

Imaging noise sources: comparing and combining a matched-field processing technique with

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ocean bottom

secondary microseisms

Imaging noise sources: comparing and combining a matched-field processing technique with finite-frequency noise source inversions

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1. Introduction

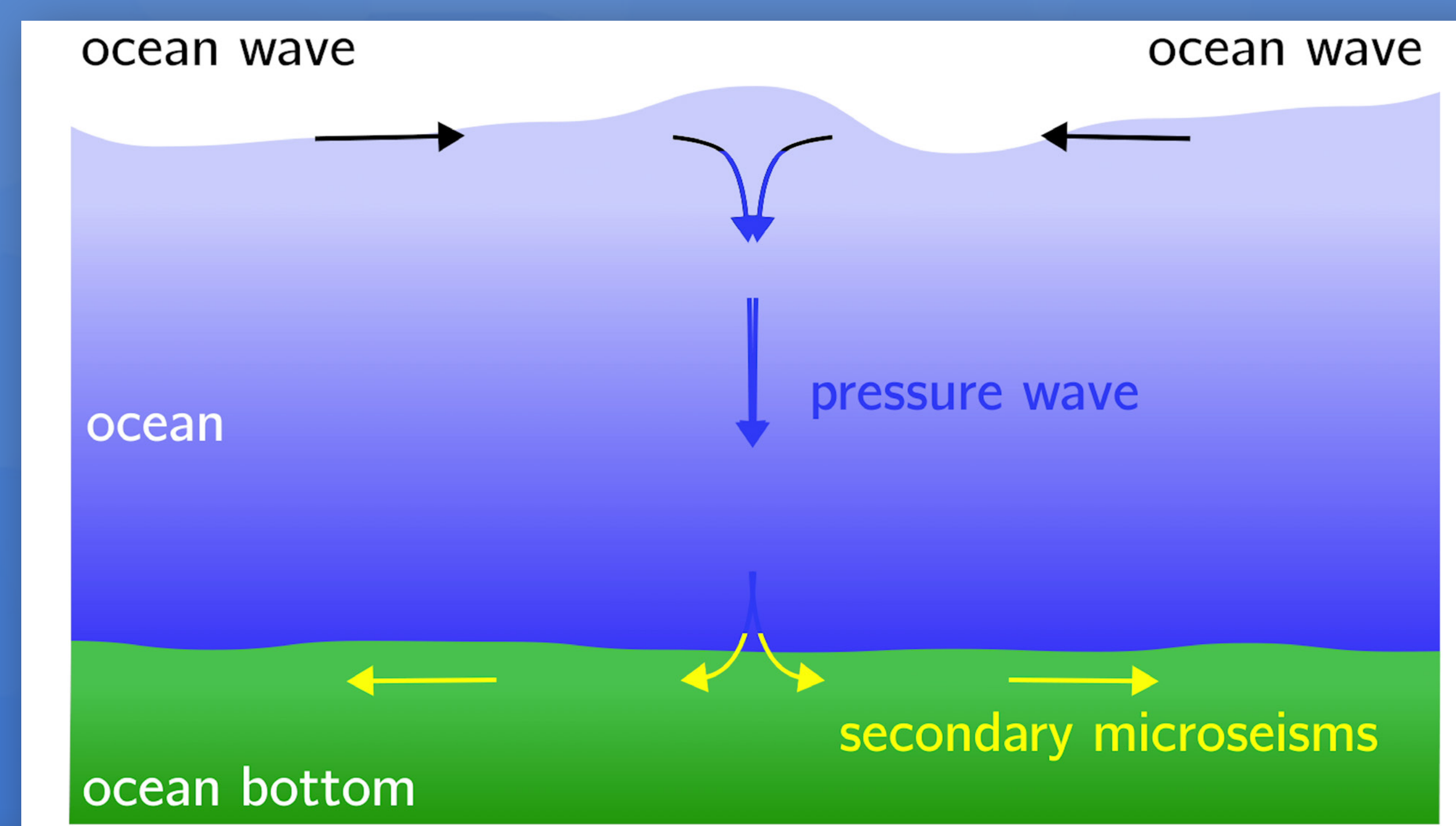
In this study we compare and combine different methods to optimise the localisation of secondary microseismic noise sources on a regional to global scale. Noise source maps can provide important information to improve near real-time monitoring and ambient noise tomography.

Firstly, we look at an efficient data-driven approach called Matched-Field Processing (MFP) which tests different noise source locations and obtains the power spectral density (PSD) by subsequent correlation and stacking.

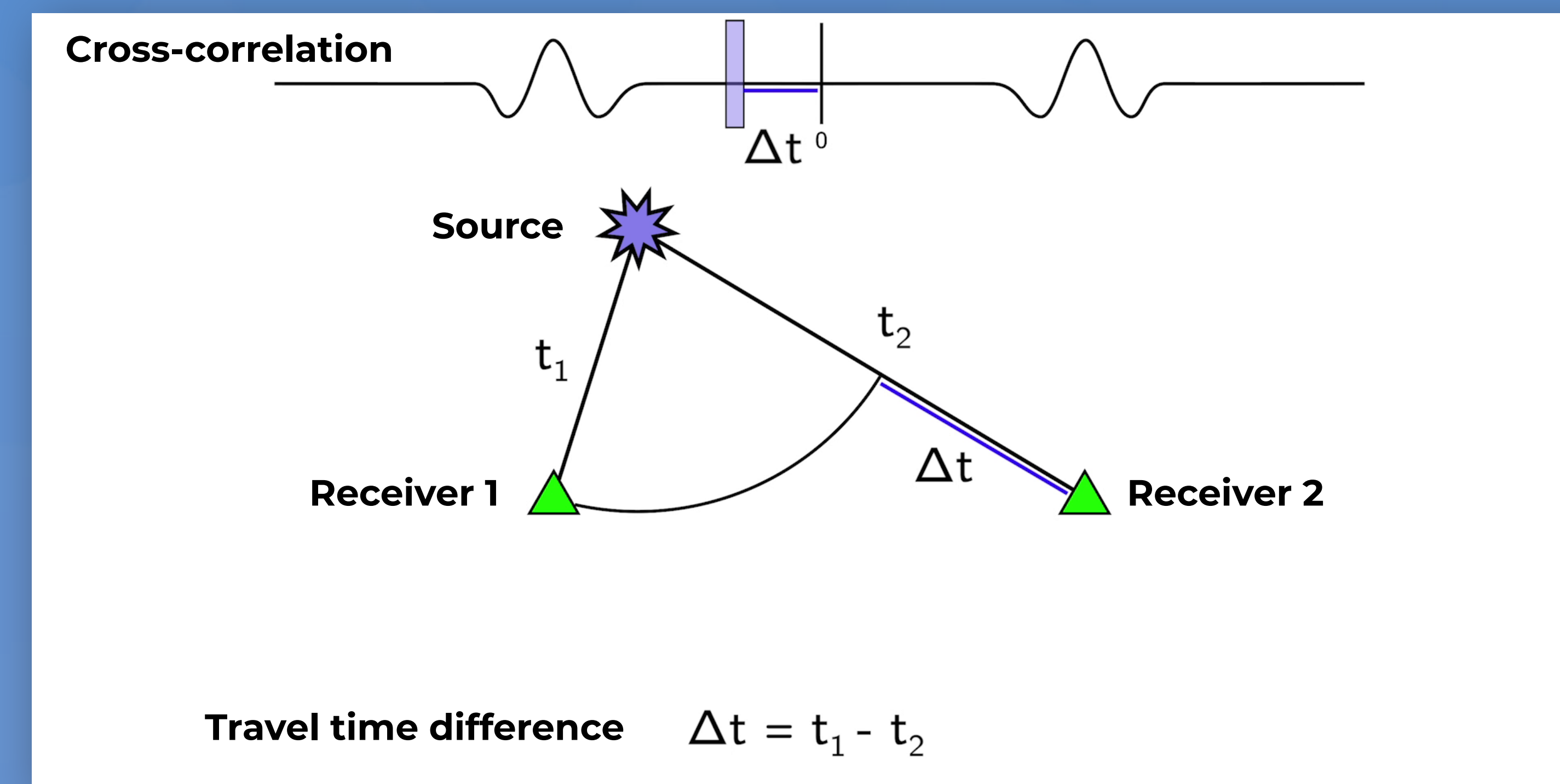
Secondly, a more elaborate finite-frequency full-waveform inversion scheme (Ermert et al., 2020) is used which iteratively updates the noise model to reduce a chosen misfit by numerically modelling correlations and sensitivity kernels. Despite the seemingly large difference, Bowden et al. (2020) discuss how these two methods are actually quite similar and MFP could be treated as the first iteration of an inversion scheme. Since MFP is computationally cheaper, the logical conclusion is to combine the two methods by using MFP to create an initial model for the inversion scheme.

