Estimation of phase velocities of Love wave from three-component microtremor array observations by using spatial auto-correlation and frequency wavenumber analysis

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Abstract

Microtremor array technique was a method to estimate S-wave velocity profiles by using dispersions of surface waves from microtremor array records. Rayleigh waves in vertical microtremors were frequently used because of convenient means of array measurements in fields. However, it was difficult to estimate parameters of Vs and thickness in the velocity profiles by using only the dispersions of Rayleigh waves. If other observable geophysical values, e.g. Love wave dispersions, can be used, the unique solvability will be better for the microtremor array technique. Our study tries to detect not only dispersion curves of Rayleigh waves but also those of Love waves from three-component microtremor array records by using three-component spatial auto-correlation (SPAC) technique and horizontal frequency-wavenumber (F-K) spectral analysis. At the ground of Iwate University in Morioka City in the northern Honshu Japan, the applicability of SPAC method and F-K method for estimating phase velocities of Love wave in microtremors using a three-component array consisting of 10 sensors was studied. As a result, SPAC method and FK method in different type triangular arrays with same sensor number with different orientations was able to obtain the same phase velocities. For the case of the circular array consisting of nine sensors on a circumstance with same radius and one at a center, both method gave better dispersion of Love wave in a wide frequency range. It was possible to obtain dispersion curves in a wide frequency band using arrays consisting of 10 sensors. In the horizontal microtremor analysis it was possible to obtain the phase velocities of the Love wave using both FK method and SPAC method in a wide frequency band.

Keywords: Three-component microtremor array observation, Love wave dispersion, Spatial Autocorrelation (SPAC) analysis, frequency-wavenumber (FK) analysis

1. Introduction

The Microtremor survey method is one of method to determine the underground S-wave velocity structures from phase velocity dispersion relations of surface waves in microtremors [e.g. 1]. Many previous studies were to utilize vertical components of microtremors because it was easy to identify the Rayleigh wave dispersion from vertical microtremors. On the other hand, a few studies were to try to utilize horizontal components of microtremors [2, 3, 4, and 5]. The authors had tried to apply the three-component spatial autocorrelation method [6, 7, 8] to estimate a phase velocity of Love wave from horizontal microtremor array records observed in Morioka City at the northern Honshu, Japan [2, 6]. However, because of the accuracy of the measurement equipment, one of the AD resolution, the lack of the number of the sensor and the lack of the coverage of correlation distances, the estimation of the phase velocity was not completely successful [2]. As the other method to estimate phase velocities, there is a frequency-wavenumber analysis [e.g. 9, 10]. Saito (2007) developed a new frequency-wavenumber analysis method with respect to the analysis of the horizontal component of microtremors [11]. By using the method Ohori et al. (2013) was successful in estimation of the phase velocities of Love waves in microtremors, but the theoretical or technical problems are still remained to be solved foe estimating Love wave dispersions from microtreemors [3, 4, 5].

The authors tried to examine the identification the Love wave phase velocity by applying the frequency wavenumber analysis by Saito’s horizontal FK method and three-component spatial autocorrelation method to horizontal microtremor array records observed at the ground of Iwate University in Morioka City [12]. As a result, even though by using FK method by using SPAC method, they were able to estimate the phase velocity of the Love wave. However, the degree of variation in the estimated value of the phase velocity was large and the reliability was low. The reason for the problem of the placement and the number of sensors had been pointed out.

FK method has the advantage that the degree of freedom of the shape of the array is high. However, it has also the disadvantage that many sensors are required. When using the FK method with only five microtremor measure sensors owned by the authors, it was difficult to detailed examination [12]. Further, it is difficult to compare the characteristics of the method is the observation sites with a lateral heterogeneity possibilities.

Therefore, at a ground of Iwate University where the authors had used many times in the previous studies, using a three-component array arrangement consisting of 10 sensors, about the analysis applicability of FK method and the SPAC method, the authors examined the following discussions.

1) Discussion on the array records with a different orientation in the same number of sensors,

2) Discussion on the number of sensors,

3) Discussion on the approaches of FK method and SPAC method.

2. Microtremor Observation and Analysis procedure

The authors carried out microtremor observations at the ground of Faculty of Science and Engineering, Iwate University in Morioka City at the northern Honshu, Japan in the midnight April 22, 2015. Ten microtremor sensors (JU310) producted by Hakusan Co., Ltd. were used for observations. Five were owned by the authors, but five were borrowed from The National Research Institute for Earth Science and Disaster Prevention (NIED).

