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# SANS: Publicly Available Daily Multi-Scale Seismic Ambient Noise Source Maps

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# Outline

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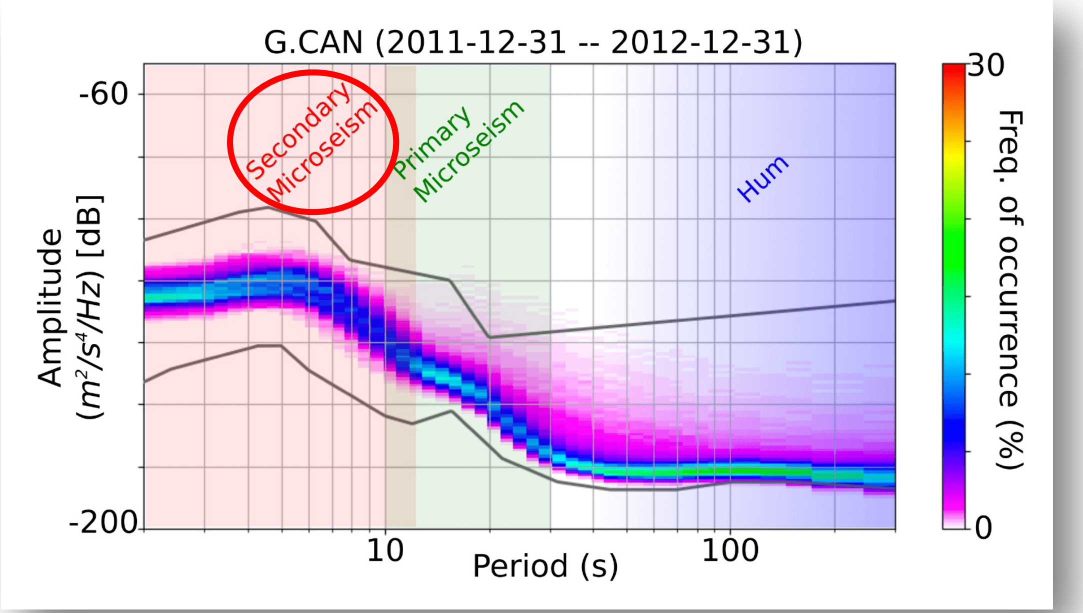
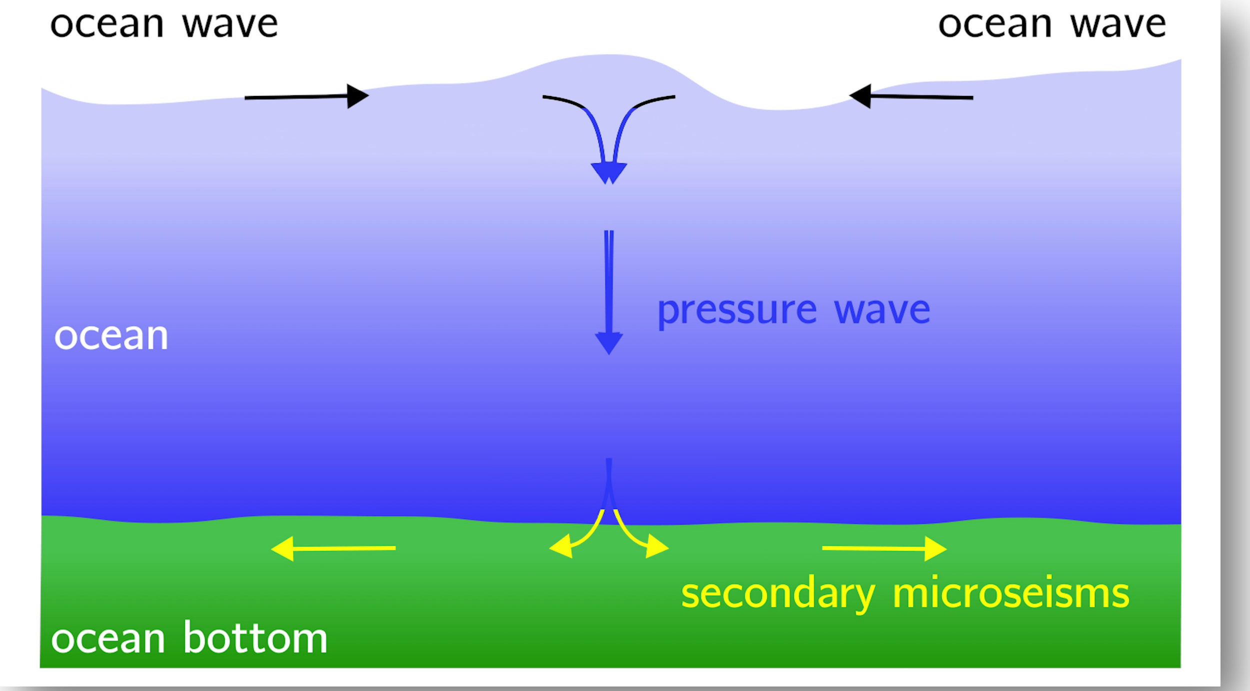
- Secondary microseisms
- Matched Field Processing (MFP)
- Finite-frequency Inversion
- SANS: Publicly Available Daily Seismic Ambient Noise Source Maps
- Conclusions and Outlook