Here, we show results for synthetic and real data applications to illustrate how the combination of the two methods improves the inversion results and leads to a better noise model.

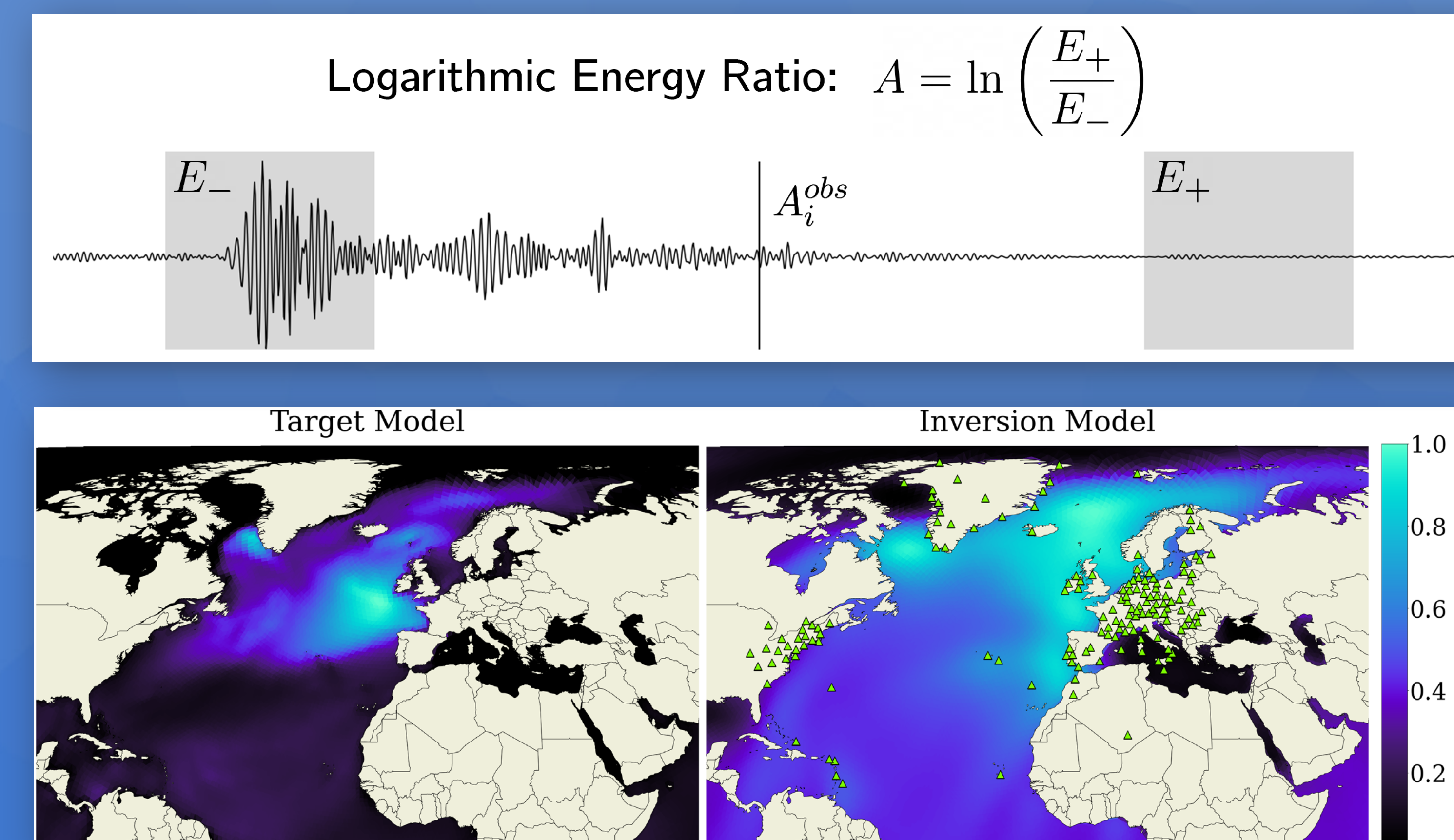
2. Seismic Ambient Noise



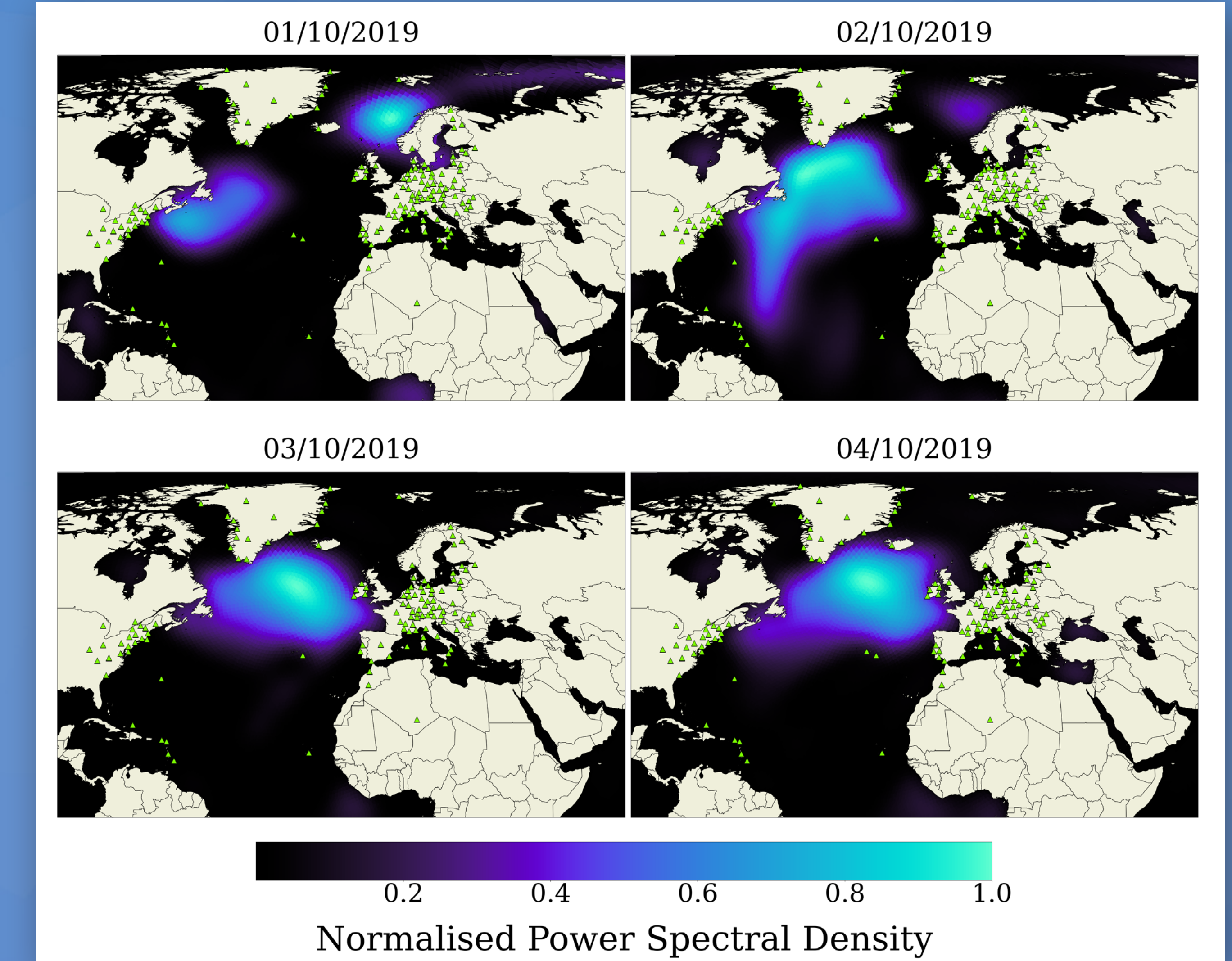
3. Matched-Field Processing



4. Sensitivity Kernel Inversion



5. MFP + Inversion: real data



6. Conclusions & Outlook

Combining two different noise imaging methods by using the MFP maps as starting model for the inversion is feasible and leads to better final noise source distribution maps in the inversion. We apply this approach to a real noise data set for the first 4 days of October to observe the spatio-temporal variations of the secondary microseismic noise sources in the North Atlantic during Hurricane Lorenzo. Due to the efficiency of the inversion framework with pre-computed wavefields and spatially variable grids we aim to create publicly available daily ambient noise source maps on a regional to global scale in the near future.

References

- Bowden, D., Sager, K., Fichtner, A. & Chmiel, M. (2020) Connecting Beamforming and Kernel-based Source Inversion. *Geophys. J. Int.*, 1-14.
- Ermert, L., Igel, J., Sager, K., Stutzmann, E., Nissen-meyer, T. & Fichtner, A. (2020) *noisi*: A Python tool for ambient noise cross-correlation modeling and noise source inversion. *Solid Earth*.
- Gal, M., Reading, A.M., Rawlinson, N. & Schulte-Pelkum, V. (2018) Matched Field Processing of Three-Component Seismic Array Data Applied to Rayleigh and Love Microseisms. *J. Geophys. Res. Solid Earth*, 123, 6871-6889.

2. Seismic Ambient Noise

Secondary microseisms

Secondary microseisms are generated in the open ocean by overlapping ocean waves travelling in opposite directions which in turn create vertical pressure waves that cause tiny displacements along the ocean bottom. The strength of the ocean bottom displacement is directly proportional to the wave height, hence higher waves lead to stronger secondary microseismic noise sources. This results in strong spatio-temporal variations in the source distribution on a daily basis which we aim to image.

