Authors point-to-point response on Referee Comment #1 to tc-2022-200

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

Review to Zeising et al. 2022, The Cryosphere

Summary
Zeising et al. present a technical development using phase-sensitive radar polarimetry to estimate ice crystal orientation fabric near the EastGRIP ice core. The key point of novelty is to enhance the polarimetric coherence (a method used by previous radar polarimetry studies) by adjusting the range- bin offset between orthogonal polarizations. This allows them to obtain high coherence throughout the ice column, which is then used to infer two-way travel time differences, dielectric anisotropy, and azimuthal fabric anisotropy. They then compare with the ice core fabric eigenvalue differences, showing very good agreement down to ice depths ~ 1500 m.

I like the general concept, and enjoyed reading the paper. Whilst the coherence optimization/ range-bin offset method is a relatively simple refinement from previous studies, it produces agreement between ice-core fabric data and the radar asymmetry estimates (probably the best I have seen to date). However, as it stands, I think the paper needs to better demonstrate how it has improved coherence and fabric estimation from methods used in previous studies. Additionally, fabric orientation information should be provided (both from the radar, and comparison with the ice core if it is available) as other similar radar polarimetry studies have all done this. I also do not agree with the physical interpretation related to the `half-wavelength limit' (regarding why previous applications of polarimetric coherence will be ineffective) and have given some counter arguments and suggestions to rephrase the discussion.

At < 200 lines and 3 figures the study is significantly shorter than a typical TC article, and closer to what I would expect for a `TC brief communication'. I see no issue with this, but potentially the editorial team and authors will want to change the format for the final publication.

Best regards,
Tom Jordan, Plymouth Marine Laboratory, UK

Specific/major comments

1. *Demonstration of improved coherence and fabric estimates over previous methods.*

A central weakness of the study is that it does not explicitly demonstrate the improvement of the coherence magnitude and fabric estimates over previous methods. A reader less familiar with the field will therefore be uncertain about the progress made in the paper.
I think this can be fixed relatively easily by showing:

(i) A depth profile for |chvv| calculated *without* the range-bin offset, similar to the second column in Fig 2. My guess is that this will decay rapidly with depth, showing the coherence method in the paper to be more effective than previous.
(ii) Adding fabric asymmetry estimates, where possible, using the previous approach: i.e. using vertical gradient of the co-polarized phase difference (no offset) employed by Dall 2010, Jordan et al. 2019, 2021, 2022, Young et al. 2021.

Related to this point, I would put a qualifying statement that the study can only be directly compared with methods that have used multi-polarized data (e.g. Jordan et al. 2019, 2020) rather than quad-pol approaches (e.g. Brisbourne et al. 2019, Young et al. 2021, Ershadi et al. 2021, Jordan et al. 2022). A consequence of using quad-pol is that it enables reconstruction of multi-polarization data at higher angular resolution, which gives a particular advantage to inferring fabric orientation.

Thanks for raising this point. We are happy to demonstrate the improvement of the polarimetric cross-correlation approach over the previous coherence method. The updated figure 3 in the manuscript (figure 1 below) shows in panel (a) the result of the improved method in comparison with the previous coherence approach by using the code from Young et al. (2021).

The previous approach from Young et al., 2021 which is using the vertical gradient of the co-polarised phase difference, shows a similar vertical profile of the fabric asymmetry between 100 and within the upper 260 m. Below, the asymmetry drops and stays close to zero to a depth of 1000 m. Thus, the new cross-correlation approach is able to retrieve the fabric asymmetry over 5 times larger depth.

This comparison demonstrates the significant improvement over the previous methods in case of a strong fabric asymmetry as it is the case at the EastGRIP drill site.

We decided not to show the depth profile obtained from the new method but without the range-bin offset. In theory, it would be possible to follow the same phase-shift minimum to a depth of 250 m, but the 200 m-window over which the slope is calculated, prevents reliable results between 150 - 250 m.

We agree that one advantage of quad-pol data is to infer the fabric orientation from synthesising the data set. We will make this point clear in the manuscript.

