Response to reviewer comments: "Downhole distributed acoustic seismic profiling at Skytrain Ice Rise, West Antarctica" by Alex M. Brisbourne et al., The Cryosphere Discuss., TC-2021-1"

We thank the editor and reviewers for their constructive and valuable comments on the manuscript. We address the comments below with our responses highlighted in red.

Both reviewers commented on the presentation style of the synthetics. Our response to this has resulted in the addition of Figure 7, and also forced us to re-analyse our synthetic results. This led us to examine the depth distribution of traveltimes in more detail and identify greater azimuthal variation than previously recognised. This process also highlighted an incorrectly parameterised S-wave velocity gradient in the model. We have therefore reproduced Figure 6 with synthetics using the corrected velocity profile. The trends in results do not change but the magnitude of the amplitude anomalies is now greater and we discuss this further in the body of the text. Although the results have not changed we can now conclude that both amplitudes and traveltime anomalies may both be diagnostic measurements of ice divide fabric.

Reviewer #2 - Hugh Horgan

Brisbourne et al present results from the first Antarctic Distributed Acoustic Sensing (DAS) experiment. The manuscript is a useful contribution. It focuses on a novel method with the potential to make a significant scientific contribution. The preliminary results presented provide some constraints on the compressional wave velocity of the lower half of the ice column, and an estimate of seismic quality factor. The manuscript's main intent is to act as guide for future experiments and it provides an extensive list of recommendations. The manuscript is generally well written and presented but there are a few areas that would benefit from improvement. My main comments pertain to communicating the justification for this type of experiment, discussion/comparison with other borehole seismic methods, and consistency in the data presented.

1. Main comments

Introduction

The introduction could be improved by better justifying this style of experiment. First, the connection between velocity, amplitude, and crystal orientation fabric (COF) needs to be outlined. Readers will be confused by the use of a seismic method where ice core physical properties are available. To address this, the introduction should emphasise where DAS is possible but direct measurements are not. The introduction should also outline what DAS brings that other seismic methods don't. This will require other borehole seismic methods (clamped borehole seismometers, direct measurements of recovered core, acoustic borehole logging) to be summarised. Highlighting the suitability of DAS deployments in irregular hot water drilled holes where other seismic methods are not possible is a real selling point for this method. The other justication often used is to inform surface observations and improve surface based methods. Does DAS provide any advantages here? The description of fabric evolution is also brief. Presenting the typical ice divide COF progression would be helpful here as would a mention of how impurities, temperature, and strain, influence fabric evolution. Addressing these points should make the manuscript more accessible. At present the first two paragraphs of the introduction are not so relevant for the rest of the manuscript, although a focus on COF could make them so.

We have reworked and extended the entire introduction to address the shortcomings highlighted by the reviewer.

Data and results presented

Data are presented from a range of offsets. It would be helpful if a consistent set of offsets were used. 0, 200, 400, 600 m would makes sense. As it is, in Fig. 2 we see the bandpassed checkshot with and without FK&Decon, then a zoom of the 100 m shot, then the 500 m offset shot. In Fig 3. we see the 150 m shot and synthetics. Then in Figure 4 we see results from the 0, 50, and 100 m shots and in

Figure 6 we see estimates for 200 m and 400 m offsets. Presenting the same offsets make it easier to follow along and give the reader more confidence.
This is a good point. We now present 0/200/400m in Figure 2. We have re-run the synthetics in Figure 3 at 200 m offset for consistency. This is also then consistent with Figure 6 which presents 200/400 m. By its nature, Figure 4 requires the nearest offsets to obtain reliable velocities so we retain 0/50/100 m offsets here.

The diamond shaped noise source is nicely explained.
Thanks

As these data are new to most of us, it would be good to see the waveform of the arrival. In my experience the devil is in the picking. It would be instructive to see waveform wiggles overlain with picks. After conversion to velocity would be the most useful.
We have included sample example waveforms Figure 2. As velocities are calculated using relative arrival times we do not rely on first breaks for arrival times but use peak arrivals. We have added this to the body of the text.

Is it possible to present the results in Figure 6 in a similar way to the field data displayed in Figures 2, and 3? If so it would make interpretation by the readers much easier.
We now present synthetic VSP gathers of the isotropic and girdle/cluster fabric in an additional figure (Figure 7). This process has led us to investigate the synthetics in more detail, with some interesting conclusions, which we now discuss in more detail.

2. Minor points

L46 `gravitaionally driven' is too general. Be explicit about what's not going on and why that's useful.
L47 `preserve recent' and the not so recent. COF evolution depends on the existing state.
Unravelling the strain history is not as straightforward as this statement suggests.
We have expanded the introduction to include the description and referencing of ice flow at ice rises.

L54 `as with all surface geophysics' is a sweeping statement. Again be explicit.
We have reworked and extended the entire introduction to address the shortcomings highlighted by the reviewer.

L138 and Fig2 b) reverse-moveout coherrent noise has made it through the FK filter implying the not just positive dips preserved or maybe filter tapers.
This is the most likely explanation. We have added a sentence to the figure caption.

L151 `snow compacting' - snow compacting and metamorphosing.
Done.

L198-199 First 2 sentences of this para belong in the introduction.
We have reworked and extended the entire introduction to address the shortcomings highlighted by the reviewer.

L210-212 What is the impact of the assumption of straight ray-paths. It would be good to assure the reader this is insignificant.
Good question. We have now ray traced with the isotropic velocity model to determine the angle at the fibre for the calculation of true velocity from apparent. Calculation of the true angles is an

inversion problem as it requires a velocity model fit specifically to these data. Unfortunately, our data are insufficient to determine a fully anisotropic velocity model.

L238-244. If I follow this correctly each trace is replaced by a stack from a 10 m bin after the removal of traces that fail to cross correlate at > 0.95. With this procedure if the central trace is the outlier trace it will remain dominant. Also, this stacking will lower the frequency content. Will this change the result? Regardless of this the reader should know what percentage of traces were removed by the editing procedure.
If the central trace is an outlier it will result in most if not all of the adjacent traces being discarded due to low coherency, and therefore not produce a result. We now report the number of traces removed by the 0.95 threshold (45%). The DAS system deployed here utilises a gauge length of 10 m so the selection of a 10 m window is consistent with this and will not change the frequency content further.

L264-265 `...and seismic methods provide...' citation needed.
Done. Brisbourne et al. (2019)

L282 `Skytrain' - SIR (for consistency).
Done

L287 refer to Fig 6 c).
Done

L287-290. Please elaborate on this. If possible, seeing these results in the same gather form as Figs 2 3 would be very helpful.
We have created Figure 7 which presents synthetic VSP gathers for the isotropic and divide fabric cases to highlight some of the features expected. We discuss these details further in the text.

L293 `..very small' How small? Possible to pick in real data?
Good question. We have added “However, in our model the effect is small. For example, the azimuthal variation in P-wave traveltimes is less than 4 ms with either a 200 or 400 m source offset.”

L376-377 `multimode' - multi-mode (for consistency) also introduce/define single-mode and multi-mode and elaborate on benefits.
We have added more detail to the introduction describing the DAS method, including fibre types.

L384-385 `As variation....is therefore critical' Combine this with recommendation 1).
Done

3. Figures

See comments above regarding presenting similar offset shots and results.
See responses above.

Figure 1. Coordinates required on either b) or c), preferably both.
We have added the borehole location to the figure caption to avoid clutter on the figures.