Response to comments on paper "Designing small-aperture seismic arrays to enhance earthquake monitoring on ocean islands: application to Antikythera island, Greece" – 1^{st} round of revisions

Konstantinos Lentas, Christos P. Evangelidis, Vassilios Karastathis

October 16, 2025

We would like to thank the Editor for handling our manuscript and both Reviewers for their effort to strengthen our work with their comments. We have taken all of the Reviewers' comments into account in the preparation of this revised version of the paper, which contains some changes and additions, to fully address their requests.

More importantly, we revised our synthetic dataset by excluding the largest distance sources (> 200 km), as it may be unrealistic to detect seismic events in such epicentral distances using a small aperture array. We reworked our technique to relax some of the spatial constraints (although necessary), we included topographic corrections in the synthetics, and a noise level model to realistically simulate synthetic seismograms, and we implemented beamforming in higher frequencies. The result was a larger aperture irregular-shaped array that showed clearer distinction in backazimuth calculations compared to regularly-shaped array layouts. Finally, we discussed some limitations by applying spatial constraints in the optimization process and highlighted their necessity in our implementation.

Here follows our response (*in italics*) to each one of the Reviewers' comments and an explanation of the points that we have changed. The corrections are highlighted in red in the manuscript to make it easier to track down.

1 Reviewer B

1.1 Major comments

1. To begin with, the manuscript presents an inconsistency in the number of stations used for the array design. In some parts, the array is described as

having eight seismic stations plus the permanent ANKY station, while in others it appears to consist of nine stations in total. This lack of clarity creates confusion and makes it difficult to interpret the configuration and results. A consistent definition and a schematic representation of the array layout are essential to evaluate the proposed design.

We apologize about the confusion on the total number of array elements. We attempted to make this clear since the beginning of the revised manuscript, thus, we added some new text in the abstract (see line 12) and Methods (see line 79, 107 and lines 110-111, 114-115). We believe that the existing figures (i.e., Fig.6a) already show that the array is consisted of nine elements. Only the permanent station which is not allowed to change location is shown in different colour, even though it will be part of the array.

2. Another issue concerns terminology and the apparent conflation of distinct signal processing techniques. The manuscript refers to a "frequency (f)-wavenumber (k) beamforming" method. This phrasing is technically incorrect, as fk analysis and beamforming are two separate techniques that, although related in purpose (estimating slowness vectors and enhancing signal coherence), rely on different assumptions and mathematical formulations. fk analysis operates in the frequency-wavenumber domain and is well-suited for regularly spaced arrays, while beamforming works in frequency domain and can be more flexible regarding array geometry. It is essential that the authors clearly distinguish between these two methods, specify which one was actually used in each analysis step, and correct the terminology throughout the manuscript to avoid conceptual confusion.

   We agree with the Reviewer that we have caused some confusion regarding which method is used in our work. Therefore we removed the "frequency (f) - wavenumber (k)" part throughout the text and only kept the term "beamforming" which is the technique used in our study (see for example line 140).

3. Another critical issue lies in the resolution of the optimization grid. The use of a 500 m $\times$ 500 m grid cell (around 1/3 of the array aperture) to define candidate station locations is coarse relative to the total aperture of the array, which limits the diversity of achievable inter-station distances. Since the spatial sampling directly impacts array performance across frequency and slowness space, this choice constrains the optimization space in a way that likely prevents more effective configurations from emerging. A finer grid would strengthen the validity of the method.

   We apologize for the confusion but this is not the optimization grid. In order to make it clear to the reader we added new text in section "Spatial constraints" (see lines 132-136). We also corrected the grid cell dimensions (see line 129) as it was mistakenly written as 500 m $\times$ 500 m.

4. The manuscript also does not incorporate local topography into the optimization process, despite the authors noting that the study area includes non-negligible elevation variations. An informal check on Google Earth reveals elevation differences of up to 160 meters within the proposed array site-differences that are significant enough to affect seismic wave coherence and slowness estimation. A realistic design must consider these effects, either by correcting for elevation or incorporating a constraint or penalty term into the optimization framework.

We agree with the Reviewer that taking into account the elevation in the synthetic waveforms is key to properly model the incoming wavefield in order to design an array effectively. We chose to calculate synthetic seismograms by incorporating the topographic corrections since it was already feasible by the method used for the theoretical seismograms used in our study. We added new text in the "Synthetic seismograms and waveform processing" section to highlight this (see lines 151-152 and a comment at lines 390-391).

