ON THE STABILITY OF SPAC AND LINEAR ARRAY METHODS

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ABSTRACT :

The modified SPAC methods such as 2sSPAC and linear array methods allow estimating shear wave structure by using only two sensors, but in these cases the instability problem of the spatial autocorrelation coefficient could arise in frequency range higher than 1Hz. We carried out observations in Tsukuba city, Japan, with four 25m arrays size. We also used 25m triangles' sides as linear arrays. Results obtained from four 25m triangular arrays with four sensors, as well as from four 25m linear arrays with two sensors, showed good stability of SPAC coefficient for 2-4, 5Hz frequency range.
To check the influence of the anthropogenic sources on the results of microtremor array observation the arrays were deployed in different distances from the road passing near by.

KEYWORDS: SPAC, linear array, stability

1. INTRODUCTION

The basic theory of the spatial autocorrelation method was proposed by Aki (1957). Okada (1990, 1998) developed the theory to determine phase velocities of Rayleigh and Love wave in conventional way as an exploration method by using horizontal and vertical components of microtremor array observation. In order to extract the Rayleigh wave SPAC method requests simultaneous recording of the vertical component of microtremors, with at least 3-4 sensors. Ling and Okada (1993), proposed the extended spatial autocorrelation method (E-SPAC), which allows obtaining the phase velocity by fitting the SPAC coefficients to Bessel function versus distance, from the several different shaped arrays deployed not simultaneously, but in different time. Tsuno and Kudo (2004) showed the efficiency and precision of the SPAC method in practical engineering use, especially for shallow underground structures.
Later, Morikawa et al. (2004) developed two-site SPAC method (2sSPAC), which requires only two sets of seismographs, and concluded, that the 2sSPAC method provides reasonable values for phase velocities in the frequency range lower than about 1.0 Hz, and have mentioned that the spatial autocorrelation coefficients are not stable in the frequency range higher than 1.0 Hz.
Another application of the SPAC method proposed by Chavez-Garcia et al. (2006), where the seismometers dispose along a line with different inter-station spacing. They conclude that the SPAC method is not restricted to a particular geometry of the array, provided that the basic requirement of stationarity is fulfilled.
Margaryan (2006) verified the accuracy and applicability of the 2sSPAC method for the array size of 50m and 100m with 7 sensors. The results of dispersion curves obtained by the SPAC and 2sSPAC methods have been compared and showed good agreement up to 2.3 Hz.
The practical aim of this study is to show the stability of the conventional SPAC and linear array methods, for the frequency range higher than 1.0 Hz and to check the influence of the anthropogenic sources (e.g. cars, vehicles etc) on the results of microtremor array observation. For these purposes we carried out array observation of microtremors with four 25m triangular and four 25m linear arrays, deployed sequentially at different time in different distances from the road passing near by.

2. ARRAY OBSERVATION OF MICROTREMORS

We carried out the experiments on the array observation of micrtotremors in Tsukuba city, located in the Kanto basin, Japan, where the PS logging data up to 1300m is also available (Suzuki and Takahashi, 1999). For further analysis we used two distances, which are distance between the central station and stations located on the circumference as well as inter-station distance between the stations located on the circumference. For all arrays vertical-component velocity type seismographs have been used, and data were synchronized by Global Position System (GPS) clocks. The geometry of the arrays is shown in Figure 1. The L22D sensors with a natural frequency 2.0 Hz have been used. The duration of the microtremors records for each array was 11 minutes, obtained by 22 datasets with a sampling interval of 0.002 seconds. We used triangles' sides s1-s4, s4-s8, s2-s6, s6-s10 as linear arrays.

