Microtremor Array Survey in Active Fold Area Niigata Japan – Using SPAC and V-method

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SUMMARY:
Microtremor array survey with long observation (more than 10 days) has been conducted in active fold area in Niigata prefecture, central Japan to estimate S-wave velocity structure. Thirteen surveys each with 12 temporal velocity seismometer stations, arranged as three centred equilateral triangle arrays whose radii ranges from several hundred meters to several kilometers, have been set in the area of 50 km x 15 km. Each observation is carried out for more than 10 days to assure reliable survey, since the survey needs statistically enough data especially at lower frequency where spectral change is slow. Seismometers with natural period more than 5 sec. are deployed to obtain continuous microtremor data. Each data are segmented to hourly data sets, and are analysed with SPAC method and V-method to estimate phase velocity. The phase velocities in the frequency generally between 0.1 to 1.0 Hz are obtained utilizing the best of the long observation. S-wave velocity structure of each site is derived from the phase velocity using GA inversion. Obtained velocity structures well reproduced the SPAC and V coefficients for every array at lower frequency while at high frequency they tend to fail indicating heterogeneous velocity structure beneath each array. Our observation shows importance of longer interval observation to obtain reliable phase velocity estimates with microtremor array survey.

Keywords: Ambient noise, dispersion curve, array observation, velocity structure

1.INTRODUCTION

Shear wave velocity structure is one of the most important information for ground motion evaluation. Among many techniques for investigating velocity structure, microtremor (or ambient noise) array survey is efficient and cost-effective especially for exploration on a deep sedimentary basin. Spatial auto-correlation method (SPAC) invented by Aki (1957) developed in Japan (e.g. Okada, 2003) is robust method to evaluate the phase velocity of Rayleigh wave from microtremor array data. Cho et al. (2006a,b) generalized SPAC method and proposed centerless cirlular-array (CCA) method as a powerful tool, of which maximum valid wavelength is triple or more than that of the SPAC method though the minimum wavelength is inferior to. Tada et al. (2007) explored wealth of circular-array method and proposed many enhanced methods. Among them the V-method seems most effective having wide valid wavelength range: maximum wavelength is comparable to the CCA method and the minimum wavelength is similar to the SPAC method.

Equations for SPAC and V-method are as follows,

$$\rho(\omega, r) = J_0(kr) \qquad (1)$$
$$\rho_V(\omega, r) = J_0(kr)/J_1^2(kr) \qquad (2)$$

,where J_m is the m-th order Bessel function, ω is the angler frequency, r is the array radius, $k = \omega/c(\omega)$, $c(\omega)$ is the phase velocity of Rayleigh wave, ρ is SPAC coefficient defined as azimuthally averaged coherence, and ρ_V is azimuthally averaged spectral ratio for V-method (See. Tada et al(2007)). Difference of the two methods is clear when kr is close to zero (corresponding to large wavelength): SPAC converges to unity whereas V diverges. Both equations are defined for vertical-motion field and single mode domination is assumed.

Key issue in the survey is how to achieve credible dispersion curves and eventually the velocity structure. To obtain the velocity structure of a deep (say several kilometers) sedimentary basin, microtremor records with high coherency down to low frequency (i.e 0.1 Hz) are essential. Since a low frequency noise is likely to be generated by natural excitations, such as sea waves, its energy fluctuates in longer term (several days, weeks, or months). In this paper, we show results of microtremor array survey with more than 10 days observation at each.

2. MICROTREMOR ARRAY OBSERVATIONS

Observation site is southern part of the Niigata sedimentary basin. The seismic basement lies at the depth around 3 to 8 km below thick Neogene sediments (e.g. Sekiguchi et al. 2009). Because of the active tectonics from about three million years ago, folding is developed in the area. Deformed hills of this area are elevated up to 400 meters or so and they are composed of sediments in age from middle Miocene to Pleistocene, mainly of muddy or sandy sediments.

Field survey was conducted at thirteen sites, K01-K13, covering 50km x 15 km area (Fig. 1.). Every observation is consisted of twelve simultaneous temporal stations composing three centered equilateral triangle arrays. Their radii range from about 0.3 km to 3 km (Table 1). Small array is omitted because the observed site is hilly and uniformity of the velocity structure especially of shallow one is not expected.

In obtaining ambient noise data, low self-noise seismometer is preferable. Two types of 3-component velocity seismometers are deployed. One is Lennartz LE-3D/5s (400V/m/s, T=5s.), being deployed at all the stations. The other is a broadband seismometer, Nanometrics Trillium Compact (750V/m/s, T=120s.), being added and set at only the largest aperture array stations (L-array). Each seismometer is connected with Hakusan DATAMARK LS-8800 data logger (24bit A/D, GPS time correction). Sampling rate is 100 Hz and linear filter is applied. Each system is powered with a lead-acid battery. Each sensor is covered with bucket and insulation material is added to avoid wind and heat transfer.

Each temporally observation with LE-3D/5s continued more than 10 days whereas some observations with the broadband seismometers lasted for 5 days.