Fig. 1 shows the array configuration. Red squares indicate the triangle array named as '3_1', blue triangles one named as '3_2', and green circles one named as '3_3'. We will show estimated results from the different triangle array records by using same color as Fig. 1. The nonagon array consists of one sensor at a center and nine sensors on a circumference with a radius of 44 m. We can also analyze the records of the nonagon array as records of three regular triangle arrays with different azimuths. By setting up a total station theodolite to the center of the array, the author determined the observation point positions so as to be equal spacing in every 40 degrees. Since it was possible to arrange microtremor sensors at equal intervals on the circumference, the arrangement of the regular triangle arrays of three equal intervals on a circumference are three kinds with a different azimuth of 40 °. Therefore, a comparison with a triangle array of a nonagon array was examined.

Sampling period was 5ms, AD conversion resolution 24bit, gain was 16 times, and the filter was set to minimum phase delay type. Measuring time was about 1 hour. Fig.2 shows the three-component acceleration waveforms of measured microtremors during one hour. Red waveforms indicate EW component, green indicate NS component, blue indicate UD component. A top waveform for each component is located at the north position. A bottom waveform for each component is located at a center. The 4th from top vertical microtremor waveform contains some high-frequency vibration contents, but had no effect on most analyzes because different from the frequency range for estimating phase velocities.

SPAC method [6, 7, 8] and FK method [11] is used for the analysis of the phase velocity estimation. In the case of SPAC method, two types of correlation distances, namely, radius and the side length, are used in the analysis of the regular triangular array, and five types of those, up to the shortest 30m, the longest 86.6m, are used in the analysis of the regular nonagon array.

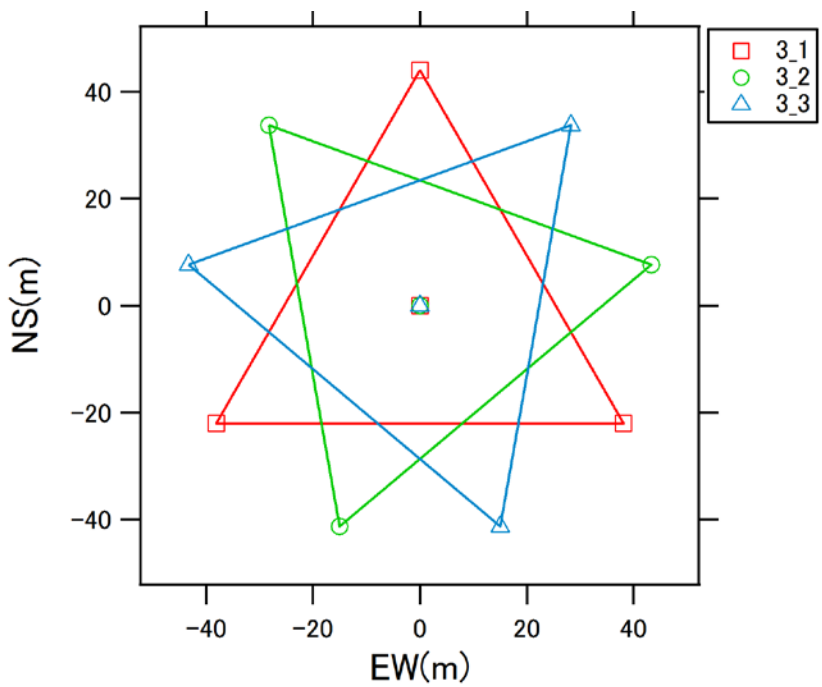

Fig.1 Array configuration for measuring microtremors. The nonagon array consists of one sensor at the center and nine sensors on a circumference with a radius of 44 m. We can also analyze the records of the nonagon array as records of three regular triangle arrays with different azimuths. Red squares indicate the triangle array named as '3_1', blue triangles one named as '3_2', and green circles one named as '3_3'. We will show estimated results from the different triangle array records by using same color as Fig. 1.