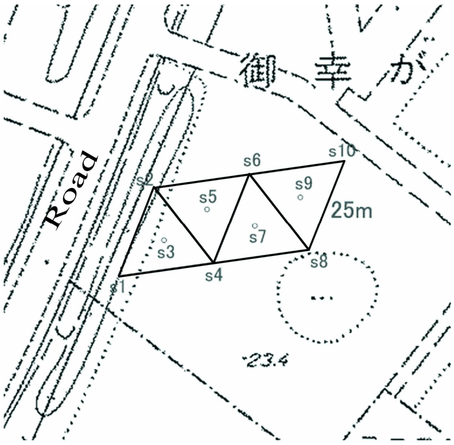


Figure 1 Geometry of the deployed four 25m arrays

3. DATA ANALYSIS

3.1. SPAC And Linear Array Methods

The SPAC coefficients, $\rho(\omega, r)$ can be directly calculated from the microtremor observed data using equation (3.1)

$$\rho(\omega;r) = \frac{1}{2\pi}\int_{0}^{2\pi}\frac{\mathrm{Re}\{[S_{CX}(\omega;r,\theta)]\}}{\sqrt{[S_C(\omega;0,0)]\cdot[S_X(\omega;r,\theta)]}}d\theta \qquad (3.1)$$

where Re[·] stands for the real part of a complex value, Sc(ω,0,0) and Sx(ω,r,θ) are the power spectra of microtremor at two sites C and X, respectively, and Scx (ω,r, θ) is the cross spectrum between the two sites, [ ] denotes the block average over time. In the linear arrays case, based on the assumption, that microtremors traveling in various directions, the SPAC coefficients were calculated by using the equation (1), but without averaging of the cross-correlation coefficients azimuthally.

3.2. Phase Velocity

Next, we visually examined the SPAC spectrums obtained from each dataset, and removed the blocks where it had relatively significant perturbations (Figure 2b). In Figure 2 examples of averaged autocorrelation functions obtained from a single dataset the first 25m arrays are shown. After above mentioned procedure for the estimation of the data quality, the applicable datasets, so-called "reliable" data, were used for further analysis and determination of the shear-wave velocity structures, the rest of the datasets, "not-reliable" data have not been used.

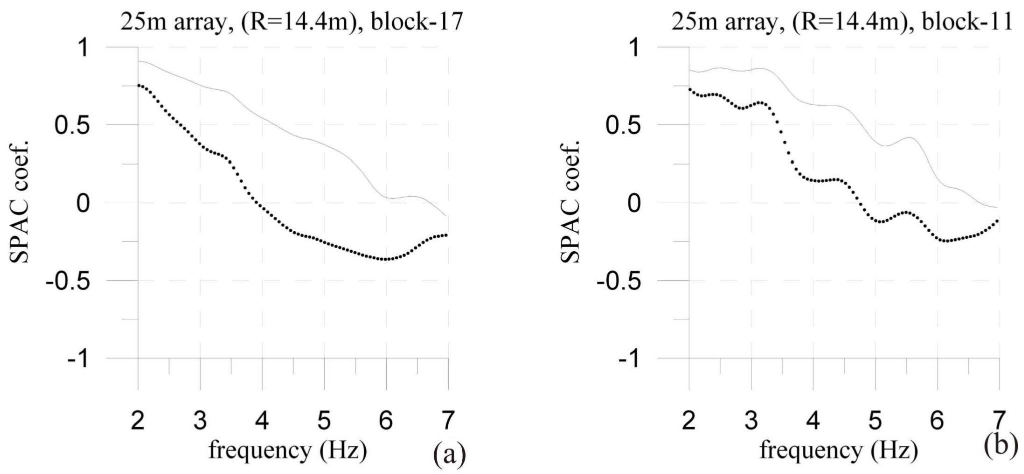


Figure 2 SPAC coefficients for different datasets (blocks) of the first 25m arrays. Dotted and thin lines are the SPAC coefficients obtained for 25m and 14.4m distances respectively: (a) example of data classified as "reliable", (b) examples of data classified as "not-reliable".

The phase velocities were obtained by fitting the SPAC coefficients, to Bessel function of the first kind of zero order by using equation (3.2)

$$\rho(\omega;r) = J_0\left(\frac{\omega r}{c(\omega)}\right) \tag{3.2}$$

where $J_0(\cdot)$ is the Bessel function of the first kind with the zero order and $c(\omega)$ is the phase velocity at frequency ω for the fundamental mode of the Rayleigh waves. The phase velocity at frequency ω is obtained as the argument of the Bessel function.