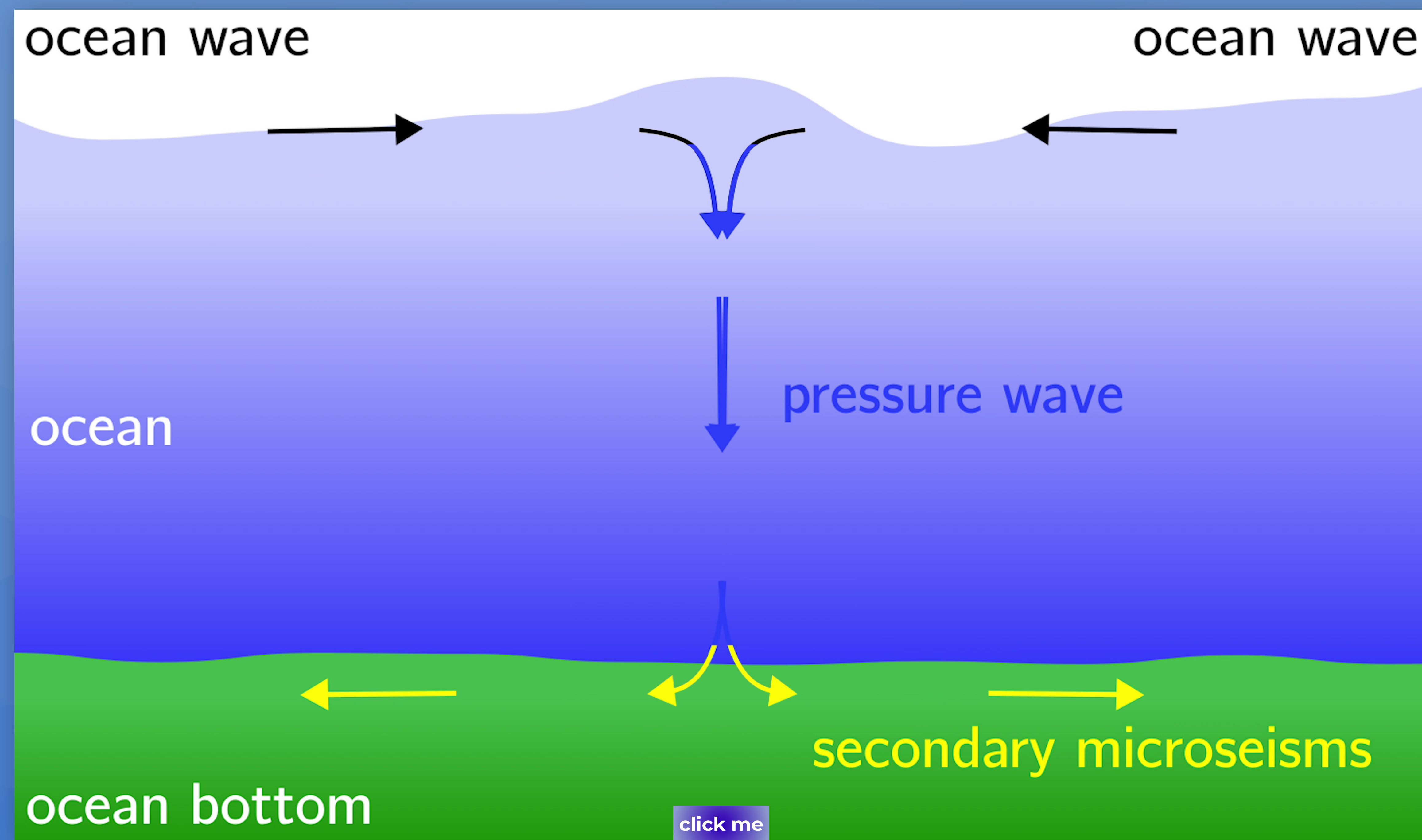


Figure 1: Illustration of the generation of secondary microseisms by two overlapping ocean waves.
Animation: <https://youtu.be/ThGMvzow5QU>

Seismic noise correlations

To study the noise source distribution we look at cross-correlations of ambient seismic noise data. A completely homogeneous distribution would correspond to a symmetric cross-correlation whereas a heterogeneous distribution usually leads to an asymmetric cross-correlation. Thus, the asymmetry in the cross-correlation provides us with important information about the location of ambient noise sources.

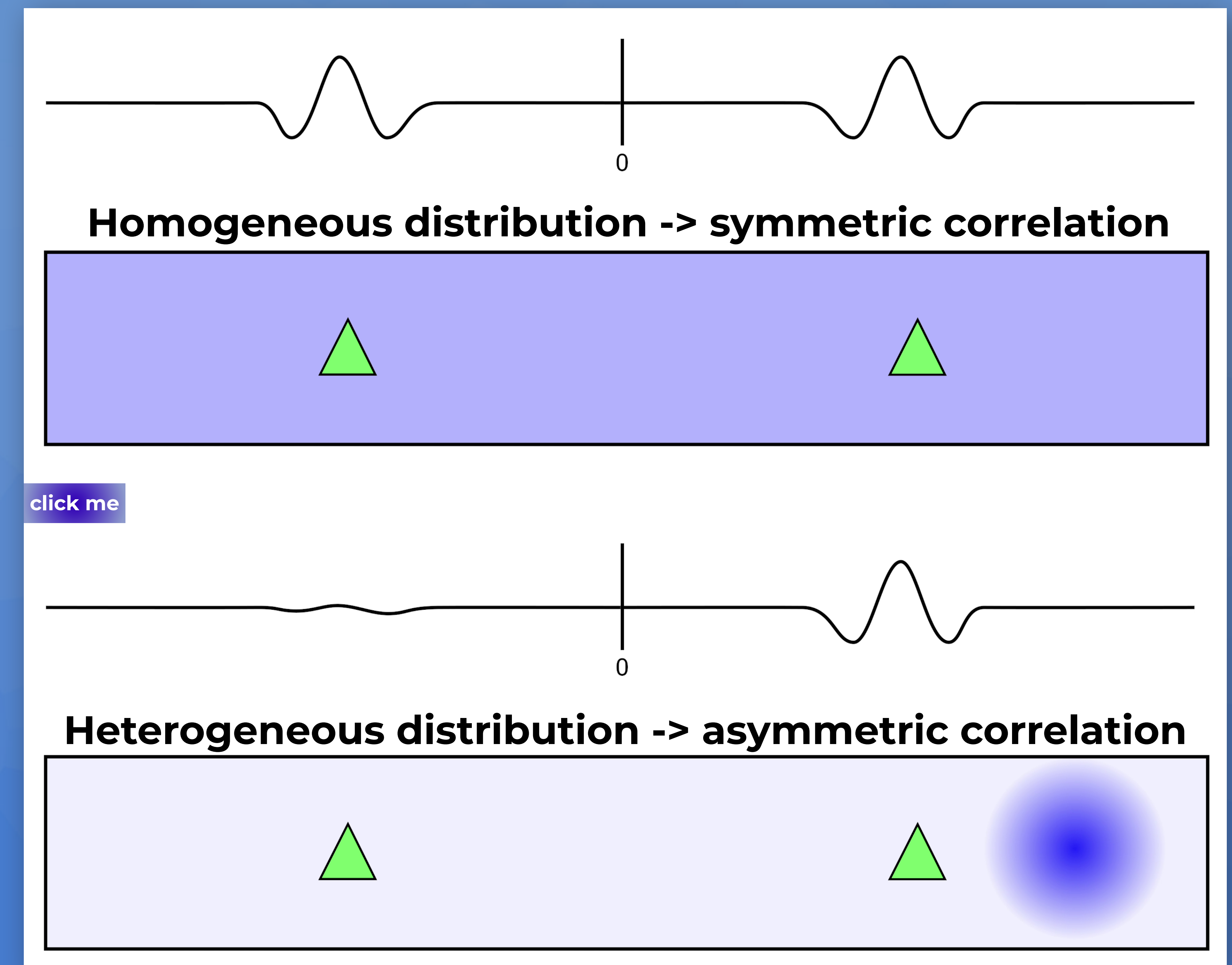


Figure 2: Ambient noise cross-correlation illustration. A homogeneous distribution results in a symmetric correlations, heterogeneous in asymmetric. Animation: <https://youtu.be/w5C9ch0WXVM>

3. Matched-Field Processing

Matched-Field Processing

Various different beamforming techniques to locate noise sources have been developed over the years. We choose Matched-Field Processing (Gal et al., 2018) due its simplicity and ability to map out noise sources on any grid. After picking a surface wave speed, the travel time difference for the station pair is computed. Subsequently, the value of the cross-correlation at this travel time difference is added to the specific noise source location resulting in a map of noise source 'power'. By using a larger array of stations surrounding the expected noise sources, we are able to spatially restrict the locations of the noise sources further.

