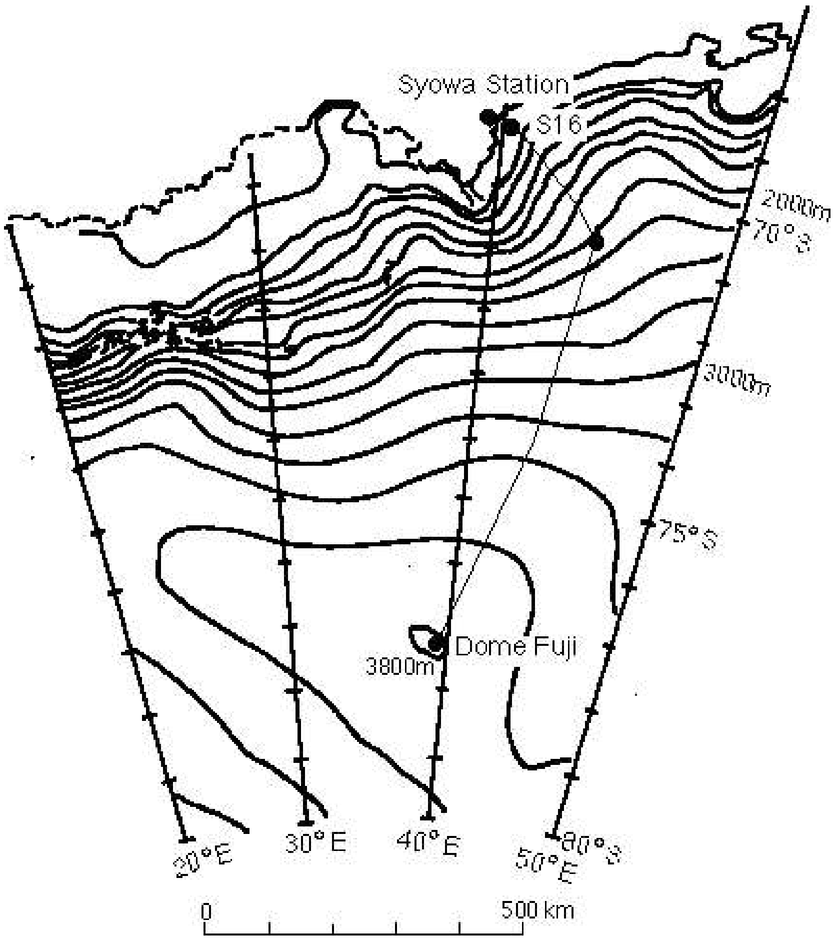


*Figure 1.*

*Location map showing the over-snow traverse route from near the coast at S16 to Dome Fuji. Elevation contours are presented at 200 m intervals from 1000 m.*

The surface microrelief were morphologically classified into three types: the erosional forms of "small sastrugi" and "large sastrugi" according to whether they were less than or more than 30 cm in height, and "dunes" which represent the depositional stage in deposition-erosion processes according to the classification of Watanabe (1978). Figure 2 shows the distributions of frequencies of small and large sastrugi, and dunes, as well as surface and bedrock elevations along the traverse route from the coast to Dome Fuji. We use the frequency of surface microrelief occurrence to represents the degree of surface roughness. Furukawa et al. (1996) also measured the orientation of the dunes, sastrugi, and etch pits in the surface of the snow each 10 km along the traverse route. This gives the preferred orientation of the surface microrelief.