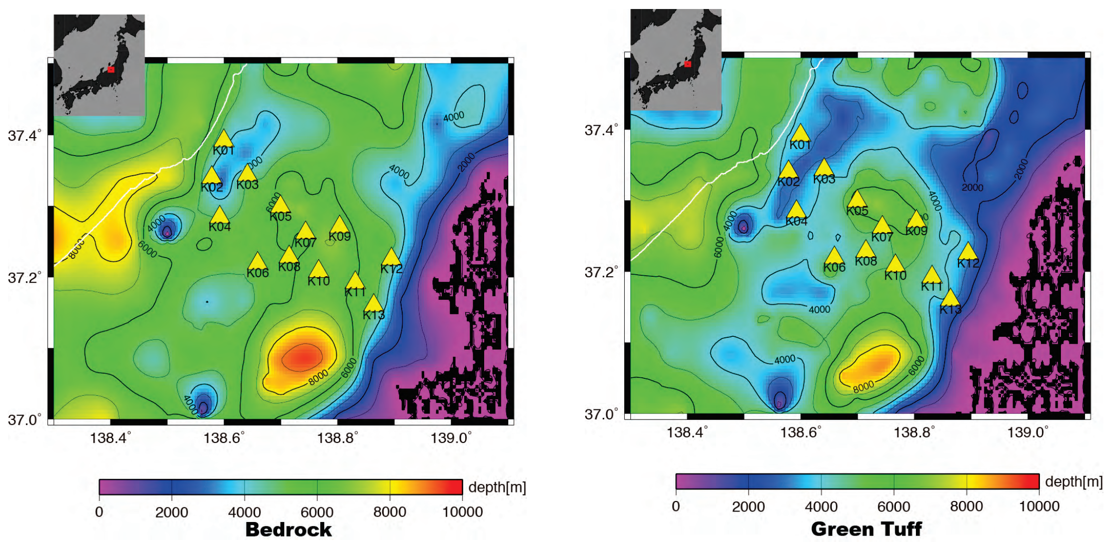

Figure 1. Locations of microtremor arrays, K01-K13, with contour illustrating depth to the basement (Vs=3.3 km/s) and green-tuff (volcanic rock, Vs=2.9km/s) of GSJ model (Sekiguchi et al. 2009)

Table 1. Features of microtremor array obvservations

Array name	Array radius (m)			Center location		Observation period (yy/mm/dd)
	L, LT	M	S	Latitude	Longitude	
K01	2,019	1,153	288	37.39161	138.59943	12/01/11-12/01/25
K02	3,029	1,153	311	37.34006	138.57825	11/12/12-11/12/26
K03	2,250	1,153	288	37.34344	138.6409	11/12/27-12/01/10
K04	3,115	1,211	303	37.28430	138.59197	11/11/25-11/12/11
K05	3,114	1,009	288	37.29899	138.69901	11/07/08-11/07/24
K06	3,464	1,040	317	37.21900	138.65919	11/07/25-11/08/08
K07	3,114	980	274	37.26215	138.7433	11/08/09-11/08/23
K08	3,204	1,096	317	37.22818	138.71469	1108/24-11/09/07
K09	3,291	1,096	260	37.270406	138.80358	11/09/13-11/09/26
K10	3,460	1,153	312	37.20790	138.76666	11/10/11-11/10/25
K11	3,460	1,125	317	37.19224	138.83085	11/10/26-11/11/09
K12	3,460	1,096	288	37.22534	138.89470	11/09/27-11/10/10
K13	3,806	1,125	317	37.16004	138.86351	11/11/10-11/11/24

3. TEMPORAL VARIATION OF DATA

3.1. Temporal variation of the observed noise spectra

Observation sites are located near the Japan Sea, which is calm in summer and stormy in winter because of strong seasonal wind. Two weeks observation provides information about stability of the noise field. Fig. 2. illustrates temporal variation of the observed power spectra of vertical motion in summer and winter. In drawing the figures, spectra are evaluated as average of segmented data (168.34 sec. each) during one hour. Spectra at frequency higher than 1 Hz show 24-hour periodic fluctuation indicating cultural activity is main source of the microtremor at this frequency. On the other hand, the observed spectra at frequency lower than 1 Hz show amplitude variation with more than 1-day period. Noise field of this frequency band is spatially stable as shown in Fig. 3. This implies microtremor at lower frequency is excited by natural perturbations, as had been pointed out by predecessors (eg. Okada 2003).

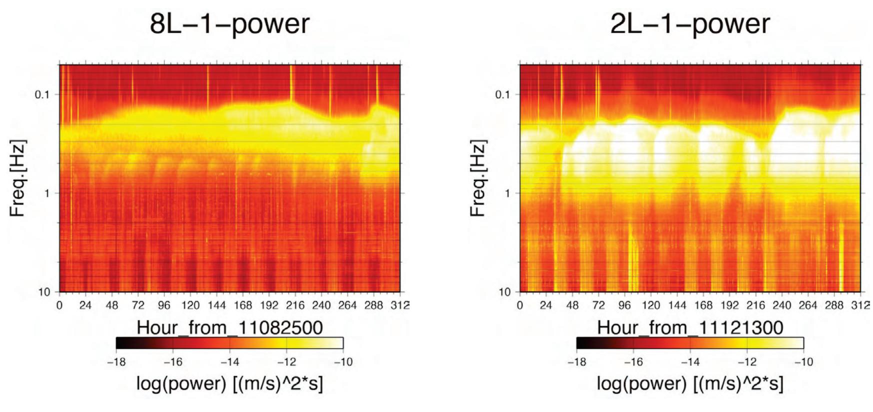

Figure 2. Temporal variations of noise spectra during 13 days of observation in summer (left: K08L-array) and in winter (right: K02L-array). Note that the data is observed by LE3D/5s, no instrument correction is made to draw these illustrations.

