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Interactive comment on "Imaging Seismic Wave-Fields with AlpArray and Neighboring European Networks" *by* Marcel Tesch et al.

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We thank Petr for his detailed and constructive review of the manuscript!

note A: I have made my opinion on the proposed manuscript before the other (anonymous) review was published on SED online discussion web page. Some of my suggestions may be close to those mentioned in the other review, however, my review was written independently.

note B: Two of the papers where I, P.K., am the first author, were already used in the original manuscript. I am using these references throughout my review. These are then not new references which I would ask the authors to add to the manuscript.

General remarks The paper uses a data from hundreds (up to 1600) of stations over the entire Europe. Big portion of the data comes from the AlpArray experiment complemented also by the denser Swath D project. The data are uniformly processed, records are shown, animations presented. The work systematically browse the records in time and space commenting on many interesting features of wave propagation and presenting original way of plotting the seismogram section using binning of amplitudes in space and time. Showing and discussing the core of the seismological observation – the earthquake records – deserves an attention and should be acknowledged. The paper describes fundamental seismic phenomena, some of them visible and observable only thanks to the networks covering large region as well as thanks to the dense station coverage of the region at the same time. As it is one of up to now only a few papers exploiting AlpArray data in its entirety and showing the capability of such a project to advance or knowledge about the wave propagation, it should deserve an attention. Everything what has been done in the paper is concise, well described, documented in figures. However, my impression is, that the work ends up at half of the way. After such a beautiful observation, one would expect quantitative measurement of at least some of the phenomena mentioned. Even without modeling and inversion for structure, the effects – observed and commented based on visual inspection – could be maybe quantified and compared with papers observing similar distortion of the wavefield, both in case of body wave as well as surface waves. Below, I am giving more focused suggestions and comments.

As mentioned in our response to Review No. 1, any kind of detailed quantitative analysis would require the room and focus of an entire dedicated publication on its own. It is well beyond the scope of this paper to quantify the observed wavefield deformations and it would not serve the overall purpose of illustrating seismological phenomena using wavefield animations.

Abstract The abstract promises a lot and after reading it, one gets easily excited and motivated to read the whole paper. However, the expectations are then not fully confirmed later.

We have revised the abstract to better reflect the goals of this paper.

Introduction The Introduction starts with historical overview, it gives a broad point of view but it is still reasonably short, showing the most important steps in building networks. As it is all about Europe, I would maybe even mention the PASSEQ project (2006 – 2008).

We have added PASSEQ to the list of networks as suggested.

The end of the Introduction already bit lowers the expectations talking about “imaging of the propagation”. Which the paper is about, true. But after “imaging”, one would expect some quantitative measurement, hypothesis or explanation.

(see above)

Events Data – Seismogram section Single-station approach allows for the measurement being applied independently of the network density. This is good in principle – you can obtain the same measurement both inside and outside of the dense AlpArray (Swath-D) networks. All processing steps are clearly explained and the record sections and animations are based on properly documented data processing. All the comments of observed phenomena, however, are based on the visual impression of the wavefield propagation over the dense networks. My main point is: is there is a way how to take advantage of the dense networks (let’s say inside the AlpArray region at least) to map the wavefronts in time and space with some reasonable smoothing among the stations? How to quantify the distortions of the wavefield?

These are all very relevant questions which are in part the topic of ongoing research by the authors, the results of which will be presented in separate future publications.

Discussion This section should be more properly called “Observation” or maybe “Measurement”. It describes qualitatively the observation. It uses a lot terms like: “varies considerably”, “mostly aligned”, “slight deformations”, “visibly deformed”; “heavily interfering”, “severely deformed”, “significant deformation”, “phase bundles”, “unaffected by distortions", "rather coherent", "seems aligned", "notably sensitive", "perceptibly different". This would be alright, if it was supplemented by numbers and plots showing the distortions. Could it be possible to somehow track the wavefronts for distinct phases, maybe similarly like in Kolínsky et al. (2020), see Fig. C1 – bottom panel, where the zero-crossings of surface waves at given period are plotted and smoothed over the map. This is also purely one-station measurement. Or, at the top panel of the same figure, the group maxima are plotted, again a one-station measurement (see also animations in the online-only Supplement to the latter paper).

Here, I list some questions, which can be maybe answered or at least documented if a quantitative measurement is applied on the wavefield:

- Horizontal wavelength of body waves. You give rough estimates for some of the earthquakes of the apparent wavelength of the body waves striking the network. Can you evaluate the connection with the incidence angle? Does the apparent horizontal wavelength of later arrival as PP correspond to the geometry of P and PP incidence angles (for different epicentral distances)? How does this trade off with frequency? Apparent horizontal wavelength could be caused by different frequency as well as different incidence angle, or both.

(see above)

- Diffraction of body waves. If you quantify the distorted wavefronts, what are the time delays by which the real wavefronts deviate from the circular 1D wavefronts? Do you see some systematic behavior, connected to frequency, incidence angle, number of bounces (P, PP, PPP, ...), epicentral distance? What about comparison with the papers using the body wave diffraction like Cottaar and Romanowicz (2012) and Yuan and Romanowicz (2017) (both using S/Sdiff phases, though)?

