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Array measurements adapted to the number of available sensors: Theoretical and practical approach for ESAC method

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ABSTRACT

Array measurements of ambient noise have become a useful technique to estimate the surface wave dispersion curves and subsequently the subsurface elastic parameters that characterize the studied soil. One of the logistical handicaps associated with this kind of measurements is the requirement of several stations recording at the same time, which limits their applicability in the case of research groups without enough infrastructure resources. In this paper, we describe the theoretical basis of the ESAC method and we deduce how the number of stations needed to implement any array layout can be reduced to only two stations. In this way, we propose a new methodology to implement an N stations array layout by using only M stations ($M < N$), which will be recording in different positions of the original prearranged N stations geometry at different times. We also provide some practical guidelines to implement the proposed approach and we show different examples where the obtained results confirm the theoretical foundations. Thus, the study carried out reflects that we can use a minimum of 2 stations to deploy any array layout originally designed for higher number of sensors.

1. Introduction

Array techniques based on ambient noise records constitute a valuable tool for soil characterization. They allow obtaining the dispersion curve at the study area and subsequently, estimating a Vs profile representative of the ground characteristics by means of an inversion procedure (Xia et al., 1999; Ohrnberger et al., 2004; Parolai et al., 2007; Endrun et al., 2010). Three of the most used array techniques are the frequency-wavenumber (f-k) method (Capon, 1969; Lacoss et al., 1969; Asten and Henstridge, 1984), the spatial autocorrelation (SPAC) technique (Aki, 1957; Roberts and Asten, 2004) and the extended spatial autocorrelation (ESAC) method (Ohori et al., 2002; Okada, 2003).

Though the methodology is especially suited for zones where other geotechnical or geophysical techniques are difficult or even prohibitive to implement (e.g. Souriau et al., 2007; D'Amico et al., 2008; Mundepi et al., 2010), it also presents some important limitations on its practical application. The main ones regarding the experimental approach are related to economical and logistical constraints, which limit the number of stations available for the field experiments. To overcome this drawback, researchers have traditionally focused their efforts on optimizing the selected array size and geometry, as two key factors to enhance the resultant dispersion curve (see SESAME, Site Effects assessment using AMbient Excitations 2005).

In this way, several papers have studied the array optimization in terms of geometry and number of stations by using the f-k and the SPAC methods. Concerning the first technique, Barber (1959) and Haubrich (1968) showed ways in which the beam pattern can be understood and optimized for a given number of sensors. Later, Kind et al. (2005) pointed out that the array configuration plays an important role controlling the wavenumber resolution properties of the array.

More recently, Picozzi et al. (2010) proposed to correct the f-k power spectral density function (PSDF) estimate for the effects introduced by the array transfer function, in analogy to the correction for the instrumental response of seismological data. Whereas, Rosa-Cintas et al. (2014) experimentally optimized the number of stations in three array geometries: triangular, circular with central station and polygonal, using the f-k approach.

Regarding the SPAC method, several works have studied this issue. Asten et al. (2004) and Asten (2006) numerically analyzed the expected behavior of the SPAC spectrum with different array configurations and azimuth samplings. Chávez-García et al. (2005), proposed an alternative approach to the SPAC analysis where the crosscorrelation functions were computed between all the pairs of stations that constitute the array and then averaged for different station pairs. Chávez-García et al.

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(2006) also applied the SPAC method using five broadband stations disposed along a line, and repeating the experiment with different inter-station spacing. Cho et al. (2004, 2006 and 2008) further evaluated the maximum expected errors on SPAC spectra, with respect to frequency and number of sensors, using different wavefield scenarios. In a similar way, Okada (2006) considered the minimum number of stations required by a circular array for efficient data collection, in terms of analytical efficacy and field effort. Bettig et al. (2001) and Köhler et al., (2007) assessed the reliability and applicability of a modified SPAC (MSPAC) method, which works with non-circular arrays. More recently, Claprood and Asten (2010) proposed a methodology to experimentally assess the reliability of the SPAC method on observations made with a limited number of sensors. They investigated parameters such as the number of sensors, the length of the time series and the frequency interval, by analyzing the behavior of the real and imaginary components of the observed coherency spectra.

Thus, researchers have traditionally focused their efforts on optimizing the selected array size and geometry, as two key factors to overcome the use of a limited number of stations in the field experiments. However, there is another way of facing this drawback. The number of available stations might be limited, especially by economic constraints, but both the recording time and the position of each station on the field are not. Therefore, in this paper we propose a new methodology to implement an N stations array layout by using only M stations ($M < N$), which are recording in different positions of the original prearranged N stations geometry at different times. The ESAC method is used for dispersion curve calculation.