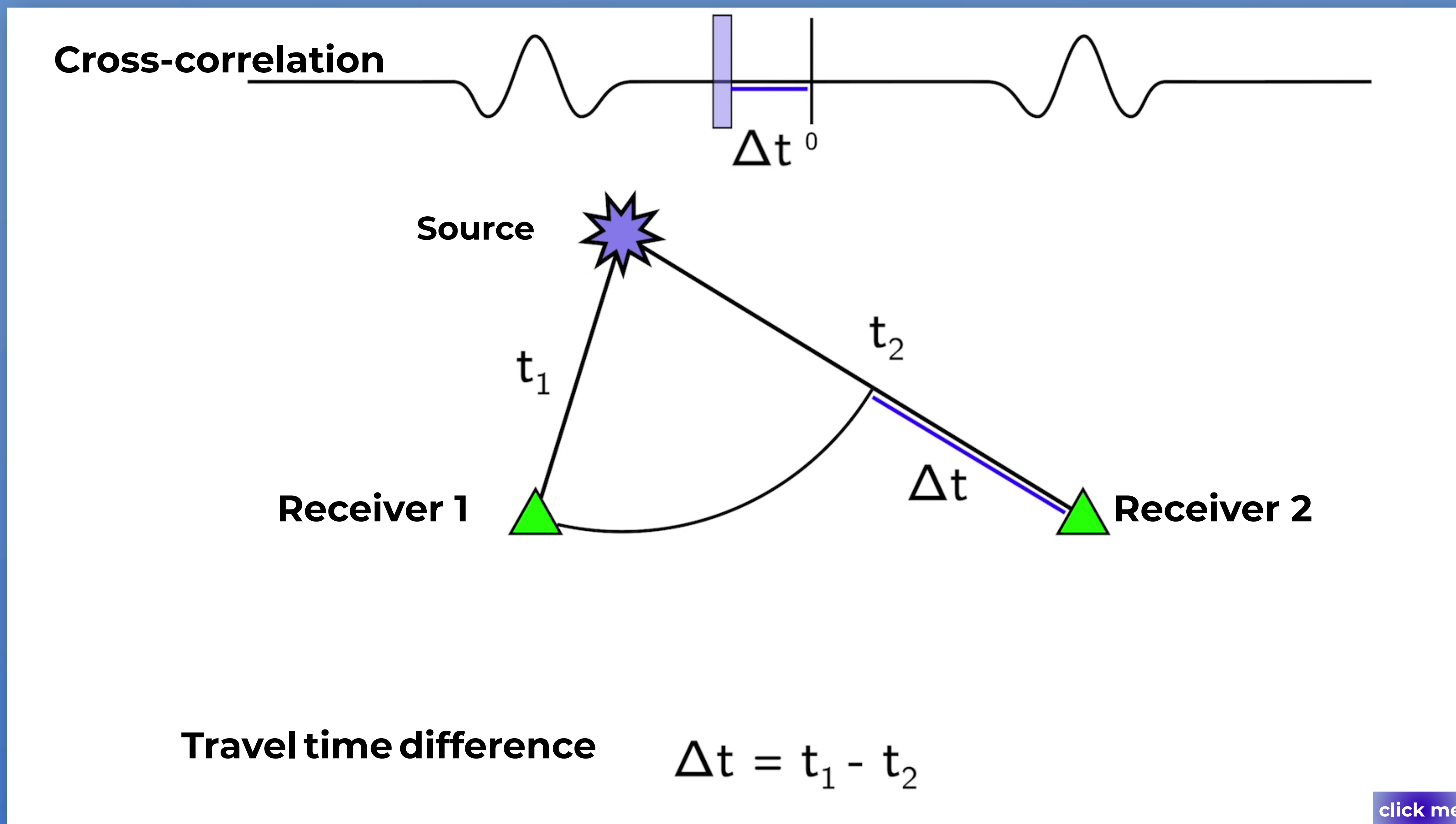


Figure 3: Illustration of the MFP method. The travel time difference is calculated for each source location and the corresponding value is added to the power of that location. Animation: <https://youtu.be/lr4tmck02Yo>

Measurement: square envelope

To increase the signal-to-noise ratio for the MFP maps we take the value of the square envelope of the cross-correlation. This also improves the spatial resolution of the noise source maps.

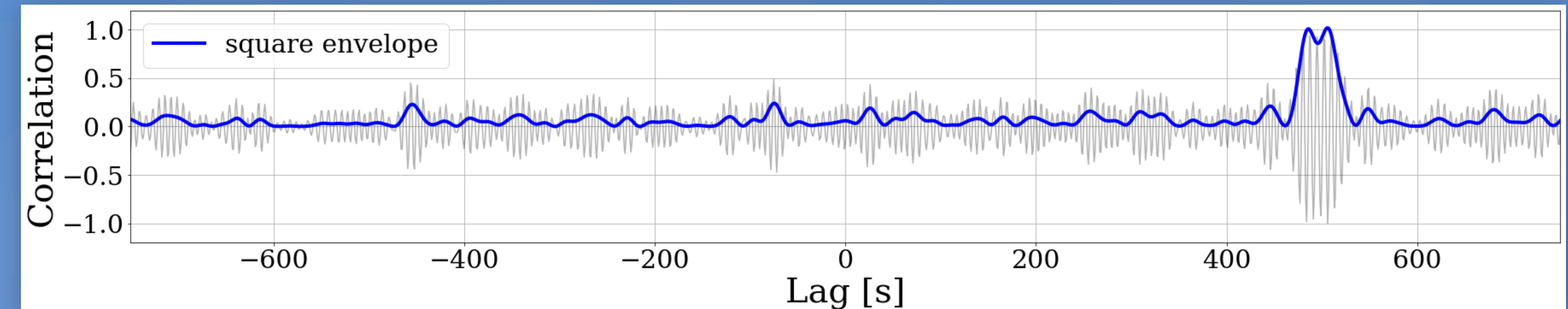


Figure 4: We take the value of the square envelope to compute the MFP maps.

Synthetic Tests

To test this method we forward model a synthetic set of cross-correlations for a target model based on a significant wave height map and add some random noise to make the correlations more realistic. We then apply the MFP square envelope method to obtain a noise source map. As we can see the MFP map contains the dominant noise sources in the North Atlantic from the target model.

