Review Reports

Reviewer A Comments

For author and editor

This article provides a useful account of the suitable designs for arrays constructed from DAS cables, but unfortunately makes over-simplifying assumptions to allow use of a standard synthetic seismogram and array response packages.

A comprehensive account of array stacking using DAS data has been provided by Näsholm et al (2022), corroborated by independent work by Kennett (2022) - already referenced in article. These works demonstrate that the effect of the inclination factors in DAS recordings mean that the behaviour is not simply described by a single array response function but depends on backazimuth and slowness.

The authors endeavour to escape this issue by using straight array segments for which DAS data can be transformed to equivalent velocity (assuming a plane wave).
The transformation factor between ground velocity and strain along cable (e.g. Lindsey et al., 2020)
$H(\omega) = Vx(\omega)/[-cx(kx, \omega)Exx(kx, \omega)]$.
needs knowledge of cx the phase velocity of the wave - which is an unknown being sought by stacking!
Thus there is a hidden unknown that compromises the description of the array response.

The standard array treatment is still somewhat helpful for distant sources, and the observation of the merits of a regular heptagon will be valid.
But, for closer sources where the plane wave approximation breaks down the current treatment does not adequately treat the situation. It is not enough to simply stack using the same approach since the synthetics do not represent actual DAS results.

Figure 3 is somewhat strange - the signal disappears much more rapidly between nominal SNR of 2 and 1 than would be expected. A clearer definition of what is being used is required.

References:

Lindsey, N. J., Rademacher, H., & Ajo-Franklin, J. B. (2020).
On the broadband instrument response of fiber-optic DAS arrays.
Journal of Geophysical Research: Solid Earth, 125, e2019JB018145.
https://doi.org/10.
1029/2019JB018145

Näsholm, S. P., Iranpour, K., Wuestefeld, A., Dando, B. D. E., Baird, A. F., &
Oye, V. (2022).

Array signal processing on distributed acoustic sensing data:
Directivity effects in slowness space.
Journal of Geophysical Research: Solid Earth, 127, e2021JB023587.
https://doi.org/10.1029/2021JB023587

Reviewer Statement

Journal:	Seismica
Manuscript title:	*Performance of synthetic DAS as a function of array geometry*
Authors:	T. W. Luckie and R. W. Porritt
Review submitted:	20 December 2023

SUMMARY

The authors of this work aim at generating a better quantitative understanding of the effects that spatial cable layouts have on distributed acoustic sensing (DAS) based seismology. They place particular emphasis on performance in beamforming- and backprojection-based signal processing approaches.

This is an interesting topic. In contrast to classic seismic array design, there is not yet a consensus established on what the optimal DAS array designs are and what are the most appropriate metrics to assess DAS array designs. There is also a need for more empirical assessments of DAS performance as function of array design and other parameters.

The current paper makes some attempts to assess DAS geometries calculations of the classic array response function, as well as synthetic wave propagation modelling.

MAIN CONCERN

The paper uses the array response function to assess DAS array layout responses. However, as shown in Näsholm et al. (2022) (see Section 3.1 and in particular equations 33, but also equations 16 and 17), the DAS cable directivity makes the classical array response function concept invalid:

For non-rectilinear DAS layouts, we simply cannot parameterize the array response function in terms of a difference $(\mathbf{k} - \mathbf{k}_0)$ between the wavenumber $\mathbf{k}_0$ of the impinging wave and the wavenumber $\mathbf{k}$ of the beam steering (or similarly for the slowness $\mathbf{s}_0$ of the impinging wave and the slowness $\mathbf{s}$ of the beam steering). The same conclusion is reached in Kennett (2022), see the beginning of Section 5.

Hence, instead of an analysis of a generic *array response function*, the DAS layout has to be assessed based on a *steered response* that varies with the source direction and distance for near-field cases and source direction in far-field cases.

Therefore, the bulk of the Results section in the current paper have to be re-analyzed and greatly expanded. I am not sure the conclusion that a heptagon layout is ideal will remain after this analysis.

[Even when just looking at the classical array response function as the authors do in Figure 4, I am not confident that the heptagon in panel C is the one with the largest mainlobe-to-sidelobe ratio compared to the response in panel A – at least not before the calculated numbers of this ratio are provided. As an additional note, I am not fully convinced that the fact that the sidelobes of Figure 4 happen to occur within the expected range of crustal velocities is a main concernt (statement on line 220 in the manuscript) – see, e.g., the example in Figure 4 of the already cited paper Koper et al. (2009).]

