ICE SHEET ANISOTROPY MEASURED WITH POLARIMETRIC ICE SOUNDING RADAR

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1. INTRODUCTION

For polar ice sheets, valuable stress and strain information can be deduced from the crystal orientation fabric (COF) and its prevailing c-axis alignment, e.g. in central Greenland, where the ice is stretched in the direction perpendicular to the ice divide. The anisotropy of the ice can be observed with radar polarimetry [1][2] as it leads to birefringence and reflections at abrupt COF changes.

This paper is based on data acquired with POLARIS (POLarimetric Airborne Radar Ice Sounder), which is a P-band demonstrator developed for ESA by the Technical University of Denmark [3][4]. POLARIS is a coherent system featuring aperture synthesis, pulse compression and, quite uniquely, full polarimetry.

2. OBJECTIVE

The objective is to analyze and interpret polarimetric POLARIS data from a Proof-of-Concept (PoC) campaign and an Additional Test Campaign (ATC) in Greenland. These data are interpreted in terms of a simple electromagnetic model accounting for both propagation and reflection processes. First results from the PoC campaign have already been presented [5], but the PoC campaign provided only shallow, dual co-polarized data from the ice divide, while the ATC data are fully polarimetric and acquired with overlapping shallow and deep windows.

In this extended abstract, the birefringence is estimated from the polarimetric radar data. In the full paper, the COF alignment will be estimated as well.

3. METHOD

The PoC data were acquired in May 2008 at the central ice divide of the Greenland ice sheet at 69°29'N 37°52'W. The ATC data were acquired in October 2009 at the NEEM ice core drilling site at 77.5°N 50.9°W, which is also at the ice divide. Both campaigns comprised flight tracks perpendicular and parallel to the ice divide. The H and V polarizations are defined to be parallel and perpendicular to the flight track, respectively.

The POLARIS data are analyzed in terms of the complex covariance matrix. The magnitudes of the matrix elements are a measure of the similarity of the polarimetric channels, and the phases depend on differences between the reflection coefficients as well as differences between the electrical two-way propagation path lengths. To account for these effects the complex signal received from an interface between two internal ice layers at a depth of z_0 is expressed as

$$s(z_0, \mathbf{p}) \propto R(z_0, \mathbf{p}) \cdot P(z_0, \mathbf{p}) \tag{1}$$

where $\mathbf{p}$ is the polarization vector, R the reflection factor and P the propagation factor

$$R(z_0, \mathbf{p}) = r^2(z_0, \mathbf{p}) \cdot G(z_0, \mathbf{p}) \tag{2}$$

$$P(z_0, \mathbf{p}) = \exp\left(\int_0^{z_0} -\alpha(z) dz \right) \exp\left(\int_0^{z_0} -j \frac{4\pi}{\lambda} n(z, \mathbf{p}) dz \right) \tag{3}$$

The reflection factor in turn is the product of the Fresnel reflection coefficient r^2 and a geometric term G, while the propagation factor is the product of an attenuation term and a propagation phase term proportional to the refractive index. In Eq. 3, the transmit and receive polarizations are assumed to be identical.

According to Eq. 3 the covariance between two channels with polarizations $\mathbf{p}_1$ and $\mathbf{p}_2$ has a two-way propagation phase contribution of

$$\varphi_p = \frac{4\pi}{\lambda} \int_0^{z_0} \left(n(z, \mathbf{p}_1) - n(z, \mathbf{p}_2) \right) dz \tag{4}$$

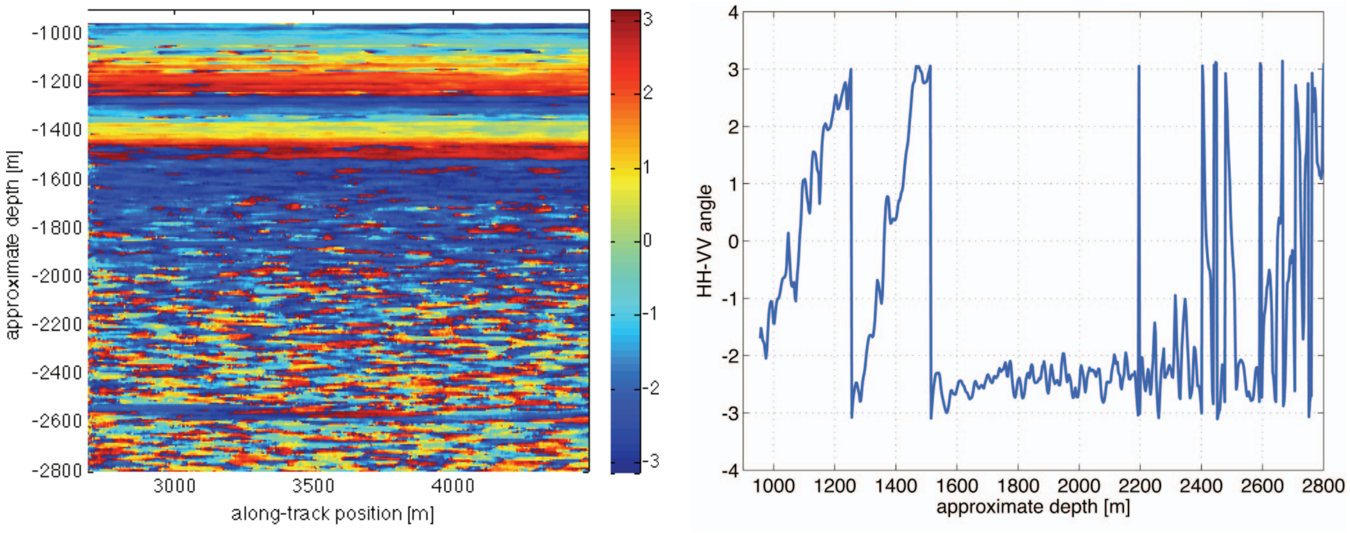
For an anisotropic media with a depth-independent refractive index n the propagation phase increases linearly with the depth of the reflecting layer z_0

