Dear anonymous reviewer,

Thank you very much for the valuable comments. We will consider them in our final version. Please find our detailed answers to your comments below.

Abstract:

- In the abstract it sounds like no a priori information are necessary anymore, but as stated in the conclusion, selection of damping parameter and polynomial order is still based on deviation measurements.

We have rephrased the respective part of the abstract:

"With the sequential inversion, the number of artefacts in the velocity model decreases compared to a velocity inversion without borehole adjustments. In combination with a rough approximation of the borehole trajectories, for example, from additional a priori information, heterogeneities in the velocity model can be imaged similar to an inversion with correct borehole coordinates."

- Line 20: I suggest to replace "Therefore" with "Based on the modelling results we propose/determined", because this is not the conclusion of the previous explanation, but of the investigation you described in the manuscript.

Agreed.

- Line 22: Compensation for velocity anisotropy is minimized not avoided.

Agreed.

Section 3:

- It is not clear when the seismic acquisition happened and if the deviation measurements were done on the same days. An overview in form of e.g. a small table would help. As I understood there was ~ 10 days between the acquisition days. It does not get clear how the inversion incorporates borehole deviation for the same borehole on different days. As I understand the polynomial coefficients are adjusted with the whole dataset, but the deviation is different for the subsets collected on different acquisition days. Please give insight on how this is done.

In principle, a separate borehole trajectory would have to be computed for the acquisition of every tomographic plane, because there are ongoing movements and deformations of the glacier. However, this would lead to a poorly constrained inversion problem. Instead, we have designed our experimental schedule, such that a single borehole is occupied for a minimal time span (up to 4 days), and we assume that the trajectory changes within this short time span are acceptably small. We acknowledge that this may lead to minor inaccuracies, but, in our view, they are unavoidable. We have clarified this in the revised text.

- The model includes anomalies that are not resolved by the tomography, because there is no ray coverage in this area. When an anomaly like this is incorporated in the model this should be mentioned in the discussion of the results to avoid confusion.

Indeed, some of the anomalies remain unresolved, because they are not covered adequately with rays. We have added a clarifying comment in the discussion.

- Line 169: How many geophones are installed at the surface? In which setup? It is also not clear whether the data from the surface geophones is used in the inversion. This would also make the model setup in line 187 more understandable ("…and added a total of 828 receivers…")

We describe the setup with some additional details in the revised text.

- Line 172: "…explained in more detail below." State where it is explained "…explained in more detail in section 4."

Added.

Section 4:

- Line 201: The damping factor of 0.1 is selected. In Line 300 a damping factor between 1000 and 10000 is recommended. It is not clear if these are different factors and why the magnitude changes.

Indeed, our formulation in the original text is rather confusing. The damping factors indicated are relative numbers with relatively little physical meaning (they relate to the magnitudes of the sensitivities of the individual model parameters). After considering a variety of options, we finally concluded that it would be most useful to rather describe our regularisation strategy instead of providing numbers that are difficult to interpret.

- Table 1: For evaluation of the combined inversion adding the RMSE of velocity inversion with true trajectory should be a benefit.

We have considered this during our revisions.

- Line 220: Here add a reference to the supplementary video material [Hellmann,2022a]

Added.

- Line 215 and 224: I do not agree with the statements, that in Figure 4 the lower channel "could not be recovered", while in the combined inversion in Fig. 5 "the upper and especially the lower channel are correctly resolved". The anomaly associated with the channel is well visible in both results. I agree, that there is less artefacts and the channel is better resolved in the combined inversion results which supports the papers objective. Please clarify this.

When comparing the differences between true and inverted data, they are very large for the lower channel without borehole adjustments. Nevertheless, we agree that the velocity inversion also roughly recognises the channel. Therefore, we mitigate the statement "could not be recovered" to e.g. "is only weakly recovered".

- Line 247 / Fig. 7b: It is not clear which values are in the range of >0.99 since the colorbar ends at 0.2. The allocation of the polynomial coefficients on x- and y-axis is not intuitive. Label the polynomial coefficients on the axes. For better visibility only a fragment of the matrix could be shown in order to gain the space for labels.

