

Solid Earth Discuss., author comment AC2
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Reply on RC2

Carola Leva et al.

Author comment on "Multi-array analysis of volcano-seismic signals at Fogo and Brava, Cape Verde" by Carola Leva et al., Solid Earth Discuss.,
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We thank the reviewer for the careful review and comments and for appreciating our efforts.

R2: The manuscript presents an interesting study to locate earthquakes using a number of arrays. Potentially it is a good manuscript for the journal. I However, before this I have several comments and concerns that I think will have to be addressed. Especially I have the feeling there are two different ideas here. I am not sure the multi-array analysis is the important part? Or is it? The discussion seems to focus on the events rather than the method. Maybe that makes the manuscript somewhat difficult to read?

The first main point I have is that the manuscript is fairly difficult to read because of the organisation of the text. For example the introduction talks about the methods and results in far too much detail without the necessary background that then comes in the chapters afterwards (but a bit more introduction and references would be useful in the introduction).

A.: This manuscript presents a relatively new method (use of multi-array and time-domain array analysis) applied to volcanic seismic signals on Fogo and Brava. Therefore, it contains a more detailed description of the method and a discussion of the events analyzed.

We will rephrase the introduction slightly. However, we will focus on previous studies using multi-array analysis at volcanoes and on previous observations in our study area.

R2: In chapter 3.2 the first sentence has nothing to do with the rest of the paragraph, while the remaining paragraph seems to fit better in chapter 3.1. Part of 4.1 should be in methods (it discusses errors of the analysis and should be with methods..). The part on error estimation should follow directly from the methods for better flow before then talking about the locations and the discussion, which focusses on the events rather than the method. Please re-write. Also the discussion introduces new results, so these should be in

the results section?

This whole organisation makes the reading hard work. Re-writing would clear up much of this difficulty. Indeed the writing in many places could be much more concise there is often unnecessary detail and repetitions.

A.: The first two sentences of section 3.2 introduce the multi-array analysis. This is essential and all following descriptions are based on that idea. This is what follows after the beamforming, which is performed for each array individually. The section 3.2 contains the information on how the results of the beamforming of each array are combined to a multi-array solution.

However, we agree that the structure can be improved and we will revise the manuscript and move section 4.3 to the method section 3.

R2: Using beamforming, information on the velocity is needed, I am not sure how the authors can say that there is no need for knowledge of a velocity model? Have they tried to run the analysis with a non-fitting velocity model? I assume this would greatly worsen the resolution? This should be shown... (it comes back in line 90, so please comment on the size of these uncertainties and what it means to the location errors.)

A.: In array seismology, during the beamforming, no information about the underlying velocity structure is needed. The method is based on the idea, that a plane wave travels across the array. By shifting the traces and summing them up, the direction and the magnitude of slowness of the wavefront are determined (lines 82-86). For details see Rost and Thomas (2002) and Schweitzer et al. (2012), as also cited in the text. As the beamforming does not rely on a velocity model, the combination of the beams allows us to determine the epicenter of the earthquake from the intersecting beams alone, without knowledge about the velocity structure.

R2: Has stacking been done using a plane wavefront or a circular one? Is the wavefront already plane in this distance? Has this been tested?

A.: This is a good point, we assume a plane wavefront. This approximation is in accordance with conditions given in Schweitzer et al. (2012). We estimated that for distances of more than 6 km the plane wave approximation holds. This is the case for the majority of events we analyzed. However, for the few events being located closer to one of the three arrays, the magnitude of slowness becomes small at this particular array and the backazimuth shows a broad uncertainty due to the broadening of the beam. This uncertainty is accounted for during the localization with the multi-array method.

R2: Has the stacking been done with one backazimuth? How different is the backazimuth for each station? This should be shown.

A.: The stacking is done for a complete range of backazimuths by a grid search over the range of horizontal slowness components. Therefore, it is not determined per station but for the whole array.

R2: How much does out-of-plane travelling influence the results? In the presence of strong velocity changes (as possible in volcanic environments), the waves will not travel on the great circle path. Has this influence been tested? This is different from mislocation vectors as discussed later.

A.: If the velocity changes are strong enough to impact the propagation of the wave, this should also lead to errors in a classical localization method. We constrain the possible errors by comparison with the network localization.