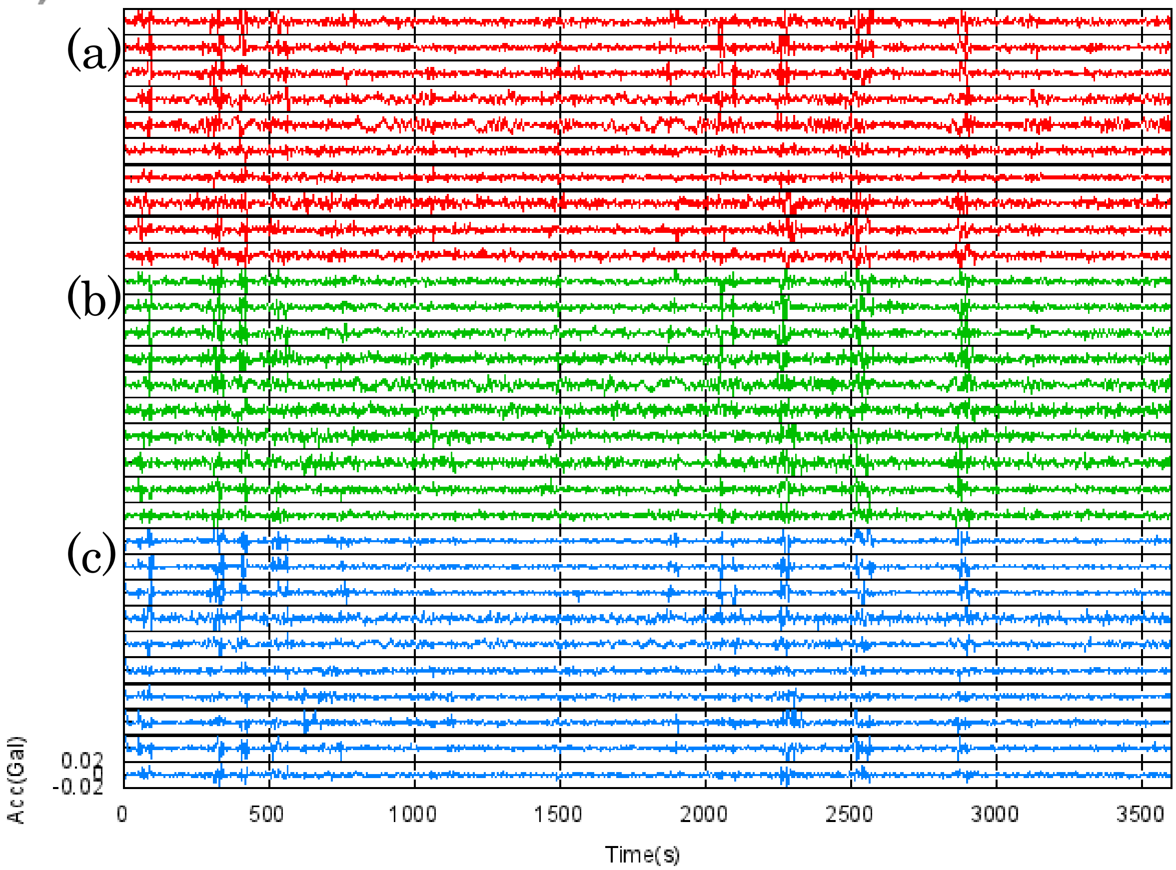

Fig. 2 Acceleration waveform of observed microtremor array records. (a) Red waveforms indicate EW component, (b) Green indicate NS component (c) Blue indicate UD component. A top waveform for each component is located at the north position. A bottom waveform for each component is located at a center.

3. Phase velocity estimation for vertical microtremors

First, in the case of a vertical microtremor array analysis by SPAC method, we discuss on the analysis results of three orientation-different types of triangular array records and the analysis result of the nonagon array record. Figure 3 shows the spatial autocorrelation coefficients for vertical microtremors. A left figure shows SPAC coefficients for a distance of 44 m and a right figure shows those for a distance of 86.6 m. The figures show the relation between regular triangle type array and regular nonagon type one. At the high frequency range a blue SPAC coefficient obtained from the regular triangular array records shows slightly different shapes from others. The result implies that the vertical microtremor arrival orientations may not be uniformly distributed but it is considered that the contribution is almost negligible from the results of estimated phase velocities which will be described later. Figure 4 shows phase velocities of Raleigh wave estimated from vertical microtremors by SPAC method. A left figure shows normal view. A right figure shows enlarged view. A minimum distance in the case of a regular nonagon type array is about 30 m. Three phase velocities obtained from the triangle array records with different orientations are found to exhibit approximately the same values in the frequency range from about 5Hz to 6 Hz. Those are same as phase velocities obtained from the regular nonagon array record. The difference of the phase velocities resulting from the triangular array records in the vicinity of 6Hz was recognized. This reason is suggested by the variation pf spatial autocorrelation coefficients as can be seen from Fig.3.

