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# POLARIMETRIC ICE SOUNDING AT P-BAND: FIRST RESULTS

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## ABSTRACT

For polar ice sheets valuable stress and strain information can be deduced from the crystal orientation fabric (COF) and its prevailing c-axis alignment. Polarimetric radio echo sounding is a promising technique to measure the anisotropic electromagnetic propagation and reflection properties associated with the COF. In this paper, dual-polarized P-band data acquired with the airborne POLARIS system near the ice divide of the Greenland ice sheet are analyzed. The internal layers in the uppermost few hundred meters of the ice sheet look the same at HH and VV polarizations, whereas the layering differs further down. Accordingly, the magnitude of the complex HH–VV correlation coefficient decreases with depth and, interestingly, the phase gives evidence of polarization dependent reflection and birefringence effects.

*Index Terms*— Radar, sounding, P-band, polarimetry, birefringence, anisotropic reflection, ice sheets.

## 1. INTRODUCTION

In explaining present ice sheets velocities and in inferring past climate, stress and strain are important parameters. Strain in turn results in formation of a crystal-orientation fabric (COF) characterized by ice crystals having a preferred alignment, e.g. near the ice-divide in Greenland, where the ice is stretched in the direction perpendicular to the ice divide and compressed in the vertical direction, the c-axes change from a random orientation near the surface to a preferred orientation parallel with the ice divide deeper in the ice sheet [1]. Since single ice crystals have a dielectric anisotropy [2], also a COF has anisotropic electromagnetic properties, but they depend on the degree of alignment of the ice crystals [3].

The anisotropic dielectric permittivity leads to two phenomena: birefringence and reflections at abrupt COF changes, which can be observed by polarimetric radio echo sounding (RES). Polarimetric RES has already proved a promising glaciological tool [4], [5], but polarimetric RES data are scarce, as most radar ice sounders operate at a single, fixed polarization. Some systems allow the antenna

to be rotated, thereby offering dual polarized multi-pass data, which are not necessarily co-registered in a phase preserving manner. This paper is based on data acquired with the fully POLarimetric Airborne Radar Ice Sounder (POLARIS).

## 2. POLARIS RADAR

POLARIS is a P-band demonstrator developed for ESA by the Technical University of Denmark. The aim is to obtain more knowledge about the electromagnetic properties of the Antarctic ice sheet at P-band and to test novel ice sounding techniques in preparation for a potential spaceborne ice sounding radar [6]. A recent ITU allocation of a 6 MHz radar band at 435 MHz has increased the interest in space-based sounding of the Earth's ice caps.

POLARIS is a fully polarimetric system [7], [8], characterized by a maximum bandwidth of 85 MHz, corresponding to a vertical resolution (in ice) of about 1 m. In order to increase the dynamic range, a shallow/deep sounding approach is adopted, i.e. when necessary, overlapped near-surface and near-bottom windows are covered separately. This is done simultaneously by alternating the receiver gain on a pulse-by-pulse basis.

## 3. TEST DATA

In mid May 2008, a Proof-of-Concept (PoC) campaign was carried out in Greenland with the aim of testing the newly integrated POLARIS system, i.e. the focus was on the system functionality and technical performance, not on the acquisition of science data.

Though POLARIS is a fully polarimetric system, only dual polarized data were acquired simultaneously: HH polarized data are transmitted and received on a linear polarization parallel to the flight track, while VV data are transmitted and receive on the orthogonal linear polarization. Consequently, polarization synthesis cannot be applied to determine the principal axes of the birefringence like in [4]. Instead, data were acquired from two flight tracks, one perpendicular to the ice divide and one parallel to the ice divide as indicated in Figure 1. Hence, at the cross-over, the HH data from one flight track are expected



Figure 1 PoC flight tracks (red) at 37°52' W, 69°29' N.

to be similar to the VV data from the other flight track and vice versa.