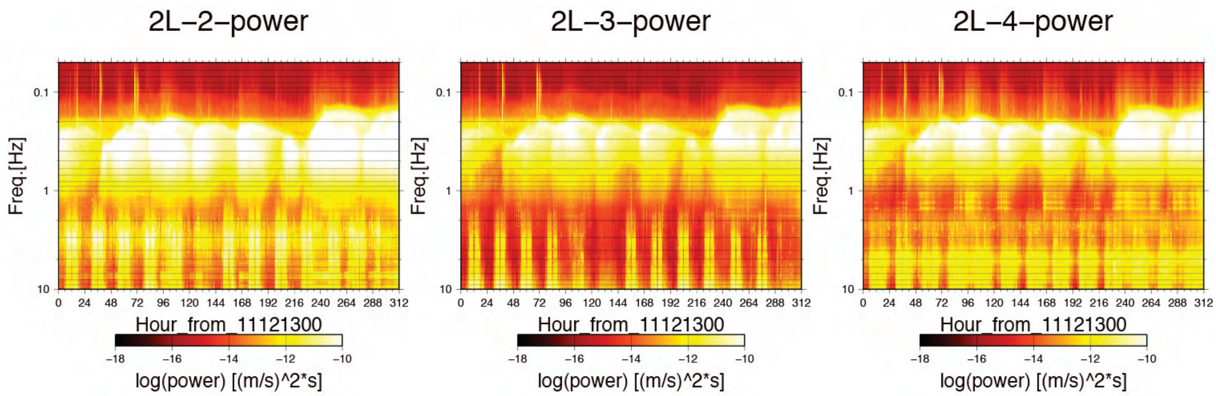

Figure 3 Temporal variation of noise spectra for K02-L array stations.

3.2. Temporal variation of the SPAC coefficient

Our concern is how the temporal variation of the spectra affects to SPAC coefficient. Fig. 4. illustrates temporal variations of SPAC coefficient. Up to 0.2Hz the natural period of the sensor, SPAC coefficient is stable. On the other hand, at lower frequency the coefficient varies somewhat corresponding to the spectral amplitude (Fig. 2). Fig. 5. illustrates SPAC coefficient fluctuation for other K02 arrays (LT, M, S arrays). Here, only difference between LT and L arrays is type of the sensor used for observation. Even with the broadband sensor, the coefficient fluctuates below 0.2 Hz and fluctuation pattern in the frequency range 0.1-0.2 Hz is similar to those obtained with LE-3D/5s. This indicates that the fluctuation of SPAC may have been arose by characteristic of the wave field other than observation conditions such as poor S/N ratio, though further analysis is necessary.

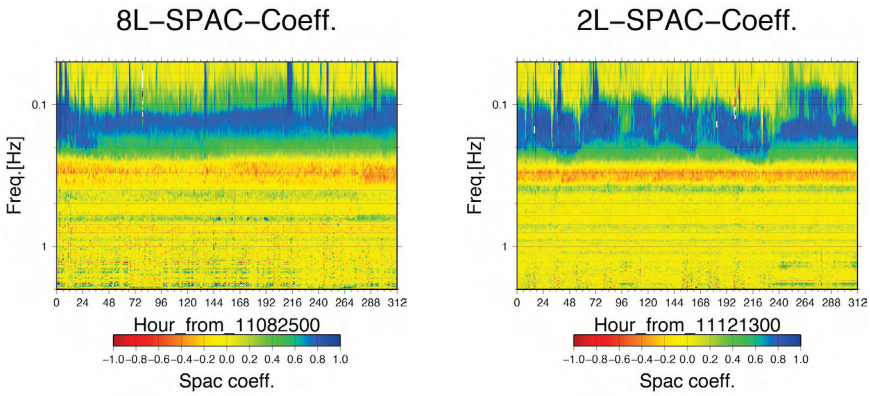

Figure 4 Temporal variations of SPAC coefficients for K08 and K02 array.