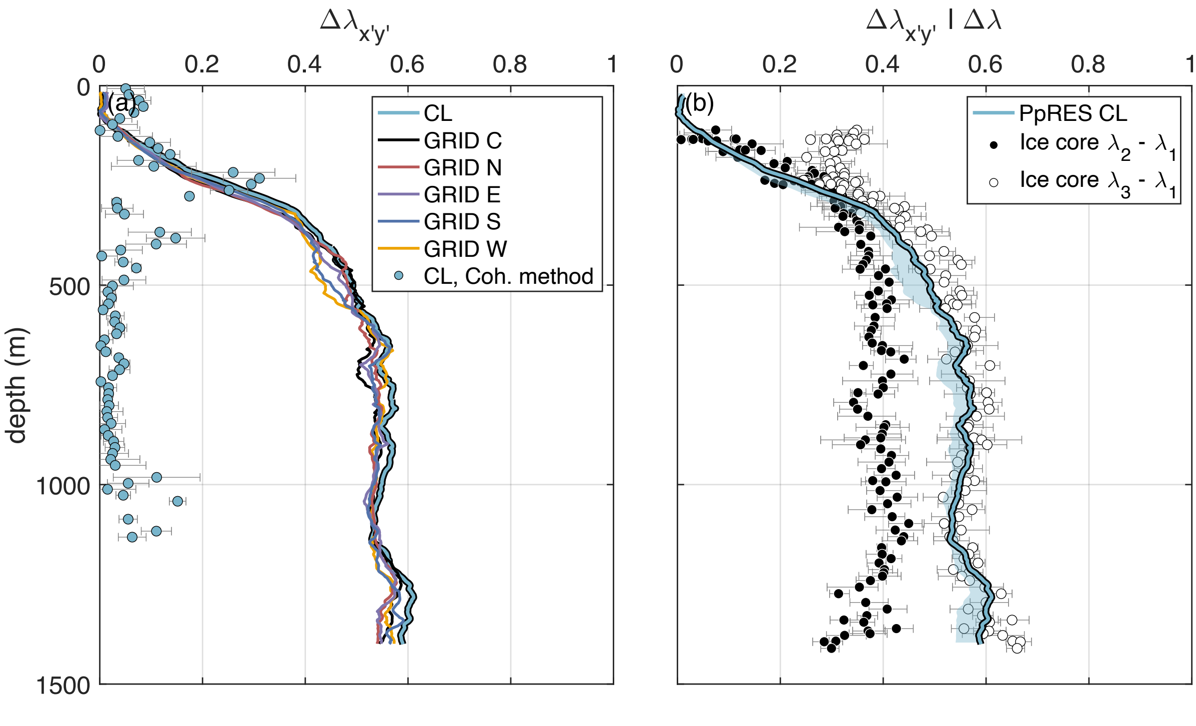

Figure 1: Comparison of horizontal fabric asymmetry determined from different measurements and analysing methods. (a) Fabric asymmetry determined from cross-correlation analysis (lines) of pRES measurements at CL (light blue line) and at the 20×20 m GRID outside drill site as well as from the previous coherence method (Young and Dawson, 2021) at CL (light blue dots). (b) Fabric asymmetry determined from cross-correlation analysis (lines) of pRES measurements at CL (light blue line) and from weighted horizontal eigenvalues from EastGRIP ice core (black and white dots). The blue shaded area in (b) marks the range of the polarimetric pRES-derived asymmetry from the measurements in the GRID and at CL.

2. Fabric orientation information.

In addition to azimuthal asymmetry, polarimetric radar enables estimation of the orientation of (assumed) horizontal eigenvectors. This can be done by comparing data with the polarimetric backscatter model (Fujita 2006, Jordan et al. 2019) and using sign of the coherence phase gradient (Dall 2010). Fabric orientation is very useful information, as it informs about past deformation, aswell as being key information for understanding the impact of fabric on anisotropic rheology.
I therefore find the current study incomplete, and I think it would be significantly strengthened, by including fabric orientation panels in Fig 3 (i.e. azimuthal angle of horizontal eigenvectors as a function of ice depth). I appreciate that the angular resolution will be limited as multi-polarization rather than quad-pol was used, but I still think this will be a nice inclusion.
Additionally, does the EastGRIP core have azimuthal fabric orientation to compare with? If it does, then this should be included in the orientation plots.

> The presented study aimed to describe a new method that significantly improves the determination of the fabric asymmetry from polarimetric radar measurements. Here, we used a data set from the EastGRIP drill site as an example, as it is the first deep ice core with analysed fabric eigenvalues that was drilled into an ice stream. We fully understand the demand of the fabric orientation at the EastGRIP drill site. However, we would like to address this in an additional manuscript in which we will analyse the spatial variability of the ice fabric (strength of the asymmetry and the orientation) in the NEGIS-region around EastGRIP.