5. A central concern arises from the formulation of the objective function (Equation 2). The first two terms of the function are taken from Karamzadeh et al. (2018), whose contributions to array design methodology are well established. These terms are indeed appropriate for the stated purpose. The additional three terms introduced by the authors raise further concerns. The third term restricts stations to be placed within specific preselected tiles, introducing a hard spatial constraint that limits geometric configuration and prevent the algorithm from identifying better-performing configurations. The fourth term penalizes distance from the ANKY station, essentially forcing the array to remain centered on ANKY. While understandable from a logistical point of view, this introduces geometric bias that may conflict with other optimization goals, such as inter-station distance range and azimuthal coverage. The result of these constraints is evident in the proposed designs, where several stations share identical latitudes or longitudes - a pattern that contradicts known principles in array design, which typically favor irregular or fractal station distributions to enhance performance. Another aspect that deserves attention is the weighting scheme for the objective function terms. The manuscript does not explain how these weights were selected or whether they were tuned. Without this information, the function operates as a kind of "black box", making it difficult to reproduce or validate the optimization results.

   The Reviewer raises concerns regarding the objective function and specifically, about the terms that impose geometrical constraints. The Reviewer refers initially to the forth term of equation 2 in the original manuscript that restricts stations to be placed within specific preselected tiles arguing that this may restrict the algorithm to find better-performing configurations. While this is somewhat true, unfortunately, this term is necessary since we must prevent the algorithm from placing stations at the sea (see for example line 126 in the revised manuscript). In addition, the third term in the original manuscript forces the array to remain centred on ANKY. This is true and it was our initial idea to build the array around ANKY. The Reviewer is right that this applies a strong bias and in a second thought it is not necessary. Therefore, in our algorithm we revised this term and removed the part that control the centre-to-station distances and only kept the part that monitors the inter-station distances. Therefore, in our revised manuscript ANKY is just another element of the optimal array and not necessarily its central point (see lines 196, 199-205, 209-214 in the revised manuscript). We also added new text in the revised manuscript to explain how the weighting factors have been tuned (see lines 230-240) and we added the weighting factor values in the newly added Table 2.

6. The fifth term of the objective function is less clearly explained, and the rationale behind it should be clarified. Overall, these additions to the objective

function give the impression that the final array design is more the result of predefined constraints than a genuine optimization outcome.

We agree with the Reviewer's comment, slightly reworked equation 2 in the revised manuscript (see line 196) and removed this term in order to avoid placing the centre of the array at a fixed point and also allow for irregular array configurations during the optimization process. By relaxing our geometrical constraints less bias is introduced also evident by our optimal model in the revised manuscript.

7. Another issue arises from the application of equation 2 to a set of seismic sources scattered across a region nearly 5° in length. The authors did not take any measures to exclude sources whose nodal planes may be aligned with the array, a factor that can significantly distort beamforming amplitudes. Designing a seismic array under such conditions is challenging, especially since the authors did not account for these effects in their approach.

   It is true that we aim to cover a wide range of sources and locations and depending on the source mechanism characteristics some locations may not be resolved as well as others. We may design another array to the north in the future, in order to focus on the more distant earthquakes presented in this study. Nevertheless, we do not want to exclude earthquake sources with mechanisms that we already know that exist in the study area. Therefore, we added new text to discuss these limitations (see lines 215-223). It is worth highlighting that we reduced the total number of seismic sources since we removed the more distant sources in our revised manuscript based on a comment of Reviewer C who argues that a much wider aperture array is needed in order to locate events in such distances, but we are limited by the dimensions of the island.

8. These limitations are reflected in the array geometries and performance metrics. For example, Table 2 shows 2 pairs of seismic stations are aligned along identical latitudes and one pair of stations are aligned in identical longitude, which is undesirable in array layouts. The array response function presented in Figure 7b is also difficult to evaluate, given the narrow slowness range shown. The choice of a cutoff at ± 0.4 s/km may obscure potential side lobes or resolution limitations and should be more thoroughly justified.

   The Reviewer is right about arguing that some stations were aligned in latitude or longitude in the original manuscript as a result of the small array aperture, which is not the case in the optimal model obtained in the revised manuscript. In addition, we increased slightly the ± 0.4 s/km slowness range in our figures to adequately cover any side lobes and we calculated transform functions in different frequency bands in the revised manuscript (for example see Fig. 6).

9. A critical aspect ignored in the research is the effect of seismic noise. In fact, the authors included white noise on the synthetic waveforms but did not simulate the SNR in the array. In such approaches, it is critical to address this topic to take into account noise levels at potential deployment sites as demonstrated by Karamzadeh et al. (2018).