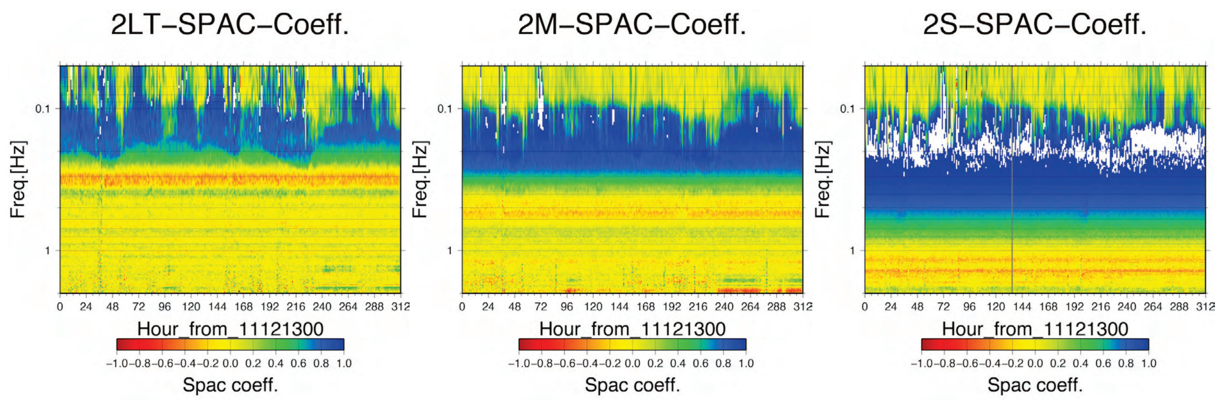

Figure 5. Temporal variations of SPAC coefficients for K02 array. (LT: L-array observed with Trillium Compact, M,S: observed with LE-3D/5s).

4. PHASE VELOCITY DETERMINED WITH SPAC AND V-METHOD

The phase velocity of Rayleigh wave can be calculated from hourly averaged spectra with Eqn. (1) or (2). In calculation, we assume SPAC and V coefficients are single valued function, so the obtained phase velocity is valid only when $kr < 3.83$. Larger kr range can be also used to obtain phase velocity (e.g. Asten et al. (2004)) though it is not shown in this paper.

Time variation of the calculated phase velocity is shown in Fig. 6. for the K02-LT array. The phase velocities are fluctuated below the frequency 0.2 Hz likewise the SPAC coefficient. Since the fluctuation might relate to deterministic wave field characteristics, simple statistical operation such as taking mean or median does not seem to produce reliable estimation especially for lower frequency.

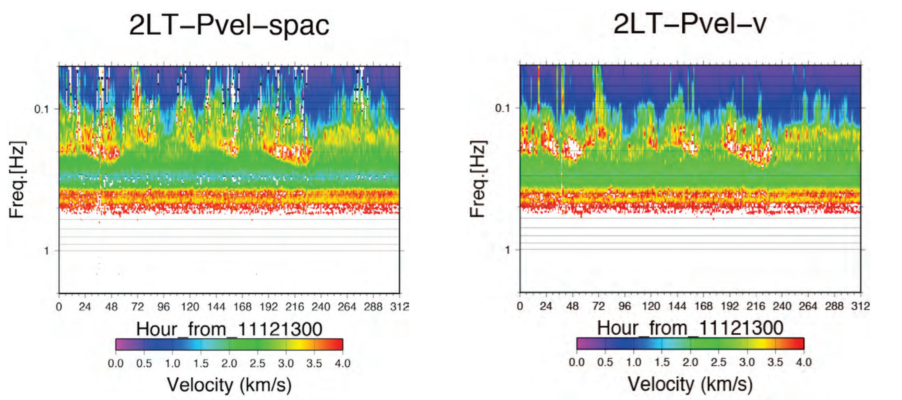

Figure 6. temporal variation of calculated phase velocity with SPAC and V-method (K02-LT-array)

We select observed data under a criterion of SPAC > 0.8 at the frequency 0.05 Hz for L and LT array expecting there exist informative wave field. Then, by taking mean the phase velocity at lower frequency is determined (below about 0.2 Hz). For higher frequency range (> 0.2Hz) the phase velocities are determined with M-, S-array as mean values among all the observed data. Finally all the phase velocity is combined to obtain dispersion curve. Since we use $kr<3.83$ range of the SPAC and V coefficients, resultant dispersion curve reflects velocity structure averaged over an observation site. Fig. 7. displays dispersion curves determined for 13 observation sites. Two methods give generally similar results while the V-method has resolution in lower frequency below 0.1 Hz, which our long observation contributed to this remarkable resolution.