3. Accuracy of the discussion on the `half-wavelength limit'

In their discussion, the authors focus on the `half-wavelength limit' (for the polarimetric phase difference) as an explanation why the polarimetric coherence method has previously been limited. e.g. `Due to the ambiguities caused by phase wrapping, the previous methods which are based on the coherence phase gradient were limited to the derivation of phase shifts of a maximum of half a wavelength, (Line 61)'. I don't agree with this interpretation, and I have given some counter arguments and suggestions for revision below.

First, I don't think previous methods based on phase gradient are limited by the phase wrapping. Jordan et al. 2019 used an identity (equation 23) to differentiate the phase. This approach (adapted from the InSAR literature) gets around the issue of phase wrapping, as the real and imaginary components of the coherence are continuous functions, enabling the derivative to be taken. Figure 5 and 6 from this paper illustrates that the phase gradient can be obtained at the phase discontinuities.

There are other examples in the literature that illustrate that the coherence magnitude, phase difference, and fabric estimates are not physically limited by the phase discontinuities and the proposed `half-wavelength limit'. Notably, Young et al. 2021 (Fig. 4) shows high coherence persisting over multiple (~4) phase cycles.

It therefore follows that `strong azimuthal asymmetry' (and rapid phase-cycling) should not be a singular limitation on the previous method. I think it is probably coincidence that the fabric in Jordan et al. 2022 is often only obtained in the first phase cycle (line 171). This study proposed a degradation in the radar stratigraphy as the reason for the coherence drop-off with depth. Despite discounting the `half-wavelength limit' interpretation, I do agree with the authors that their optimization should lead to higher coherence, and therefore improve the fabric estimates. This is because their method should act to better co-register the signal from a given radar layer. I think, if they better show the impact of the optimization on the coherence (following my comment 1), then they will be able to refocus the discussion around improved co-registration being the physical mechanism that improves the coherence and fabric estimates. (As an aside, I don't think it is strictly necessary for the reflection to occur from the same layer for each polarization. As long as the layers behave as flat, specular, reflectors, the original coherence method should still work to some degree).

As well as the discussion, lines 35-38 and line 186, will also need addressing regarding this point.

Thanks for raising this point. We tried to understand the raised arguments and we agree that it can be possible to analyse the phase gradient from the polarimetric phase difference that exceeds half a wavelength in some cases. However, we argue that this is not possible in general and all cases.

The strong fabric asymmetry at EastGRIP causes a rapid phase-cycling and a reduction in coherence after a few hundred meters. Already the third phase cycle shows a different phase gradient and low coherence. We attribute this to the fact that, due to the difference in propagation velocity, the correlated segments do not overlap sufficiently. We see this as the main limitation of the coherence method for strongly developed asymmetries that we can overcome with the co-registration by the cross-correlation.

In the revised version of this manuscript, we will rewrite this part of the discussion.

However, we prefer to keep the sentences on lines 35-38 and 186 (previous version) as we consider them correct. We are aware that Jordan et al. 2022 proposed that a degradation in the radar stratigraphy is the reason for the reduced coherence. However, the application of the polarimetric cross-correlation method to their measurements showed that this limit can be overcome, which speaks against this explanation.

The new part of the discussion will be:

"The previously used coherence method estimates the fabric asymmetry by determining the phase gradient of the polarimetric phase difference. This is also possible for high coherence persisting over a few phase cycles (e.g., Young et al., 2021a). However, in case of a strongly developed fabric asymmetry and thus a rapid phase-cycling, the coherence is reduced over depth because the segments that are correlated do not completely overlap and therefore contain different scatterers (Leinss et al., 2016). At ice divides or domes with very little asymmetry, such as at NEEM (Jordan et al., 2019), WAIS divide (Young et al., 2021a) or EDC (Ershadi et al., 2022), the fabric asymmetry could successfully be determined using previous coherence method up to the onset of noise. However, in fast moving areas like the Rutford Ice Stream, Antarctica (Jordan et al., 2022) or NEGIS, Greenland (this study) rapid phase-cycling limits the application of the previous coherence method to a few hundred meters below the surface. With the improved polarimetric cross-correlation method, we overcome this limitation through co-registration, which allows to determine even strong horizontal fabric asymmetries to a much greater depth."

Minor comments/typos

Title - The MS title is quite generic (in effect all COF/radar polarimetry studies estimate horizontal asymmetry!). As the phase co-registration/optimization of the coherence is the key point of novelty, I recommended changing to something like: \`*Improved estimation of ice COF from polarimetric phase co- registration'* or \`*Improved estimation of ice COF from optimization of the polarimetric coherence'*

We are grateful for your title suggestions and will change the title to:

"*Improved estimation of the bulk ice crystal fabric asymmetry from polarimetric phase co-registration"*

L 4, L 25, etc – I would use the term \`polarimetric radar' rather than \`radar'.