# Secondary microseisms

1. We focus on the secondary microseisms which are in a frequency range of 0.1 – 0.2 Hz.

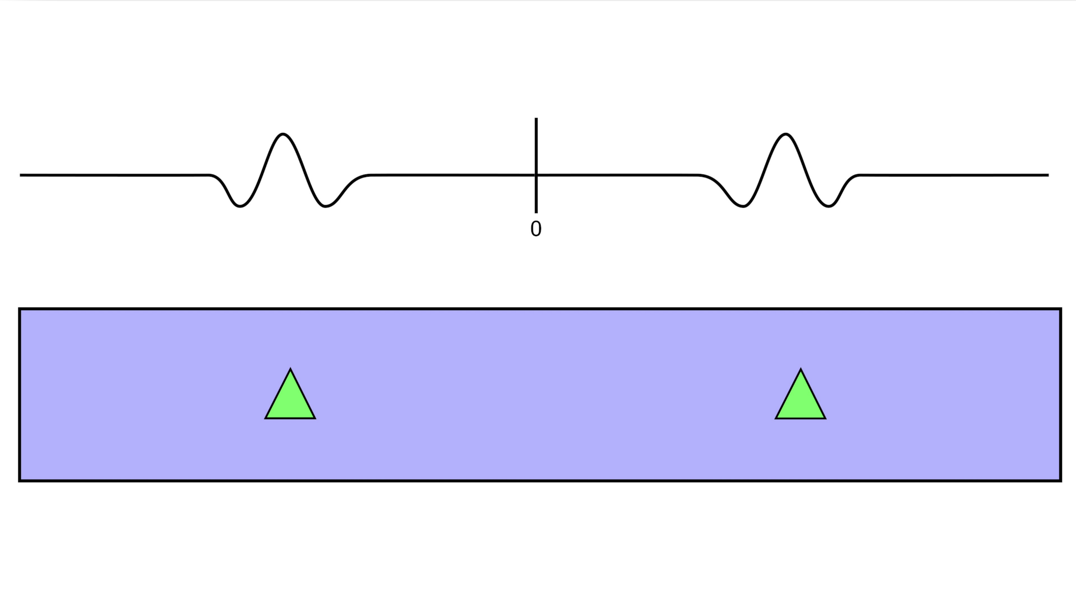


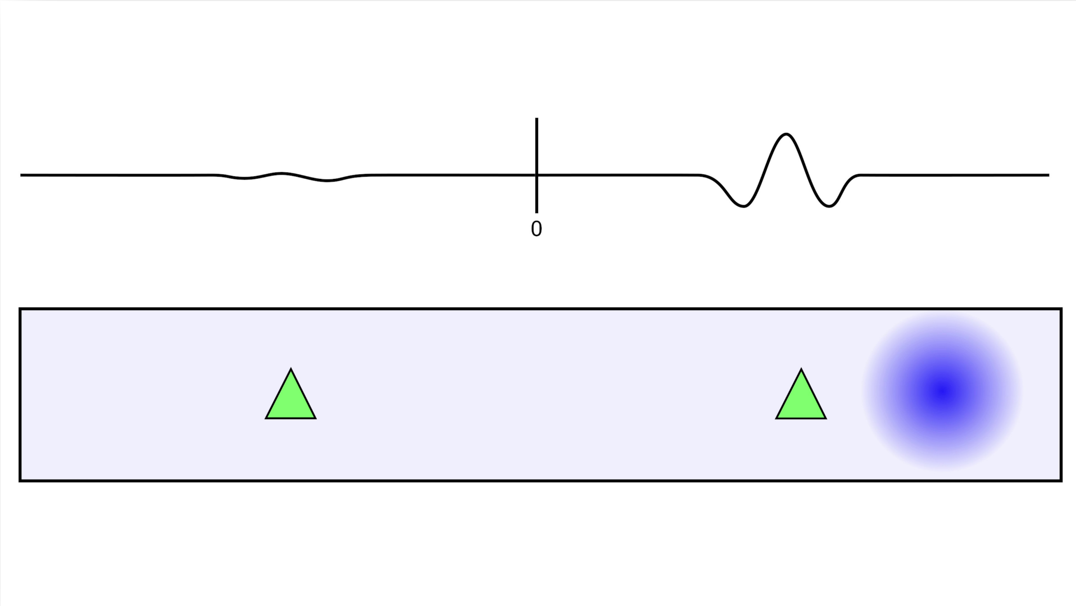




2. Generation mechanism: Two overlapping ocean waves travelling in opposite directions create vertical pressure waves which leads to a tiny displacement at the ocean bottom.

# Seismic Noise Cross-Correlations

1. To study the seismic noise source distribution we use cross-correlations, specifically their (a)symmetry.



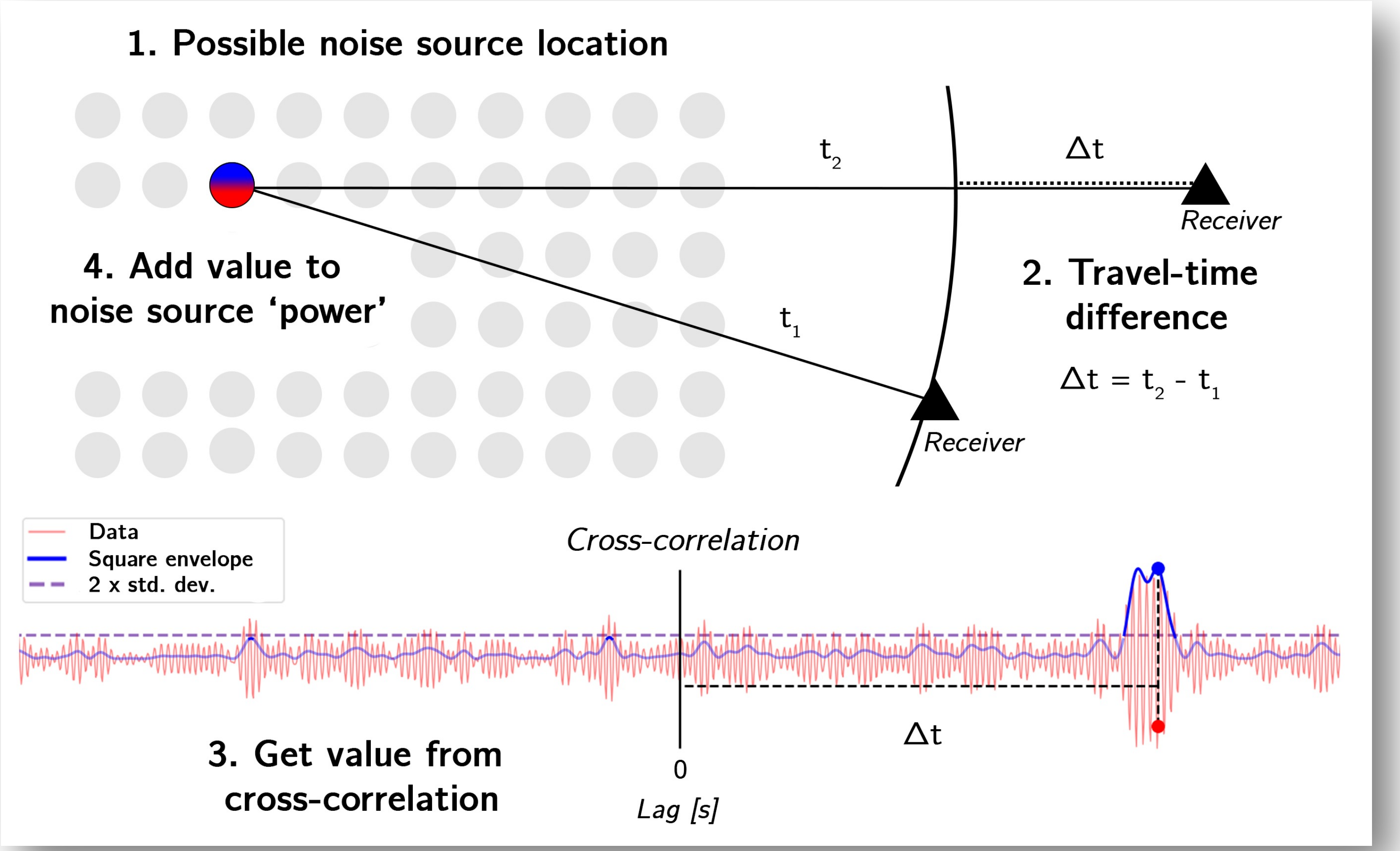

2. If the noise source distribution within the domain is homogeneous we would get a symmetric cross-correlation.

3. A heterogeneous distribution would result in an asymmetric cross-correlation.

# Matched Field Processing



1. One method to locate noise sources is Matched Field Processing (MFP) [1]. It is an efficient data-driven method that allows us to get a rough idea of where the dominant noise sources are.




2. MFP works by iterating over a grid of possible noise sources and calculating the expected travel times to each station.

3. The expected travel time difference indicates at what lag in the cross-correlation we would expect a source for this location given a constant surface wave speed.

4. The value of the cross-correlation (or in our case the square envelope of the cross-correlation) is added to the 'power' of that noise source location.