CONCLUSION

Given the important methodological insufficiencies mentioned above, I cannot recommend this paper to be published. Still, the author's ambition is relevant and I believe a significantly expanded and revised manuscript has potential to become interesting to the DAS community. I am happy to help out with more detailed and granular feedback once a new manuscript is submitted.

References

B. L. Kennett. The seismic wavefield as seen by distributed acoustic sensing arrays: local, regional and teleseismic sources. *Proceedings of the Royal Society A*, 478(2258):20210812, 2022.

K. D. Koper, B. de Foy, and H. Benz. Composition and variation of noise recorded at the yellowknife seismic array, 1991–2007. *Journal of Geophysical Research: Solid Earth*, 114 (B10), 2009.

S. P. Näsholm, K. Iranpour, A. Wuestefeld, B. D. Dando, A. F. Baird, and V. Oye. Array signal processing on distributed acoustic sensing data: Directivity effects in slowness space. *Journal of Geophysical Research: Solid Earth*, 127(2):e2021JB023587, 2022.

Dear Bradley Lipovsky:

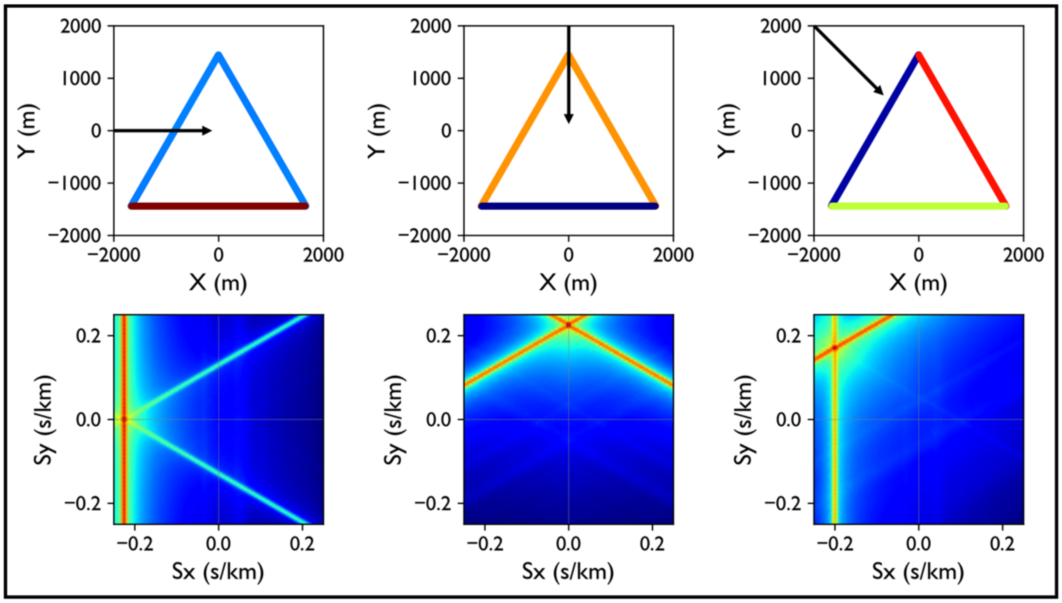
Thank you for allowing us the opportunity to revise our manuscript. The reviewer's comments brought to our attention the DAS-appropriate steering response function described in Näsholm et al. (2022). We have incorporated this methodology into our analysis presented in the updated manuscript. These updated results, while visually different from our original calculations, do not majorly change our original conclusions.

A summary of changes made to the manuscript include:

- Steered response function calculations have replaced traditional array response function calculations in our revised manuscript. The methodology outlined in Näsholm et al. (2022) was implemented (see workflow in Näsholm et al. Section 3.2). To verify our numerical workflow against their results, we replicated their steered response results presented in Näsholm et al. Figure 7 (see Figure below). Thus, our figures have been updated to show these newly calculated steered response functions. Additionally, the Methods and Discussion sections have been updated and expanded.
- Inclusion of mainlobe-to-sidelobe ratios for geometries discussed in the paper, as well as lobe ratio as a function of number of sides for 3 to 25 sided polygons.
- Minor copy-editing throughout the document.

