

# Passive seismic depth sounding by statistical array analysis

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## Abstract

We can determine efficiently the Rayleigh wave dispersion curve for a frequency range between 2 Hz and 80 Hz by analyzing the seismic noise recorded on mini-arrays. Due to the short recording time of 15 min we are able to map an area up to 6 ha per day. The dispersion curve gives us a first qualitative image of the subsurface.

## Keywords

archaeological prospection; array analysis; seismic noise; seismic structure; surface wave

## Introduction

Surface waves are analyzed in different scales to determine the seismic structure of the earth. This includes investigations of the lithosphere but also investigations which targets are close to the surface. Surface wave have a frequency dependent penetration depth which leads to a frequency dependent propagation velocity (dispersion). The dispersion is characteristic for the underground model. The dispersion curve can be used to investigate the seismic structure of the subsurface.

The observed surface waves (in most cases the Rayleigh wave) can origin from a known source like an earthquake (2-station method) or a seismic source (Multichannel analysis of surface waves). Another approach is the analysis of the seismic background noise which is dominated by surface waves by an ambient noise tomography or with the spatial autocorrelation method (Okada 2003).

We present another approach to analyze the seismic noise and to determine the dispersion of the Rayleigh wave. Our target is to investigate the seismic structure of the uppermost 20 m. The data recorded on a mini-array is analyzed by the beamforming algorithm and statistical evaluated. This results in the dispersion curve of the Rayleigh wave between 2 Hz and 80 Hz.

## Determination of the Rayleigh wave dispersion

### Seismic arrays

Seismic arrays are widely used in global seismology for earthquake detection, earthquake location and for the monitoring of the Comprehensive Nuclear-Test-Ban Treaty (CTBT). The benefit of the usage of seismic arrays are an increased signal-noise-ratio for an improved detection of seismic events (earthquakes, nuclear tests, explosions, ...) and the determination of back azimuth and slowness of the propagating seismic waves allowing the location of the event. The aperture (largest distance between two stations in the array) is in the range of  $10^3$  m –  $10^5$  m due to the large observed horizontal wavelengths.

We need to analyze Rayleigh waves with a wave length between 1 m and 50 m to investigate our target, the uppermost 20 m of the surface. Therefore, we need a much smaller array of a size of 2.7 m x 2.7 m. Due to the small size, we call it a “mini-array”.

A mini-array consists of 9 geophones (Fig. 1). 4 geophones are placed in the corners of two squares with side length of 2.7 m and 0.75 m, respectively. The smaller square is located in the center of the bigger one. The 9<sup>th</sup> geophone is placed in the center of both squares. This arrangement has been proven to be sufficient for the determination of the Rayleigh wave dispersion.

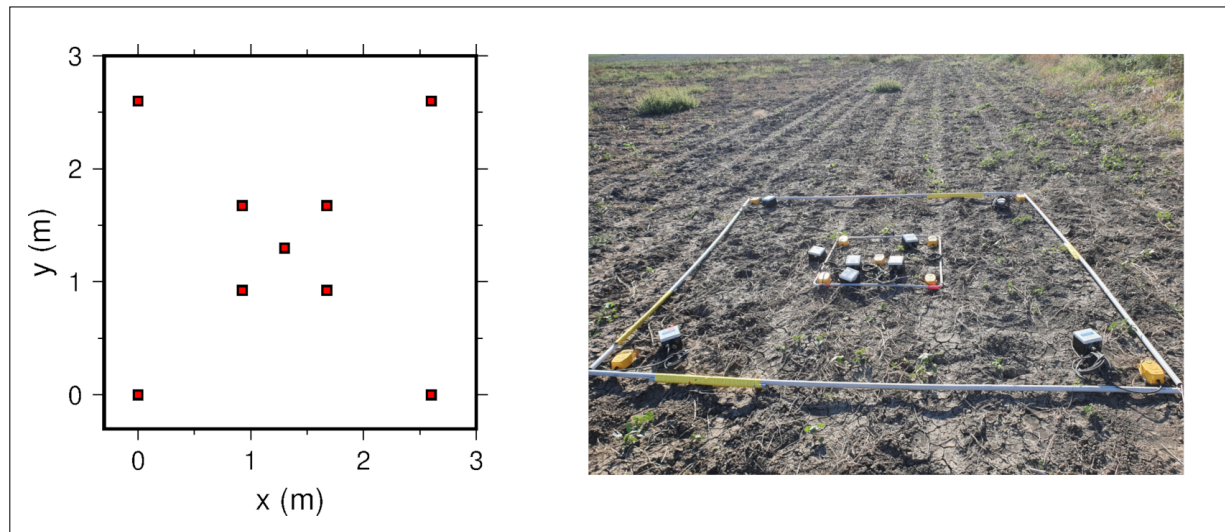


Fig. 1: Left: Layout of the mini-arrays. Right: installed mini-array in the field (photo by D. Schulte-Kortnack).