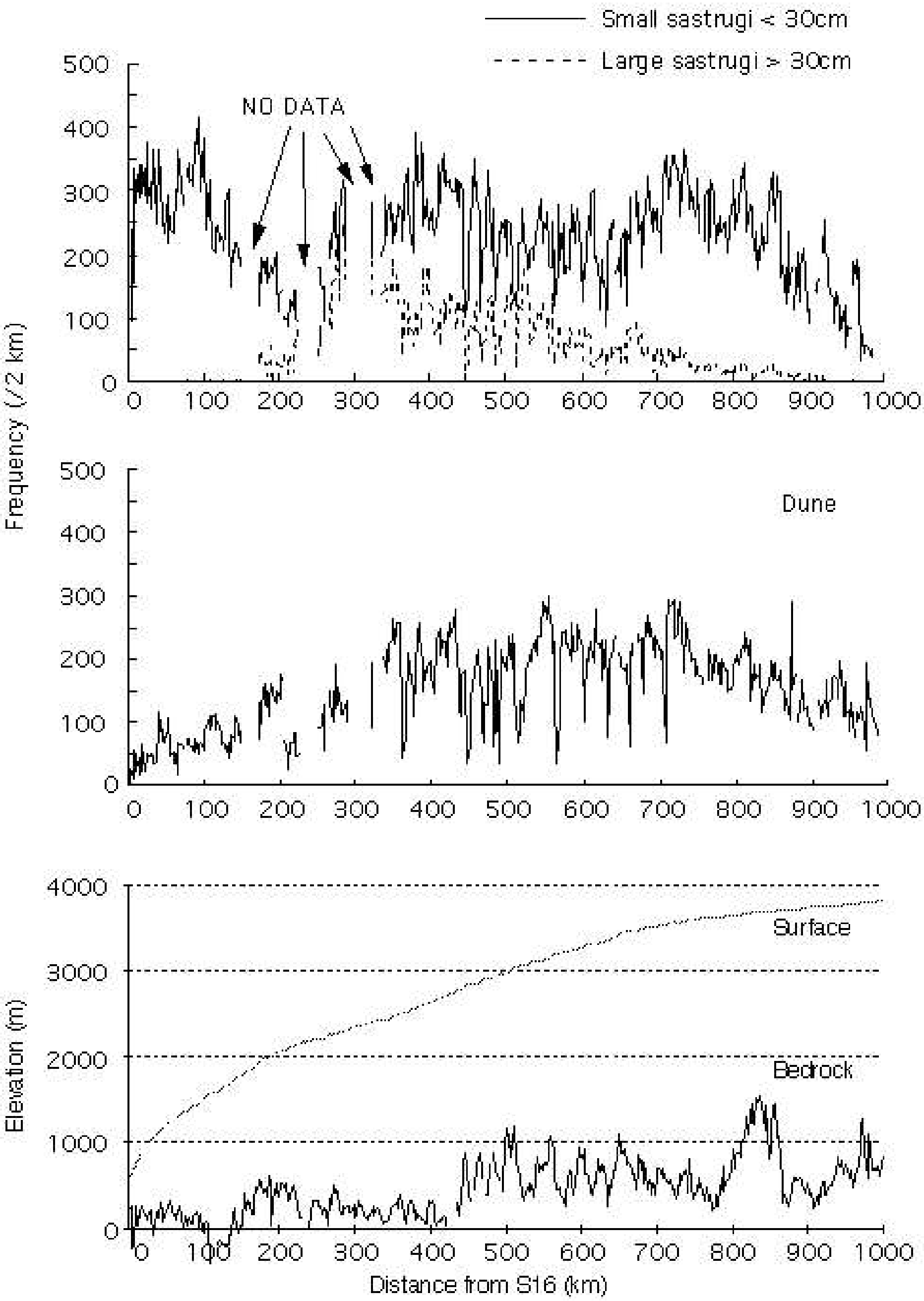


*Figure 2.*

*Frequency of occurrence of small and large sastrugi, and dunes, and profiles of surface and bedrock elevations along the traverse route from the coast to Dome Fuji.*

### 4. Comparison of scatterometer data with field observation data

The directional anisotropy parameters of amplitude and orientation computed for December 1992 are used to coincide with the period of field observations of surface microrelief. The microrelief frequency data are smoothed using a 50 km running mean to produce a statistical measure of the average surface roughness at a spatial scale comparable to the large footprint of the scatterometer instrument. The footprint has a nominal diameter of about 50 km and each value of the backscatter coefficient represents the integrated response of the sensor to the backscatter within the footprint.

### 4.1 Comparison of the amplitude of the directional anisotropy with frequency of surface microrelief

Figure 3 shows the amplitude of the directional anisotropy calculated for December 1992 at 10 km intervals along the traverse route. Also shown are the values from the 50 km running mean of the sum of the frequencies of the two sizes of sastrugi and the dunes. The section of the route with the largest anisotropy amplitude occurs around 300 km from the coast where the total frequency of surface microrelief is highest. Except for the near-coastal region up to 200 km, the amplitude of the anisotropy appears to vary consistently with the total frequency of surface microrelief.