5. This is repated for all cross-correlations.

# Matched Field Processing

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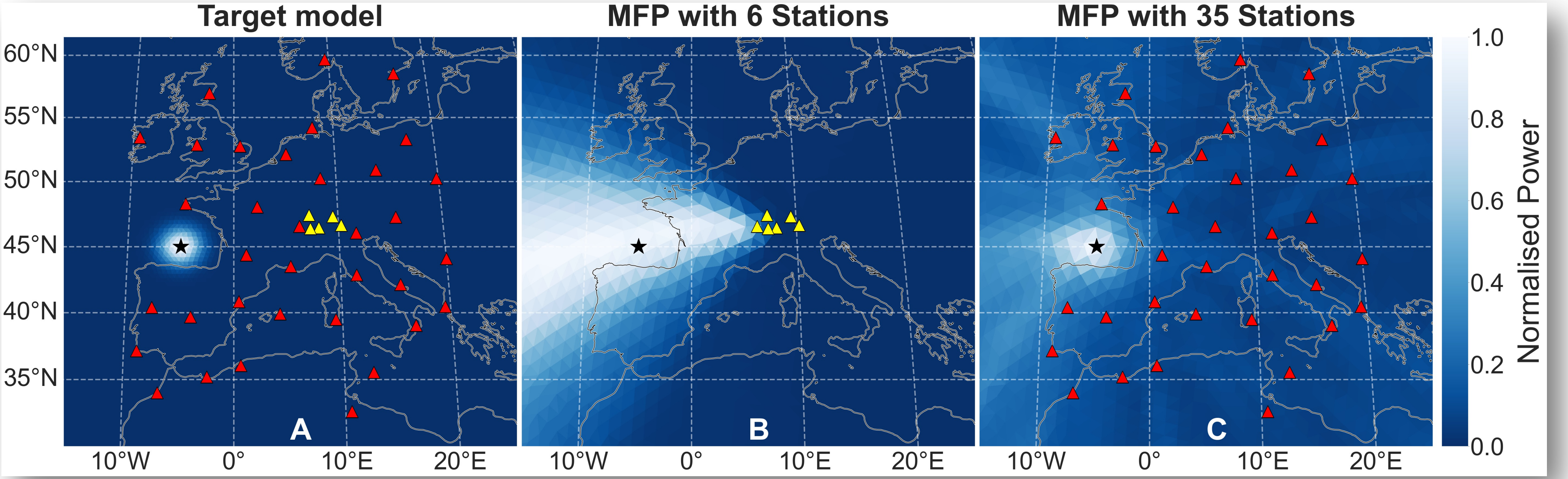
1. Here we show a synthetic example of the MFP algorithm. We forward model cross-correlations using the target model (A) and run MFP for two different station distributions (B) and (C).




2. When the stations (△) do not surround the source (B) MFP is not able to spatially restrict the noise sources but mainly provides a direction.

3. When the stations (▲) surround the source more (C) MFP can also restrict the spatial extent ot the noise source.

# Finite-frequency Inversion: Correlations



1. A more complex method to locate noise sources is to perform a finite-frequency inversion [2,3]. This requires more computational power but models the wave propagation more accurately.

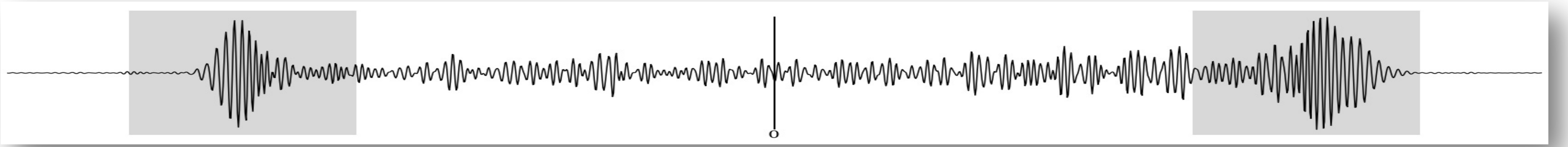
$$C(x_1, x_2, \omega) = \int G(x_1, \xi, \omega)[G^*(x_2, \xi, \omega) S(\xi, \omega)] d\xi$$

C = Cross-correlation wavefield

G = Green's Function

S = Power Spectral Density of Source Distribution

2. This equation allows us to forward model a cross-correlation C for any noise source distribution S if we have the Green's functions G for the stations at locations $x_1$ and $x_2$.

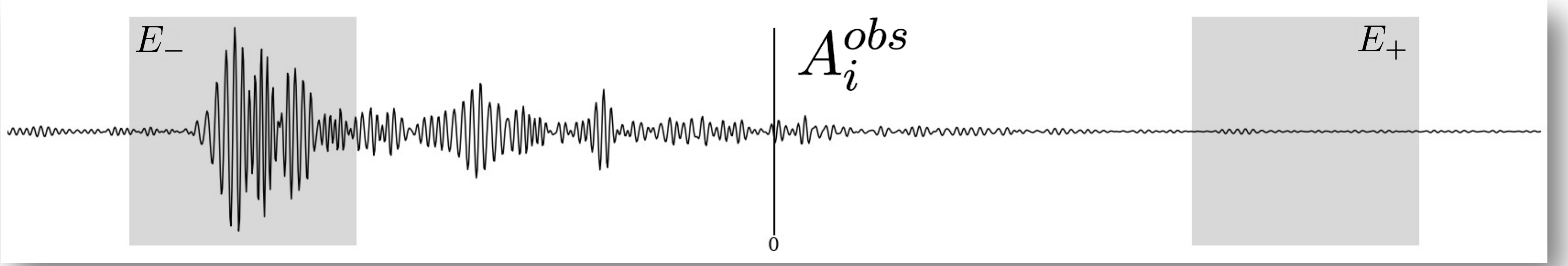


# Finite-frequency Inversion: Measurement

1. For the inversion we use a certain measurement in the cross-correlation: the logarithmic energy ratio. This is chosen due to its relative insensitivity to unknown 3-D Earth structure.

*Logarithmic Energy Ratio*

$$A = \ln\left(\frac{E_+}{E_-}\right)$$




2. It measures the asymmetry in the cross-correlation by taking the natural logarithm of the ratio of energies in the expected surface wave arrival windows in the causal ($E_+$) and acausal ($E_-$) part of the correlation.

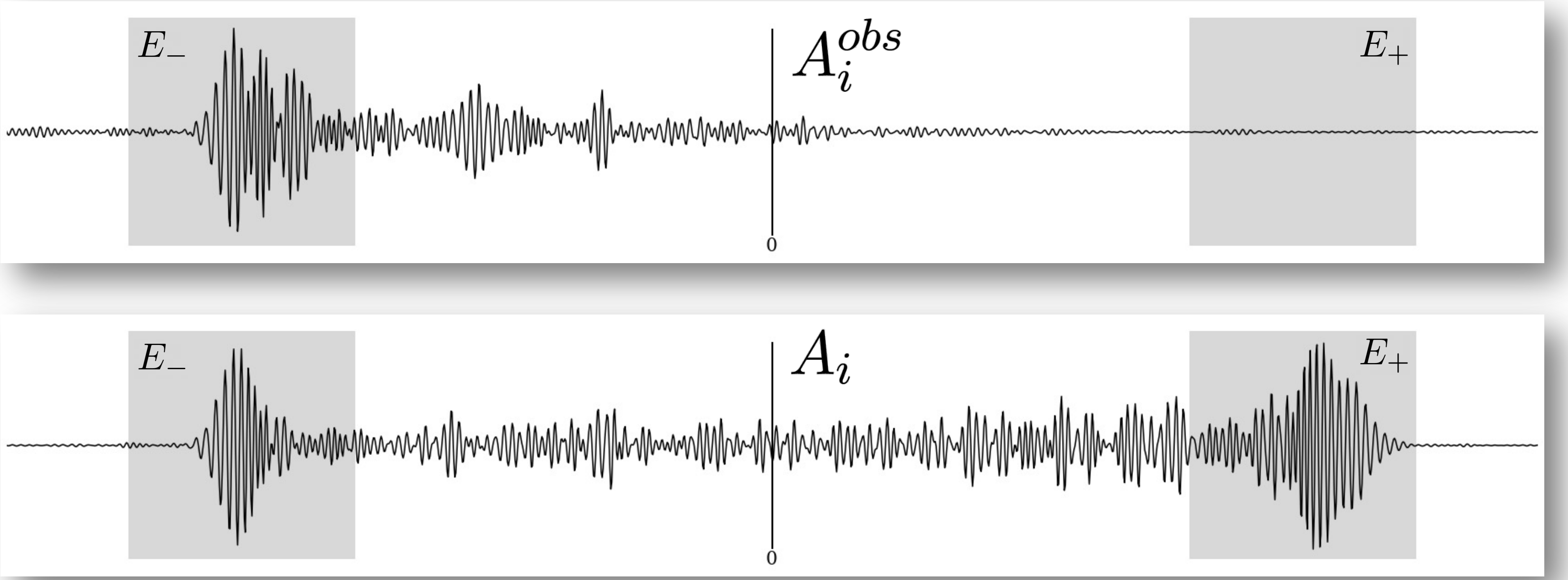
# Finite-frequency Inversion: Misfit



1. We take the logarithmic energy ratio measurement on the synthetic ($A_i$) and observed cross-correlation ($A_i^{obs}$) and compare the two using the $L_2$ norm. We aim to minimise this misfit during the inversion.