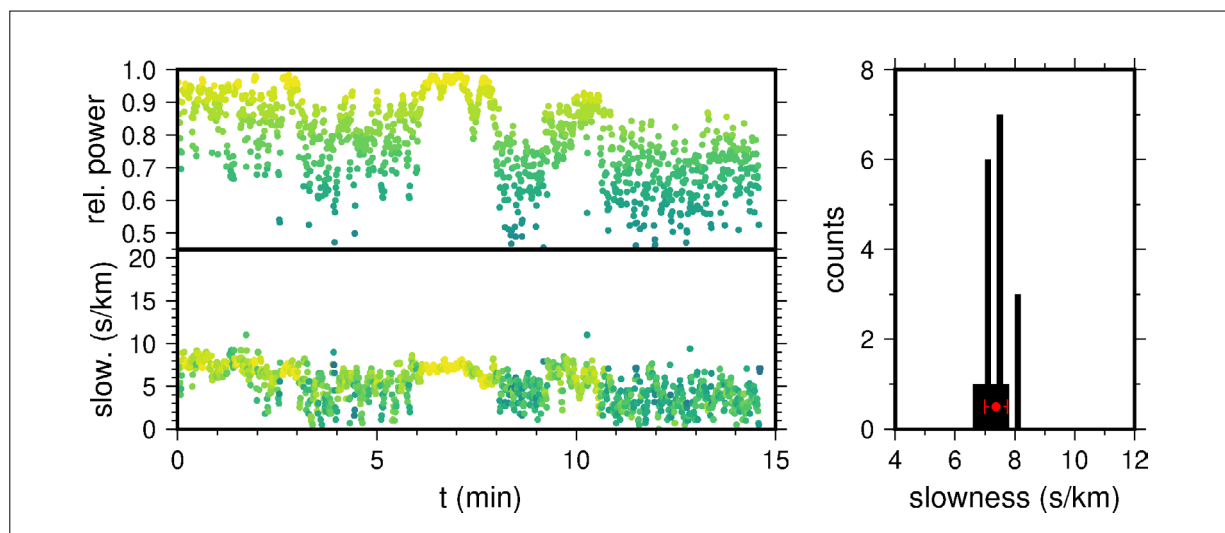


Fig. 2: Left: Pairs of slowness and relative power as the result of the beamforming algorithm. Right: statistical evaluation of the best 20 slowness values. Red dot with error bars indicates the mean and the standard deviation of the slowness values.

The seismic noise is recorded on DataCubes<sup>3</sup> from DiGOS Potsdam. The recorders are operated with a sampling rate of 400 Hz. The total recording time for a mini-array is 15 min.

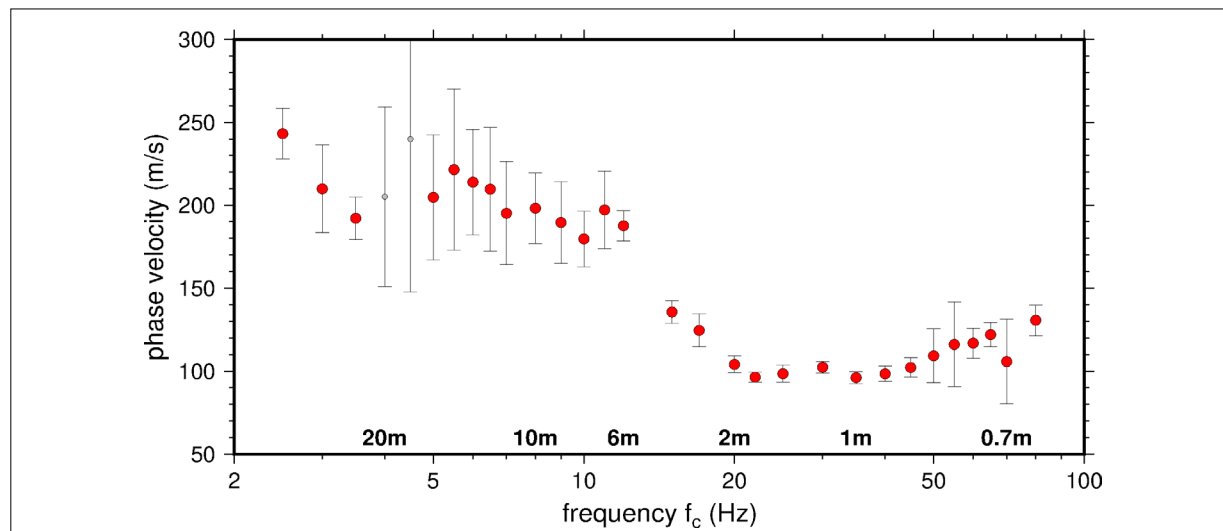
**Statistical analysis of the seismic noise**

There are two approaches to determine the dispersion of surface waves from seismic noise data recorded on seismic arrays (Okada 2003): the spatial auto-correlation method (SPAC) and the beamforming method. We are applying

the beam forming method to determine the Rayleigh wave dispersion in a frequency range between 2 Hz and 80 Hz.