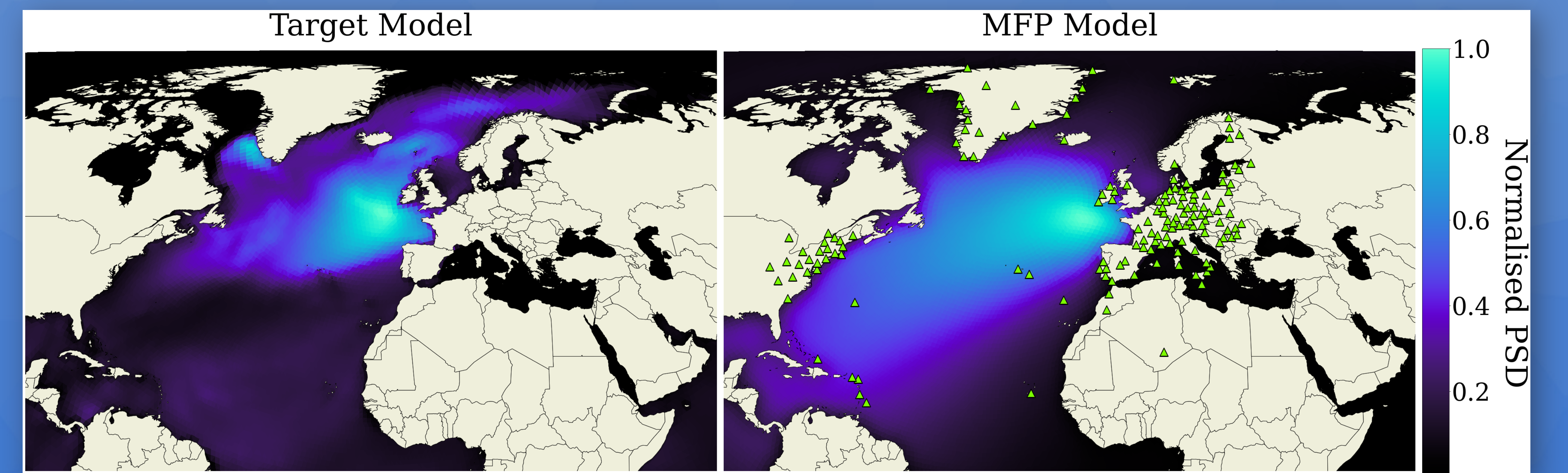


Figure 5: Synthetic test for the MFP square envelope method.

4. Sensitivity Kernel Inversion

Sensitivity Kernel Inversion

Performing a sensitivity kernel inversion for the noise source distribution requires more computational power as we need to model cross-correlations and the corresponding sensitivity kernels in each iteration. To reduce the computational cost of the modelling, we implement pre-computed wavefields and spatially variable grids based on the method by Ermert et al. (2020).

To compute the sensitivity kernels we need to calculate the adjoint sources using a measurement taken in the cross-correlations. As measurement we use the logarithmic energy ratio, which computes the ratio of the energy in the expected surface wave arrival window in the causal and acausal parts of the correlation. The misfit is defined as the L_2 -norm of the two measurements in the synthetic and observed correlations.

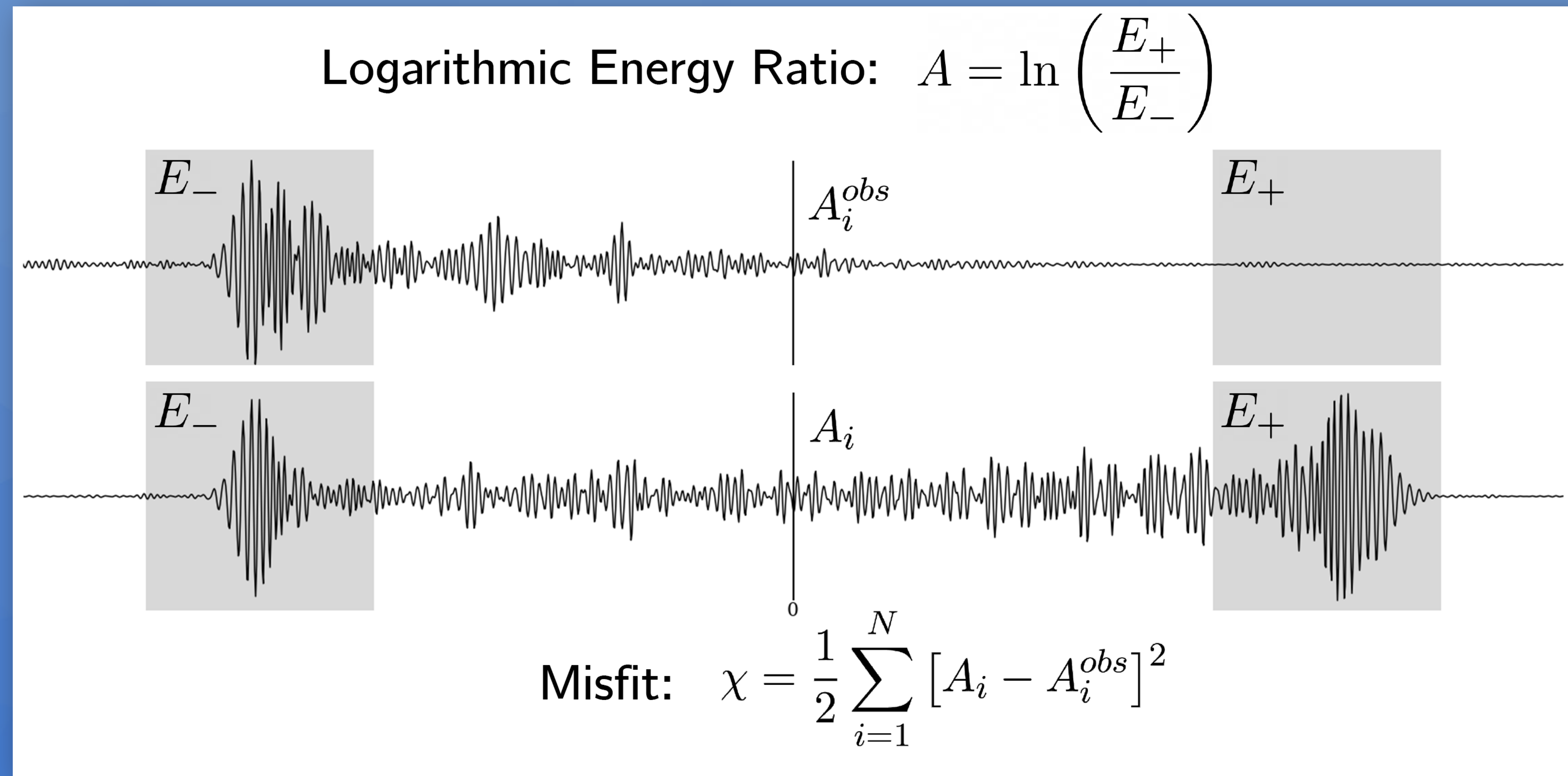


Figure 6: To invert for the noise source distribution we use the logarithmic energy ratio measurement. The misfit in combination with adjoint techniques then allows us to compute the sensitivity kernels.

By summing up the sensitivity kernels for all possible station pairs we obtain the gradient. The gradient tells us where an increase or decrease in noise source strength will decrease the misfit. After performing a step length test and smoothing the gradient we update the initial model and repeat the process until the misfit has converged.