   The Reviewer argues that instead of simply adding random noise in the synthetic waveforms, a better approach would be to add different levels of noise *based on a realistic noise model for each site in order to simulate the signal-to-noise ratio. We agree in principal with the Reviewer's comments and the reason that we did not follow such approach in the original manuscript was that there is only one station installed in the island. Therefore, a noise model would had to follow some assumptions, which we did in the revised manuscript. We added new text in the "Synthetic seismograms and waveform processing" section in order to explain how we built our noise model (see lines 155-164 and Fig. 2).*

10. Perhaps most critically, the results presented in Figure 10 show that the optimized array performs no better than two non-optimized - a cross and a rectangular array - in terms of beam power, backazimuth estimation, and event mislocation. This is a strong indication that the optimization procedure did not lead to a meaningful improvement in array design. I expected distinct results from the cross and rectangular seismic arrays in contrast to the optimized design. It raises a fundamental question: if the optimized geometry yields results that are indistinguishable from those of non-optimized layouts, what is the practical value of the proposed approach? This outcome suggests that either the optimization was over-constrained, or that the criteria used in the objective function do not capture key factors that influence array performance.

    Overall, we agree with the Reviewer that the initial objective function was over-constraining the optimal model, thus, we removed a few terms from equation 2 that were associated with spatial constraints. This way, we obtained a larger aperture optimal array that now shows small but clear differences in backazimuth and location errors. We believe that if no spatial constraints were not applied an even better performance would have been possible, but the concept of the current study is to present how to take spatial constraints into consideration (see Fig. 10 and lines 405-413). Moreover, since we made so many changes in our algorithm and rerun the optimization routine we updated all the relevant figures (Figs. 4, 5, 6, 7) and text in the "Results" (see lines 263-273, 277-335) and "Discussion" sections (see lines 366-382).

1.2 Minor comments

1. lines 39-40: "As a consequence, seismic arrays and local networks of seismic stations mainly differ by the techniques used for data analysis". The distinction made between arrays and networks is misleading. The key difference lies in the array principle, not in the signal processing techniques used.

    We removed this sentence (see line 40).

2. lines 45-51: The references on seismic array applications are too limited. Many foundational and recent contributions are omitted and should be included for proper context.

    We added new references (see lines 43-53).

3. lines 87-92: This section digresses from the main topic and could be removed to improve focus.

We removed this part (see line 86).

4. Fig. 2b: This figure appears redundant with Fig. 1 and could be omitted without loss of clarity.

   We moved this to the supplementary material. We hope that the Reviewer will accept this correction.

5. Fig. 3a and 3b: These do not contribute directly to the main argument and might be better suited to supplementary material.

   We moved it to the supplementary material.

6. line 141: The term "frequency (f)-wavenumber (k) beamforming" is unclear. Please clarify whether you are referring to standard fK analysis, conventional beamforming, or a hybrid method. These are distinct techniques based on different assumptions, and it is important to specify which is being used and why.

   We agree with the Reviewer that we may have caused some confusion. We corrected the whole manuscript clarifying that the applied technique is beamforming.

7. lines 159-160: This sentence is physically unclear and needs revision to reflect a valid interpretation in the context of seismic processing.

   We changes the text to make it simple and concise (see lines 170-171).

8. lines 172-176: The authors should explain the reasoning for not applying bounds during optimization. This choice should be justified based on expected parameter variability and site constraints.

   We are not sure what the Reviewer means in their comment. Lines 172-176 in the original manuscript offer a general description of the NA tuning (see Section 4.1 for details).

9. Fig. 4: The figure would benefit from labeling the expected P-wave and SH-wave arrivals in panels 4a and 4c, respectively.

   We added vertical lines to highlight this (see Fig. 3 in the revised manuscript).

10. line 158: paragraph (Ethical citation issue): The use of the Neighbourhood Algorithm and Voronoi cells needs proper attribution. Please cite Sambridge (1999) and Okabe et al. (1992) where appropriate, especially alongside Lentas and Harris (2019). The Neighbourhood Algorithm is a key component in this optimization context, and proper citation is essential.

    Line 158 in the original manuscript does not refer to the Neighbourhood Algorithm. In fact, we had already cited Sambridge 1999, (see lines 164 and 357 in the original manuscript, now in lines 176 and 425 in the revised manuscript). We added Okabe et al. 1992 (see line 180).

