Relating Microwave Backscatter Azimuth Modulation to Surface Properties of the Greenland Ice Sheet

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***Abstract*— Azimuth modulation of the normalized radar cross-section in satellite data sets over Greenland is investigated. Data sets from the NASA Scatterometer (NSCAT) and from the European Remote Sensing Advanced Microwave Instrument (ERS) are employed. Azimuth dependence is clearly observed. The largest azimuth dependence occurs in the C-band ERS data with peak-to-peak azimuth modulations up to 3.0 dB. The Ku-band NSCAT data exhibits slightly smaller modulations of up to 2.0 dB.**

Azimuth modulation is largest in the lower dry snow zone for ERS and in the dry to percolation transition zone for NSCAT. The incidence angle dependence of the azimuth modulation is parameterized over the ice sheet. In general, the azimuth modulation is found to either decrease with increasing incidence angles, or be relatively independent of incidence angle. Regions of large incidence angle dependence for the azimuth modulation include the western dry snow zone for ERS and the northeast dry snow to percolation transition zone for NSCAT. The second order azimuth modulation orientation is highly correlated with wind direction. A new simple surface model is introduced to relate azimuth modulation to surface properties. Using this model, the size and orientation of surface sastrugi are estimated.

I. Introduction

The Greenland ice sheet is a critical area of study in estimating effects of global climate change. With only a limited number of in situ measurements due to the considerable effort associated with on site studies, remote sensing is an essential tool for studying the dynamics of this region. While satellite based normalized radar cross-section (σ^o) data have been used in a variety of successful studies over Greenland, past studies have generally ignored microwave measurement dependency on azimuth angle.

This work is an extension of previous work found in [1]. Data from the C-band European Remote Sensing Advanced Microwave Instrument in wind scatterometer mode (hereafter ERS) and the Ku-band NASA Scatterometer (NSCAT) are employed. Both sensors cover a large range of incidence angles. For NSCAT, only the vertical polarization (v-pol) measurements have sufficient azimuth coverage to be used in the study. The ERS measurements are also v-pol. The data shown herein is from the time interval Julian Day (JD) 330 to 360, 1996. This is during the winter when the Greenland surface is relatively constant.

Although scarcely studied in Greenland, azimuth modulation is common in microwave remote sensing studies over other areas of the Earth. The primary application of azimuth modulation is in using scatterometers to measure vector wind speeds over the ocean surface.

The azimuth modulation over Greenland is attributed to a complex snow surface structure created by wind driven snow deposition, aeolian transport, and the formation of wind slabs and hoar layers. The scale of the surface roughness varies from dunes on the km scale to meter scale erosional features known as sastrugi.

First, the location and properties of the azimuth modulation are discussed. In particular, the incidence angle dependence of the azimuth modulation is addressed and the locality of the maximum modulation with respect to the different ice facies is addressed. Then the orientation of the azimuth modulation is presented to compare with Greenland wind models. Finally, a simple surface model is presented which relates the azimuth modulation to the geophysical properties of the snow surface.

II. Observation Model

The observed azimuth modulation is parameterized using a second order Fourier Series [2]:

$$\sigma^o(\theta,\phi) = A+B(\theta-40)+M_1\cos(\phi-\phi_1)+M_2\cos(2\phi-\phi_2)$$

where A represents the unmodulated backscatter at $\theta = 40$, B gives the incidence angle dependence, M_1 and M_2 are the magnitudes of the first and second order modulation respectively, and ϕ_1 and ϕ_2 are the orientation of of the azimuth modulation. A second order fit matches the data well. The first order term relates to surface features that are not symmetric such as surface slope, whereas the second order term relates to surface features with 180 degree symmetry such as sastrugi.

Long and Drinkwater extend this model such that M_1 and M_2 are linear functions of incidence angle [2]:

$$M_j = c_j + d_j(\theta - 40).$$

Images of the magnitude parameters of the extended model are shown in Fig. 1 for ERS and NSCAT.