*$L_2$ norm*

$$\chi = \frac{1}{2} \sum_{i=1}^{N} \left[ A_i - A_i^{obs} \right]^2$$



# Finite-frequency Inversion: Sensitivity Kernel

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1. Adjoint techniques allow us to use this measurement to calculate the adjoint sources f and thus the sensitivity kernels. They indicate where an increase or decrease in noise source strength would decrease the misfit.

$$K(\xi, \omega) = 2 f(\omega) \cdot (G^*(x_1, \xi, \omega) \cdot G(x_2, \xi, \omega))$$

K = Sensitivity Kernel
G = Green's Function
f = Measurement-dependent Adjoint Source

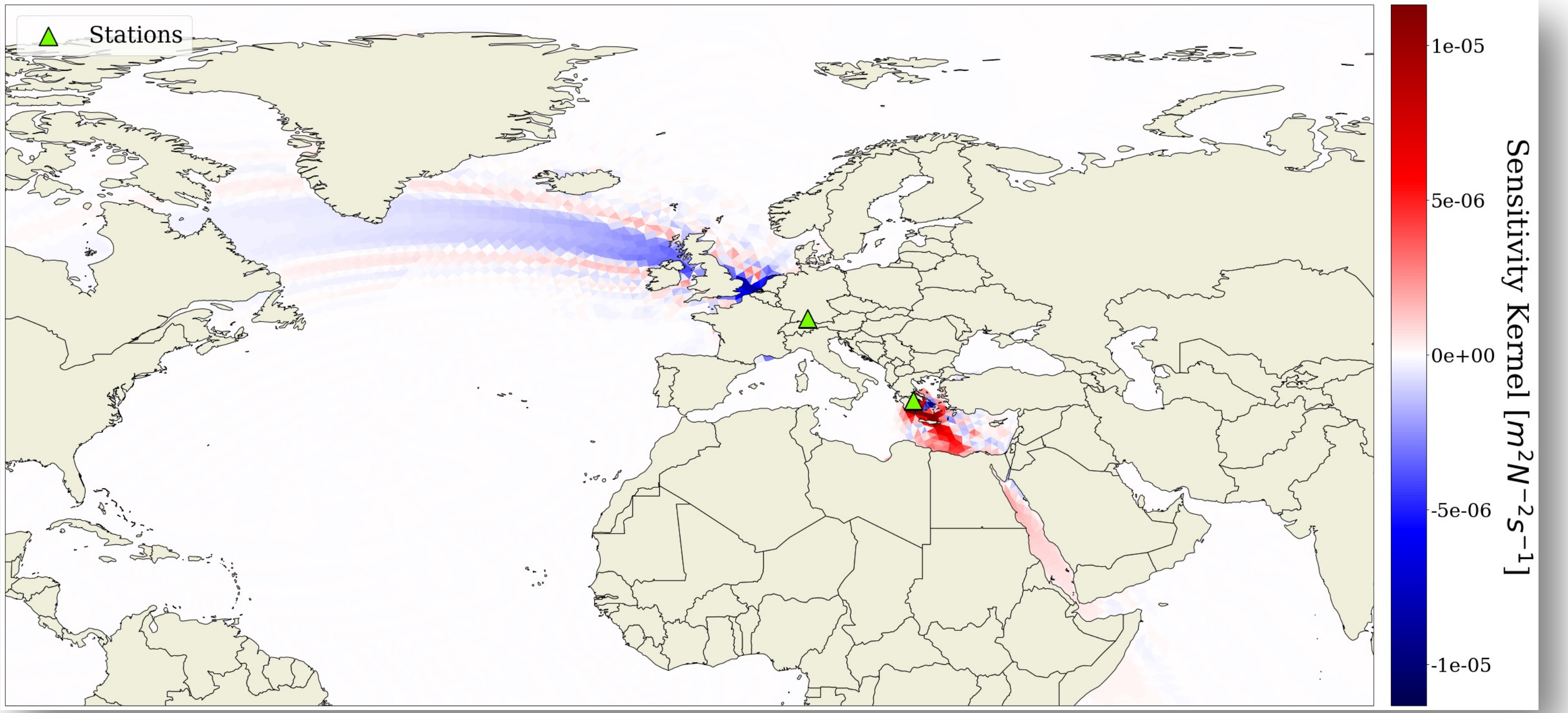
2. Similar to the correlation equation, the sensitivity kernel equation uses the Green's functions G for the stations at location $x_1$ and $x_2$.

3. We reduce the computational cost of the forward model by (i) pre-computing the Green's functions G using AxiSEM with a simple PREM 1-D velocity model and (ii) using a spatially variable grid to reduce the number of source locations that need to be modelled.

# Finite-frequency Inversion: Gradient



1. Here we see an example of a synthetic sensitivity kernel. Blue indicates that an increase in noise source strength would decrease the misfit.



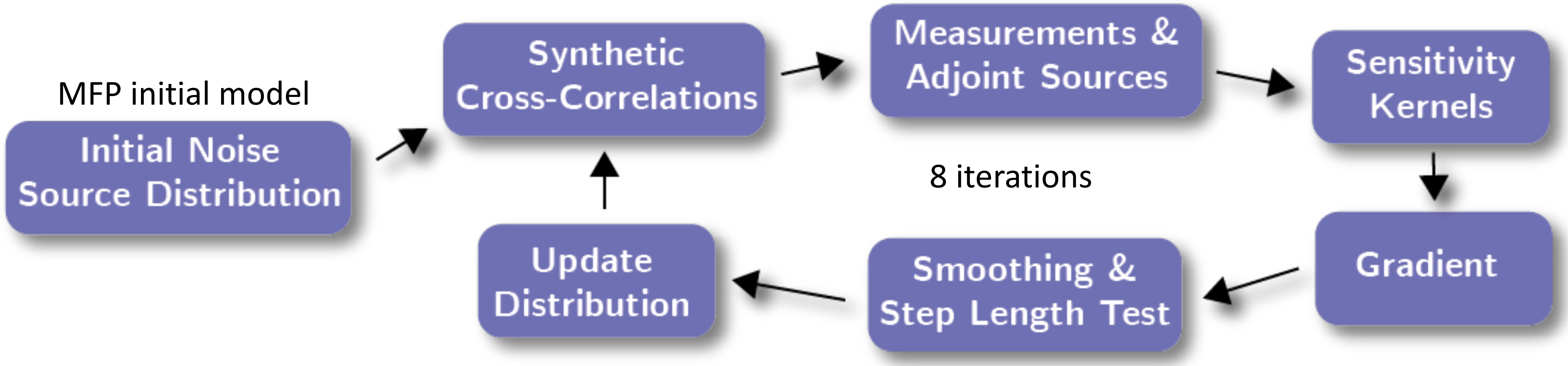

2. For multiple stations we sum up all the sensitivity kernels to obtain the gradient. This is then used to update the noise source distribution for the next iteration of the inversion.