R2: The discussion seems to be disconnected from the rest of the manuscript? Where do all the results come from? They were not shown in results? This needs to be better organized as well. Please re-write

A.: The approximations described in the discussion section serve as additional information on the interpretation of the events analyzed. However, these estimations are only rough approximations (e.g. the estimation of the ray path of hybrid events to estimate the depth) and are often too simple to give a reliable result (for example the depth estimation of the hybrid events results in too large depths, which are in contrast to the observations pointing to a shallow source region). Therefore, such approximations should not be shown in the result section, as this may give the impression that these results are considered reliable. We therefore think that these approximations are best discussed in the discussion section.

R2: What are the systematic aberrations? Is this a mislocation vector? This needs a reference! - ah pages later I find that it is indeed the mislocation vector as given by Krüger and Weber. Please move this part of the manuscript when first discussion aberrations. It is out of place that far back.

A.: Thank you for pointing this out, we will add a reference at the corresponding position in the text.

R2: Has for the estimation of the mislocation vectors in part 4.3 the topography been taken into account? I assume that the stations are located at different heights? Jacobeit et al., 2013 show that topography has a large influence on the mislocation, not only heterogeneity...

A.: It is true, that the station elevation difference can have a strong influence on the result of the array analysis. Therefore, we carefully tested possible influences under the assumption of the different station elevations according to Schweitzer et al. (2012). It turned out that the station elevation differences are small enough to be neglected.

We will add this information to the text.

R2: Is the criterion of 10 times wavelength (line 86) given in this case?

A.: Yes, see above.

R2: How does the chosen filter (which? Please state per event?) influence the resolution?

A.: The influence of the filter has been tested carefully (lines 190-197; Figure S4). It turned out, that the influence of the choice of the cut-off frequencies is very small and entirely covered by the error of the standard deviation of the backazimuth. Therefore, the contribution of the choice of the filter may be neglected.

R2: I am missing a table with station information? Please add to Supp. Mat.

A.: As described in the data availability section, the data including all station locations are available for download at GEOFON (<https://geofon.gfz-potsdam.de>; <https://doi.org/10.14470/4W7562667842>).

R2: Where are the locations of all events (2709, line 154) comes from? Have they been located before? By whom? or from catalogue? And how much better is this multiple array beaming? Why can only be 112 of 2709 events be located with the new method? How much better do the locations become when using multi-array methods? This could be part of the discussion

A.: There seems to be a misunderstanding. The 2709 is the total number of events, which we recorded with our network on Fogo and Brava (line 154). Out of these 2709 earthquakes, we located 112 by applying the multi-array analysis. The first reason for this discrepancy is that most earthquakes are of relatively small magnitude and they occur close to (or beneath) Brava. If they are too small, they are covered by noise at the stations on Fogo. As we operate only one array on Brava, this precludes the usage of multiple arrays. The next reason for this discrepancy are the requirements, which have to be fulfilled during the array analysis. If the result at one array is unstable, this array is not

used for the analysis. This further reduces the number of events. (see lines 155-162)

Nevertheless, if the noise conditions are good (especially during nighttime), we are able to determine the epicenters of very small earthquakes ($M_L < 0.5$), where it can be hard to find the onset of the P-wave at all stations. This is one of the strong advantages of the array analysis. If we combine multiple arrays, we are able to determine the epicenter of an event without the knowledge of a velocity model.

We will add this point in the revised manuscript.

R2: Line 149-151: how do you know the events are volcano-tectonic or hybrid? Have they been located and classified before? Where does that information come from? Reference?

A.: In contrast to a volcano-tectonic earthquake, a hybrid event shows a smooth transition from higher to lower frequencies. In the case of a hybrid event there is no S-phase identifiable and in the coda (for about 15 to 20 seconds) there is still more energy available in the 0-10 Hz band than before the event (and in comparison with a VT earthquake). In contrast, even for the small VT earthquakes on Fogo two phases are detectable. To make this point clearer, we will replace the example earthquake displayed in Figure 7a with an earthquake from Fogo. By this, the difference between the event types should become clearer. Additionally, we will add a figure to the supplementary material which shows the spectrogram of all components of a hybrid event. In this figure the low frequency content of the coda becomes evident.

A description of such events in previous literature on volcanic seismicity is e.g. found in McNutt (2000) or Wassermann (2012). The references are given in the introduction, lines 50-52.