Next, also in the case of a vertical microtremor array analysis by FK method, we discuss on the analysis. Fig.5 shows phase velocities of Raleigh wave estimated from vertical microtremors by FK method. A left figure shows normal view. A right figure shows enlarged view. A purple inverted triangle indicates phase velocities estimated from records of the nonagon array. A red square, a green square and a blue triangle indicates phase velocities estimated from the records of the triangle arrays. A minimum distance in the case of a regular nonagon type array is about 30 m. In the case of FK method as well as SPAC method, although the three types of phase velocity values obtained from a regular triangle-type arrays are found to exhibit approximately the same values, the variations of phase velocities obtained by FK method are found to be larger than those by SPAC method. For the analysis of the nonagon array recording, a good dispersion curve having continuous is obtained. This is suggested that the estimation accuracy is lowered in three number of sensors on the circumference by FK method.

Fig.6 shows phase velocities of Raleigh wave estimated from vertical microtremors by SPAC method and FK method. Red circles indicate phase velocities by SPAC method and green square indicate phase velocities by FK method. A left figure shows normal view. A right figure shows enlarged view. A minimum distance in the case of a regular nonagon type array is about 30 m. In the analysis of FK method and SPAC method, both the phase velocity show almost the same values. However, those show different values at the long wavelength range (low frequency range). One possible reason is due to reduction of the correlation coefficient at the low frequency range for SPAC method, and it is due to the broadening of the peak of FK power spectrum for FK method.

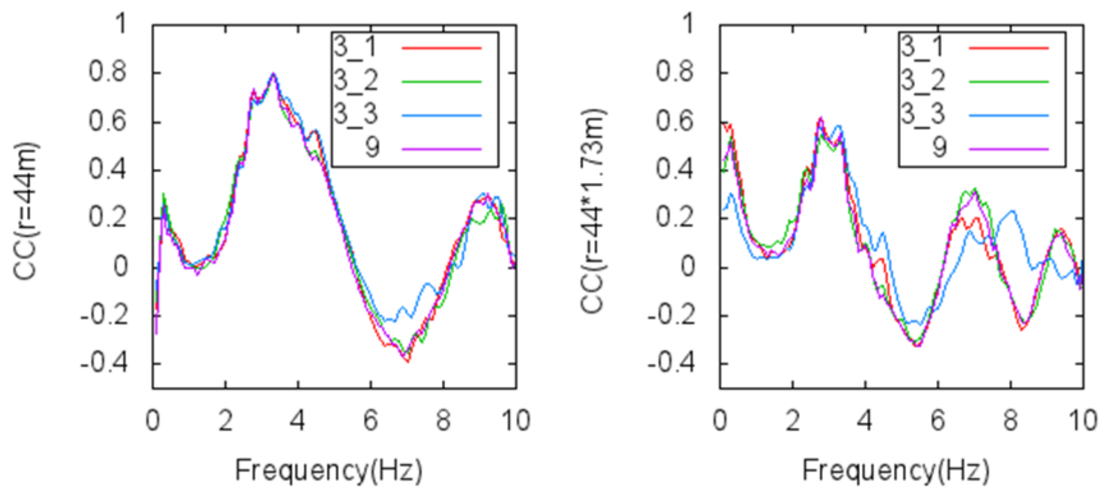

Fig.3 Spatial autocorrelation coefficients for vertical microtremors by using SPAC method. Left figure shows SPAC coefficients for a distance of 44 m and right figure shows those for a distance of 86.6 m. The figures show relation between regular triangle type array and regular nonagon type one.