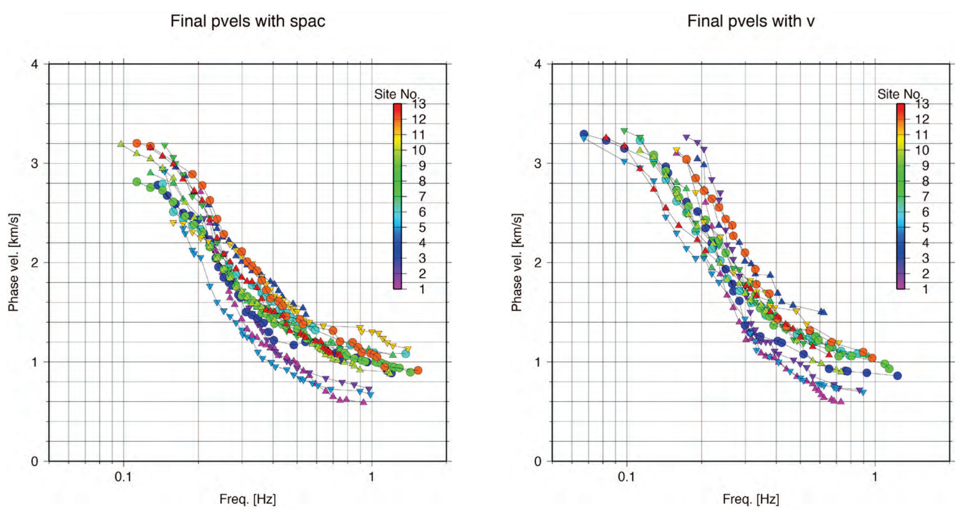

Figure 7. Phase velocities for 13 sites determined with SPAC and V-method

5. VELOCITY STRUCTURE

5.1 Phase velocity inversion

S-wave velocity structure at each site is inverted from the dispersion curve using GA (genetic algorithm) inversion proposed by Yamanaka and Ishida (1996). In the inversion, we assume 15 layers (13 sediments of velocity 0.4-2.8 km/s with interval of 0.2 km/s, bedrock 3.3 km/s and lower crust 3.8 km/s) each with constant shear wave velocity, since clear velocity contrast had not been observed in the sediments of this region (e.g. Sekiguchi et al. 2009). P-wave velocity and density is defined as a function of the S-wave velocity after Ludwig et al. (1970). Thus, the thickness of each velocity layer is the variable to be solved. Fig. 8. shows the resultant 1D velocity structures inverted from the dispersion curve obtained with SPAC and V-method. Fitting of the phase velocity is good though figures are omitted here.

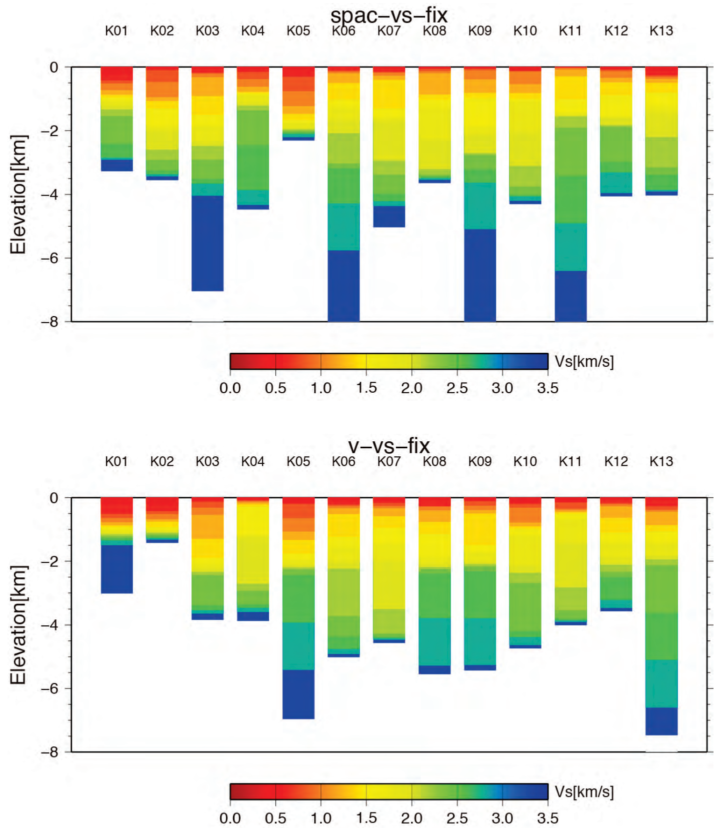

Figure 8. 1D velocity structures inverted from dispersion curve (upper: SPAC, bottom: V-method)

5.2 Comparison of observed and theoretical SPAC, V coefficients

As we retrieve phase velocity from the SPAC and V coefficients within kr < 3.83 range, fitting of both coefficients of inverted velocity model at large kr range is not assured. Fig. 9. shows comparison of theoretical and observed SPAC coefficients for six observations sites. Fig. 10. shows similar comparison but for absolute value of the V coefficient. Every first local minimum corresponds to kr=3.83. Theoretical SPAC and V coefficients for ten candidates during the inversion are calculated assuming dominance of the fundamental mode of Rayleigh wave. Below the frequency corresponding to kr=3.83, fitting of the coefficient is quite well. On the other hand, above the kr=3.83 especially for large array (L, LT) fit of the SPAC or V coefficient with regard to its peak and trough become worse as the frequency grows while coefficient of small array (M or S) fits well. This indicates that the phase velocity averaged over different array is not same. In other words, the velocity structure beneath the observation site is not uniform within several kilometers. Since the sites are on hilly active fold area where sediment layers are deformed, velocity structure may be heterogeneous even in short distance.

Finaly we show in Fig. 11. comparison of the observed SPAC coefficients and theoretical ones of 1D structure picked from several velocity structure models (Sekiguchi et al. 2009, Fujiwara et al., 2009, JNES 2005, 2008).