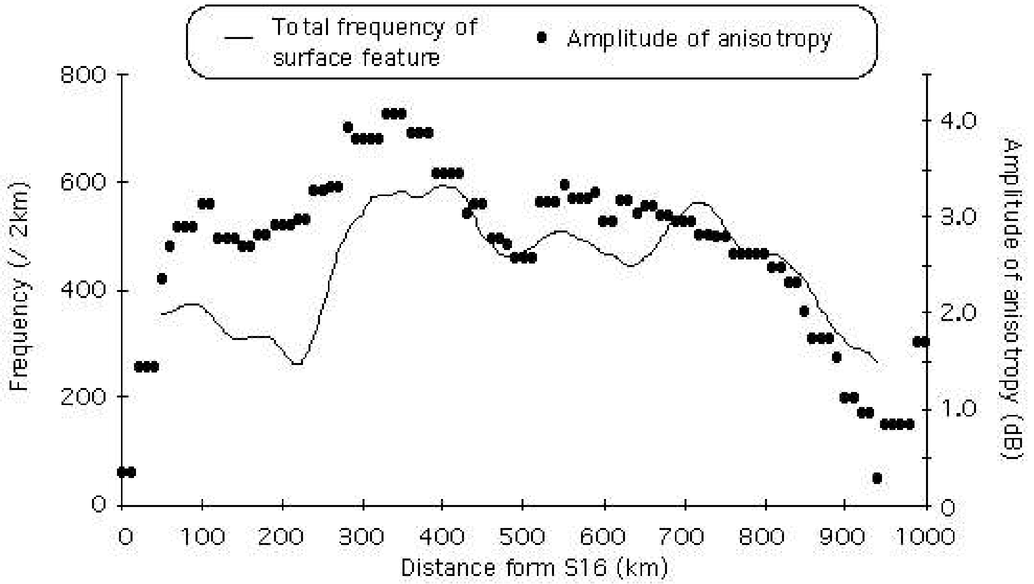


*Figure 3.*

*50 km running mean of the total frequency of occurrence of surface microrelief features. The total frequency is the sum of the individual frequencies of small sastrugi, large sastrugi and dunes. The amplitude of the backscatter anisotropy is shown at 10 km intervals along the route. The amplitude value presented corresponds to the central value of the (25 km * 25 km) cell containing the point. Apparent sharp changes in amplitude are an artefact of that sampling procedure.*

In order to explore which type and size of surface microrelief has a stronger association with the anisotropy effect, the amplitude of the anisotropy is compared in Figure 4 with the frequency of each type of surface microrelief: small sastrugi, large sastrugi and dunes. The section at around 300 km from the coast with the largest amplitude corresponds approximately to the peak in the frequency of large sastrugi. The increase in the amplitude around 500 km is similarly associated with an increase in the frequency of large sastrugi. There are similar variations along the route in the frequency of small sastrugi or of dunes, but in general these are not associated with marked changes in the amplitude of the anisotropy. This suggests that the directional anisotropy is more strongly associated with larger surface microrelief and of ridged shape such as sastrugi.