Figures 3 and 4 shows the SPAC coefficients and phase velocities of Rayleigh waves obtained from the triangular and linear arrays respectively.

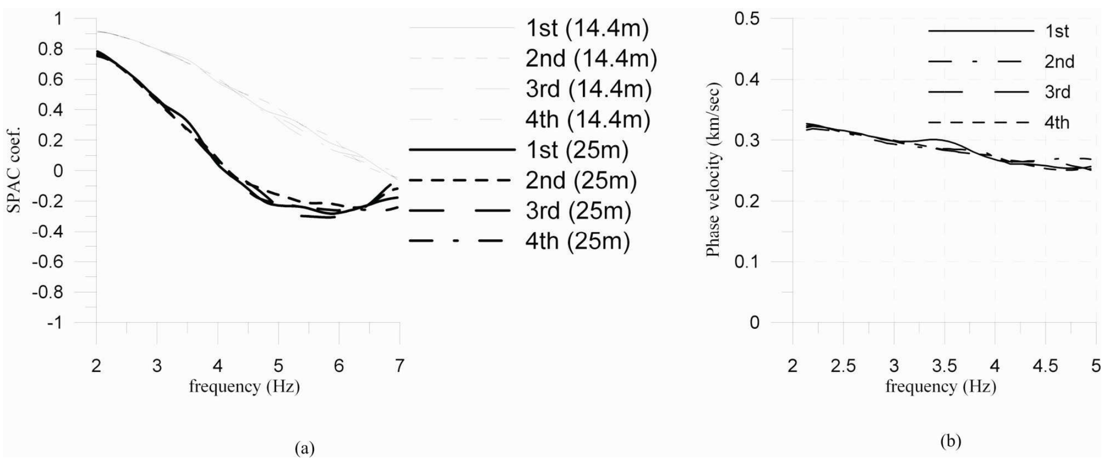


Figure 3 SPAC coefficients and phase velocities obtained from the four triangular arrays: (a) thin and solid lines show average autocorrelation coefficients obtained from the 14.4m and 25m distances respectively, (b) Phase velocities determined by the triangular arrays.

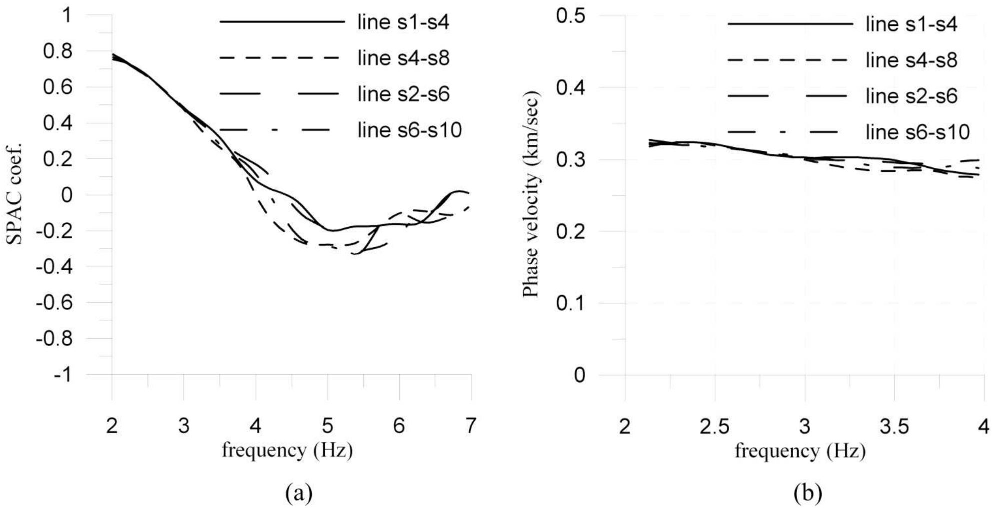


Figure 4 SPAC coefficients and phase velocities obtained from 4 linear arrays: (a) autocorrelation coefficients obtained from the pairs s1-s4, s4-s8, s2-s6, s6-s10 with distance of 25m, (b) Phase velocities determined by the 4 linear arrays.

