Review of: Anisotropic scattering in radio-echo sounding: insights from Northeast Greenland
Submitted to: The Cryosphere
Reviewer: Nicholas Holschuh

General Comments:

I want to start my review by saying that the data and analyses in this paper are amazing. This would be one of the first published datasets capable of unambiguously identifying the role for physically (rather than chemically) controlled radar scattering at shallow depths in the ice sheet. The data show clearly that the physical properties of the glacier vary as a function of depth (/age) and location (/glaciological context) in ways that were surprising and informative. These data could change our understanding of microphysical processes playing out within the ice column, and change the way we use radar to understand the structure and dynamics of ice sheets. The fact that different layer packages exhibit qualitative differences in the polarization dependence of scattering means that radar might be capable of uniquely identifying packets of ice across Greenland and Antarctica ***even when they are discontinuous***. This could enable significantly improved estimates of the depth-age structure of ice sheets from radar data, and provide a valuable constraint for ice sheet models. The analysis was robust, and the figures present an incredible amount of data. Overall, I highly recommend this paper for publication.

However, even as someone who has thought deeply about the effects of ice-crystal anisotropy in measured radar backscatter, I found that reading the paper involved a very high cognitive load. At the sentence level, the writing is clear, but at the paragraph and section level, there are many places where the structure gets in the way of the narrative. In the technical and line-item comments below, I highlight places where I stumbled, was confused, or had questions, and provide some recommendations for how the authors might make the text more accessible.

In addition to those structural recommendations, I have one more significant criticism that I think should be addressed. In the main text of the manuscript, the authors fully redescribe the model derived by Fujita et al., (2006) for propagation and scattering, as well as the approach to full-azimuth synthesis from quad-polar data and the calculation of coherence phase from Ershadi et al. (2022). Even though the authors directly invite the reader to skip over that text, I think it goes against best-practices to fully restate the work of other authors and present it in this way. It discourages readers from going back to (and ultimately citing) the original works, and it introduces the possibility that errors might creep into the literature, as we play a game of academic "telephone" that has the potential to corrupt or misrepresent original ideas. As important as the ethical and practical implications of removing that text, I actually find much of the current text in section 3 of this manuscript distracting, as it takes quite a bit of thinking (even as an expert reader) to work through it despite the fact that the forward modeling of the EGRIP data contributes very little to the major conclusions of the paper. I recommend that the restatement of Fujita et al. and Ershadi et al.'s works be mostly removed from the text, and you refer the reader to the original manuscripts for the details.

With that change, I would strongly recommend this paper for publication. Very cool work!

Technical Comments:

Here I provide two high-level recommendations that I think might strengthen the work. To improve access to the key conclusions of the paper, I would (a) try to shorten your discussion of the forward model at EGRIP and (b) work to shorten and focus your paragraphs, especially later in the manuscript. I'll provide examples of why those changes might help below.

When I finished reading this paper, my primary takeaways were the following:

- Below 1000 m, anisotropic scattering induces larger variability in measured backscattering (as a function of polarization) than birefringence. Birefringence only plays a larger role in modifying measured back-scatter in the shear margin.
- While several mechanisms have been proposed for anisotropic scattering (including scattering from rough interfaces and elongate bubbles), small-scale variability in ice fabric is the mechanism most consistent with your observations.
- The nature of the anisotropy seems to vary systematically with ice age, and may be related to (and therefore indicative of) the climate conditions at the time of deposition.
- While cross-polarized extinction is related to the COF, path-effects make it difficult to use deep extinction nodes to determine the local fabric orientation. Anisotropic scattering does not suffer from that same limitation, and could be used to uniquely determine the fabric eigenvector directions through the full ice column.

I think these are the things you hoped I would get out of the paper, which is a testament to the current manuscript! But as a reviewer, I am required to be a patient reader, and I came into this paper with significant expertise – not all of your readers will be so patient. None of those conclusions (except maybe the role of fabric in driving anisotropic scattering) really rely on your forward model at EGRIP. And yet, pages 6-12 of the manuscript are devoted to its derivation and description, all of which is text that requires very deep understanding of anisotropy, wave-splitting, and polarization changes to fully process. That is a lot for the reader to have to get through before they arrive at the empirical analysis which is the primary basis for the conclusions of the paper. I think that section 3 could be made much shorter -- once you've motivated the fact that anisotropic scattering and birefringence have different periodicity and that it is possible to synthesize the full azimuthal response using quad-pol data, you could (in theory) present figure 6 and figure 9, which (in my view) are the basis for most of the conclusions of the paper. You really want your reader to get to the content currently on pages 15-18, and I'm not sure every reader will make it through the earlier sections as currently drafted.