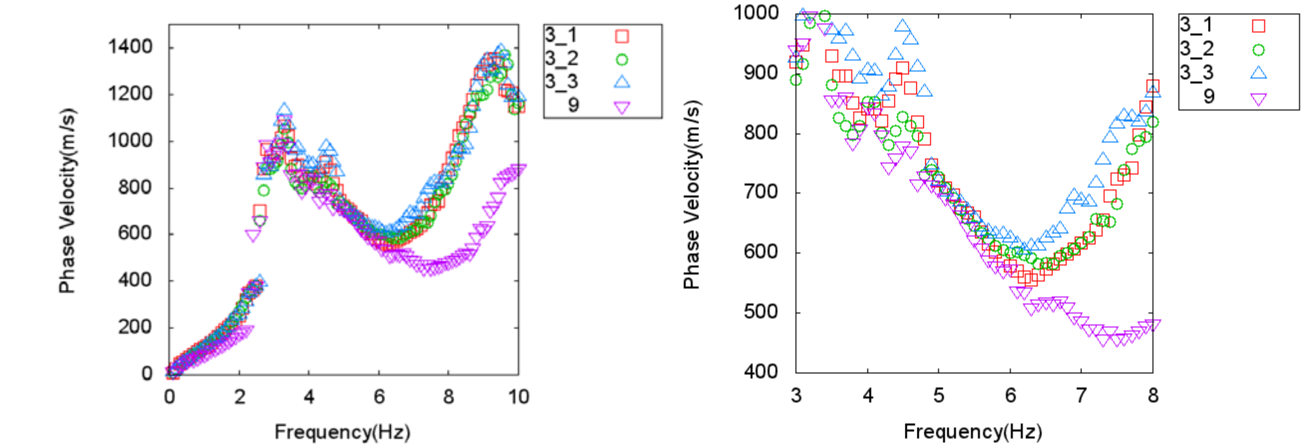

Fig. 4 Phase velocities of Raleigh wave estimated from vertical microtremors by SPAC method. Left figure shows normal view. Right figure shows enlarged view. A minimum distance in the case of a regular nonagon type array is about 30 m.

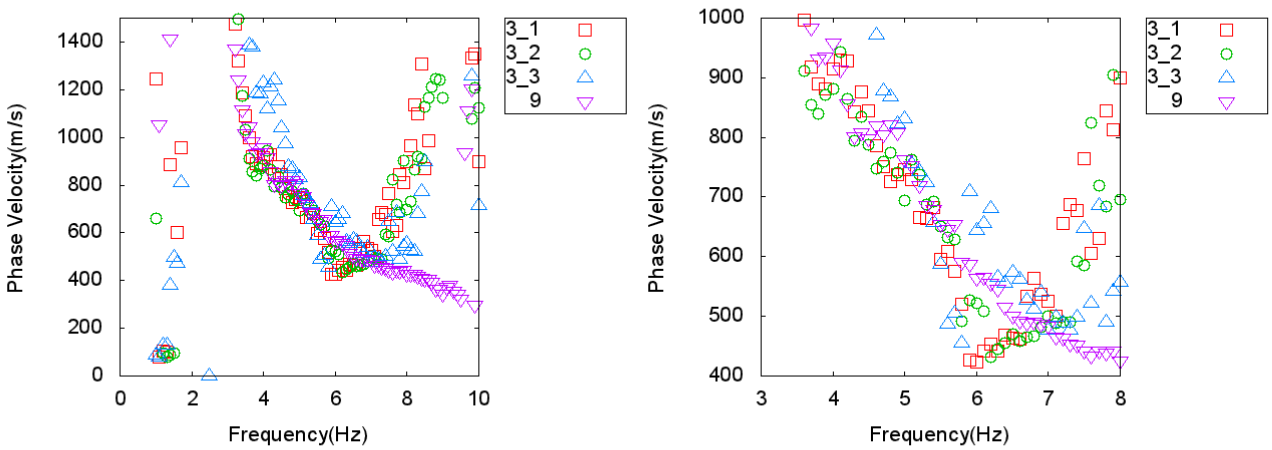

Fig. 5 Phase velocities of Raleigh wave estimated from vertical microtremors by FK method. Left figure shows normal view. Right figure shows enlarged view. A purple inverted triangle indicate phase velocities estimated from records of the nonagon array. A red square, a green square and a blue triangle indicate phase velocities estimated from the records of the triangle arrays. A minimum distance in the case of a regular nonagon type array is about 30 m.