6. CONCLUSIONS

Microtremor array survey with long observation has been conducted in active fold area in Niigata prefecture. Noise spectra observed in each ten-day observation have provided information about stability of the noise field. Spectra at frequency higher than 1 Hz showed 24-hour periodic fluctuation indicating human activity, while that lower than 1 Hz showed amplitude variation with more than 1-day period. Spectra variation seems to be a cause of the SPAC coefficient fluctuation at lower frequency, while the characteristic of the wave field itself may be other factor. Phase velocity dispersion curve has been retrieved from array observation data using SPAC and V-method, while data in high coherence time periods have been used for large array. Two methods have provided generally similar results while the V-method has resolution in lower frequency. Then, S-wave velocity structure of each site has been derived from the dispersion curve using GA inversion assuming 15 velocity layers with constant shear wave velocity. Resultant velocity structures have well reproduced the SPAC and V coefficients for every array up to the frequency corresponding to kr=3.83, whereas above the frequency they tended to fail to reproduce. These indicate the velocity structure beneath the observation site is heterogeneous within several kilometers. Further study is needed for effective velocity structure survey in folding region.

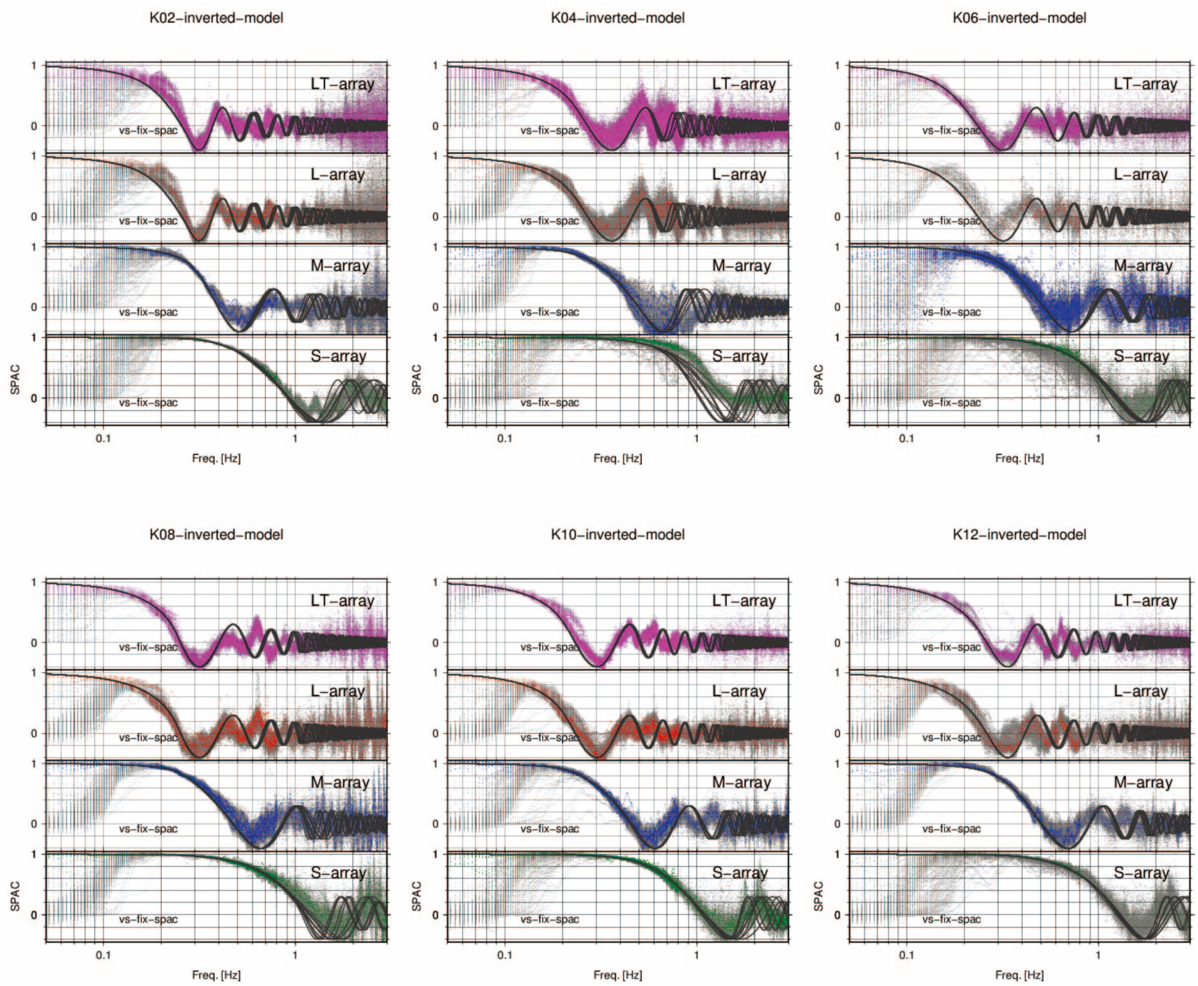

Figure 9. Comparison of theoretical (gray curves) and observed SPAC coefficients for inverted velocity structures. Dots are observed SPAC coefficients, the colour dots are those satisfy SPAC>0.8 at 0.05Hz.