(see above)

- I see two options, how to visualize the wavefronts of various phases. You can plot the picks in the sections of records directly, what would, however, miss the azimuthal dependence. But it would allow you to plot several (all) phases into one record section. Or you plot the picks in the maps as a contours of arrival time. This would allow to see the spatial distribution (and distortion), but each phase would need a separate figure.

(see above)

- Surface waves: Can you plot some of the standard deviation maps only for the surface-wave time window? Or better even for filtered narrow-band of frequencies? Does it show the stripes as expected (and also shown) by the studies from USArray and AlpArray? Can you then say, to which extend the amplitude variations come from the local structure and which portion must have been brought to the region from outside thanks to the propagation complexities? Are there similarities between the earthquakes?

(see above)

- You comment both on the amplitudes and distortion of the wavefronts. These are probably mutually connected. Focusing and defocusing takes place whenever the wavefront is curved. Can you compare the two observations?

(see above)

Minor comments technical:

- The animations are amazing. The files are, however, bit too huge. It is difficult to download them and even difficult to playback them on a reasonable computer as the memory demands are high. Also, the background topography map includes unnecessary details (contours), which can be removed to make the image less busy.

We amended the supplementary materials with lower resolution versions of the animations.

- The reference to EGU abstract “Kolínsky, P., Bokelmann, G., AlpArray Working Group, Upper Mantle Imaging with AlpArray Surface Wave Diffraction: The Cameroon Volcanic Line, Geophysical Research Abstracts, Vol. 21, 2019" can be replaced by the paper "Kolínsky, P., F. M. Schneider G. Bokelmann, 2020. Surface wave diffraction pattern recorded on AlpArray: Cameroon Volcanic Line case study, J. Geophys. Res: Solid Earth, 125, e2019JB019102, doi: 10.1029/2019JB019102.". It would also help to avoid two references with the same citation in the text "Kolínsky et al., 2019". Moreover, the citation in the text is used only once and hence one of the references in the reference list is probably not needed.

The reference has been corrected.

comments line by line: line 102 "They ..." –> "The records ..."

Changed.

line 103 "half a sample width due to station effects" –> "half the sampling interval due to different digitizer time stamping"

Changed.

lines 101-104: This sounds like if the records were FIRST resampled to 1sps and THEN rounded to the nearest second. It would be better to first align the seconds in the original sampling and then resample it as the error would be much smaller.

This is correct, but this spurious error will not affect the animations. Yes, for detailed quantitative analyses this should be corrected.

lines 122 – 131 Here it is not clear to me, how the labels of SS, SSS, 4S and so on made it into the plot. You talk about observation. However, when removing the 4S to 9S labels, it is difficult to see six different phases coming in the given time window. How did you "observe" these six distinct phases? Or are the labels marked at times predicted by some 1D model? There are clearly coherent arrivals, I just wonder, how can you distinguish between them. The caption to Fig. 2 says: "Corresponding theoretical traveltimes were computed with TauP". But where do we see these theoretical travel times? Should it be the position and size of the labels? I would also add the sentence about the theoretical times into the main text.

Yes, the labels mark theoretical arrival times that we calculated for a number of body wave phases. We agree that it is probably not possibly to distinguish 6 discrete phases between 4S and 9S by eye, but it is clear that we can see some coherent arrivals in that region and we have confirmed while creating the figures that they do indeed match up with the theoretical arrival times. The labels are there to put them into context. The text has been amended accordingly.

line 139: This follows my previous point. Visually, I can see the phases, but to say, you have “detected” them, I would expect some quantitative analysis, some picks, or maybe a line drawn over the plot in Fig. 2 to show how can we really separate 8S from 9S.

We experimented with plotting the theoretical travel times as lines on top of the section but ultimately decided that this was visually too cluttered and the signals themselves became less visible. Furthermore, the seismogram section is not intended to state that we have detected these phases in any kind of formalized way but rather that based on comparable single-event datasets it is *possible* to do so (which is far from self-evident without looking at the data), as we think is unequivocally shown by Fig. 2. This has been made more clear in the text.

A general remark to the whole Section “Seismogram Section”> It is all about the vertical component, right? Wouldn’t all the S-phases be better visible on the transverse component?

Yes, it is the vertical component. It’s true that some phases might have benefited from being viewed on the transverse or radial components. We added a remark in the text.

Fig. 2> The red/blue color behind the selected traces probably shows the envelopes, the same as in the animations (reference trace)? If so, please, say it in the caption or in the text.

Yes, that is true. It has been added to the caption.

line 159> “to indicating” –> “indicating”

Corrected.

line 163> “Discussion”. As already mentioned above, I would call this section probably “Observation”.

Renamed to "Discussion of the Animations".

line 170> “small circles” –> “theoretical wavefronts”; even “small circles” is not wrong, here it is bit misleading and could make a confusion with all the small circles showing the amplitude of ground velocity

Good point. Has been changed.

lines 170-174> While the first point about the theoretical wavefronts being apparently curved in “wrong” direction could be commented as “an artifact of the map projection”, the second, however, is not a problem of the projection, but simply reflecting the fact, that the waves really do arrive from northeast, as it is the shortest way to the epicenter. So, in fact, the source IS located to the northeast. When sitting in the Alps and pointing your finger to Taiwan, you will point to northeast.