$$\varphi_p = \frac{4\pi}{\lambda} \left(n(\mathbf{p}_1) - n(\mathbf{p}_2) \right) z_0 = \frac{4\pi \Delta n}{\lambda} z_0 \tag{5}$$

4. RESULTS

The HHVV covariance phase of the POC data from the southern test site has large excursions at depths between 500 and 900 m. The propagation phase term cannot change rapidly, as an unrealistically large difference between the refractive indices at HH and VV polarizations would be required for the phase to integrate up to a large change over a short depth interval, cf. Eq. 4. The phase excursions must be attributed *anisotropic reflections* (cf. Eq. 2) in combination with the fact that every resolution cell covers many internal layers (speckle).

The effect of birefringent *propagation* is seen in the POC data below a depth of some 900 m, where the phase basically changes monotonously with the depth. The same is seen in Figure 1a where the ATC deep sounding data from the NEEM site are shown. The bedrock is visible at a depth of about 2560 m. In Figure 1b the



(a) (b)

Figure 1 HH–VV phase difference at NEEM. The V polarization is parallel to the ice divide.

azimuthally averaged phase appears to increase approximately linearly, except for the phase wrap. The linear trend ends at a depth of about 1500 m, where the well-known echo-free zone (EFZ) begins (see Figure 2). It should be noted that the data acquired from the orthogonal flight track, where the V polarization is perpendicular to the ice divide, result in a similar but phase-reversed curve. This verifies that the results are due to physics, not a system artifact.

The permittivity of anisotropic polycrystalline ice can be expressed as [6]

$$\varepsilon' = \varepsilon_{\perp} + \Delta\varepsilon' D_a \tag{6}$$

where $\Delta\varepsilon' \approx 0.037$ is the dielectric anisotropy, i.e. the difference between the permittivity for polarization parallel to the c-axis and perpendicular to it. D_a expresses the degree of orientation of the crystals with respect to the electrical field vector, e.g. $D_a = 1$ for a fully oriented COF aligned with the field vector. If the c-axes of the ice crystals were randomly oriented in the vertical plane parallel to the ice divide, the difference between the refractive index at polarization parallel to the ice divide and the refractive index at the orthogonal polarization would be

$$\Delta n = \sqrt{\varepsilon_{\perp} + \Delta\varepsilon' D_a} - \sqrt{\varepsilon_{\perp}} \approx \frac{\Delta\varepsilon' D_a}{2n} \approx 0.01 D_a \tag{7}$$

The corresponding phase is found from Eq. 5

$$\varphi_p = \frac{0.04\pi D_a}{\lambda} z_0 \tag{8}$$

The measured phase slope is 0.021 rad/m corresponding to $D_a = 0.11$, which is within the expected range.

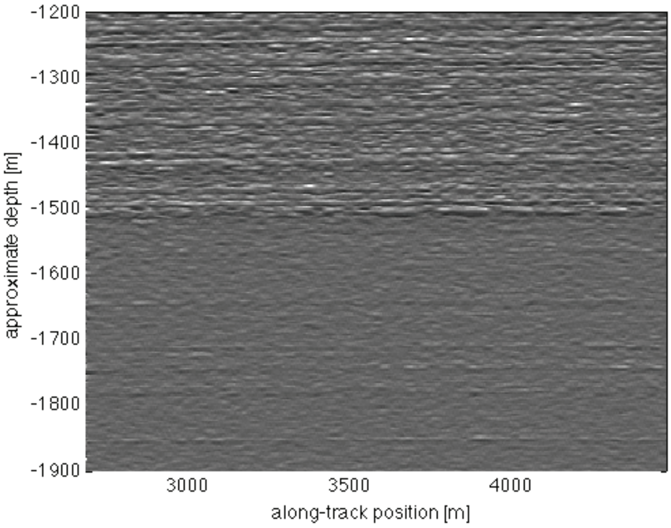


Figure 2 Internal layers at NEEM.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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