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Interactive comment on "Crustal structures beneath the Eastern and Southern Alps from ambient noise tomography" *by* Ehsan Qorbani et al.

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Dear Editor,

We are pleased to submit the authors' response of "Crustal structures beneath the Eastern and Southern Alps from ambient noise tomography". We appreciate the time and attention by the editor, associate editor, and referees. The comments and questions were insightful and enabled us to improve the quality of the manuscript.
All points raised by the reviewer1 have been addressed. In the following we list the reviewer's comments in bold face following by the authors' response to each of

comments and questions. As suggested by the reviewer, we have completely redone the group velocity inversions using larger smoothing parameters. In turn, we have updated 10 Figures (Fig. 6 to Fig. 15). We have also included new Figures and replaced Figure 4 (see details below).

Sincerely,
Ehsan Qorbani on behalf of the co-authors

Referee 1

1-Why is the phase velocity information not included in the tomography?

In the present study we decided to process only group velocity maps because of the relatively high computational cost of inversions. Indeed, we compute for the whole resolution matrix which increases significantly the computation time for a single period.

2-The tomography and final inversion results reflect lots of small-scale anomalies and artifacts, which indicates the tomographic results are not robust. I suggest the authors trying to adjust the smoothing parameter and correlation length, during the phase velocity map construction.

In the initial version of the final inversion, there were indeed some small-scale anomalies that were mainly produced by the interpolation used to produce the maps. In addition, some small-scale features were small artifacts produced by low path density in some regions. Note however that all the main bodies identified and discussed in the manuscript were well defined. But we generally agree with the reviewer that the final maps displayed were perturbed by small scale problems.
In order to solve those issues, we completely remade the group velocity inversions

which resulted in significant changes in the manuscript (figures from 6 to 15 have been updated). Several changes have been made to improve the inversion results. First, as the goal of the work is to study large scale bodies in the crust, we increased the grid size from 8km to 12km. This significantly increases the path density in the whole study region. Secondly, as suggested by the reviewer, we adjusted the inversion parameters using L-curves analysis that are now provided as a new figure in the manuscript. Finally, we carefully check the interpolation used to plot the final images. The new inversion is now smooth with clear marked bodies that are discussed in the geological interpretation section.

3-The synthetic reconstruction analysis with synthetic models is useful to assess the relative spatial resolution, since the ray path coverage is not uniform, especially after the introduction of AlpArray. Even though the synthetic tests, such as the checkboard test, cannot indicate the range of resolvable scale-lengths, it still could reflect the noise sensitivity and parameterization sensitivity. (Rawlinson and Spakman, 2016)

We do not include a checkerboard test in our study, because we agree with Lévêque et al. 1993 (reference see below) that these tests can be misleading mainly due to the arbitrary choice of the synthetic models to be tested. Assessing the resolution directly from the resolution matrix, as done in the manuscript (see section 4.1), is a more robust way of quantifying resolution (e.g., Barmin et al., 2001, 2012) and the increased computational and storage cost associated with this matrix is manageable. With the Barmin et al. (2001) method, each row of the resolution matrix is a map representing the resolution for one cell of the model. It quantifies how the obtained group velocity at one node depends on the measurements performed at other nodes. This matrix allows to simply define a correlation length as the distance at which the value in the resolution matrix is decreased to half (Barmin et al., 2001; Stehly et al., 2009). Studies combining both resolution matrix analysis and checkerboard tests show similar results

(e.g., Poli et al., 2013) with more information for the resolution matrix approach (e.g., Barmin et al., 2001; Stehly et al., 2009). In particular, as the spatial projection of the individual resolution matrices for each cell are not symmetric, this analysis allows to look at the different size of the resolution spot in the best and worst direction for each cell (we now included these figures to Fig. 6). As a result, we believe that the analysis presented in section 4.1 is the best way to assess the quality of our model.

- Lévêque, J.-J., Rivera, L. and Wittlinger, G. (1993). On the use of the checkerboard test to assess the resolution of tomographic inversions. Geophys. J. Int. 313–318.

4-The data coverage is bad for the boundary region and in the long period. It's hard to convince me that the anomalies around the boundary and at deep depths (such as I, II, III, V, and X in Figs 11 and 12; high Vsv anomaly in Figs. 11f and 11g; profiles AA and DD in Fig 14) are realistic. So, I suggest the authors avoiding overinterpreting these features.

In the new version of the manuscript we increased the grid size in order to improve the path density in the whole study region. Therefore, the new images are now better constrained regarding the discussed features. In addition, we include sentences when it's necessary to remind the reader that some features have to be interpreted carefully in regions with low path coverage.

5- Several figures are not decent, such as Fig. 3, 5, 6, 7, and 8. In addition, the font-size of the labels and titles is too small in some figures.

We improve the quality of the Figures and modify the titles and labels in the revised manuscript.

Specific comments

Section 2.3:

Figure 3: I do not think the Figure 3 of the 9 components correlation tensor is necessary. The figure is obscure and hard to distinguish the signal from the background.