The recorded data is band pass filtered around a center frequency  $f_c$  between  $[0.95 \cdot f_c, 1.05 \cdot f_c]$  and divided into small overlapping time windows. The time window is chosen to be 40 periods long.

For each time window the beam forming algorithm is applied by the command “array\_processing” from the python toolbox ObsPy (Beyreuther et al. 2010). The algorithm shifts first the data relative to each other in time for a given slowness (inverse of the propagation velocity)



**Fig. 3:** Dispersion curve of the Rayleigh wave. Red dots are reliable values, small gray dots are unreliable. Error bars represent the standard deviation. Pseudo depths estimated for this dispersion curve are placed above the x-axis.

and back azimuth. It calculates then the relative power of the stacked data. The relative power is a measure for the quality of the beam forming (Fig. 2, left).

The 20 pairs with the highest relative power are selected. The mean and standard deviation of these 20 slowness values and the average of the relative power are calculated (Fig. 2, right).

Applying this analysis scheme to all the frequencies within the range between 2 Hz and 80 Hz result in the dispersion curve for the Rayleigh wave (Fig. 3). We consider values of the phase velocity as reliable, if the standard deviation of the slowness is lower than 25% of the mean value and the average relative power is larger than 0.8. The dispersion is a depth sounding curve since different frequencies represent different depths.

## Discussion

The investigation of the seismic structure is rarely done in archaeological prospection on land due to the lack of efficiency. It is a common method in marine and amphibian environment due to an easy application (e.g. Wilken et al. 2019; Schwardt et al. 2021).

Our approach is an efficient way to determine the Rayleigh wave dispersion on land. The simple layout makes it easy to install the mini-array in the field in less than 10 min. Using two mini-array simultaneously it is possible to install and operate a mini-array at 3 – 4 site per hour and 20 – 35

sites per day. It is possible to cover an area of 1 ha – 6 ha per day depending on the spacing between the sites and to map the underground structure of the upper most 20 m.

Schwellenbach et al. (2020) performed a similar approach at the archaeological park of Selinunte. They recorded the seismic noise at four sites on arrays with changing spatial dimensions between 3 m and 60 m. The total recording time was up to 4.5 h per site reducing the efficiency of the measurements. The data was analyzed by the SPAC and by the beam forming method. They could determine Rayleigh wave dispersion over a frequency range between 0.2 Hz and 50 Hz and derive the underground structure in a good agreement with other methods applied.

With our approach we determine the dispersion curve is reliable over a frequency range of the order of 1. The exact frequency range depends on the observed wavelengths and the seismic velocity of the underground. The standard deviation normally increases towards the lower frequencies ( $f_c \leq 10$  Hz) due to the large wavelength compared to the array dimensions. To extend the dispersion curve to deeper frequencies the dimension of the array has to be increased as Schwellenbach et al. (2020) did. The standard deviation can be also large at the high frequencies ( $f_c > 50$  Hz). This could be caused by more complex interference pattern or the presence of higher modes of the Rayleigh wave.

The disadvantage of the SPAC method is the need of an isotropic distribution of the seismic sources around the

array. This can be difficult in urban areas or close to the coast where the main seismic source is the surf. In contrast, the beamforming algorithm will result in the correct phase velocity if only one dominant seismic noise source is present. It is likely to find some time windows within the recording time of 15 min where a source dominates the seismic noise. This could be passing cars, the surf or activity of other seismic measurements.


The dispersion curve is sufficient for a first qualitative image of the subsurface structure. But it is essential to derive a one-dimensional model from the dispersion curve by modeling of inversion. Unfortunately, this inverse problem is ambiguous. The dispersion curve can be explained by different one-dimensional models. Therefore, additional constraints have to be considered. Those constraints could be achieved by active refraction seismic tomography, cone penetration depths or in situ measurements through a direct push equipment.

This method is applied in several ongoing investigations. The method shows that the tell at Chiselet (Romania) is located next to a silted lake or river which may have been the reason to settle there in the first place and then to abandon it again. We find also indication for former lagoons in the Hebros plain close Greek-Turkish border and in the Chora plain on Samos (Greece). A possible application would be the mapping of the Xerxes Canal in Greece.

## Conclusion

We are able to determine efficiently the Rayleigh wave dispersion curve for a frequency range between 2 Hz and 80 Hz by analyzing the seismic noise recorded on mini-arrays. Due to the short recording time we are able to cover an area up to 6 ha per day. The dispersion curve gives us a first qualitative image of the subsurface.

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