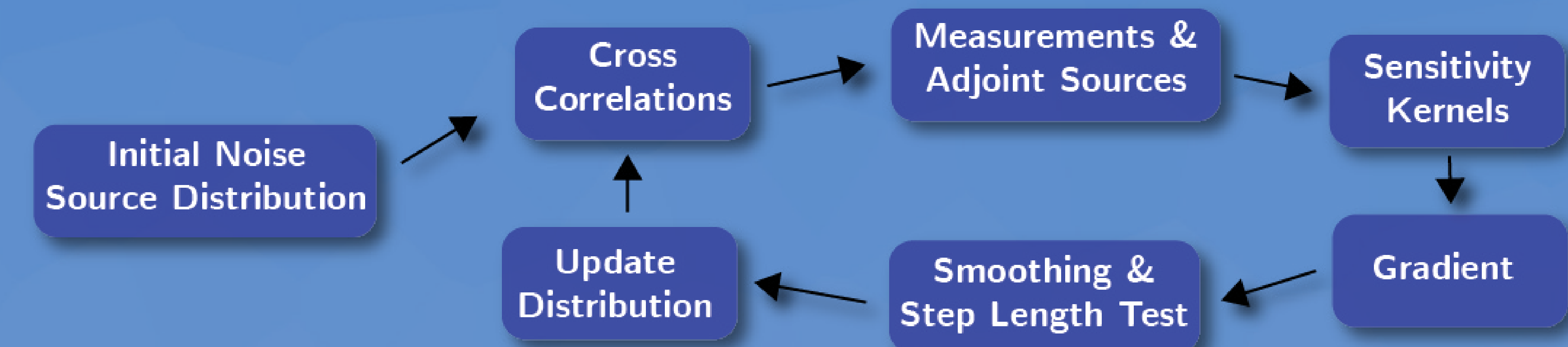


Figure 7: Sensitivity Kernel Inversion Framework

Synthetic Tests

We test this approach with the same synthetic cross-correlation set that we used for MFP before and perform 5 iterations of the inversion scheme. As a starting model we use a homogeneous noise source distribution in the ocean. The final inversion model contains all dominant noise sources from the target model with some additional noise sources in other areas due to the added random noise.

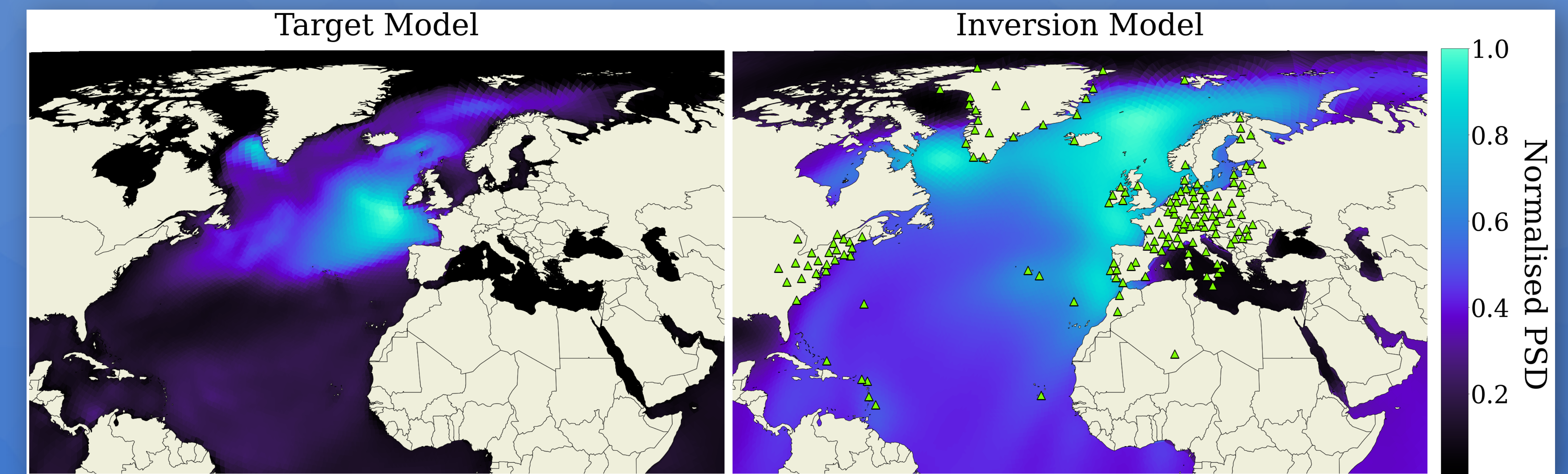


Figure 8: Synthetic test for the sensitivity kernel inversion framework.

5. MFP + Inversion

Combining MFP and Inversions

To combine the two methods we simply run the MFP before we start the inversion and use it as the starting model. This helps to steer the inversion in the right direction and leads to a better inversion model after 5 iterations. In this example we use a real correlation data set from the 3rd October 2019. As a comparison we run the MFP and the inversion with a homogeneous starting model. Combining the two by using the MFP model as starting model for the inversion yields a higher spatial resolution and a lower misfit.