That is correct. We have rephrased the sentence to better express this.

line 180> “dispersion of body waves”; here I would add a reference or some more explanation about this effect. This is actually very interesting topic, which could be reflected also later in the discussion.

Further explanation and references have been added.

lines 181-190> Here one tackles the main issue, that the wavefronts of the wavefield are compared with the theoretical wavefronts. However, as opposed to the theoretical ones, which are drawn by solid lines, the observed wavefronts are not drawn, one can only visually guess them. Here I would expect an animated “measured” wavefront overlaid on top of the figure and based on connecting the same phase (maximum/minimum/zero crossings) over the network, maybe similarly as in the animations in the Supplement to paper by Kolínsky et al. (2020), see above, where this is done for zero-crossings of the Rayleigh waves.

(see above)

line 198> You say, that “They cannot be properly imaged by the available station density.” (meaning waves shorter than 20 s), but at line 145 you said, you have anyway removed all waves shorter than 20 s.

They have been removed exactly *because* one cannot expect to properly image them with the available station density. Text has been amended.

line 201> “previously discussed event” – This is the first event described here, so it is not clear which is the previous one.

Clarified.

line 207> What could be the precision of the timing errors you are able to spot here? Units of seconds? 1 sec? 5 sec?

In our case the smallest possible timing error is about 2s, but this is purely a function of the chosen sampling rate for the animation. A remark has been added to the text. It is now pointed out in the text that dense arrays provide new options for quality control of the data.

line 209+210> Yes, I do see the outliers. It would be nice, if directly the (five?) station names were given here.

Examples have been added.

Fig. 7> If I got it right, the color shows the standard deviation, and the size of the circles shows the amplitude? Which is somehow the same information here? Is this why the blue circles are small and the red circles are big? If the color and size really show the same, I would keep the color scale but I would draw all the circles by the same size, so that the red does not dominate over the blue. Or is the size of the circles showing the instantaneous amplitude of the moment of the snapshot and the color the deviation over the 2:45 hour? Please, specify it in the figure caption. However, still, the correlation between the size and the color is striking.

Color and size of the circles always encode the *same* information. Small blue circles indicate a low standard deviation, big red circles a large one. Again, to enforce visual consistency across figures. This has been made clearer in the text.

lines 216-221> The deviations are given for a very long time window of 2:45 hrs. All the different arrivals of body waves as well as surface waves and coda are included in the deviations. I think, that the discussion about if the deviations indicate the scattering outside of the array or some heterogeneities beneath the array would be better constrained, if the deviations are split by the wave types, meaning, if they are calculated and discussed by smaller time windows.

The deviations are always comparable if they include R1. Hence, they were calculated for the same length as the animations. An quantitative analysis of amplitude variations of different wave types is beyond the scope of the paper.

line 229> “small-scale local seismic activity” – This sounds really interesting, do you have a suspicion on some local earthquake or quarry blast to produce these signal? Or what could it be, that “small-scale local seismic activity”?

Yes, the dense networks can also be used to detect local seismicity including quarry blasts or induced events using various algorithms. This is now pointed out in the text.

lines 271 – 276> This is really interesting. Can you tell, if the effect of non-decreasing amplitudes with distance is rather connected to the local structure or to the propagation effects? You speculate about both.

It has to be both. Both local structure and propagation have the potential to reshape amplitude distributions significantly.

What about comparison with other earthquakes? Fig. 13 may look like if there were stripes of high and low amplitudes, similarly as in Kolínsky and Bokelmann (2019). As the time window is, however, that long, it is difficult to say it clearly. What if you plot the same only for the time window when R1 arrives?

It doesn't much matter how wide the window is, as long as R1 is included.

line 332 and Fig. 21> Here come the clear stripes! Exciting! Let's discuss it more also with respect to Fig. 13. You have one sentence here, but this is a topic to spent bit more text on it. (Here the reference K+B(2019) is ambiguous, probably pointing to the paper in GJI? and not the EGU abstract?, see my comment above.)

Yes, indeed. We elaborated on the discussion of this observation.

line 361+362> Yes, this is the main point. How to extract local structure from wavefields distorted by propagation effects.

As mentioned in the text Helmholtz tomography is one of the options.

line 366> "frequently observed" ... I would add the references here, namely the USArray papers by Pollitz (2008), Liang and Langston (2009), Lin et al. (2012), Foster et al. (2014), Liu and Holt (2015), and Chen et al. (2018) from NECESSArray, and maybe repeat also Kolínsky and Bokelmann (2019) for AlpArray.

References added.

To conclude, I am considering the proposed observation to be of high interest. To fully exploit the data and to make clearer conclusion or at least hypothesis about the origin of the distortions, I would suggest to complement the study with quantitative analysis of the observation. I suggest the manuscript goes for major revision.

Thank you for your feedback! To reiterate, quantitative analysis of spatial wavefront distortions is an area of high interest deserving further research.

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