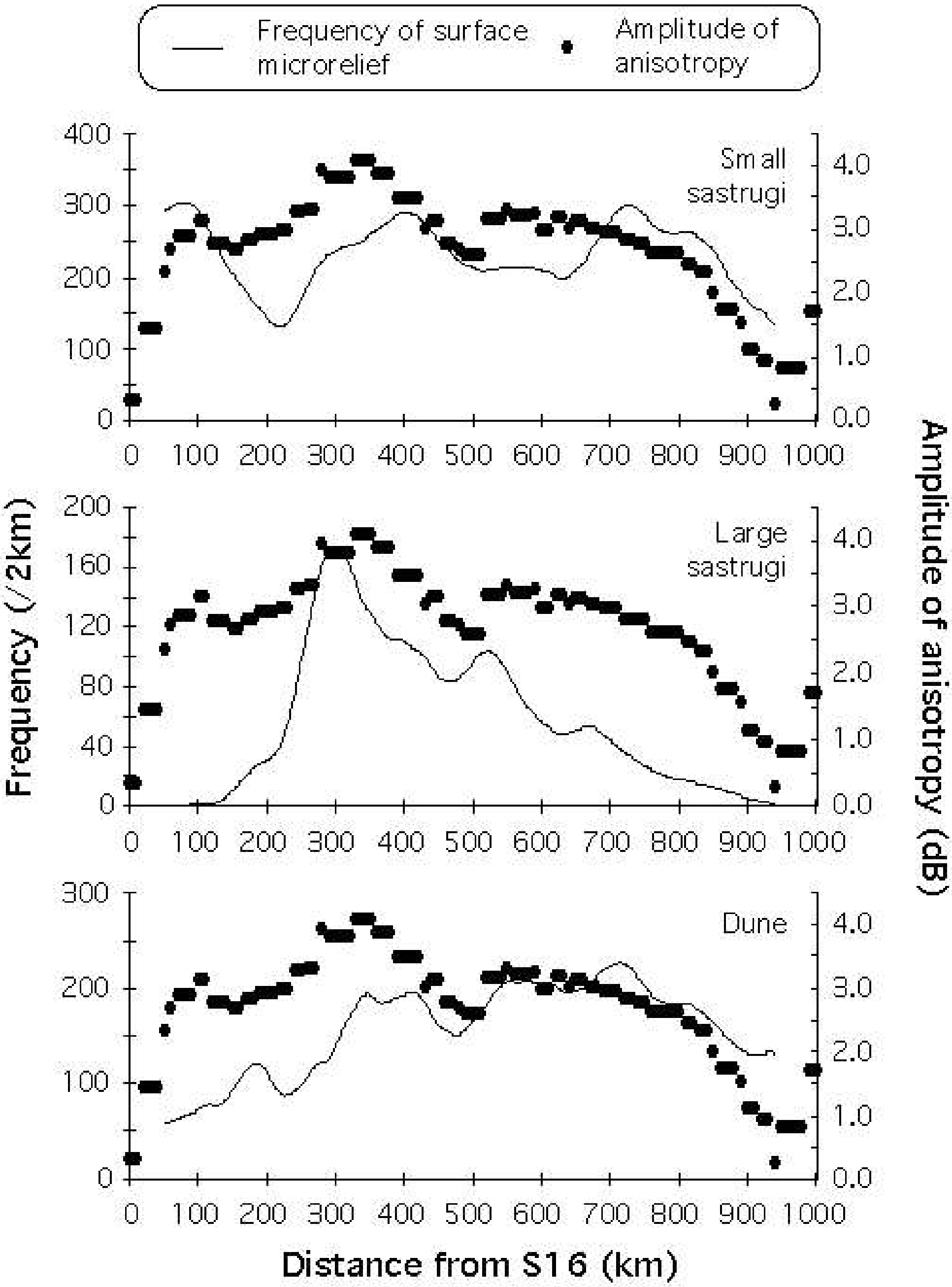


*Figure 4.*

*Distributions of frequency of each surface microrelief of small sastrugi, large sastrugi and dunes and the amplitude of the directional anisotropy obtained using the same sampling procedure as for Figure 3.*

The rate of decrease from 500 km to 800 km is consistent with the decrease in the frequencies of small sastrugi and dunes. The numbers of large sastrugi are becoming insignificant by about 700 km. From 800 km to Dome Fuji, the decrease in the amplitude is more rapid than might be expected from the decrease in frequency of dunes or small sastrugi. Here the weakening of the anisotropy effect can be explained by the greater variability in the orientations of dunes as discussed below.

### 4.2 Comparison of the orientation of the anisotropy with the directions of surface microrelief

The orientation of the directional anisotropy derived from the scatterometer data is compared with the orientations of sastrugi, small erosional forms (e.g. etch pits in the surface of the snow cover) and dunes observed at intervals of about 10 km along the traverse route from the coast to Dome Fuji in Figure 5. These observed orientations give an indication of the prevailing wind direction when each snow surface feature was formed. For the section from the coast up to 700 km the orientations of sastrugi and erosional pits vary mostly within 10-15° of their local mean over an interval of 50 km. The orientations of dunes show much greater variability and appear to include two populations of orientations from 200 km to at least 600 km.