# Finite-frequency Inversion



1. We use a gradient-based iterative method to decrease the misfit in our inversion. The initial noise source distribution is a normalised smoothed MFP model.

2. Synthetic and real data tests have shown that the noise source distribution does not change much after roughly 5 iterations. We run 8 iterations to ensure that the model explains the data well.



# Finite-frequency Inversion

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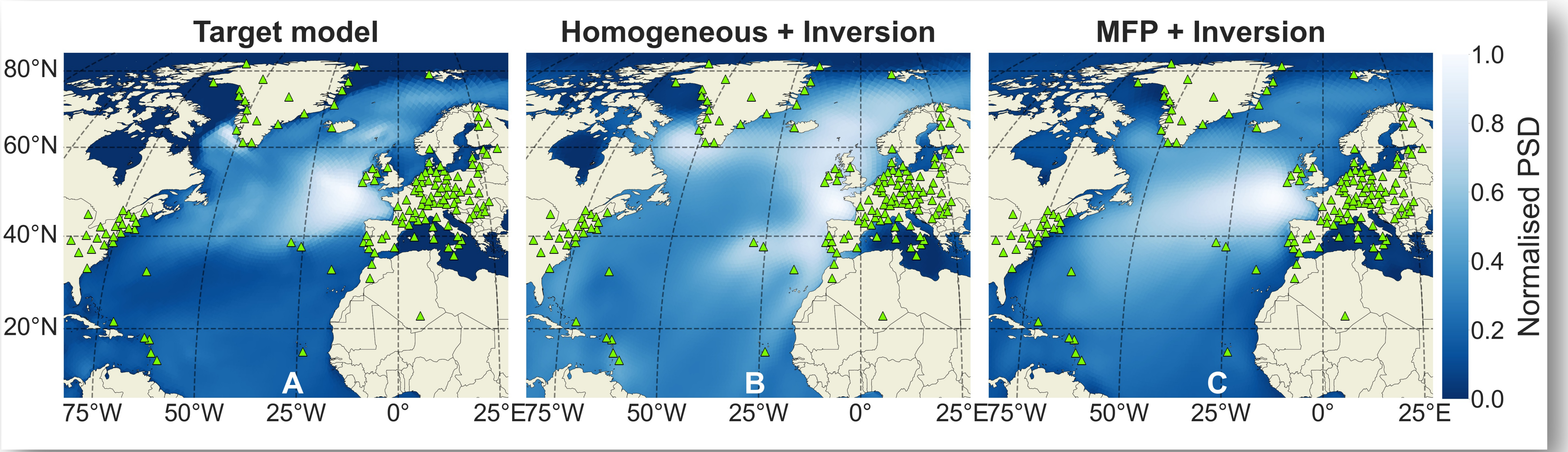
1. The MFP initial model is able to steer the inversion in the right direction and helps to ensure that we are not in a local minimum in the inversion.

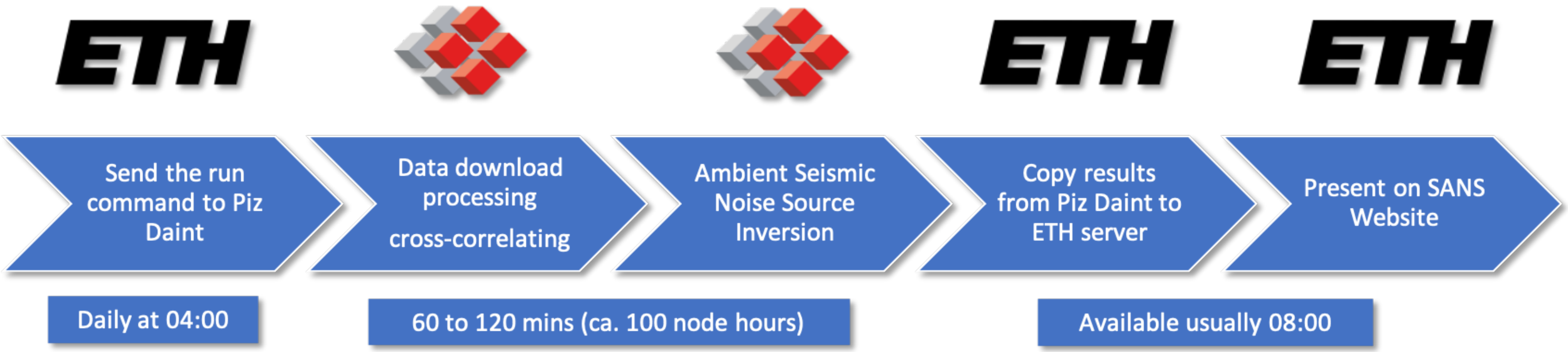



2. Here we forward model synthetic correlations with added noise for a target model (A) and stations (▲) surrounding the North Atlantic.

3. The MFP starting model (C) leads to a more accurate noise source distribution compared to a homogeneous starting model (B) after 8 iterations.

# SANS: Daily Seismic Ambient Noise Sources

1. SANS is a framework where the previously mentioned inversion method is run on a daily basis on a regional to global scale. The daily Seismic Ambient Noise Source maps are made available to the public on the website: sans.ethz.ch. The workflow of this framework is illustrated here where Piz Daint is a supercomputer at the Swiss National Supercomputing Centre CSCS:




2. Users can study the noise source maps online or download them for implementation in their own studies. We provide example code on how to open and plot the files.

# SANS: Daily Seismic Ambient Noise Sources

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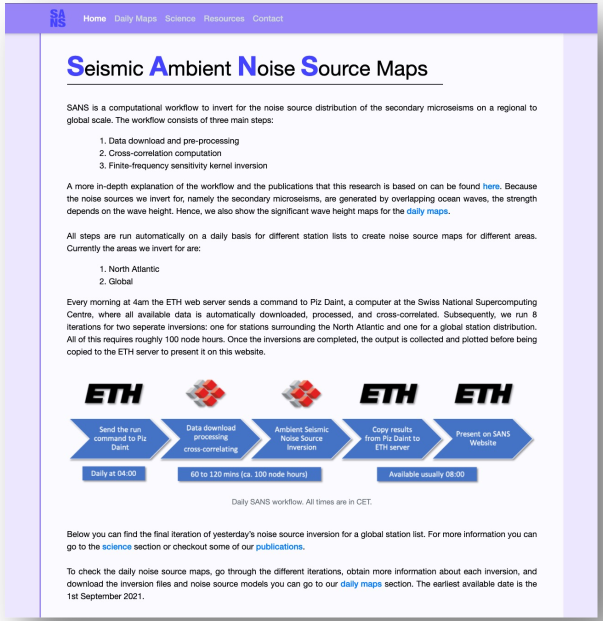
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## Seismic Ambient Noise Source Maps

SANS is a computational workflow to invert for the noise source distribution of the secondary microseisms on a regional to global scale. The workflow consists of three main steps:

1. Data download and pre-processing
2. Cross-correlation computation
3. Finite-frequency sensitivity kernel inversion

A more in-depth explanation of the workflow and the publications that this research is based on can be found here. Because the noise sources we invert for, namely the secondary microseisms, are generated by overlapping ocean waves, the strength depends on the wave height. Hence, we also show the significant wave height maps for the daily maps.