#### 4. RADIOMETRIC ANALYSIS

The profiles in Figures 2 and 3 show internal layers near the ice divide. By visualizing the relative range derivative  $s_d(n_r, n_a)$  of the multi-looked amplitude data  $s(n_r, n_a)$  the layers are enhanced (high-pass filtered) and the range attenuation is suppressed (assuming an exponentially attenuated signal). In practice the sample-to-sample difference of the amplitude is computed and divided by the amplitude at the same range

$$s_d(n_r, n_a) = \frac{s(n_r + 1, n_a) - s(n_r, n_a)}{s(n_r, n_a)} \quad (1)$$

Here  $n_r$  and  $n_a$  are the sample indices in the range and along track directions, respectively. The bright line at the top is the surface echo, and the double bounce echo (surface-aircraft-surface) is seen below the 350 m marker (the flight altitude was 2000 ft). The lines above the surface

are range sidelobes. The relative range derivative show does not show that the sidelobes are actually suppressed by more than 40 dB compared with the internal layers just below the ice surface (and much more compared with the surface echo).

When comparing the shallow sounding windows in Figure 2 and 3 it is seen that the layers in the upper half look the same at the HH and VV polarization unlike those in the lower half of the figures. This dark line under the double bounce reflection is a prominent example..

#### 5. COHERENCE ANALYSIS

A quantitative analysis of the anisotropy can be based on the complex VV-HH covariance, or coherence

$$c_{hhvv}(n_r, n_a) = \frac{\sum s_{hh}(n_r, n_a) s_{vv}^*(n_r, n_a)}{\sqrt{\sum |s_{hh}(n_r, n_a)|^2} \sqrt{\sum |s_{vv}(n_r, n_a)|^2}} \quad (2)$$

The magnitude of this coherence is a measure of the similarity of the HH and VV data, as differences in the local amplitude and phase reduce the coherence amplitude compared to its unity maximum value.

An example of a coherence plot is shown in Figure 4, where it is seen that the coherence is almost maximum for the topmost 200 m beyond which it drops to about 0.3 and finally increases to about 0.4. This trend is also seen in the (enhanced) radiometric plots where the polarization in the North-South direction (i.e. VV for EW tracks and HH for NS tracks) has much less contrast at large depths than the East-West polarization has. The fact that the low-contrast channel change when the track angle change shows that the phenomenon is not an artifact associated with the radar.

The phase of the complex coherence is a measure of

- the difference between the reflection coefficients at the two polarizations
- the electrical two-way propagation path length of the HH and the VV signals.

For an isotropic media the coherence phase is zero, provided the radar is properly calibrated. However, in case of birefringence the speed of light is polarization dependent, and the same *physical* propagation path corresponds to two different *electrical* path lengths at the two polarizations.

Figure 2 shows that the coherence phase is zero at the ice surface, but at depths between 500 and 900 m it has large excursions, which might be due to a phase wrap modulo  $2\pi$ . This is also illustrated by the range profile in Figure 3, which is the along-track average of the 2D phase plot in Figure 2. An attempt to unwrap the phase does not lead to a monotonous phase in this area, whereas data acquired on an EW track a bit further to the west do have a monotonous phase after unwrapping.



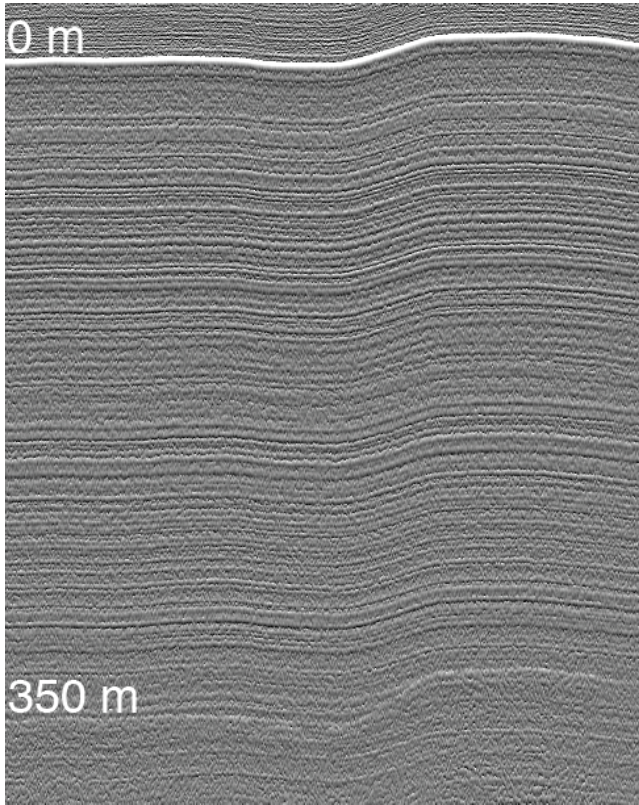


Figure 2 Internal layers mapped at HH polarization.