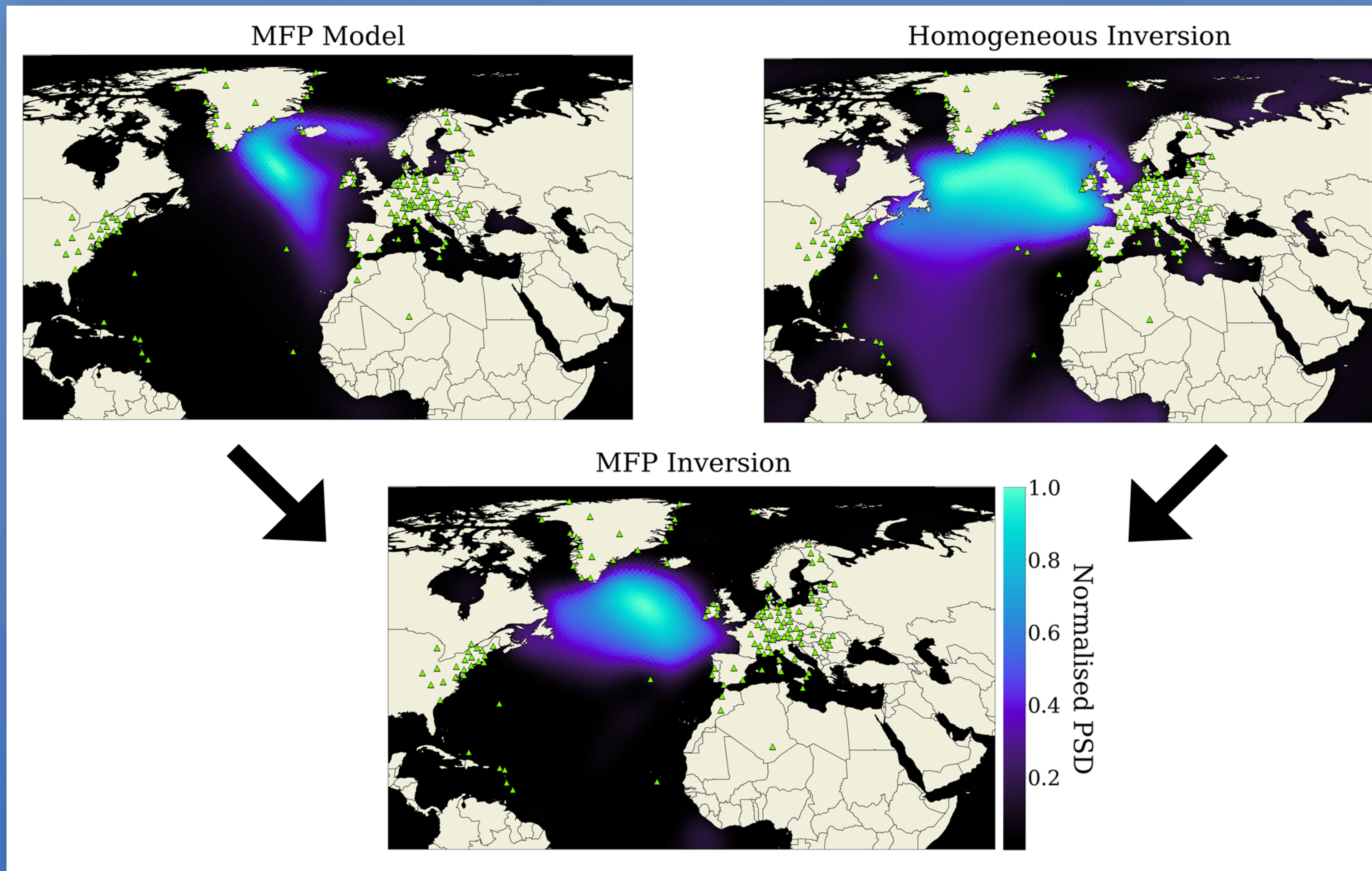


Figure 9: Real data application for the combination of MFP and the sensitivity kernel inversion. The MFP model is used as initial model for the inversion resulting in a higher spatial resolution and lower misfit compared to a homogeneous initial model.

MFP + Inversion: 4 consecutive days

We now apply the combined technique to real data sets for the first 4 days of October 2019. We choose those days as Hurricane Lorenzo was in the North Atlantic at the time which should generate strong secondary microseismic noise sources. Note that the noise sources are not necessarily generated exactly where the storm is as the mechanism requires two overlapping ocean waves travelling in opposite direction.

As the hurricane moves across the Atlantic towards the British Isles we see that the source strength starts to increase south of Iceland and Greenland from the 2nd October. Comparing this to significant wave height maps shows that the areas of dominant noise sources correspond to areas of high waves. The spatio-temporal variations of the secondary microseisms are clearly visible.

Due to the efficiency of the inversion each noise source map was produced in less than one hour on 600 cores, including data download, processing, and cross-correlating. This paves the way for publicly available daily noise source maps.

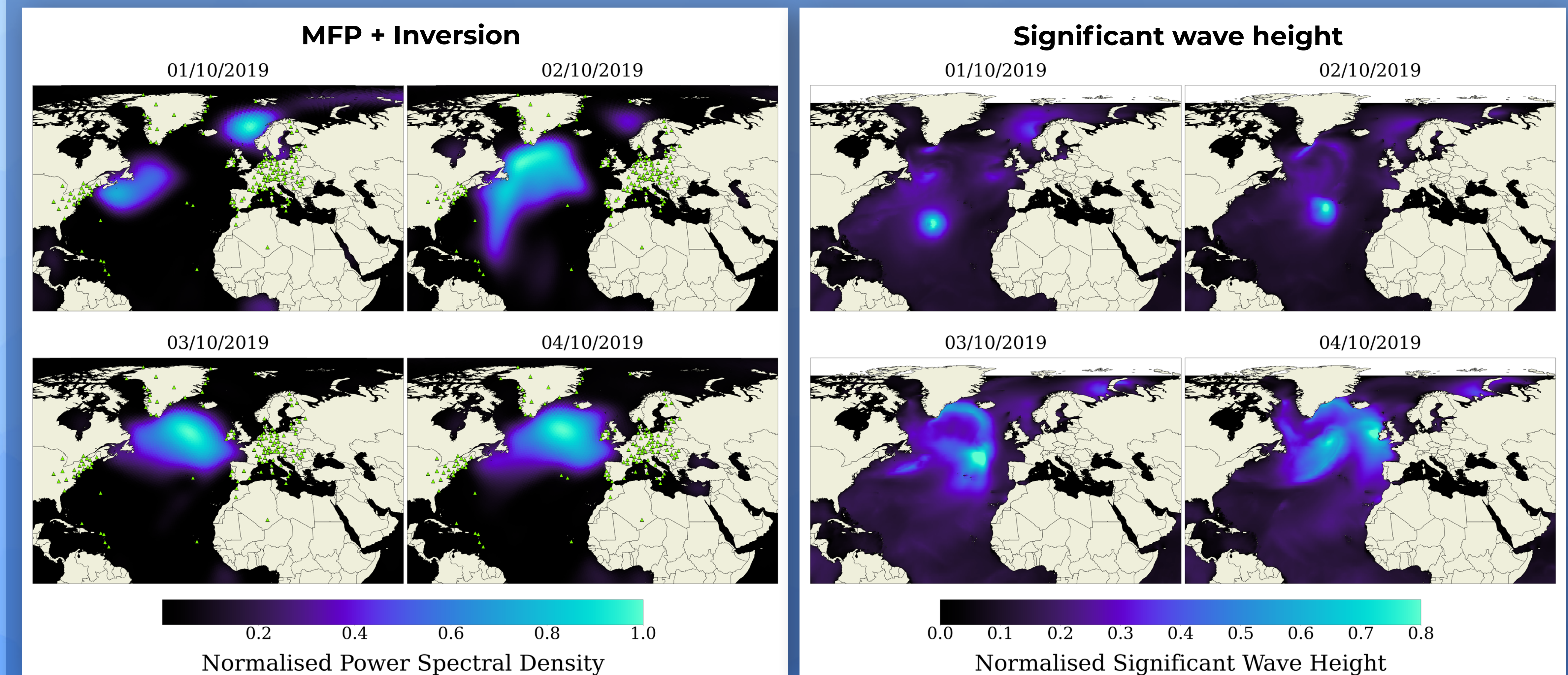


Figure 10: Real data application for the combination of the two methods for 4 consecutive days at the beginning of October 2019 compared to the significant wave height.