Review of "Anisotropic Scattering in Radio-Echo Sounding: Insights from Northeast Greenland"

This manuscript presents new quad-polarized ground-based radio-echo sounding data from the Northeast Greenland Ice Stream. The authors synthesize the full polarimetric azimuthal radar response from the quad-pol data and then analyze how the azimuthal periodicity of the power difference between polarizations varies spatially and with depth. Their analysis demonstrates that anisotropic scattering is present at almost every depth below 630 m and that birefringence only dominates the polarimetric response near the surface. They also show that there is an abrupt shift in the orientation of the anisotropic scattering at the Holocene-Wisconsin ice boundary, suggesting that radar polarimetry may be a powerful tool for identifying ice from different climatic periods.

Overall, I think this is an excellent piece of work! The demonstration of the ground-based quad-pol radar data alone is very exciting, since this opens the door for applying polarimetric analyses of fabric over larger areas, compared to current approaches with ApRES. The implication that we may be able to identify ice units from different climatic periods based on their polarimetric response could be incredibly useful for placing broad age constraints on discontinuous ice units or in places where we do not have easy connections to dated ice cores. I think this paper will also be a key in forcing the community to acknowledge and account for the impacts of anisotropic scattering on estimates of COF anisotropy from birefringent effects. I have no major concerns with the technical aspects of the manuscript. Most of my comments are directed towards ways that the authors can streamline and clarify what is currently a very dense technical paper that can sometimes obscure its exciting core results with tangents in the narrative.

Major Comments:

[1] Since most of the conclusions are based around the idea that anisotropic scattering signatures will have 180-degree periodicity vs 90-degree periodicity for birefringence, it would be incredibly helpful to the reader to spend a few sentences describing why this is the case. I think I've convinced myself that it must be due to the integrated two-way path propagation effects for birefringence, but discussing these ideas explicitly would be great for readers who are not deep experts in radar measurements of fabric.

[2] Section 3.1 rederives a polarimetric scattering model from Fujita et al. (2006) to model the radar response to COF at EGRIP. In the end, this model does not seem to be central to the paper's major conclusions, especially since there are some significant differences between the modeled and measured polarimetric responses. To my reading, the model provides a very broad sanity check on the measured polarimetric response and is briefly used to justify the argument that COF variability drives the deep anisotropic scattering. Considering this, I think that the discussion of the model can be much more concise and probably just point readers to Fujita et al. (2006) model, which will lighten the mental load for readers.

[3] Almost a quarter of the paper (pages 6-12) is devoted to convincing the reader that the quad-pol synthesis can be trusted. I actually do not think that level of detail is necessary and bogs the reader down in a long technical discussion before they ever get to the main methods of the paper. The quad-pol synthesis method is firmly rooted in the governing equations of electromagnetics, has been demonstrated multiple times with quad-pol ApRES in our field, and is routinely used outside the field in other radar applications. If anything, the turning circle may be less reliable because it aggregates the polarimetric response over a series of radar footprints that do not fully overlap and may be subject to effects from layer slope, for example. Therefore, I think it is totally sufficient to just cite the quad-pol synthesis method and make this section as concise as possible. To me at least, the main value of the comparison with the turning circle is to demonstrate that the quad-pol instrument has sufficient radiometric calibration and phase synchronization across channels, a motivation which was surprisingly not mentioned in the paper.

[4] You might consider breaking out the discussion of the sinusoidal fit into its own section. This is the main analysis method that is used throughout the rest of the paper, so it would be very valuable to give it a clear emphasis rather than burying it at the end of the discussion on the quad-pol synthesis.

[5] Overall, I would encourage you to think carefully about the specific purpose(s) of presenting the turning circle-synthesis-model comparison and be explicit about this purpose at the beginning of the section. Then limit the technical details and discussion of the comparison to the most salient points that are needed to support that purpose.

[6] I found Figures S7-S13 really helpful for following the discussion of how anisotropic scattering vs. birefringence varied with depth. If at least one of those plots could be added to the main paper, I think that would be very valuable. For example, perhaps adding a fourth panel to Figure 6 (or Figure 7) with the amplitude of each sinusoid as a function of depth for each location a-j.

In-Line Comments:

Line 40 – since dual or quad-pol satellite SAR is also used in many glaciological applications and has a different viewing geometry, it would be good to specify something about radio-echo sounding here.

Line 58-60 – the mention of optical anisotropic scattering seems unnecessary since this entire paper is about radio frequency measurements.

Figure 2 – you might consider marking ice flow directions and adding labels for inside vs. outside the ice stream and the shear margins in this image, just to help the reader who otherwise has to flip back and forth with Figure 1 quite a bit.

Line 110-111 – I would recommend adding a few comments on the final horizontal resolution and trace spacing after processing, and perhaps why SAR focusing was not employed.

Figure 3 – the colors in panel a are hard to distinguish due to the black outlines, particularly the purple.

Line 196-197 – where does this reflection ratio come from and what justifies this choice?

In Figures 6-7, it would be fantastic to add markers in some way for the same isochrones which are shown in Figure 9. This would help the reader better visualize how changes in the azimuthal response with depth are related to stratigraphic units and age. It would also be very helpful to have some annotations showing the key features that a reader should take away from the dP_{HV} and ϕ_{HHVV} plots.

They only get 3-4 sentences in the discussion, and I found it a bit hard to track the key points that I should take away from these plots.

Figure 8 – I find the high frequency spatial variations in the apparent horizontal eigenvalue difference hear the eastern shear margin very notable. Do you have an idea of what might cause this? Is this “real” or an artifact of low signal to noise ratio and the vertical “streaking” that we commonly see in shear margin radargrams due to dipping layers and/or damage?

Lines 293-294 – how can we know that there is isotropic scattering if the region is “echo-free”? I would guess this just reflects the isotropy of thermal (e.g. white Gaussian) noise rather than something about the ice sheet?

Section 5.1.2 – I’m not entirely convinced by this discussion on the direction of folding vs. scattering. In the citations in this section (Bartalis et al., 2006 for example), anisotropic scattering occurs because the radar is side-looking and so in one orientation the folds act like corner reflectors (high backscatter) and in the other orientation they do not (low backscatter). It’s less clear to me how this would work for a nadir-looking radar sounder. My first thought is that you might have stronger co-polarized scattering parallel to the folding axis in the same way that backscatter from a half cylinder can (in some cases) be strongest when the wave polarization is aligned with the long axis of the cylinder, rather than perpendicular to it (see for example (Scanlan et al., 2022)). Anyway, this would further support your argument that roughness is likely not the cause of the anisotropic scattering you observe, but it is worth thinking through the mechanisms in this discussion in the context of radar sounders a bit more.

399 – is there any evidence for a COF-induced reflection at this transition (e.g. an englacial layer in the radiostratigraphy marking what appears to be a quite abrupt transition)?

Lines 407-415 – this is a very interesting and important piece of the discussion! I will admit I found it a bit hard to visualize how the COF would be changing with depth to achieve the anisotropic scattering, and I wonder if you might consider adding a conceptual diagram. Maybe some idealized Schmidt diagrams as a function of depth to explain how you envision the fabric changing?

Line 441 – I am not entirely following how the folding/overturning of stratigraphy would lead to this expression of anisotropic scattering – perhaps you can expound on this a bit? (Maybe this is something else that could be part of an idealized fabric as a function of depth sketch?)