All steps are run automatically on a daily basis for different station lists to create noise source maps for different areas. Currently the areas we invert for are:

1. North Atlantic
2. Global

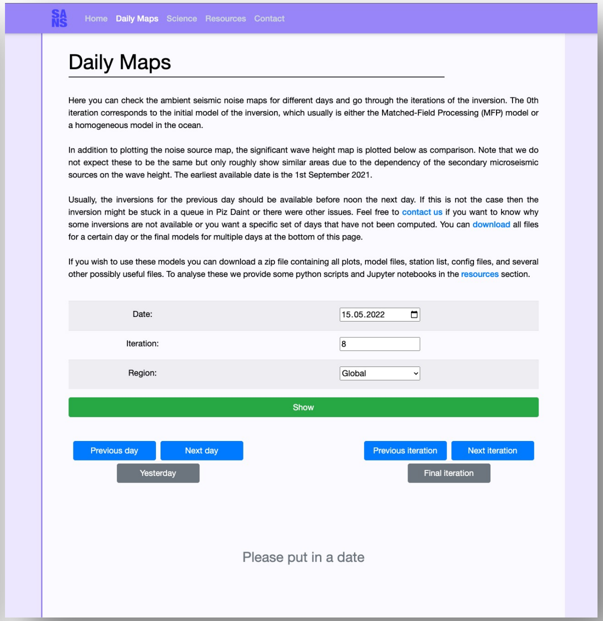
Every morning at 4am the ETH web server sends a command to Piz Daint, a computer at the Swiss National Supercomputing Centre, where all available data is automatically downloaded, processed, and cross-correlated. Subsequently, we run 8 iterations for two seperate inversions: one for stations surrounding the North Atlantic and one for a global station distribution. All of this requires roughly 100 node hours. Once the inversions are completed, the output is collected and plotted before being copied to the ETH server to present it on this website.



Daily SANS workflow. All times are in CET.

Below you can find the final iteration of yesterday's noise source inversion for a global station list. For more information you can go to the science section or checkout some of our publications.

To check the daily noise source maps, go through the different iterations, obtain more information about each inversion, and download the inversion files and noise source models you can go to our daily maps section. The earliest available date is the 1st September 2021.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## Daily Maps

Here you can check the ambient seismic noise maps for different days and go through the iterations of the inversion. The 0th iteration corresponds to the initial model of the inversion, which usually is either the Matched-Field Processing (MFP) model or a homogeneous model in the ocean.

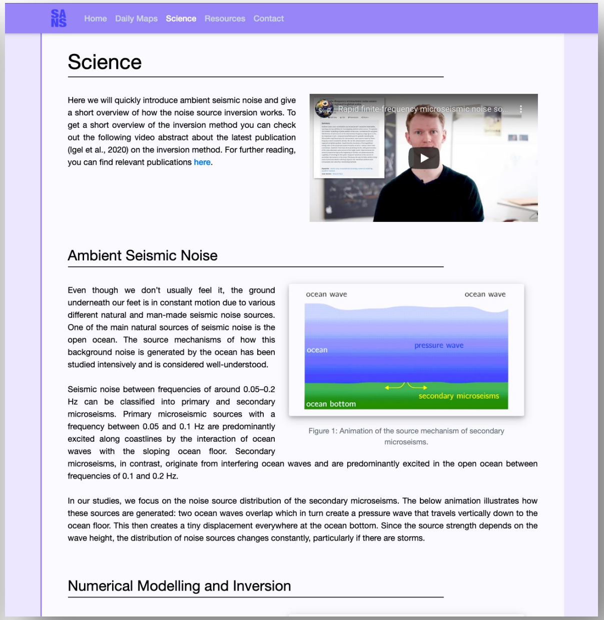
In addition to plotting the noise source map, the significant wave height map is plotted below as comparison. Note that we do not expect these to be the same but only roughly show similar areas due to the dependency of the secondary microseismic sources on the wave height. The earliest available date is the 1st September 2021.

Usually, the inversions for the previous day should be available before noon the next day. If this is not the case then the inversion might be stuck in a queue in Piz Daint or there were other issues. Feel free to contact us if you want to know why some inversions are not available or you want a specific set of days that have not been computed. You can download all files for a certain day or the final models for multiple days at the bottom of this page.

If you wish to use these models you can download a zip file containing all plots, model files, station list, config files, and several other possibly useful files. To analyse these we provide some python scripts and Jupyter notebooks in the resources section.

Date: 15.05.2022
Iteration: 8
Region: Global
Show
Previous day | Next day | Previous iteration | Next iteration
Yesterday | Final iteration

Please put in a date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## Science

Here we will quickly introduce ambient seismic noise and give a short overview of how the noise source inversion works. To get a short overview of the inversion method you can check out the following video abstract about the latest publication (Igel et al., 2020) on the inversion method. For further reading, you can find relevant publications here.

### Ambient Seismic Noise

Even though we don't usually feel it, the ground underneath our feet is in constant motion due to various different natural and man-made seismic noise sources. One of the main natural sources of seismic noise is the open ocean. The source mechanisms of how this background noise is generated by the ocean has been studied intensively and is considered well-understood.

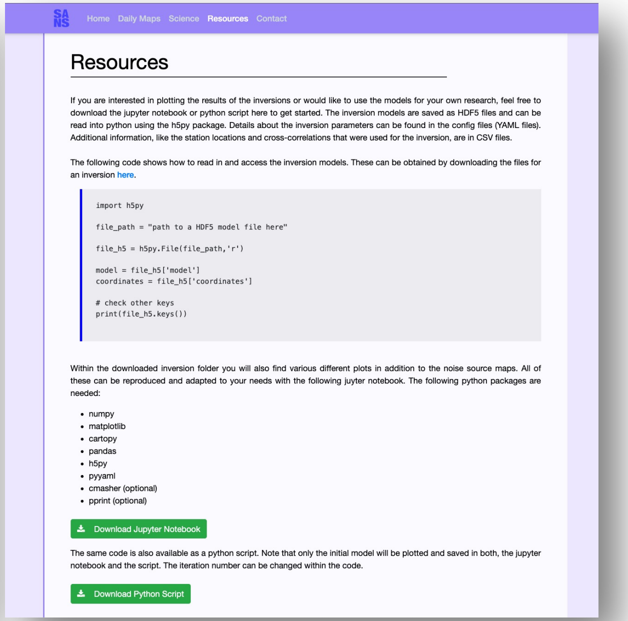


Figure 1: Animation of the source mechanism of secondary microseisms.

Seismic noise between frequencies of around 0.05–0.2 Hz can be classified into primary and secondary microseisms. Primary microseismic sources with a frequency between 0.05 and 0.1 Hz are predominantly excited along coastlines by the interaction of ocean waves with the sloping ocean floor. Secondary microseisms, in contrast, originate from interfering ocean waves and are predominantly excited in the open ocean between frequencies of 0.1 and 0.2 Hz.

In our studies, we focus on the noise source distribution of the secondary microseisms. The below animation illustrates how these sources are generated: two ocean waves overlap which in turn create a pressure wave that travels vertically down to the ocean floor. This then creates a tiny displacement everywhere at the ocean bottom. Since the source strength depends on the wave height, the distribution of noise sources changes constantly, particularly if there are storms.

### Numerical Modelling and Inversion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## Resources

If you are interested in plotting the results of the inversions or would like to use the models for your own research, feel free to download the jupyter notebook or python script here to get started. The inversion models are saved as HDF5 files and can be read into python using the h5py package. Details about the inversion parameters can be found in the config files (YAML files). Additional information, like the station locations and cross-correlations that were used for the inversion, are in CSV files.

