Review: Besson et al._Birefringence in South Pole ice

This paper discusses the lack of birefringence seen in broadband reflection traces recorded at South Pole Station. By "birefringence" is meant no anisotropy in the general or any local refractive index. The reflections originate englacially and were recorded using orthogonal polarizations. The matching of reflection events at the same time delays provides evidence for lack of birefringence, and the alignment of several reflections suggests there is no anisotropy within any individual layer. The findings have immense implications for the utility of deep radar soundings at much higher frequencies than presently used, are important to cosmologic research at South Pole where ice homogeneity has been assumed for the interpretation of Cerenkov radiation or RF showers, but hardly have any glaciological implications given the minimal information provided about the rest of East Antarctica. Consequently, glaciological implications stated in the abstract are almost pointless. Consistently, the lack of any statements regarding purpose, hypotheses and objectives within the Introduction reflect this wandering off course from electrical properties into ice sheet dynamics.

1. Birefringence

The data are well presented and I find the argument for lack of birefringence convincing. I find these arguments improved over previous efforts (cited in the text) where traces were integrated to show general differences in received power. The authors also show that there is a difference in polarization amplitude. I would find it more convincing if reflection profiles were recorded and compared so that more than only one point within the giant ice sheet could be examined to generalize their arguments and give significant glaciological implications for ice fabric. However, given the bandwidth of 200–1400 MHz, an one trace would require at least 32000 samples for quality reproduction, which is likely possible at CRESIS but not yet practical.

I would like to see better qualification on why "local horizontal ice flow….produces an azimuthal asymmetry in the horizontal plane," (p. 4698, line 12). The previous lines in this paragraph state that the main cause of birefringence is crystal orientation relative to the c-axis, and it is currently believed, with good documentation, that the c-axes cluster around vertical with depth. Are the authors suggesting that it is possible to have horizontal flow reorient c-axes?

2. Transmitted Pulse Shape

What pulse shape and bandwidth are not stated but should be. The VSWR plot in Fig. 1 shows that the horns were broadband but what exactly was transmitted? No practical pulse has such a bandwidth. Fig. 2 suggests it was a multi-cycle pulse centered near 200 MHz, while later figures suggest it might have been centered near 500 MHz. And, how sharp were the lo pass and hi pass filter cutoffs?

3. Electrical properties

The text suggests that the causes of the reflections are conductivity contrasts, which is the standard paradigm for HF (3–30 MHz) reflection profiles. If so then an approximate formula for the magnitude of the reflection coefficient, R, is

$$|R| = \Delta\sigma/\omega\varepsilon\varepsilon_0,$$

where $\Delta\sigma$ is the conductivity contrast, $\omega = 2\pi f$, $\varepsilon = 3.15$ and $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m (Arcone et al., 2009). I have assumed that $\Delta\sigma$ is on the order of 10^{-5} S/m because background ice sheet values are about 10^{-6} S/m, and because conductive sulfate anomalies, measured in ppb, appear to be about 10x higher (and likely, with no change in mobility) than background levels. At 1 GHz $|R| = -97$ dB and still a very large –77 dB at 100 MHz. Given other losses during propagation, balanced by the low noise of the environment, the two-way gain of the antennas and the system sensitivity, I suggest the authors consider whether such a low reflectivity (and from very smooth layers, of course) could be detected; if not then there are certainly complex dielectric properties at work, and, an immense amount of interface smoothing at depth. In any case, I know of no other soundings higher than 150 MHz. Radar profiles at 0.5–1.0 GHZ would greatly increase our understanding of ice sheet evolution. I think such a discussion of these implications belongs in the Conclusions.

4. Glaciology

Statements regarding the ice fabric and effects of flow (to cause anisotropy) should be eliminated, or at least relegated to minor statements in passing. For example, "the lack of observable birefringence *over the upper half of the ice sheet*," is a poor choice of wording because it implies generality throughout the region, as does the ensuing phrase, "a dramatic difference in *the character of the ice sheet in the intervening 1400 km*." Both previous measurements and this paper report only point measurements and so it is unfair to make such generalizations. The second example is, "an evident correlation with the local surface ice flow direction." You should at least say that it is the amplitude that correlates. More importantly, given no knowledge of the englacial conditions and from where the echoes originate, such statements should be omitted, at least from the Abstract.

The previous work cited by the Japanese and this work cover too limited an area to make generalizations. The presence of these generalizations led me to ask what the stated purpose of this paper is, but there is none.

5. Purpose

The paper needs one or two paragraphs at the end of the Introduction that state why the work was done, the objectives (to measure traces at various polarizations) and a brief summary of approach, all of which is standard science paper construction. It seems that the motivation was not to find changes in "ice fabric" but to test the inhomogeneity of the ice for ICE CUBE and other deep space projects. If glaciological dynamics was the motivation then this paper is far from adequate and would require thorough review of why "ice fabric" should change or not at South Pole and be any different than other deep ice in Antarctica.

In short, I think the paper should minimize discussion of glaciological implications, add discussion of purpose and objectives to the Introduction, and a discussion of deep sounding 0.5–1 GHz radar to both generalize their findings and enhance glaciological research.

Reference

Arcone, S. A., and Kreutz, K., 2009, GPR reflection profiles of Clark and Commonwealth Glaciers in the Dry Valleys, Antarctica, *Ann. Glaciol.*, **50**, 121–129.