We agree with the reviewer and move the Figure 3 to Supplementary materials.

Section 3:

Figure 4: Typically, we concern more about the period dependent SNR during FTAN, which more related to the quality of the dispersion measurement, rather than the SNR of CC. The SNR in Figure 4 is meaningless. I suggest adding the figure showing the period dependent SNR curves for both Rayleigh and Love wave (similar to Fig. 4 in Bensen et al. 2008). The analysis of variation of the SNR with inter-station distance and azimuth could be considered at the fixed period. Line 161: The figure of the period dependent number of the Rayleigh and Love group velocity measurements is necessary, which could be added in the manuscript or supplement. (Similar to Lin et al. 2008)

The authors thank the reviewer for the suggestion. We replace the Figure 4 by period dependence SNR of the dispersion measurements. The figure shows variation of average SNR versus period for Rayleigh-wave and the four inter-components, ZZ, ZR, RR, RZ, which the Rayleigh-waves are constructed from. Also for Love-wave, The TT inter-component that Love-waves are appears on (Figure AC1 is attached to this letter). In the revised version, we add a supplementary table including number of measurements for each period for Rayleigh and Love waves, selected after applying a number of criteria explained section 3 of manuscript.

Figure 5: The example of FTAN seems not to be very well. The maximum period traced in the FTAN example in Fig. 5a and 5b is 30 s, while the period used in the FTAN is from 1 to 50 s. Is this already belong to the best results of FTAN? In addition, the locations of the station pair used in Fig. 5a and 5b could be marked in Fig. 5c.

The example of FTAN in Figure 5 have been randomly chosen. The max 25 and 30 sec in those examples are dependent on their inter-station distances. We now add more examples of FTAN in the supplementary figures.

Section 4:

Line 175: Why is the grid size set as 8 km? How does the grid size affect the tomography results in different periods?

We initially selected 8km as it was the smallest grid size that was still allowing sufficient number of paths per cell in most of the study region. However, in the new version of the manuscript we decided to increase the grid-size to 12km. This increases the number of measurements in each cell over the whole study region and help to stabilize the inversions.

Line 177: May need to consider to use longer correlation lengths.

As explained in major point number 2, all the parameters including grid size, correlation length (alpha) and damping parameters (sigma) have been changed in the new version of the manuscript.

Section 4.1:

Figure 6: Path density maps only show the periods of 8 and 16 s. What does the path density map look like for the longer periods, such as 30, 40, and 50 s?

We have redone the inversions with larger grid size (12 km) and smoothing parameters. Path density for longer periods for instance at the 20s, 30s, and 40s period is good enough to resolve the structures. The average number of paths per cell for Rayleigh-wave are 28, 23, 22 for 20s, 30s, and 40s respectively; and for Love-wave are 29, 26, 25 for 20s, 30s, and 40s. Please see attached Figure AC2 to the author's response.

Line 191: The resolution length is only the reflection of the relative path density and choice of parameters in the tomography. It does not indicate the true resolution.

This is true. We therefore have changed the terminology used in the manuscript to better reflect that this measurement is simply a proxy to assess the spatial averaging of the inversion rather than the true resolution of the model. "Resolution length" has been renamed "correlation length", which better explain that this value may be interpreted as the minimum distance at which two delta-shaped input anomalies can be resolved on the tomographic map (Barmin et al., 2001). However, we would like to point that assessing the "resolution" in the sense of "correlation length" directly from the resolution matrix, as done in the manuscript, is a robust way of quantifying spatial averaging and the size of the "resolution" spots (Barmin et al., 2001; An 2012). Studies combining both resolution matrix analysis and checkerboard tests show similar results in terms of extracted correlation length (e.g., Poli et al., 2013) with more information for the resolution matrix approach (e.g., Barmin et al., 2001; Stehly et al., 2009). In particular, as the spatial projection of the individual resolution matrices for each cell are not symmetric, this analysis allows to look at the different size of the "resolution spot" in the best and worst direction for each cell. We added a few sentences in the text for better explanation.

Figure 7: The true resolution actually cannot be reflected by the resolution length map, which is also controlled by the model parameterization. This figure is a little

bit redundant. I suggest removing it or put into the supplement.

We prefer to keep this figure in the main text as it better reflects the spatial averaging of the model than the number of paths per cell. This information is relevant as it provides an idea of size over which the inversions averaged the measurements to produce the model. It is therefore useful to interpret the models.

How about the average misfit of the tomography result for different periods? Could you please provide a figure to show the period dependent misfit variation for both Rayleigh and Love wave group velocity?

In inversion procedures, in general, a search is performed to find the best values of model parameters, which minimize the misfit or variance. Our standard way of selecting the optimum set of parameters (damping factor and correlation length) in the group velocity inversion is to evaluate how much the model reduces the variance present in data. In response to the reviewer's comment, we included graphs of variance reduction changes for several selections of the two parameters, damping factor (alpha) and correlation length (sigma) for a selection of periods. We have also attached this figure (Fig. AC3) to the author's response. In the figure, our selected best parameters are shown in black circles.