With our discrimination between volcano-tectonic earthquakes and hybrid events we also follow earlier studies on the seismicity of Fogo (e.g. Faria and Fonseca, 2014, references in lines 255, 298).

R2: Also this part (4. Results) happens abruptly, without much leading into. Has the multi-array method been applied to known events? Or is it used on traces without knowing that there is an event? Please re-write. Much of the discussion seems to have to move to results section for a better flow and a better understanding of what has been done here.

A.: The traces were inspected by eye after application of a trigger mechanism. We will add this information to the results section in the revised manuscript.

As stated above, we will move the part on the error considerations of the multi-array analysis to the method section 3.

R2: Especially the event in Figure 6 is determined by 2 arrays, why do you need the third one there? How much better becomes the location if using three arrays? How much worse is the result when using classical locations?

A.: Some of the events are indeed located using two arrays, if the third array shows e.g. unfavorable noise conditions or if the event cannot be analyzed with the third array due to an unstable result during the beamforming. In such a case, the event will be located at the intersection of the main beams (i.e. by "drawing" a line from the backazimuth for which the amplitude of the sum trace reaches its maximum).

However, the more arrays are incorporated in the analysis, the more information are included, too. For example, Figure 13 shows, that the event is not located at the crossover of two main beams, but rather in between. This is the case, as the highest level of overlapping occurs in the range of the errors of the main beams. This is an advantage of the multi-array method, as the errors of the beamforming are directly taken into account during the localization of the event.

R2: In the introduction, the authors mention that the lack of S-waves makes it a good event for multi array analysis. I think it is more like the lack of S-waves makes it difficult for other location methods and that's why multi-array method can help?

A.: Yes, indeed. However, if the goal is to test the advantages of a multi-array approach it also makes sense to test it on events, which cannot be located reliably with classical localization methods.

We will rephrase this in the revised manuscript.

R2: The description in 3.2 is confusing, please clarify, refer to the example (e.g. Figure 6?) and explain what it means to intersect the broad beam in steps of 1%...

A.: We will clarify this by an additional figure added to the supplements.

R2: If the velocity model of Vales et al., 2014 is used for the classical location technique, why is this not used for the other technique? There a simple generic layer model seems to be used?

A.: The determination of the epicentral distance using the S-P travel time difference is an approximation to serve as reference for the analyst. The velocity model of Vales et al. (2014) is used here to determine Moho depth, mean crustal and mantle velocities. We will include this description in lines 229-230.

R2: Technical Points:

I may be wrong but at least one trace (4) in Figure 3a seems to be reversed in polarity.

Have the traces been inspected for polarity changes? How much does the waveform complexity in this event influence the energy stacks?

A.: Trace 4 in Figure 3a is not reversed in polarity. Due to the red line overlaying the traces, it might appear like this. However, the red line is directly above the minimum of this amplitude. In Figure 3c it is better to see, that this trace shows the same polarity as the other traces. The difference between the trace 4 in Figure 3a and 3c is only a time shift, therefore the polarity does not change during this procedure.

In general, different polarities of the traces would make the beamforming impossible. It is based on the assumption, that the same phase at all traces is used for the shifting and stacking. The constructive interference of the phases leads to a reduced SNR of the sum trace. Different polarities, however, would lead to destructive interference.

We perform the array analysis manually, this means, if different polarities would occur, the analyst would recognize this. Therefore, we can assure to only perform the beamforming on the same phases. Additionally, we focus on the first arrival of the P-wave. This ensures, that the same phase is chosen at all arrays. This is important for the multi-array analysis to ensure, that the same phase is analyzed (lines 215-216).

R2: Line 166 needs a reference.

A.: This information is given in most seismology textbooks. Nevertheless, we will include the information, that this only holds true for rays propagating downward from the source.

R2: Line 81: I would add local to earthquakes. For teleseismic events this is not necessarily the case.

A.: Thank you for pointing this out. We will add this term in the revised manuscript.

R2: Figures: Please add the colour bars in slowness-backazimuth plots with relevant information.

A.: We will adjust the figures accordingly.

R2: Lines 109-111 seems to be irrelevant for the manuscript at this point? it does not fit into the flow and it knowledge that should be known.

A.: The angle of incidence is used further below to estimate the ray path of the waves of hybrid events. Therefore, it needs an introduction, which is best placed at the description of the parameters which result from the array analysis.