Further comments relating to the Reviewer's specific concerns are below. We were confused about what the Reviewer's specific concern regarding Koper et al. (2009), so we attempted to address it as best we could. If you would like, we can reproduce Koper et al. Figure 4, with the caveat that this would be forward-modeled, synthetic DAS recordings of Pn and Lg.

Thank you again for your time and consideration,
Thomas Luckie & Rob Porritt



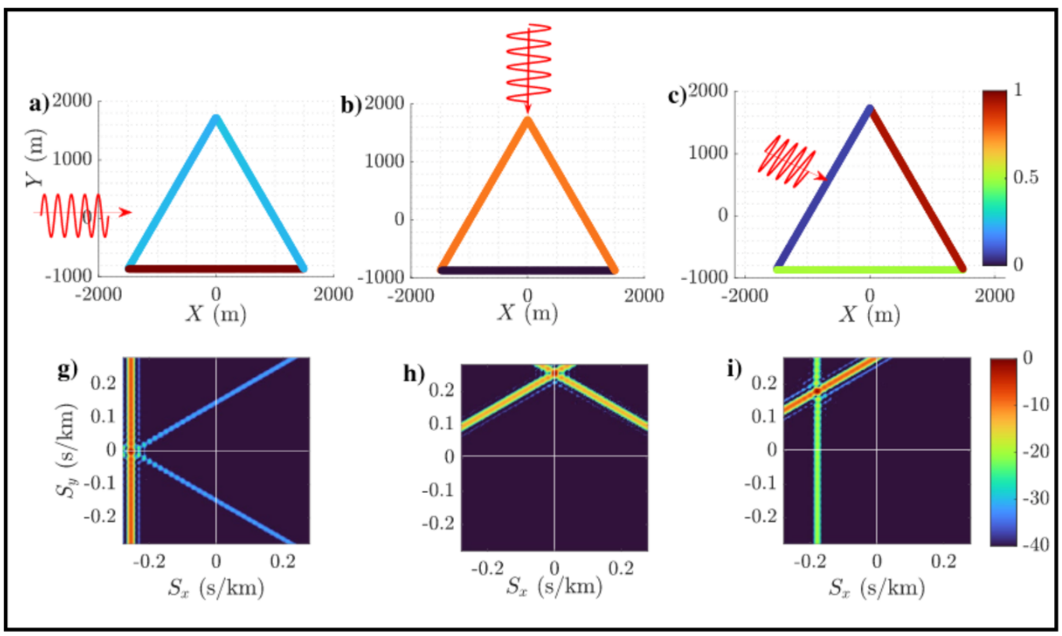


Figure: Reproduction (Top) of Näsholm et al.’s (2022) Figure 7 (Bottom). This confirms that the numerical method as described by Näsholm et al. and as implemented by us are congruent.

Reviewer's concerns (red) and responses (black), bulletized:

- The paper uses the array response function to assess DAS array layout responses. However, as shown in Näsholm et al. (2022) (see Section 3.1 and in particular equations 33, but also equations 16 and 17), the DAS cable directivity makes the classical array response function concept invalid:

  For non-rectilinear DAS layouts, we simply cannot parameterize the array response function in terms of a difference ($k - k_0$) between the wavenumber k_0 of the impinging wave and the wavenumber k of the beam steering (or similarly for the slowness s_0 of the impinging wave and the slowness s of the beam steering). The same conclusion is reached in Kennett (2022), see the beginning of Section 5.

  Hence, instead of an analysis of a generic array response function, the DAS layout has to be assessed based on a steered response that varies with the source direction and distance for near-field cases and source direction in far-field cases.

  Therefore, the bulk of the Results section in the current paper have to be re-analyzed and greatly expanded. I am not sure the conclusion that a heptagon layout is ideal will remain after this analysis.

  - Thank you for bringing this methodological shortcoming to our attention. We have re-calculated the responses presented in Figures 4, 5, 6, and 8B as well as provided updated analysis and discussion based on these new results. While the patterns of the steered responses are drastically different from the original classic array response functions, the core observations and conclusions remain relatively unchanged—that is, odd-sided polygons produce more suppressed side-lobes. This is better quantified in the next bullet point. Additionally, the improvement of beamforming performance can be seen in updated Figure 6, where the heptagon produces a smaller main-lobe compared to the star pattern, at the expense of side-lobe amplitude. These results are consistent with our original conclusions.