Throughout the document, ideas that might be interesting to a broad glaciological audience are intermingled in paragraphs with quite technical radioglaciology. I appreciate how thorough the technical descriptions are; that text is useful for someone like me who might want to build on your analysis. But I think the document could be more approachable if you clearly separate technical details from broader takeaways, and help the reader understand why you've presented the technical details you have. For example, the first paragraph of the introduction describes the goal of the paper but also lists four survey design strategies. These survey design details are probably of low interest to a non-radioglaciology audience, and coming so early in the paper, they are not clearly situated in the broader narrative. Why

should the reader care about these different survey types, especially at this point in the work? If you were to move lines 23-32 to their own paragraph later in the introduction (for example, following the paragraph ending at line 67), you motivate why the reader should care much more clearly. Then your introduction would be: (P1) Polarimetric radar tells us about the ice sheet structure, (P2) the signal is affected by birefringence (P3) and anisotropic scattering, (P4) there are several ways to collect the data, and (P5) this is what past studies have shown.

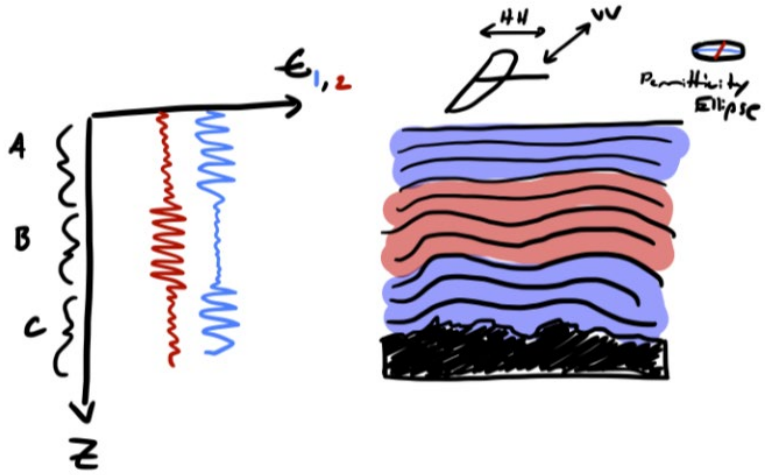
This is just one example of how slight structural changes might reduce the intellectual burden on the reader. In the line-item comments, I provide examples of other places where I think you can simplify your structure like this to make the document a bit more accessible. But independent of my specific recommendations, I would encourage you to read through the document with the goal of shortening and focusing paragraphs, pulling the more important takeaways out of deep discussions of technical detail.

Line-Item Corrections:

Page #: 1 Line #: 3-8	Something to consider -- I think these three sentences (starting "Although both…") can be made more succinct and combined into one, which gets the reader to your results more quickly.
Page #: 2 Line #: 23-32	As I mentioned in the technical comments, I think it makes more sense to pull these sentences out of your first paragraph (which is meant to provide the highest level introduction and motivation) and move them to after line 67. That first paragraph could naturally end with the sentences spanning 32-34, and I think it will improve the flow of the introduction.
Page #: 3 Line #: 56	I think "affecting the overall return power" is a slightly confusing addition to this sentence. It is clearer if it reads "Volume scattering is caused by small-scale inhomogeneities in the physical properties of the glacier, such as air bubbles, dust particles, or impurities."
Page #: 3 Line #: 58	The phrase "also observed in the optical range" assumes that the reader knows that you've been thinking about scattering in the microwave range up to this point, which isn't explicitly stated (at least in this paragraph). Might be useful to rephrase to something like "Anisotopric volume scattering is significant in the optical range..." or something like that, and then make clear in the next sentence that you are talking about RES data: "Surface scattering of radio waves occurs..."
Page #: 3 Line #: 69-72	These two sentences present another example of content that feels unrelated to the larger paragraph, and belongs somewhere else in the paper. If I were to summarize the purpose of this paragraph, it is to introduce the limitations of previous radar approaches to estimating ice fabric. But the sentences stating "The COF type" and "In-situ measurements" don't contribute to this idea at all. Without realizing it, these seeingly minor narrative culs-de-sac really increase the difficulty in reading and understanding a work, so minimizing them really helps me as a reader.