The A and B images display the basic properties of the ice sheet for the two frequencies. The A images for the two sensors are similar, with the dark region in the center identifying the dry snow zone which is surrounded by the brighter percolation zone and then the dark ablation zone on the Greenland periphery [3]. The B images display definite differences between the two frequencies. For ERS the outer boundary of the dry snow zone is denoted by a region of large incidence angle dependence. For NSCAT, the region of large incidence angle dependence encompasses most of the percolation zone with the largest dependence near the percolation zone/dry snow zone boundary. The B values for NSCAT are, in general, smaller than for ERS.

The azimuth modulation is also greater for C-band than Ku-band. For ERS the dominant azimuth modulation is second order which is indicative of 180 degree symmetry in the microwave properties of the firn. Although smaller, the first order azimuth modulation is highly correlated with the second order. An interesting feature is observed in the incidence angle dependence of the ERS azimuth modulation found in the d_1 and d_2 images. To the west the azimuth modulation decreases with larger incidence angles, whereas on the east the dependence is opposite and much smaller in magnitude.

The Ku-band azimuth modulation is smaller than C-band. It also extends further into the percolation zone. The high resolution of NSCAT compared to ERS also brings out more azimuth modulation in the mountainous coastal regions. In the NSCAT d_1 and d_2 images, the first order modulation appears independent of incidence angle and the second order modulation decreases with larger incidence angles in both the east and the west regions of the lower dry snow zone.

A. Transect

In order to better understand the inter-relationship between the different observation model parameters and the relationship between C-band and Ku-band, the parameter values are plotted across a transect. The transect begins at 54.1 W, 74.1 N and continues to 24.1 W, 79.1 N as illustrated in the ERS A image in Fig. 1. The parameter values are shown in Fig. 2.

For both ERS and NSCAT, the magnitude of the incidence angle dependence and azimuth modulation are clearly correlated. This implies an inter-relationship between the two and

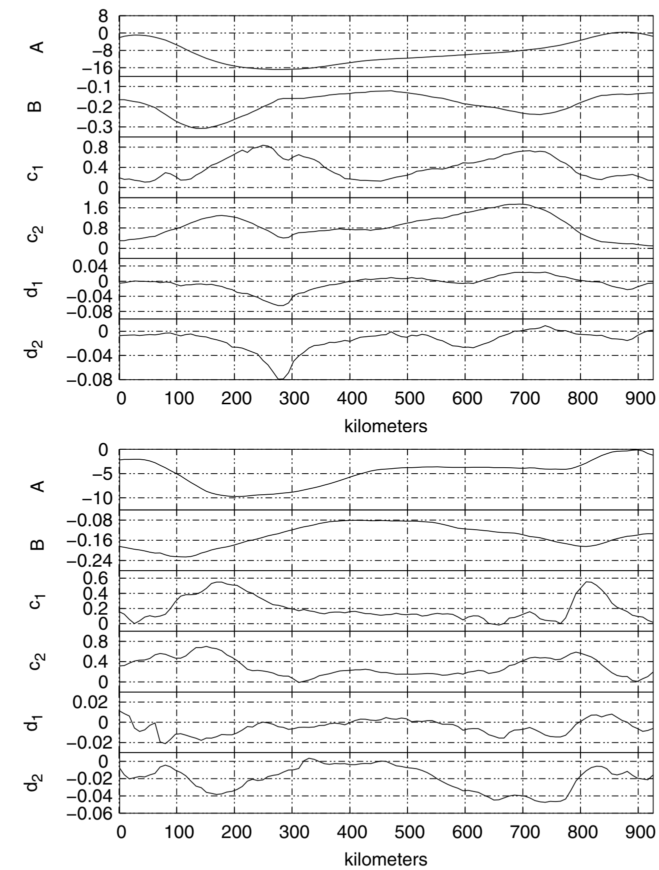

Fig. 2. Observation model parameter variation across the transect shown in Fig. 1 with left to right corresponding to west to east. Top: ERS, Bottom: NSCAT.