The following code shows how to read in and access the inversion models. These can be obtained by downloading the files for an inversion here.

```
import h5py

file_path = "path to a HDF5 model file here"

file_h5 = h5py.File(file_path,'r')

model = file_h5['model']
coordinates = file_h5['coordinates']

# check other keys
print(file_h5.keys())
```

Within the downloaded inversion folder you will also find various different plots in addition to the noise source maps. All of these can be reproduced and adapted to your needs with the following juyter notebook. The following python packages are needed:

- numpy
- matplotlib
- cartopy
- pandas
- h5py
- pyyaml
- cmasher (optional)
- pprint (optional)

Download Jupyter Notebook

The same code is also available as a python script. Note that only the initial model will be plotted and saved in both, the jupyter notebook and the script. The iteration number can be changed within the code.

Download Python Script

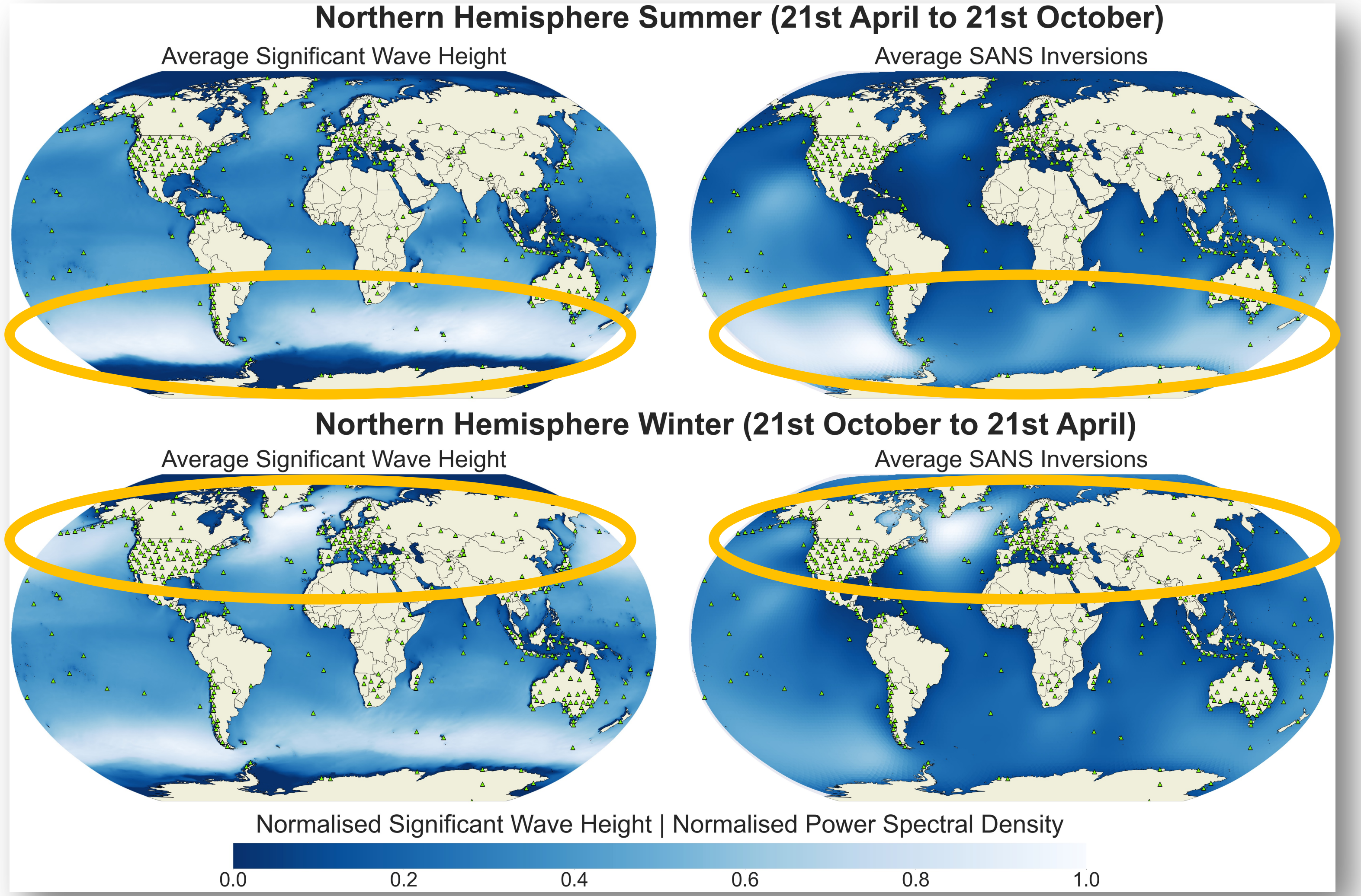
Check it out here: sans.ethz.ch

# SANS: Seasonal analysis

1. We analyse nearly a full year of daily global inversions from the 21st May 2021 to the 2nd May 2022.

2. The significant wave height maps from the WaveWatch III model [4] should only be taken as a rough reference and not a direct comparison as the generation mechanism is more complicated.

3. Averaging all inversions and wave heights for northern hemisphere summer and winter show the clear variations due to the seasons. NH summer is dominated by sources in the southern hemisphere and NH winter is dominated by sources in the North Atlantic. The wave height maps show similar features.



# SANS: Correlation comparison

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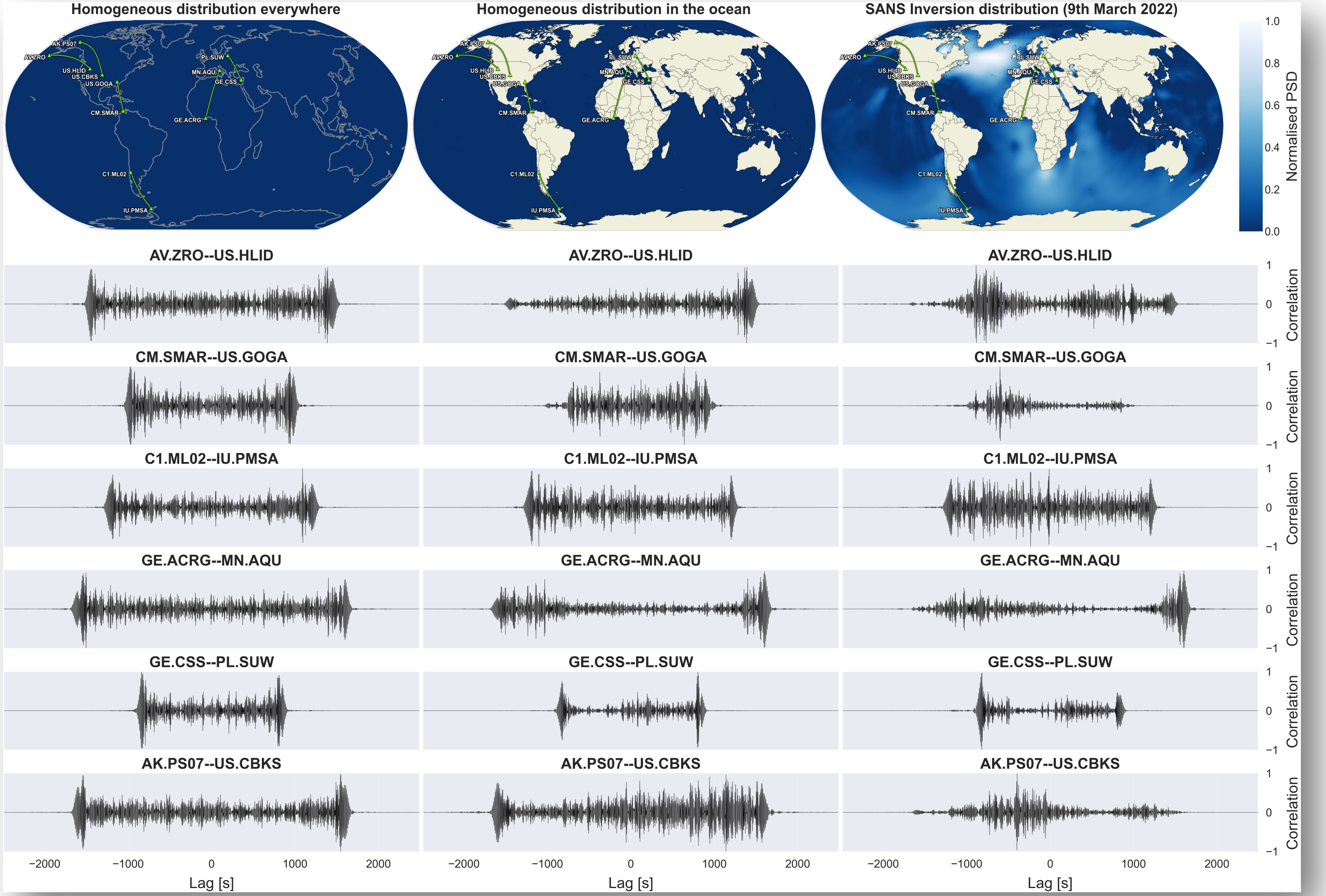
1. We compare cross-correlations for three different models: homogeneous everywhere, homogeneous in the ocean, and the final SANS map for the 9th March 2022. Note that blue for the homogeneous distributions indicates 1 everywhere.