In this case, the complete measurements associated to the original layout of N receiver positions is conformed of several recording sets performed by reduced groups of M stations, placed in determined positions of the original geometry, each time. Then, the normalized cross spectrum is computed between pairs of stations within each reduced group. The number of required measurement groups has to be enough to assure that all the pairs of stations present in the original layout of N receiver positions are analyzed at least once in the complete process.

This research is valuable to improve future array field campaigns showing the viability of using a reduced number of stations to implement bigger and denser (i.e., with more sensors) arrays, by only increasing the total recording time and moving some of the stations. It might be especially useful for small research groups, where the number of available stations is limited by economic constraints.

2. Theoretical approach: ESAC method

The SPAC and ESAC method's theory is based on the assumption of a stochastic wavefield, which is stationary both in time and space (Aki, 1957; 1965). In the case of the SPAC method, it is assumed a circular array configuration with a sensor located in the center and the other ones equally distributed along the circumference. Conversely, the ESAC method does not require a circular layout and it is applicable to arrays of arbitrary geometry, given more flexibility to the design.

Supposing an array of N stations, the first step in the ESAC method consists of estimating the normalized cross-spectra, $\rho_{jn}(f)$, for every pair of stations by means of the following expression (Ohori et al., 2002; Okada, 2003):

$$\rho_{jn}(f) = \frac{\frac{1}{W}\sum_{w=1}^{W}\mathrm{Re}\left\{{}_{w}S^{w}{}_{jn}(f)\right\}}{\sqrt{\frac{1}{W^2}\sum_{w=1}^{W}{}_{w}S^{w}{}_{jj}(f)\sum_{w=1}^{W}{}_{w}S^{w}{}_{nn}(f)}} \quad (1)$$

where f is the frequency (in Hz); ${}_{w}S_{jn}$ is the cross-spectrum between the jth and the nth stations for each wth segment; ${}_{w}S_{jj}$ and ${}_{w}S_{nn}$ are the power spectra at stations j and n, respectively; and W is the number of windows or segments in which the recorded signal is split.

The set of the normalized cross-spectra obtained for all the possible pairs of stations provides the experimental azimuthally averaged space-correlation:

$$\rho(f,r) = \left\{\rho_{jn}(f)\right\} \quad (2)$$

where j and n represent all the possible station pairs of the array, and r represents the respective inter-stations distances.

In the case of a single-valued phase velocity per frequency band, Aki (1957) demonstrated originally that the azimuthally averaged space-correlation has the shape of a Bessel function, J_0, which arguments are the frequency, the inter-station distance and the phase velocity of the Rayleigh waves, $c(f)$.

$$\rho(f,r) = J_0\left(\frac{2\pi f r}{c(f)}\right) \quad (3)$$

Thus, the phase velocity, $c(f)$, at each frequency can be estimated by an iterative grid-search fitting procedure between the experimental azimuthally averaged spatial correlation and the theoretical Bessel function values.

The key point lies in the first step, Eq. (1). As it was commented previously, the normalized cross-spectra are calculated independently for every pair of stations. In this way, the information related to the phase difference between any pair of stations is obtained for all the frequencies contained in the wavefield through the cross-spectrum, ${}_{w}S_{jn}$.

Besides, as the cross-spectra is normalized (Eq. (1)), the possible amplitude variations among the different noise recordings do not affect to the results obtained from this step. This point is crucial for the proposed methodology. It implies that variations in noise amplitude observed by several researchers (e.g. variations between day and night commented in Bonnefoy-Claudet et al., 2006) do not influence the normalized cross-spectra and then, the measurements associated to each pair of stations can be taken at different times and not necessarily all simultaneously. Indeed, the obtained results depend basically on the velocity-frequency behavior (dispersion curve) exhibited by the recorded surface waves, which is related with the characteristics of the study soil.

The usual procedure for array measurements implies the use of all the stations recording at the same time. However, the theoretical approach of the ESAC method reflects that we do not need to record simultaneously with all the stations, as it has been explained previously. In fact, it would be enough to record with only two stations at once and subsequently estimate the normalized cross-spectrum corresponding to that pair of receivers. Therefore, the measurements associated to each pair of stations could be taken at different intervals.

The only assumptions that should be fulfilled during each measurement concern the general suppositions considered for array measurements: i.e. homogeneous and isotropic soil conditions under the area covered by the array (Okada, 2003); and stochastic and stationary

Table 1
Minimum number of measurements with M stations that is required to implement arrays of N receiver positions.

Minimum number of measurements				
Number of receiver positions (N)	Number of stations (M)			
	2	3	4	5
5	10	4	2	1
6	15	6	3	2
7	21	7	5	3
8	28	11	6	4
9	36	12	8	5