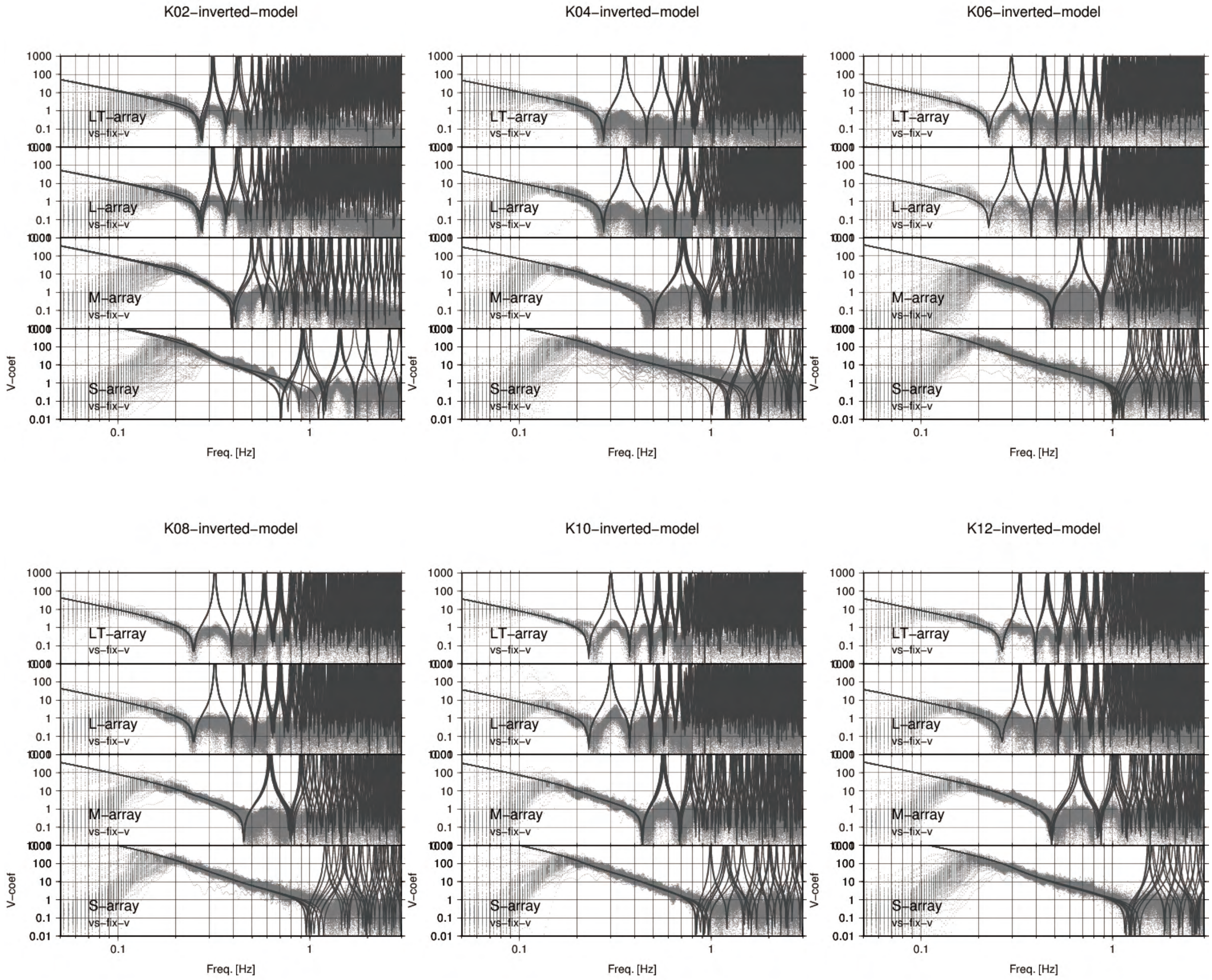

Figure 10. Comparison of theoretical (gray curves) and observed (dots) spectral ratio for V-method for inverted velocity structures.

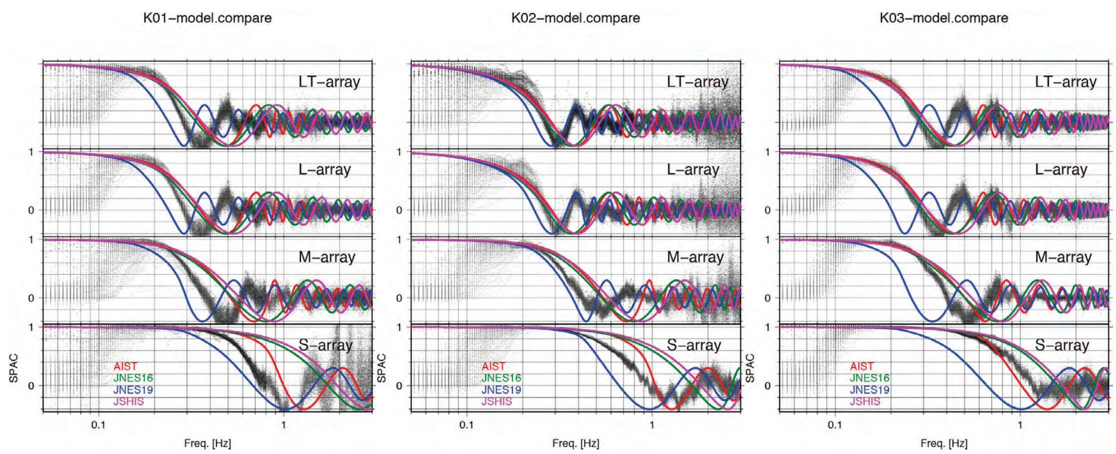

Figure 11. Comparison of observed SPAC coefficients (K01-K03) and theoretical ones for velocity structure models (red: Sekiguchi et al. 2008, green: JNES, 2005, blue: JNES, 2008, pink: Fujiwara et al, 2009).