Section 4.2:

Figure 8: The number of the path in 20 s should be good, but the tomographic result seems not stable. Why are there so many white blanks in Fig. 8d?

As mentioned in previous comments, we have changed all the figures from 6 to 15. The new models are more stable. The white blanks in the old version were simply cells for which the number of paths was not sufficient (below 5). The cell exists in the model but were simply not plotted because of the low path density.

Could you please provide the Rayleigh wave group velocity map at 30, 40, and 50 s? Besides, the region of the CZA could be labeled in the figure. The full name of SLA should be indicated in the caption.

In the study, the group velocities between 4s and 42s have been used for the inversion of shear-velocities. We provide Rayleigh-wave group velocity maps at 30s and 40s and include them into supplementary materials. We add the full name of SLA to the caption of the Figure 8 and Figure 9.

Section 5:

Line 231: The final group velocity data used in the inversion is from 4 to 50 s, which should be clarified. Why do you exclude the periods from 1 to 4 s in the step of the inversion rather than in performing FTAN? I suggest to cut off the period range during performing FTAN.

We performed FTAN for all period range that we had. We then carefully assessed the dispersion measurements by apply a number of criteria, filter them, and finally to select the period range that are well constrained to be used in the group velocity inversion. We found out that measurements below 4 sec might not represent group velocity of the fundamental mode and could be mistaken by higher modes. Therefore, we did not include periods less than 4s in to the inversion. We also did not use period larger than 42s; because of lower number of measurements, they might not have been well constrained. We now add sentences to manuscript for better explanation.

Line 237: How do you determine the thickness of the layer in depth?

The initial model for the shear-velocity inversion is coming from Behm et al. (2007a) with depth layering of 1 km. From that model we obtained our an average initial model for the region with 2km layers in depth. Since we cut off the group velocities below 4 sec, the thickness of the layers was increased from 1 km to 2 km. The choice was

made as it allows a good enough discretization of the 1D shear-velocity model with depth while limiting the number of parameters in the inversion.

The influence of Moho depth is not mentioned in the paper. What is the Moho depth distribution in this region? Will the Moho depth affect the inversion? How are other model parameters assigned in the parameterization?

The Moho depth in the region has been reported > 40 km (Behm et al., 2007a; Spada et al., 2013; Bianchi et al., 2015, Hetenyi et al., 2018). Our shear velocity model presented here ends at 40 km, therefore we are not able to observe effect of Moho in our model. During the depth inversion, no restriction was applied for Moho depth, and also no layer weighting, and no fixed velocity was set. The velocity is allowed to take a large range of values as long as the depth variation is smooth.

Figure 10: The figure showing a comparison of depth sensitivity kernel of Rayleigh and Love wave group velocity at different periods to Vp and Vs is helpful. I suggest removing the Fig. 10c and 10d and add another figure of the comparison of the depth sensitivity kernel of Rayleigh and Love wave.

We added a figure showing the depth sensitivity kernel of Rayleigh and Love waves to Vs at different periods (see Figure 10 in the updated version). We prefer to keep Fig. 10c and 10d as they provided useful information on the depth resolution of the Vs inversions.

Section 6:

Figures 11 and 12. The tectonic boundaries (dashed lines) in Fig. 11 and 12 are not clear and hard distinguished from faults. It will be helpful to label the abbreviations of the tectonic units mentioned in the paper. Figure 13: Mark anomaly IX in Fig. 13d. Also, it will be helpful to label the tectonic abbreviations mentioned

in Fig. 13a.

Having both tectonic boundaries and faults would be helpful for readers to follow the interpretation. We add the label of tectonic units to Figure 11, 12, and 13a, and mark anomaly IX to Figure 13d.

Line 346: Another reason for the discrepancies in the pattern of anomalies between your model and Kastle's is the different station distribution. The introduction of AlpArray stations increases the paths in the central region.

We thank the reviewer for comments and suggestions we include this to manuscript.

Figures caption

Figure AC1: Average signal-to-noise ratio (SNR) for Rayleigh and Love waves for all station pairs. Average SNR of ZZ, RR, ZR, and RZ are also shown, which Rayleigh waves are extracted from these 4 inter-components. Average SNR of TT and Love-waves are also represented in the figure. Love waves appears on the TT inter-components.

Figure AC2: Path density map for the group velocity inversion: a, b, c) for Rayleigh waves at 20, 30, and 40 sec respectively. d, e, f) for Love waves at 20, 30, and 40 sec. The path coverage is generally good for the entire region.

Figure AC3: Variance reduction as a function of the inversion parameters. a) L-curve analysis for damping factor (alpha) for Rayleigh waves at periods of 5, 10, 20, 30, 40 sec. b) Correlation length (sigma) for Rayleigh waves at the same period range. c,

d) Variance reduction vs damping factor and correlation length (sigma) respectively for Love waves at the same period range. The selected parameters are shown by black circles.