- Even when just looking at the classical array response function as the authors do in Figure 4, I am not confident that the heptagon in panel C is the one with the largest mainlobe-to-sidelobe ratio compared to the response in panel A – at least not before the calculated numbers of this ratio are provided.
  - Thank you for suggesting lobe-ratios be presented. We provide these values in the updated Figure 4. While the range of main-to-side lobe ratios presented here is relatively small, from 1.26 to 1.32, two basic observations can be made: (1) ratios

are higher (i.e., better) for odd-sided polygons compared to even-sided polygons and (2) the heptagon produces the highest ratio of the four. This is consistent with our original conclusions.

  - To further demonstrate point (1), we calculated the sidelobe-to-mainlobe ratio for N-sided polygons up to N=25. These new results are presented in Figure 4E. For polygons with N-sides <~10, higher ratios are observed for odd-sided polygons compared to even-sided polygons. For N-sides >~10, this difference is diminished, presumably because the side lengths of the polygons are decreasing and the overall geometry of the DAS array is approaching a circle.

- As an additional note, I am not fully convinced that the fact that the sidelobes of Figure 4 happen to occur within the expected range of crustal velocities is a main concernt (statement on line 220 in the manuscript) – see, e.g., the example in Figure 4 of the already cited paper Koper et al. (2009).
  - There are several fundamental differences between Koper et al.'s (2009) results and the results presented here which can explain the differences in observed slownesses. Firstly, the Yellowknife array footprint used by Koper et al. is ~20-by-20 km (see their Figure 1), whereas our synthetic polygonal arrays are, in the case of our Figure 4, ~500-by 500 m. Additionally, the Yellowknife array instrument spacing is ~2.5 km, where ours is 3 m. Secondly, Koper et al. is analyzing Pn and Lg phases between 0.39 and 0.55 Hz from a source ~1,518 km away (their Figure 4). Our analysis is focused on synthetic first-arrival P-waves generated by a 10 Hz Ricker wavelet from a synthetic source ~116 km away (our Figure 6). The fundamental differences between both the array geometry, source-array distances, frequencies analyzed, as well as expected differences between DAS and seismic data, will influence the respective array response patterns.

Round 2

Reviewer A Comments

For author and editor

The revised version takes into account the directional dependence associated witha plane wave impinging on a DAS array, but does not take account of the fact that this angular behaviour is modulated by the slowness of the arriving wave.
The true response of a DAS array requires full treatment of the signal as recorded by DAS, as treated by Näsholm et al (2022) and Kennett (2022) in their papers.

The authors have assumed that they are able to use ground velocity rather than the DAS strain-rate response, but this requires a transformation that is singular when the waves arrive directly from beneath.
For vertical incident waves there is no DAS response, so that the calculated "steered" response are multiplied by zero.
The situation can be rescued if a statement is made that the displayed features represent just the azimuthal component of the response as a menas of comparing array designs.Specific points:

Abstract (and elsewherte)
"ones of meters" is very clumsy, better as "a few meters"

Figure 3 is somewhat strange - the signal disappears much more rapidly between nominal SNR of 2 and 1 than would be expected. A clearer definition of what is being used as the measure of SNR is required.

Dear Bradley Lipovsky:

Thank you for allowing us the opportunity to revise and further improve our manuscript.

We have identified and addressed four concerns from the Reviewer. The Reviewer's concerns (red) and our responses (black) are summarized below:

- Replace "ones of meters" with "a few meters."
    - Thank you for this suggestion. We have rephrased "ones of meters" throughout the manuscript for clarity.
- Provide a clearer definition of the measure used for SNR in Figure 3 to help the reader understand the behavior of the signal and its relationship to the SNR.
    - Thank you for your observation. We have provided additional context for the SNR calculation on Line 211 to better explain the observed decay in signal amplitude in Figure 3.
- Clarify in the manuscript that the displayed features represent only the azimuthal component of the response, allowing for a comparison of array designs.
    - Thank you for pointing out this shortcoming in the method description. We have provided clarification on Line 180.
- Incorporate the modulation effect of slowness into your analysis to account for the angular behavior of the arriving wave.
    - Thank you for your comment. We were already using the method described in Näsholm, et al., 2022 and Kennett, 2022, so the slowness modulation was already accounted for in our results. However, we explicitly state that this method accounts for the angular behavior of the arriving wave on Line 168 for clarity.

Thank you again for your time and consideration. We look forward to your decision.

Sincerely,
Thomas Luckie & Rob Porritt