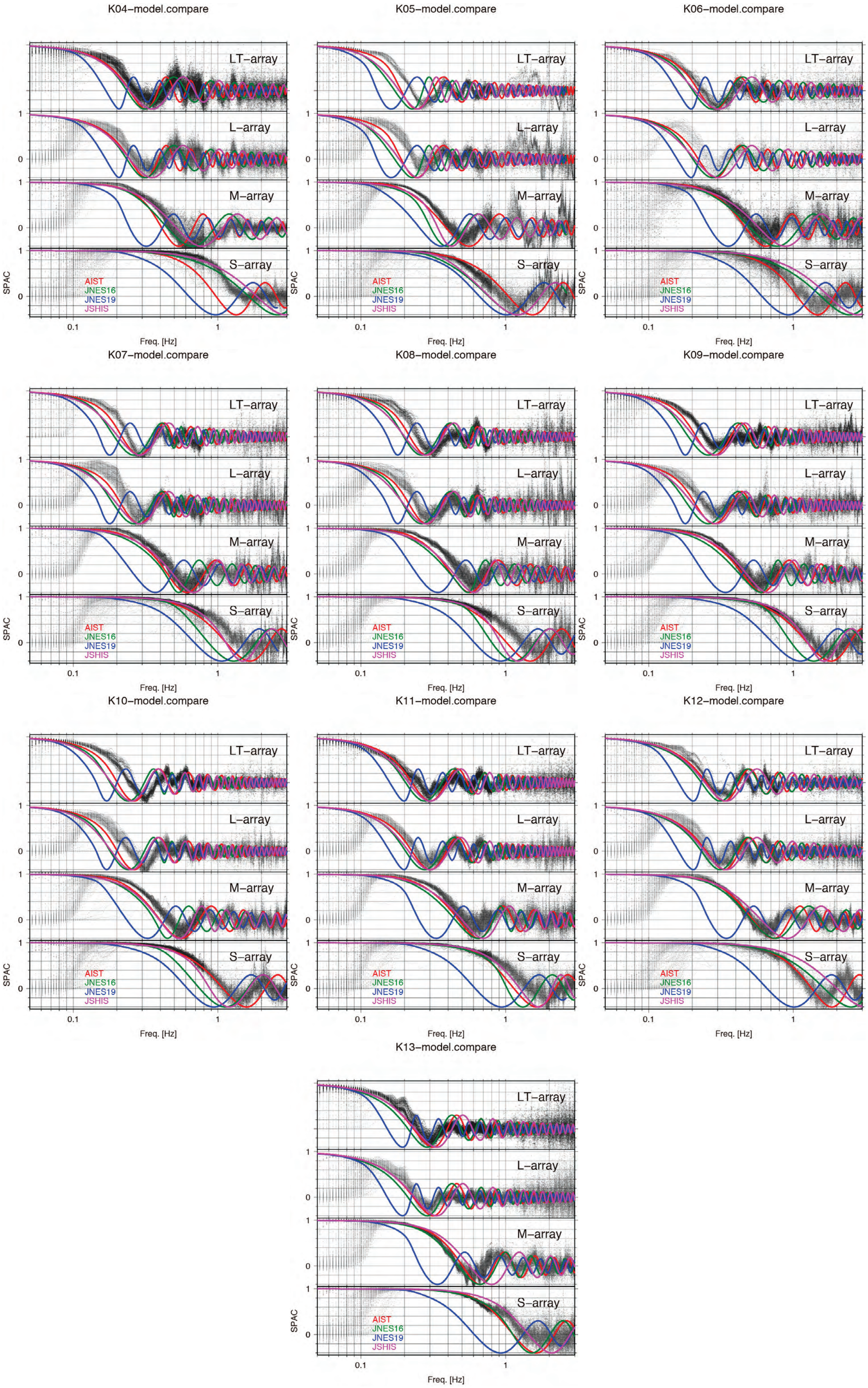

Figure 11 (continued). Comparison of observed SPAC coefficients (K04-K13) and theoretical ones for velocity structure models (red: Sekiguchi et al. 2008, green: JNES, 2005, blue: JNES, 2008, pink: Fujiwara et al., 2009).

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This research was supported by JNES (Japan Nuclear Energy Safety Organization). We used BIDO2.0 software (Tada et al. 2007) for analysing array noise data with SPAC and V methods. GMT (Generic Mapping Tool, Wessel and Smith, 1998) software is used in drawing figures.

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