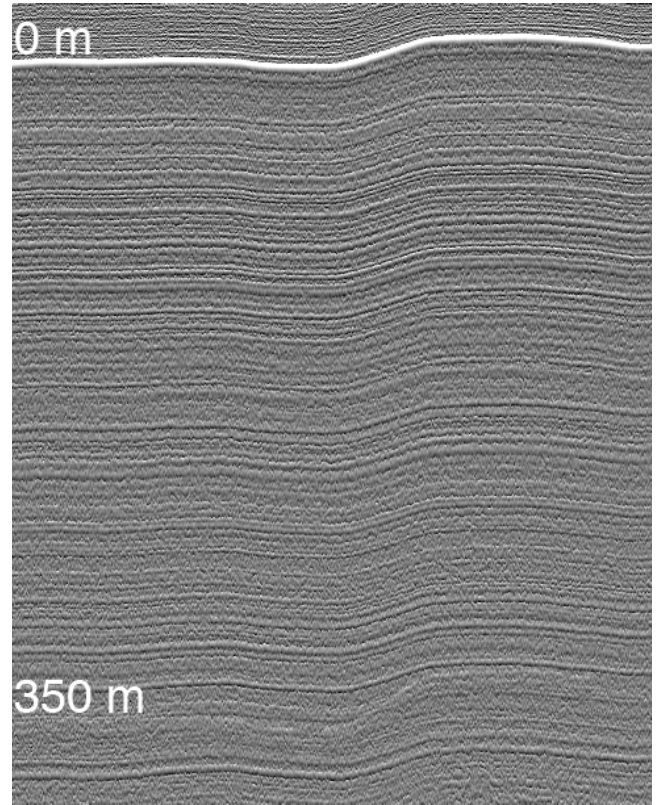


Figure 3 Internal layers mapped at VV polarization.

In order to verify that the depth variation of the HH-VV phase is not an artifact caused by the radar system the corresponding phase plot has been generated from data acquired on the orthogonal EW track as seen in Figure 4. Since the VV polarization on the NS track is aligned with

the HH polarization on the EW track and vice versa, the phase plots in Figure 3 and Figure 4 are expected to be similar but reversed, which is indeed the case. Hence, the figures are believed to illustrate physics, not an artifact.

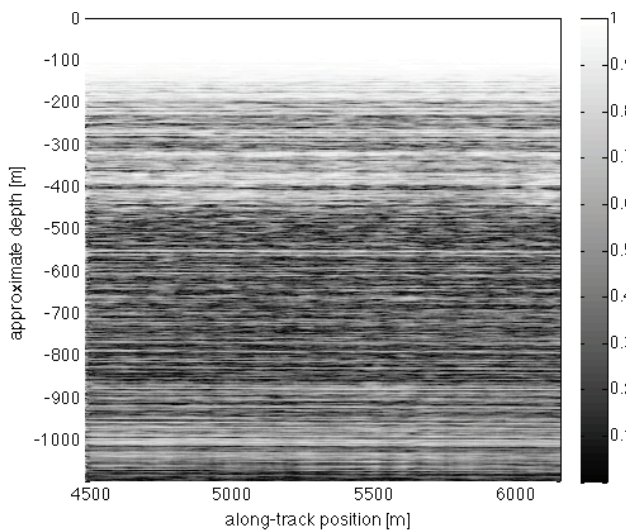


Figure 4 HH-VV coherence amplitude for the EW track.