Page #: 4 Line #: 98-124	Section 2 is great. Succinct and clear!
Page #: 6 Line #: 132	For the reasons I described in the general comments, I think lines 132-184 and 199-207 should be removed in favor of a clear set of references to the original equations in Fujita et al., 2000, 2006, and Ershadi et al., 2022. I think you want to use this space to emphasize to the reader why, exactly, you did this analysis, and be as brief as possible. Something like "Here we show that synthesis from quadpol data faithfully reproduces the results of the turning circle, and both datasets capture the primary features we would expect based on forward-modeling the radio-wave propagation problem using direct fabric measurements collected from the EGRIP core." Much of the rest of the description of the forward model results (lines 215-237) doesn't feel clearly situated in the narrative. The reader doesn't know yet why they should care about any of the things you observe. I would cut them or move them to later in the document when they become relevant for interpreting the sources of scattering.
Page #: 9 Line #: 181	While I think this section should be cut entirely, if you keep this text, this sentence is missing a concluding clause.
Page #: 14 Line #: 261-264	Why do you estimate the eigenvalue difference from travel-time differences rather than integrated phase difference from your synthesized coherence phase, using the orientation where you know you are aligned with the COF? That would let you account for lack of alignment of your driving direction and the COF. It would at least be interesting to compare those results.
Page #: 15 Line #: Fig 8	You don't present any of the radargrams crossing the eastern shear margin, but there seems to be a lot of variability in the eigenvalue differences presented (I assume, associated with the folding there?). It would be worth interpreting for the reader those signals, because they appear really coherent across the flow-perpendicular lines. Is it that the system has limited capacity to capture the folding because of its narrow beam pattern, and so those are artifacts? I didn't see any mention of focusing in your processing steps either -- how might that affect interpratation of those signals? I can't tell if I should think of them as interesting signal or artifactual in nature, a result of the limitations of the system, and it would be nice to clarify that somewhere for the reader.
Page #: 15 Line #: Fig 8	I'm also interested in that really intense eigenvalue difference found between A-2 and A-3 at the southern end of your survey. Is that real? That looks like (in Figure 9) a region where there is very low signal.
Page #: 16 Line #: 271-272	How should I think about "flow parallel" vs. "flow perpendicular" when thinking about anisotropic scattering? Is it fair to just thinkg about it as "the principle fabric axes are shifted 15 degrees clockwise(?) from the modern flow field"? I spent a long

	time trying to figure out if I should care that it is perpendicular rather than parallel, and I realized I wasn't exactly sure what that distinction meant.
Page #: 16 Line #: 293-294	I find this phrasing a bit confusing -- without echoes, how do you know it is isotropic? A bit more detail on your thinking here would be helpful.
Page #: 17 Line #: Fig 9	I think it would be helpful for the reader if you highlight and describe those features due to birefringence seen from 50-100 km in the shallow part of Profile A and from 20-40 in the shallow part of Profile B. I think those signals are really interesting and represent what most folks had been looking for in co-polarized data up to this point, so it is useful to highlight and describe them here.
Page #: 18 Line #: Section 5.1	This section justifies one of the major conclusions of the paper, but sections 5.1.1/2/3 would benefit from a slight reorganization and additional paragraph breaks. Right now, these sections have paragraphs with 10-15 sentences which tend to wander back and forth between ideas. The cleaner the structure you can provide for the reader, the better. I was going to suggest some specific paragraph breaks, but I think sentences need to get moved around in a way that makes the ideas more clearly separable before you subdivide.
Page #: 19 Line #: 360-361	Can you substantiate this statement with a bit more detail? I found this statement counterintuitive, and was having trouble understanding why the opposite wouldn't be true.
Page #: 20 Line #: 389-390	These two sentences both start with "additionally". I would restructure this paragraph in general (noting my comment on section 5.1), but try to avoid that kind of repitition.
Page #: 21 Line #: 407-415	This paragraph is really important context for the reader to have, and because it is not a discovery of this paper, I think it should come much earlier in the paper. It might be most appropriate when you introduce the forward model and the 90/180 degree periodicity. Highlighting that the two methods for azimuthal variability have distinct implications for fabric before the reader spends a long time obeserving the differences in fabric would be very helpful.
Page #: 21 Line #: 416-417	Again, I find this phrasing odd -- "echo free zone characterized by … scattering". What exactly do you mean here?

Page #: 22 Line #: 439-444	I'm not sure the conclusion you're drawing here (that because the Eemian ice at NEEM was overturned the signal in the polarimetric data here indicates local ice is overturned) is correct. My mental model of how you get changes in sign of the HH-VV power difference is the following:  When you have greater variability in the permittivity associated with one polarization than another, you have greater scattering, and therefore a higher power. But imagine you took a section of B and inverted it. You wouldn't then produce a change in the sign of the HH-VV difference; that would actually require a 90 degree rotation of ice in B. Is that consistent with your mental model, or am I missing something? I would say either explain in more detail how inversion would manifest in anisotropic scattering or remove this section here (and the reference to it in the abstract).
Page #: 23 Line #: 481	"proved" rather than "proofed"
Page #: 23 Line #: 489	At present, you don't fully explain why this is the case for the shear margin – do you think it is because the fabric variability is orientation independent and therefore anisotropy in scattering is weak, or because the effects of birefringence are particularly strong? A bit more discussion of this somehwere in text would be helpful.

As a reminder – I really enjoyed this paper. I think it is a really valuable contribution and want to see it have as much impact as it deserves!

---- Nick