We need to evaluate the options how to improve this figure. An additional excerpt showing the values for one borehole could be an option. However, just showing a part of Fig. 7b seems to be not a valid option. From our point of view, we need to show that the mentioned coefficients of lower degrees along the main diagonal are well resolved for all boreholes as discussed in the text.

Section 5:

- 279: Is 200ms correct? A 200ms window around the estimated arrival time seems very long since the highest expected traveltimes at v=3800m/s and max. distance of 100m (90m depth, 40m borehole spacing) are ~25ms.

Thank you very much for finding this mistake. Indeed, this is a wrong value and must be 4 ms. We used a window of min. 40 to max. 200 *samples* (depending on the distance between source and receiver) and the sampling rate was 20.833 us.

- Line 312: Deviations of 0.6m and 1m are seen as not realistic, while having a displacement speed of 0.06m/d and 11-14 days. This results in 0.06m/d*14d = 0.84m which seems realistic in this context.

No, this is not correct. The ice flow rate in valley glaciers usually decreases with depth. This is common sense in the glaciology community, but we should clarify this with an additional clause: "Glacier flow rates of 0.06 m d^{-1} on average measured at the glacier surface during the summer period imply that this deviation could not be caused by the ice flow, when considering a typical parabolic decrease of the flow rate with depth."

Section 3 and 5:

- What is the estimation of the borehole deviation measurement error? How does it compare to the difference between measured borehole trajectory and fitted trajectory after inversion? The comparison is important to assess the plausibility of the trajectory fitting.

This is a very difficult question. We tried to determine the borehole trajectories with various tools, and we observed discrepancies, well beyond the accuracy, specified by the manufacturers. This was the main motivation to perform this research, and to develop the inversion strategy. However, the large discrepancies observed, make it very difficult to specify the accuracy of the initial values.
We have added a corresponding statement in the introduction.

Section 6:

- Line 328: “However, there is a risk that the coordinate adjustment will suppress the appearance of real velocity anomalies in the tomogram. We avoid this by decoupling the two parts of the inverse algorithm.” Is it avoided? At the end of Section 2 Line 140 you explain that sequenced inversion and the inversion with extended set of equations do not show significant differences is the results. Could you please explain this.

The advantage of the sequential inversion scheme lies in its flexibility as described in the article. For the synthetic tests, we compared the sequential scheme with a common inversion scheme that inverts for all model parameters (i.e. velocity and polynomial coefficients) simultaneously. In the comparison, we always updated the coordinates in both schemes. However, when later applying the sequential scheme, other constraints can be considered whether an update in the current step of iteration is useful (i.e. further reduces the RMSE). If so, the new coordinates derived from the updated polynomials are used. This provides the additional and mentioned flexibility compared to a common inversion that updates all model parameter thus providing less flexibility.

We have added another sentence in Line 328 to make this more clear:
“It also provides more flexibility to decide if an update of the coordinates in the current step of iteration is beneficial and thus applied or skipped.“

- Section 6.2: This section gives important insight on trade off between trajectory optimization and anisotropy. A lot of inversion results are presented without visualizing any of them. An additional Figure is recommended. If to many Figures are already in the manuscript than add significant Figures to the supplement.

We add another Figure that demonstrates the influence or interaction between borehole trajectory adjustments and anisotropy.

Section 7:

- Line 439: Video Supplement is in [Hellmann, 2022a], not [Hellmann,2022b]

Thank you, we have exchanged the entries in the References so that line 439 and also line 437 are pointing to the correct reference.

- If possible give an outlook on how to determine inversion parameters (damping, …) without a priori information from inclinometer measurements. If these are always required the advantages of the combined inversion are mitigated.

We have added a section in the conclusion. We add two possible ways how to better determine the regularisation parameters.

Kind regards,

Sebastian Hellmann and Hansruedi Maurer
(on behalf of the co-authors)