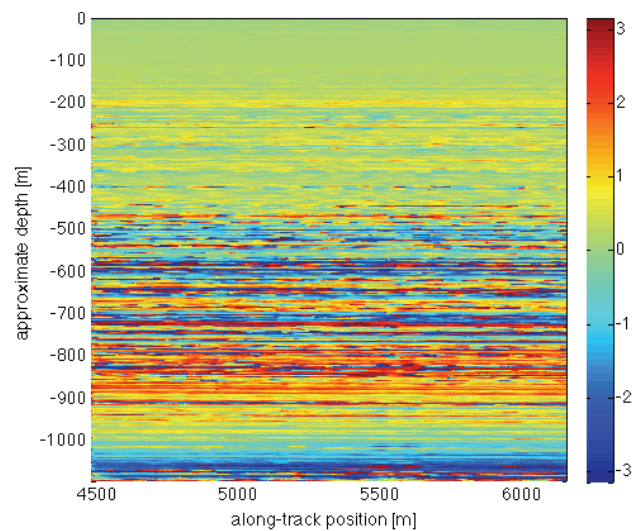


Figure 2 HH-VV coherence phase for EW track.

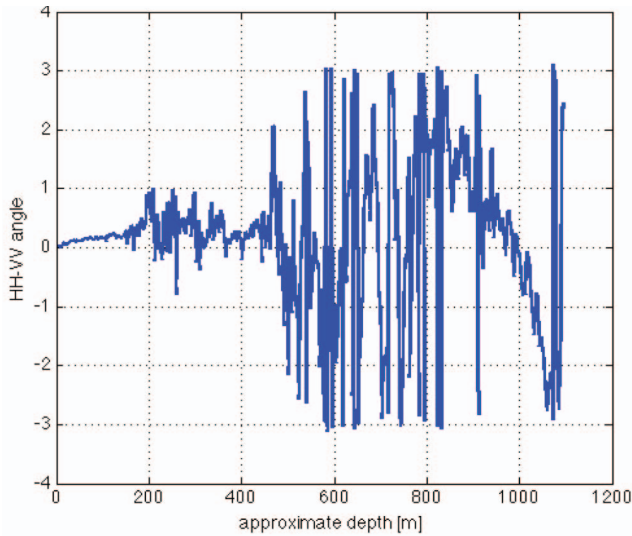


Figure 3 HH-VV coherence phase for NS track.

## 6. CONCLUSION

Two different physical phenomena should be considered in order to explain the observed anisotropy:

- birefringence
- anisotropic reflection

The effect of birefringence is large enough that abrupt COF changes could cause the internal reflections observed [9]. However, stress models and ice core analyses [1] suggest the COF to vary slowly with the depth.

Highly anisotropic internal surfaces are reported for the George VI Ice Shelf [10], where the roughness of the reflecting surfaces is attributed oceanographic processes.

The POLARIS data seem to give evidence of both phenomena. Birefringence-induced *propagation* effects are seen from the variation of the HH-VV phase difference above 500 m and below 900 m (after phase unwrapping also in between, though not monotonous). Anisotropic *reflection* effects could give rise to the internal layering observed.

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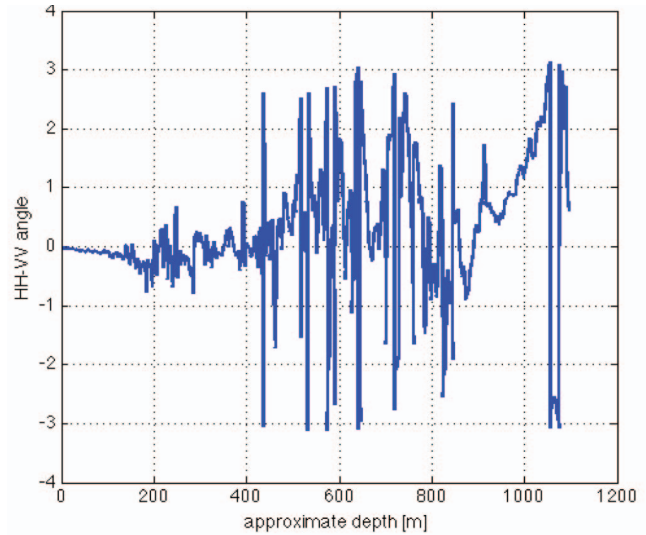


Figure 4 HH-VV coherence phase for EW track

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