Authors point-to-point response on Referee Comment #2 to tc-2022-200

Please find our answers below the original comments from the Reviewer.

Review of Zeising et al., TC, 2022

The authors introduce a method for inferring the bulk horizontal anisotropy of glacier ice fabrics with depth from travel-time differences between radar waves with orthogonal polarizations. The time-lagged cross-correlation method between the two waves represents an improvement over previous methods, which are discussed, and the case-study comparison with the (existing) EGRIP ice-core fabric profile is very convincing.

The structure and figures of the manuscript is/are well chosen, and I believe the advancements made will be received with great interest in the glaciological community.
In the end I have only minor comments in addition to the major issues #1 and #2 already raised by reviewer T. Jordan, which you may consider as you prepare the final manuscript.

Kind regards,
Nicholas Rathmann,
Niels Bohr Institute, UCPH, Denmark

Minor comments:

L1: I think it should be “ice c-axis fabric” (might be wrong).

> We think both ways are fine and we decided to keep “c-axes” as we are talking about the sum of all samples.

L13: I would suggest “deformation history that can influence”.

> Thanks, we will add this in the revised version.

L14: I would delete the comma after “magnitude”.

> Done.

L17: I would replace “obstructed” with “challenged”.

> Thanks, we will do so.

L21: I would add a comma after “Antarctica”.

> We will add a comma.

L23: Maybe mention again here that “[...] for improving ice-flow models and determining past flow/deformation”.

> Thanks, we will change this sentence accordingly.

L24-25: I would suggest rephrasing this slightly to something along:
“This means that ice crystals are dielectrically anisotropic, in addition to being mechanically anisotropic, and thus allow the horizontal fabric asymmetry to be determined from radar surveys […]”.

> Thanks for your suggestion. Also Referee #1 suggested a reformulation. We will change the sentence follows:

"This means that ice crystals are dielectrically anisotropic due to crystal anisotropy and thus allow the horizontal fabric asymmetry to be determined from polarimetric radar surveys […]."

L28: I would replace "achieve" with "conduct", and "good" with "greater".

Thanks. We will change both words in the revised version.

L36: I would delete "severely".

Done.

L54: I would suggest "ice fabric from polarimetric measurements".

We will change this sentence as suggested.

L60: More specifically I suppose you mean Fig. 1c.

Yes, thanks.

L71: Not exactly clear what this means. Maybe consider reformulating this sentence?

Thanks. We will rewrite this sentence as follows:

"Every 5–15 m of depth of the ice core a 55 cm long section was analysed for fabric data."

L73: Would replace "c-axis" with "samples c-axes", and "by a second order" with "by the second-order".

Thanks. We will change the sentence as follows:

"The grain size weighted orientation of the measured c-axes can be represented by the second-order orientation tensor."

L75: Would replace "correspond to the length of the three principal axes" with "quantifies the strength of the three principal fabric (c-axis) directions". Would also replace "derive" with "determine".

Done. Thanks!

Eqn. 2, 4, 6, 7, 8, 10, Fig. 3, and other in-text occurrences: While I appreciate the notational rigor, I think you could benefit (readability-wise) from dropping the x'y' subscripts in \delta t, \delta \epsilon, and \delta \lambda (since you are only considering horizontal anomalies in this work anyway). Your single-crystal dielectric anisotropy could then be \Delta \epsilon_c (or some other subscript).

We would prefer to keep the subscripts to avoid misunderstanding. Especially, \Delta \epsilon is something different than \Delta \epsilon_xy.

L85: Would replace "of the corresponding" with "in the corresponding".

Done.

Eqn. 5 and 6: I think you need to unfold this a bit more for the reader. How do these equations come about?