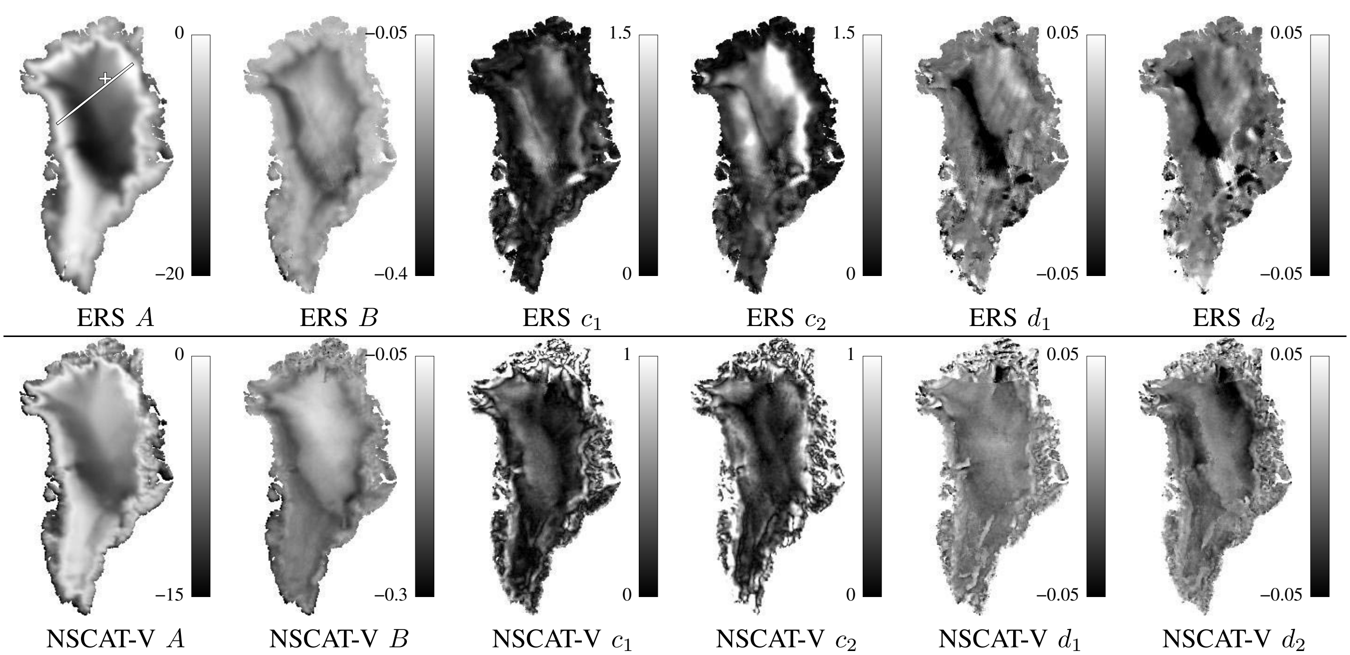

Fig. 1. Azimuth modulation parameter images. The line and "+" mark on the ERS A image indicate the transect studied and the location surface model fit respectively. Note that in an effort to maximize the feature detectability, the color-scales are different for each sensor and parameter.

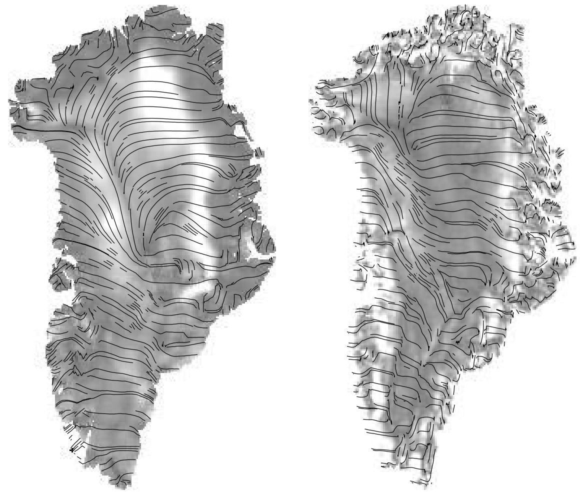

Fig. 3. Streamlines of second order azimuth modulation minimums for (left) ERS and (right) NSCAT. The streamlines are imposed over c_2 images from the respective sensors.

is used in the surface model described in Section III.

For NSCAT, the critical points in the data trends occur closer to the ends of the transect than for ERS, confirming that significant azimuth modulation extends further into the percolation zone from the dry snow zone.