3.3. Determination Of Shear-wave Velocity Structure

One of the known heuristic search algorithms which is Very Fast Simulated Annealing Method (VFSA) (Ingber, 1989). The Simulated Annealing method is based on the idea of thermodynamics where melted metal reaches to low-energy state with gradual decrease of temperature Metropolis (1953).
The shear-wave velocity structures beneath the observation sites were inverted from the dispersion curves obtained by the triangular and linear arrays by the combination of Down Hill Simplex Method (DHSM) with Very Fast Simulated Annealing Method (VFSA) (Yokoi, 2005), where layer thickness is changed independent on the S-wave velocity for the better fitting. We use the same initial velocity structures for each array. The shear-wave velocity structures obtained from the four triangular and linear arrays in comparison with PS logging data presented in Figure 5.

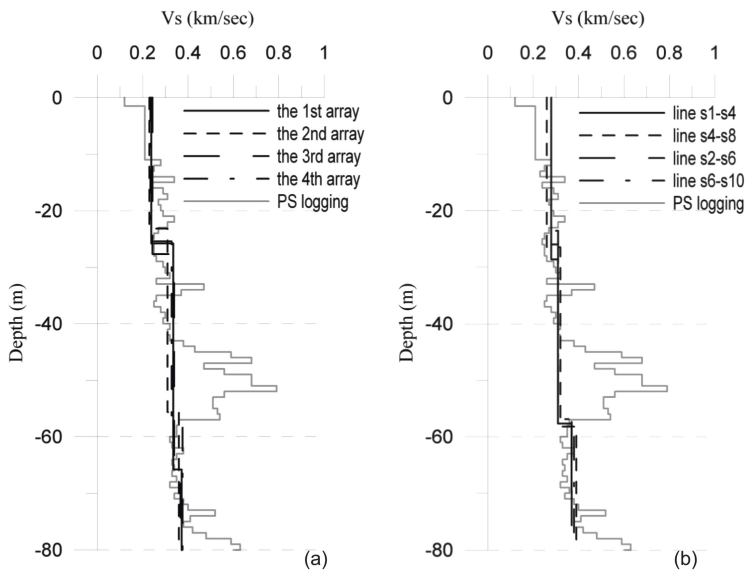
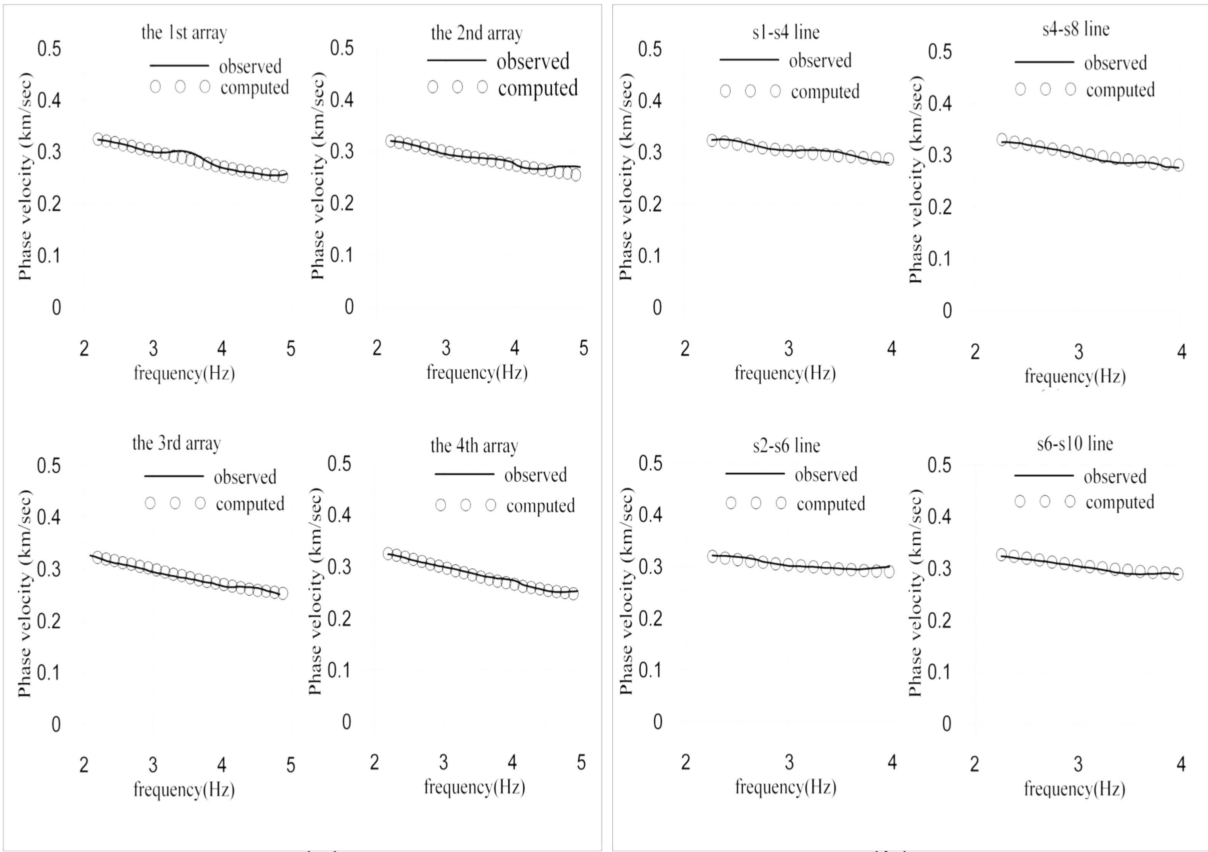