Thanks, we will add "polarimetric" to be more precise.

L 16 – is a new paragraph needed?

We will remove the line break.

L 25 – Maybe `dielectric anisotropy due to crystal anisotropy'?

Thanks! We will change this sentence accordingly.

L 34 – A better description of what is meant by the `polarimetric coherence method' is needed here (something like: polarimetric coherence refers to the strength of the phase correlation between orthogonal polarizations)

Thanks, we will implement such a description in the revised version.

L 35 – I have different interpretation of when the polarimetric coherence method will/will not work – see specific comments.

Please see our answer to the specific/major comment.

L 53 – should `accuracy ~ 1 mm ' be `precision ~ 1mm'?

Yes, thanks. Will will change this in the revised version.

L 56 onwards - I would be clearer from the offset that this study is considering muti-polarization data (i.e. co-polarized data as a function of azimuth), whereas most studies are now using quad-polarized data (also see specific comment 1).

We will make clear that this study uses co-polarised measurements and add the following sentences in the data acquisition section:

"Recent studies used quad-polarised acquisitions which additionally include hv and vh measurements, where the polarisation direction of the transmitting and receiving antenna is rotated by 90° (e.g. Brisbourne et al., 2019; Young et al., 2021a; Ershadi et al., 2022; Jordan et al., 2022). However, this study focuses on co-polarised measurements."

In the discussion section, we will also mention the advantages of quad-polarised measurements explicitly (please see comment further below).

L 71 – Does the EastGRIP core contain azimuthal orientation and tilt measurements/zenith angle for the fabric eigenvectors? (Also see specific comment 2).

Not yet. Deriving the eigenvectors is work in progress and will be published in a dedicated study on the crystal orientation within the EastGRIP ice core.

L 91 - I would replace `According to Fujita 2006 and Jordan 2019...' with `If it is assumed that the ice crystals are an effective medium at IPR frequencies…'

Thanks, we will change this sentence accordingly.

L 125 – I think a bit more context on the `fine-scale' ranging capabilities of ApRES is needed here. E.g. what is the physical interpretation of the l/Bp term in equation (10)?

Thanks. We will add an additional description like:

"The first term on the right side is the coarse time-bin offset with 1/Bp being the time-bin spacing (B = 200 MHz is the bandwidth and p = 8 is a 'padding factor' that reduces the range-bin spacing). The second term is the fine offset derived from the coherent phase of the centre frequency of f_c = 300 MHz."

L 136 – I would quote the difference with the core data after this sentence

Done.

L158 – The use of quad-polarized data was proposed a long time before Ershadi et al. 2021. Notably, the work of Doake et al. 2003: https://folk.uib.no/ngfso/FRISP/Rep14/doake.pdf. Quad-polarized acquisition has the key advantage of reconstructing co-polarized data at a high angular resolution. I therefore think that combining the authors' co-registration method with the quad-pol method (e.g. Brisbourne et al. 2019, Young et al. 2021, Ershadi et al. 2021, Jordan et al. 2022), will be what people will do in the future, so I recommend writing a paragraph along these lines.

> We agree that a quad-polarised acquisition has a clear advantage against co-polarised measurements at different azimuthal angles. We have tested the application of the new cross-correlation method to reconstructed co-polarised data from quad-polarised measurements and came to the same vertical profile of the fabric asymmetry.
>
> We will add the following paragraph to the discussion:
>
> *"However, a clear advantage of quad-polarised measurements is that they allow to reconstruct co-polarised data at a high angular resolution and additionally the determination of the fabric orientation (e.g. Brisbourne et al., 2019; Young et al., 2021a; Ershadi et al., 2022; Jordan et al., 2022). The presented cross-correlation method can also be applied to these reconstructed co-polarised data. Since only four measurements (hh, vv, hv and vh) at one azimuthal angle are necessary to perform a quad-polarised acquisition, but eight for co-polarised measurement (hh and vv) at four different azimuthal angles (0°, 22.5°, 45° and 67.5°), quad-polarised measurements should be preferred in the future"*

L176 onwards – As noted in specific comment 1, I think the comparison with Ershadi/other previous methods needs to be explicitly demonstrated to the reader.

> We are happy to compare the results of the previous methods to show the improvement of the new method. As mentioned above, we will do that on the example of the code from Young et al., 2021.