2. As we introduce more realistic noise source distributions the correlations become more and more asymmetric.

3. This can have a strong effect on ambient noise tomography studies that assume a homogeneous distribution, especially full waveform methods.

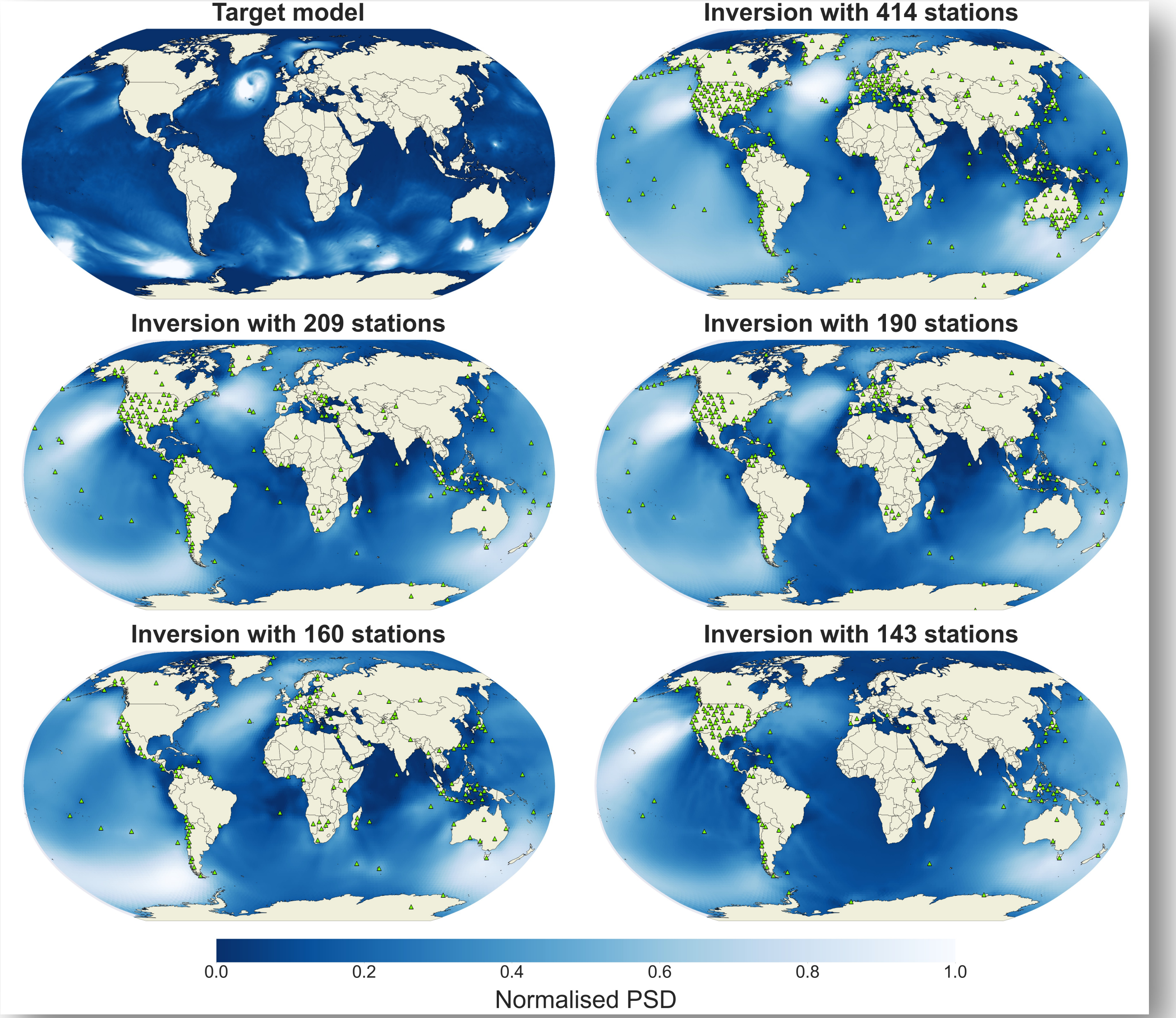


# SANS: Resolution

1. Due to lack of data or earthquakes that have to be removed from the waveforms the data availability and thus station distribution changes every day.

2. We study the effect of different station distributions by forward modelling correlations and inverting for that data using several different station lists.

3. Despite the lack of data for fewer stations the dominant noise source are included in the final model for most station lists. Generally, the resolution is lower in the southern hemisphere due to the lack of stations.



# Conclusions & Outlook

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1. We present a combination of two methods, MFP and finite-frequency inversion, to invert for the noise source distribution of the secondary microseisms on a regional to global scale on a daily basis.

2. The SANS framework makes these daily Seismic Ambient Noise Source maps available to the public: [sans.ethz.ch](sans.ethz.ch)

3. Analysis of one year of daily inversions shows the expected spatio-temporal variations due to the seasons, i.e. northern hemisphere winter has stronger sources in the southern hemisphere and northern hemisphere summer has the most dominant noise sources in the North Atlantic.

4. Implementation of noise source distribution knowledge into other ambient noise studies is strongly encouraged as it has a significant effect on the cross-correlations and possible travel time picks.

Feel free to contact us if you have any questions or want to collaborate: jonas.igel@erdw.ethz.ch

# References


1. Bowden, D. C., Sager, K., Fichtner, A. & Chmiel, M. Connecting beamforming and kernel-based noise source inversion. *Geophysical Journal International* **224**, 1607–1620 (2021).

2. Igel, J. K. H., Ermert, L. A. & Fichtner, A. Rapid finite-frequency microseismic noise source inversion at regional to global scales. *Geophysical Journal International* **227**, 169–183 (2021).

3. Ermert, L. *et al.* noisi : A Python tool for ambient noise cross-correlation modeling and noise source inversion. *Solid Earth* 1597–1615 (2020).

4. Tolman, H. L. & Chalikov, D. Source terms in a third-generation wind wave model. *Journal of Physical Oceanography* **26**, 2497–2518 (1996).