11. Model Parameters Table: A table listing all input parameters used during modeling is missing. Including this would improve clarity and reproducibility.

    We added Table 2.

12. Fig. 7a, 9a, and 9b: These are visually dense and hard to interpret. Consider reformatting or simplifying the visual design to better highlight array geometry.

    We simplified these figures by removing the colour-scaled topography and keeping only the altitude contours. We removed the yellow tiles and black circles from the original figures. We only added the noise model, but we believe that the figures are already easier to understand (see Figs. 6 and 9 in the revised manuscript). We hope that the Reviewer will accept our changes.

13. Fig, 8a and 8b: Consider merging into a single panel using numerical labels and color codes to convey both backazimuth differences and dislocations.

    We did this by using different beachball sizes for the backazimuth difference (see Fig. 7 in the revised manuscript).

14. Co-array analysis: The addition of co-array plots for each tested configuration would provide valuable insight into the spatial performance characteristics of each array geometry.

    We added Fig. 8 and Figs. S7 and S8 in the supplementary material, as well as new text in the revised manuscript (see lines 297-303, 324-331).

2 Reviewer C - Dr. Roberto Cabieces Díaz

2.1 Major comments

1. The synthetic analysis in the study focuses on waveforms generated in the 0.3-1.0 Hz frequency range, applied to an array with station spacing of several hundred meters and an overall aperture of 1.7 km. While the resulting Array Response Function (ARF) is optimized, the main lobe width (approximately 0.1 s/km) appears too broad to realistically resolve and locate events at distances between 100 km and 200 km.

    The Reviewer argues that the inter-station distances and the aperture of the array in the original manuscript is too small in order to locate events in the frequency range applied in the processing. We agree with the Reviewer's comments, thus, we revised substantially our work by excluding seismic sources beyond 200 km distance (see lines 93-99, Fig.1, Table 1 in the revised manuscript, Figs. S1, S2 in the supplementary material) as these will never be located accurately by such an array which is unfortunately limited by the size of the island. We increased the frequency content of our synthetics by including a more detailed local velocity model for the study area (see Fig. 3, lines 149-151) and we reworked the objective function (see lines 196, 199-205). As a result our optimal array layout in the revised manuscript shows a larger aperture (see lines 277-303, 366-382, 397-400, 405-413) and a much more focused beam in the array response function (see Fig. 6).

2. To strengthen the manuscript, it is crucial that the authors demonstrate the performance of the optimized ARF at higher frequencies. Specifically, they should show that it outperforms conventional array geometries and can

accurately determine backazimuth and slowness for real or synthetic events in that frequency range.

We agree with the Reviewer's comment in principal, therefore we superimposed a regional model with seven layers for the crust on top of the ak135 model and allowed for higher frequencies in our synthetics. Please note that the local crust model is not open, although we have included the appropriate citation. We added new text in the revised manuscript to highlight this (see lines 149-151, 397-400). Specifically, we raised the frequency content of our synthetics compared to the original manuscript up to approximately 4 Hz (see for example Fig. 3). As a result the optimal array layout now showed clear improvement in backazimuth and location errors compared to the regular shape arrays (see Fig. 10). It is possible that spatial constraints may have prevented the algorithm to come up with better performing layouts but the purpose of this study is to implement spatial constraints in array design optimization techniques within such environments like on small remote islands (see lines 405-413). Regarding the Reviewer's comment on using real events, we have not installed the array on the island yet, thus, we cannot use real data. The purpose of this paper is to allow for array design using synthetic seismograms only, prior to the deployment of the instruments.

2.2 Minor comments

1. line 11: "please include the aim of the array: local and regional seismicity".

   We added this in the abstract (see lines 14-15).

2. line 31: replace "special" with "numerical".

   We fixed this (see line 31).

3. line 31: add reference "Trabattoni et al., 2019".

   We added this (see line 32).

4. line 32: replace "even" with "especially in".

   We fixed this (see line 33).

5. line 34: remove "nothing more".

   We fixed this (see line 35).

6. line 34: have in mind that not always an array is geometrically set. Especially when you want avoid sidelobes in your ARF.

   We changed the text accordingly (see lines 35-36).

7. lines 35-36: waveform semblance and signal coherence is similar. please remove one of the parts.

   We removed waveform semblance (see lines 36-37).

8. line 36: replace "noise" with "random noise".

   We fixed this (see line 37).

9. line 37: replace “special digital signal processing” with “array techniques”.

   We fixed this (see line 38).