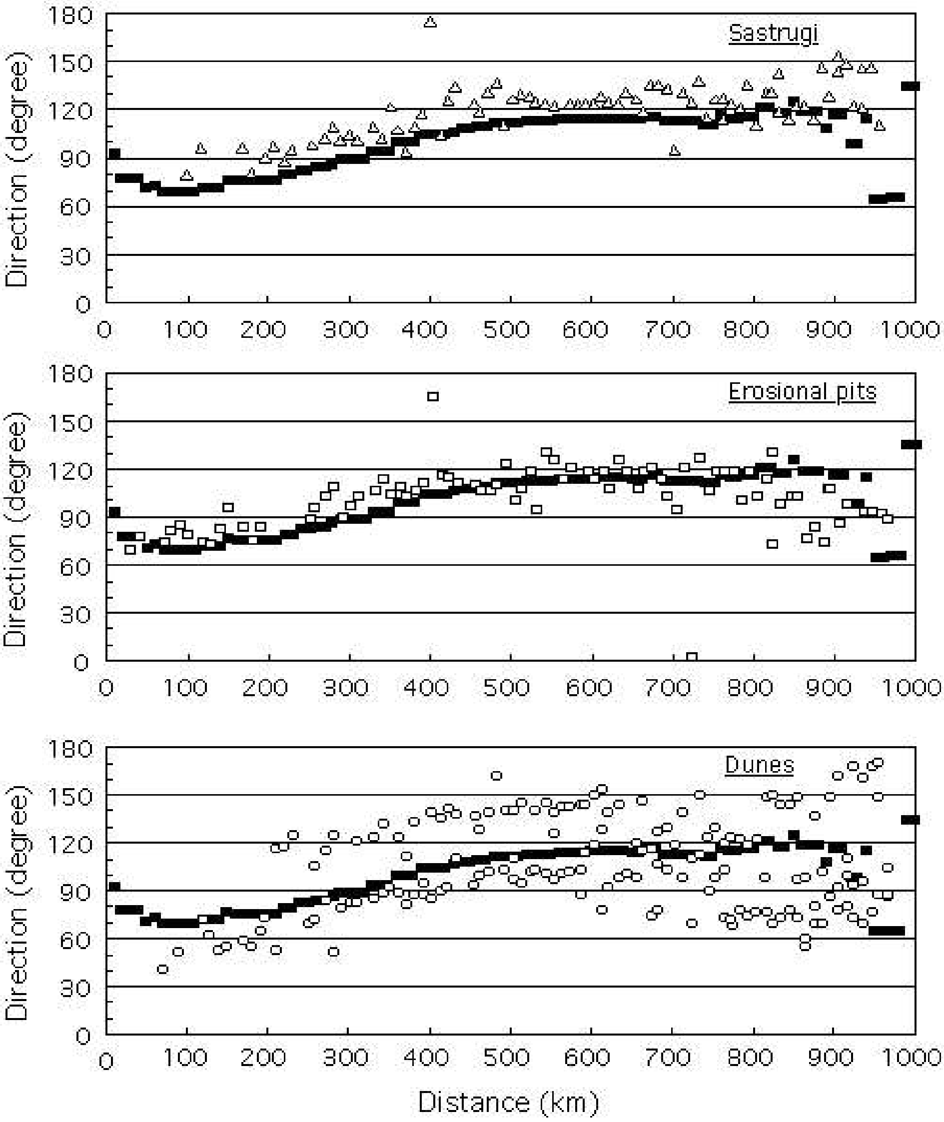


*Figure 5.*

*Comparison of the orientation of the anisotropy with the directions of three surface microrelief forms: sastrugi, small erosional pits (surface etch pits), and dunes. The orientations are given as local azimuth.*

The orientation of the anisotropy is most consistent with the orientations of sastrugi and small erosional forms. There appears to be a consistent bias in the orientation of the anisotropy of about 15-20° anticlockwise from the orientation of sastrugi, and about 10-15° from the small erosional forms, for the interval from the coast to 700 km. Inland of this point, the orientations of the sastrugi and the erosional pits are more variable. But the bias with respect to the erosional pits is now in the opposite sense to that closer to the coast.