We added new equations (eq. 2+3 in revised version)

$$\overline{v}_{x'}(z) = \frac{c_0}{\sqrt{\overline{\varepsilon}_{x'}(z)}} = \frac{2z}{t_{x'}(z)},$$

$$\overline{v}_{y'}(z) = \frac{c_0}{\sqrt{\overline{\varepsilon}_{y'}(z)}} = \frac{2z}{t_{y'}(z)}$$

as the basic equations to introduce the eqs. 3+4 (previous version; 5+6 revised version) and additionally, we explaining the transition to eqs. 5+6 (previous version; 5+6 revised version):

"These dielectric permittivities are the average values over the entire depth from the surface to the depth z. In order to calculate the vertical profile of the horizontal dielectric anisotropy Δε_x'y' = ε_y' – ε_x', the local change in two-way travel time δt_x' , δt_y' for a given infinitesimal depth window δz, needs to be taken into account: […]"

L90: "bulk" horizontal anisotropy.

Done.

Eqn. 7: Maybe note that this assumes wave lengths much longer than the average grain size.

Done.

Also, for context, I think it is worth mentioning (possibly elsewhere) that the eigenvalues represent only the strength of the coarsest degree of fabric anisotropy, and that finer fabric structure may exist although it cannot necessarily be detected with polarimetric radar (e.g. Hargreaves, 1978, or Rathmann et al., 2022).

In the introduction, we already mentioned that there are limitations and cited Rathmann et al. (2022). Thus, we think that it is not necessary to mention this more explicitly.

L94: Do you mean to say this value applies for radar frequencies similar to those used by you? It can differ quite a bit (Fujita et al., 2000).

It is true that the dielectric anisotropy for a single crystal can differ from 0.034 depending on the frequency and the temperature. However, Matsuoka et al., 1997 found the same dielectric anisotropy for 1 MHz as well as for 39 GHz. Also all recent studies that analysed polarimetric pRES measurements used a dielectric anisotropy of 0.034.

L100: Would add commas around "and advantage of".

Done.

L100-101:I am not entirely sure how to understand this. I would suggest you to rephrase it a bit.

We will simplify this sentence by removing "difference to and". So the new sentence will be:

"This is the main advantage of the in-depth analysis of the phase which is why polarimetric pRES measurements offer the chance to investigate the horizontal fabric asymmetry in the ice."

L104-105: Please define what s_ij is already here for the reader less familiar with the radio-glaciological nomenclature.

We will add the following explanation:

"(subscripts indicate the transmitted and received polarisation)"

Eqn. 9: I find the summation limits a bit confusing. Normally, summation variables are indices (e.g. j=1,2,3, ...), but you seem to mix it with the (discrete) depth variable, e.g. the upper limit z_n + N is adding two quantities with different units?

The summation variable is actually an indices: z_n is the range bin index of the beginning of the segment. Thus, z_n has no dimension. The segment itself consists of N values. Thus, the summation limit is z_n+N.

For more clearness, we will change z_n to i_n in the revised version.

L128: Would replace "we adopted" with "we changed".

Done.

L149: Would it be more accurate to replace "vertical distribution" with "vertical profile"?

Yes, we will do so. Thanks!

L150: What uncertainty, precisely?

Here, we actually meant the scatter of Delta t_xy due to the uncertainty. We will correct this:

"Despite the high range resolution, the scatter of $\Delta t_{x'y'}$ caused by the uncertainty prevented a determination of the small-scale gradient of the travel-time difference."

L161: Would delete "the" before "previous methods".

Done.

L169: Would delete "the" before "previous coherence method".

Done.

L179: Do you mean to say that the inverse method cannot handle such cases of rotation?

Yes. We will reformulate this as follows to make it clearer:

"However, the ice fabric orientation in this area rotates several times at different depths of the ice column, which prevents the application of the previous method using the inverse approach."

L180: Would re-phrase this more carefully as e.g. "[...] was unsuccessful and is another reason why we regard our method as an improvement […]".

Thanks! We will follow your suggestion.

L186: “at much greater depth”.

Thanks, we will change this accordingly.

L194: As this stands, I’m not sure it is sufficiently clear why this is the case. Maybe you could elaborate slightly.

We reformulated this part as follows:

“Such an application, which would yield the variation of the horizontal anisotropy along flow lines or across regions of fast flow, like ice streams, would significantly improve the understanding of the link between the stress state and crystal fabric evolution. This would allow us to decrease uncertainties of rheology, and thus improve estimates for response times of dynamically active glacial systems to external perturbations, e.g. from changing ocean conditions of tidewater glaciers.”