10. line 38: be careful because not all techniques are beamformers!. For example MUSIC rely on subspaces.

    We removed beamforming (see line 38).

11. line 39: “Indeed you want to find two things. Increase detectability and estimate the slowness vector”.

    We also mentioned the slowness vector estimation (see lines 39-40).

12. lines 40-42: Not necessary to say another time. In this point the reader already knows the difference.

    We removed this (see line 40).

13. line 52: remove “and financial constraints”.

    We removed this (see line 53-54).

14. line 53: remove “horizontal”.

    We removed this (see line 54).

15. line 53: “set of source mechanisms” - I don’t understand this. Either remove or explain in more detail.

    We removed this (see line 54).

16. line 54: remove “theoretical calculation of its” and add “estimate the transfer function”.

    We fixed this accordingly (see lines 55-56).

17. line 55: remove “sensitivity and”.

    We fixed this (see line 56).

18. line 55: replace “with constant geometry” with “for a specific geometry”.

    We fixed this (see line 56).

19. lines 56-57: I don’t think you need to explain what is the spatial aliasing in a paper.

    We removed this (see line 56).

20. line 58: replace “aperture” with “the aperture and the inter-distance between sensors”.

    We fixed this (see line 58).

21. lines 87-92: remove this text.

    We removed this (see line 86).

22. Fig. 2: send it to the supplementary material.

    We moved this to the supplementary material.

23. line 124: “topography” - If you do not search in elevation, why are you considering the topography?.

    We now take into account the stations’ altitude in synthetic waveforms since this was a request by Reviewer B. Thus, we left the word in the text.

24. line 124: replace “of” with “in”.

    We fixed this (see line 121).

25. lines 128-129: “for obvious reasons” - Not so obvious, there are OBSs? you need to make sentence with not so non formal style.

    We changed the text accordingly by clarifying that there are no OBS deployments (see line 126).

26. line 130: “high altitude differences” - High altitude compare with what? compare to the inter-station distance? or the array-aperture?.

    We removed this since it was causing confusion (see line 127).

27. line 141: remove “frequency (f) - wavenumber (k)”.

    We removed this (see lines 140-141).

28. line 141: remove “where the array beam is calculated in the frequency domain”.

    We removed this (see line 141).

29. line 146: “in Schweitzer et al. (2009)” - Please expand this review references for example Rost and Thomas, 2002 or Douglas, Alan. (2007). Forensic seismology revisited. Surveys in Geophysics, 28(1), 1-31. https://doi.org/10.1007/s10712-007-9018-7.

    We added new references (see line 146).

30. line 160: “best-fitting depth” - How do you estimate the depth?

    We added new text to explain this (see lines 171-173).

31. Fig. 4: I think it is also necessary to add a slowness map (S_x, S_y [s/km]) for the maximum power.

    We added slowness maps (see Fig. 3 in the revised manuscript).

32. line 200: replace“Tuning parameters” with “Parameter settings”.

    We fixed this (see line 225).

33. line 215: “tuning parameters” - please change this expression to something more formal.

    We fixed this similar to the previous comment (see line 249).

34. lines 245-246: I think you should introduce the ARF definition in methods.

    We feel that introducing the ARF definition in Methods is not so easy at this point as it will change the flow of the text, but we gave a brief definition in the Introduction where we first mention the ARF (see lines 55-56).

35. line 247: "Thus, the array is not expected to show different sensitivity with azimuth" - The different sensitivity is related to the shape of the sidelobe not to the size!

    We rewrote almost the entire section so we removed this sentence.

36. lines 270-272: Figures S3 and S4 do not show significant sidelobes for slowness below 0.4, so there is no clear improvement at least for the the analyzed frequency range

    We increased slightly the S_x/S_y range to ±0.5 s/km in these Figures, we calculated the transfer functions for three different frequency bands (now Figs. S5 and S6 in the supplementary material) and we changed the associated text in the revised manuscript (see lines 314-323).

37. lines 334-335: This is my main concern, why you don't take some real events to make the test. it would really improve your work.

    We replaced this part with new text since we have computed synthetics in frequencies up to 4 Hz in the revised manuscript (see lines 397-400). Moreover, we have not installed any instruments yet apart from the permanent station ANKY, thus, we cannot use real data. After all the point of the paper is to present a method on how to design an array prior to the installation of the instruments.

3 Additional changes

We have made some minor textual changes (without changing the content) to make it easier to read. Changes in Figures according the the Reviewers' comments are followed by appropriate changes in their captions too.