The comparison of the orientations of the anisotropy and the dunes is more complicated. Inland of the 200 km point the mean orientation of the dunes calculated over a 50 km interval exhibits a similar variation to that for erosional pits, with a similar change in the bias with respect to the orientation of the anisotropy on the section near Dome Fuji. The anisotropy orientations lie between the two populations of dune orientations. As with the other surface features, there is a greater variability in the orientation of the dunes about Dome Fuji.

## 5. Discussion

Microwave radiation at C-band wavelengths can penetrate cold dry snow to a considerable depth so that volume scattering would be expected to dominate the backscatter signal (Rott et al. 1993). In the above section we have shown a strong association between the orientation and amplitude of the directional anisotropy in the backscatter with the orientation and magnitude of the roughness of the snow surface. Young et al. (1996) showed that the surface observations are an indicator of structures within the snow pack, since the surface features can be preserved by their progressive burial with the accumulating snow cover. Each backscatter measurement represents the integrated contributions from surface scattering and a volume of snow and firn of several metres thickness. In this way the backscatter represents an integral of the time varying record of surface roughness features that have become buried in the snow.

Thus the frequency of occurrence of surface roughness features and their orientation at least give an indication, if not a measure, of the scattering elements with a preferred orientation contributing to anisotropy in the backscatter, from both the surface of the snow and the volume. Discrepancies between the spatial patterns in the surface observations and the satellite data can be partly explained by temporal and spatial variability in the roughness. Firstly, there can be considerable temporal variability in the surface roughness in response to varying surface conditions. The observations were collected at one epoch and so may not represent the longer term average conditions preserved in the snow pack. Secondly, Figure 2 shows that there is considerable spatial variability in observed surface roughness over distances of the order of 10 km. The traverse route samples a transect across the ice sheet which is quite narrow compared to the diameter of the scatterometer footprint. There could be areas to the side of the traverse route with significantly different surface roughness conditions that fall within the footprint of the scatterometer but are not sampled in the field observations.

The bias in the orientations of the directional anisotropy with respect to surface features is consistent with that first reported by Young et al. (1996) for Wilkes Land and the Lambert Glacier basin. This new finding shows that the bias occurs over a large sector of the Antarctic ice sheet, but with variable magnitude. Further work is required in order to determine the nature of the bias and its cause. The large uncertainty in the orientation of the directional anisotropy near Dome Fuji is a consequence of the weakness of the anisotropy in that region and the poorly defined peaks in the backscatter variation with look direction. The variability in the orientation of the surface roughness and thus scattering elements with a preferred orientation contributes to the weakening of the anisotropy in that region. This variability is consistent with the surface wind being weaker and more variable in direction where the surface slope is small.

## 6. Conclusion

The character of a directional anisotropy observed in the backscatter from the Antarctic snow cover can be related to the properties of the surface roughness obtained by observations of surface microrelief along over-snow traverse routes. While these observations of dunes, sastrugi, and small erosional features are obtained on the surface they do provide an indicator of the character of scattering elements with a preferred orientation contained within the snow pack. Thus the frequency of occurrence and orientation of surface microrelief features serve as a proxy measure of the scattering strength and orientation of elements contributing to the anisotropic behaviour of the backscatter.

In summary, the orientation of the directional anisotropy exhibits a close correspondence with the orientation of surface erosional features, and a weaker correspondence with the orientation of dunes, in the region from the coast to about 700 km along the traverse route in East Queen Maud Land. Apart from the first 100 km, the amplitude of the anisotropy in this section is greater than 2.5 dB. The directional anisotropy also exhibits a consistent bias in orientation with respect to the orientation of the surface features.

The frequency of occurrence of microrelief features provides a measure of the density of anisotropic scattering elements. The frequency is strongly associated with the amplitude of the anisotropy, where the amplitude is greater than 2-2.5 dB. In particular the frequency of large sastrugi appears to have a stronger association. On the high inland plateau, the anisotropy is weaker because the frequency of microrelief features is smaller, there are proportionally fewer large sastrugi, and the orientations are much more variable.

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