Figure 5 Comparison of shear-wave velocity structures determined by array microtremors with the PS logging data for (a) triangular arrays, (b) linear arrays.



(a) (b)

Figure 6 Observed and computed phase velocities of Rayleigh waves; (a) for the triangular arrays; (b) for the linear arrays.

The observed and computed phase velocities show good agreement in the observed frequency range. The comparison of phase velocity dispersions computed by VFSA with observed phase velocities obtained by SPAC and linear array methods are shown in Figure 6.

4. RESULTS AND CONCLUSIONS

In order to show the stability of the conventional SPAC and linear array methods, for the frequency range higher than 1.0 Hz and to determine the distance of the applicability of the SPAC method and its modifications in the sites close to human activities sources, such as traffic and so on we conducted measurements four 25m triangular arrays. Sequentially deployed four 25m triangular arrays, as well as four linear arrays, where we used triangles' sides, have been used to verify the stability of the SPAC spectrum in the frequency range higher than 1.0 Hz not only for the conventional SPAC method but also for linear array method, (which also can be regarded as a 2sSPAC method, because only two sensors have been used). Results presented in Figure 3a show that the SPAC coefficients obtained from the four triangular arrays for inter-station distances 14.4m and 25m are mutually consistent up to the frequencies of 4.3 and 6.75 Hz respectively. The deviation at higher frequencies may be due to the dependence of sources on azimuth, but any concrete information is not available about it. Phase velocities, however, are mutually consistent up to the frequency of 5.0 Hz (Figure 3b). Although, the SPAC coefficients obtained from the four linear arrays are not spatially averaged, it showed good stability up to the frequency about 3.9 Hz, and was possible to retrieve phase velocities up to the same frequency limit. Figures 4a and 4b show the consistency of the SPAC coefficients and phase velocities for the 2.0 to 4.0 Hz frequency range. Taking into account the above mentioned results, we concluded that:

- The phase velocity of Rayleigh waves, obtained by triangular and linear arrays (with 1 set of seismometers), in the frequency range form 2 to 4, 5 Hz are in good agreement with each other.
- The 25m triangular arrays were deployed in different distances from the light-traffic road passing near by. Results of the measurements show that a distance of about 25m between the anthropogenic noise and seismometers is safe enough to avoid perturbations on the noise signals

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