Streamlines of the minimum of the second order azimuth modulation for ERS and NSCAT imposed over c_2 images are shown in Fig. 3. The streamline directions are highly correlated with modeled katabatic wind fields [4]. The streamlines for ERS and NSCAT are similar with only slight discrepancies at the crest, which is more clearly defined in the ERS data.

III. Surface Model

A simple surface model has been developed to account for azimuth modulation over the Greenland ice sheet. Ulaby et al. [5] proposes a model for periodic surfaces where

$$\sigma^o_{ls} = \frac{1}{A}\int_A \sigma^o_{ss}(x,y)dA$$

with σ^o_{ls} being the large scale backscatter over the area A and σ^o_{ss} representing the small scale backscatter.

It is common, for a given surface, to estimate σ^o as a function of the local incidence angle ϑ. The above model can be rewritten

$$\sigma^o_{ls}(\theta,\phi) = \int \sigma^o_{ss}(\vartheta)P(\vartheta|\theta,\phi)d\vartheta$$

where $P(\vartheta|\theta,\phi)$ is the probability density function of ϑ given a large scale incidence angle θ and an azimuth angle ϕ. For the purposes of the model, the slope distribution of the surface is assumed independent and jointly Gaussian in the x and y directions with means μ_x and μ_y obtained from a digital elevation map of Greenland [6]. The model estimates the standard deviation of the local slope in each direction (σ_x and σ_y) along with the orientation of the x-axis relative to north (ψ). $\sigma^o_{ss}(\vartheta)$ is constrained to the form

$$\sigma^o_{ss}(\vartheta) = a^{-b\vartheta^2} + c^{-d\vartheta}$$

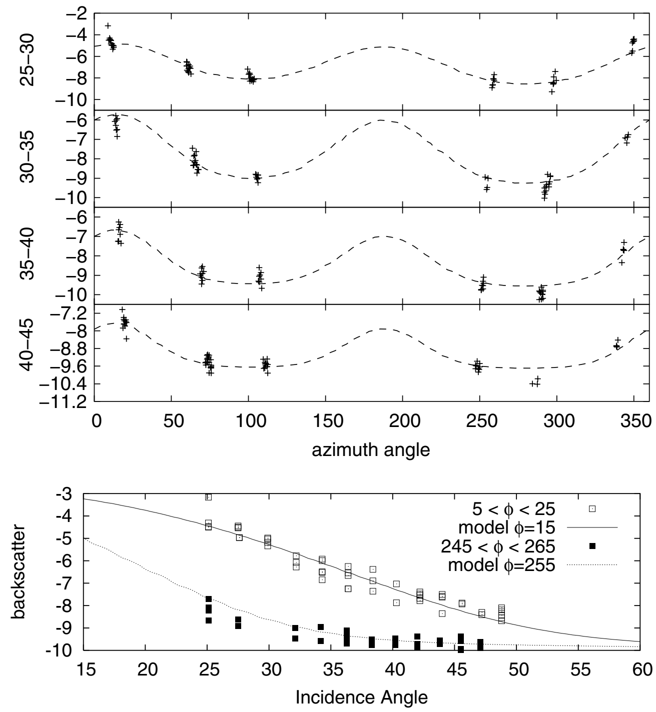

Fig. 4. Illustration of the surface model fit at 78.3 N, 37.4 W. This location is indicated with a "+" in the ERS A image in Fig. 1. The top plot shows the fit at different incidence angles. The incidence angle range for the raw data is labeled on the vertical axis. The surface model fit uses the center incidence angle in each given range. The bottom plot shows the incidence angle dependence of the raw data and the surface model fit.

in real space, which matches well with the data sets. For each surface profile, the parameters a, b, c, d are chosen to minimize

$$\sum_i(\hat{\sigma}^o_i - \sigma^o_i)^2$$

in dB. This process is repeated adjusting σ_x, σ_y, and ψ until the overall minimum squared error is achieved.

This simple model is promising for characterization of the Greenland surface. It fits the data remarkably well as illustrated in Fig. 4. Using σ^o azimuth modulation, the dynamics of the Greenland ice sheet may be better tracked, including long term wind patterns.

References

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