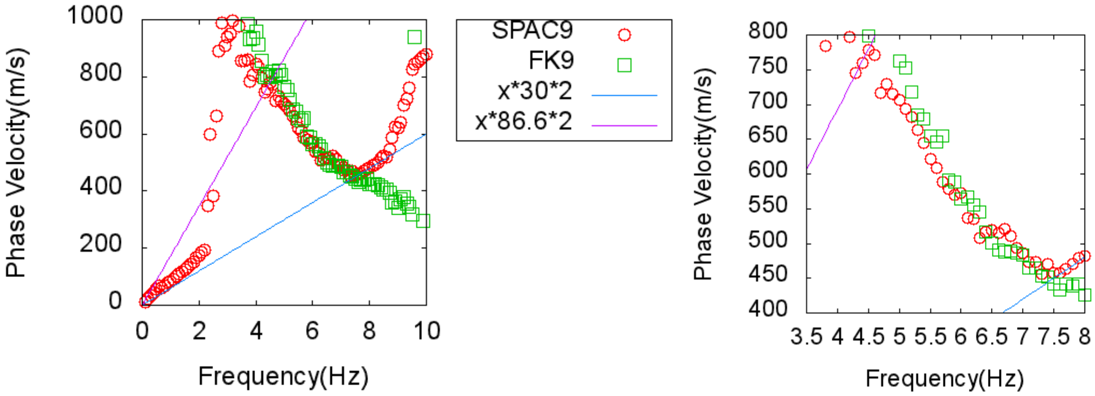

Fig. 6 Phase velocities of Raleigh wave estimated from vertical microtremors by SPAC method and FK method. Red circles indicate phase velocities by SPAC method and green square indicate phase velocities by FK method. Left figure shows normal view. Right figure shows enlarged view. A minimum distance in the case of a regular nonagon type array is about 30 m.

4. Phase velocity estimation for horizontal microtremors

In the case of horizontal microtremor analysis as well as vertical, we compare the analysis results of the three different orientation triangular array records and the nonagon array record. Fig. 7 shows F-K power spectra of horizontal microtremors at a frequency of 5.0 Hz by the method of Saito (2007). A left figure shows transverse FK power spectrum and a right figure shows a radial FK power spectrum. FK Powers are normalized by a maximum value. The peak shows the arrival azimuth and the wavenumber of microtremors. The transverse FK spectrum shows that relatively high power values were distributed on a circle. This implies that microtremor arrival orientation was isotropic for transverse component, namely Love wave. The radial FK spectrum also shows that relatively high power values were distributed on a circle. This implies that microtremor arrival orientation was also isotropic for radial component, namely Rayleigh wave. However, we can see that the location of FK peaks of the transverse FK spectrum was different from that of radial FK one. This shows that phase velocity of the transverse component was higher than one of the radial component at least at the frequency of 5 Hz. A phase velocities is calculated from the frequency divided by the wavenumber. For transvers component we can see ring-like FK power spectrum distribution. The figure suggests that microtremor azimuthal coverage is wide.

Figure 8 shows F-K power spectra of horizontal microtremors at frequencies of 4.5, 5.0, 5.5 and 6.0 Hz. We can see that transverse FK power shows strong powers on a circumstance. This suggests that transverse-type microtremors arrive from various orientations. Figure 9 shows phase velocities of Rayleigh and Love waves by FK and SPAC method. A blue triangle indicates phase velocities of Rayleigh waves estimated from radial FK spectra, a red circle indicates phase velocities of Love waves from transverse FK spectra, and a green square indicates phase velocities of Love waves from horizontal SPAC method. Phase velocities of Love waves from transverse FK spectra are almost equal to those from horizontal SPAC method. We can see that estimated Raleigh phase velocities are larger than Love phase velocities. The horizontal SPAC method must utilize phase velocities of Rayleigh wave from vertical analysis. For this reason, Rayleigh wave dispersions analyzed from the nonagon array record were used for horizontal SPAC analysis. Figure 10 shows phase velocities of Rayleigh and Love waves calculated from S-wave velocity structure model. The S-wave velocity structure were estimated from previous studies and bore hole data in this site. It is expected that phase velocitites are not the same at the frequency range in this site. From both of calculated and observed results it was shown that the estimated phase velocities of Rayleigh wave were different from those of Love wave at the frequency range.

We can recognize that phase velocities obtained from transverse component and those from radial component by horizontal FK method are able to estimate good dispersion curves of continuity in somewhat variations are observed a wide range of frequency bands. Further, we can see that the Love-wave phase velocities obtained from the SPAC method also show substantially the same value as the phase velocities of transverse components of FK method. The fact of agreement of these results shows that the analysis is reasonable.

It was found to be able to estimate the phase velocity in the horizontal motion FK method in situations where nine sensor on the circumference are arranged also sufficiently wide wavelength band (frequency band). The analysis of phase velocities of radial component of FK method shows that the variation is large, so it is difficult to use for estimating the Rayleigh wave dispersion. However, if we want to estimate Rayleigh wave dispersions, then we can get high resolution phase velocities from vertical analysis. The results shows that horizontal FK method gives us Love dispersions analysis tools. If a use of the method, we can use both Rayleigh and Love waves for microtremor survey method.

However, it is difficult to install the nine sensors in a uniform arrangement on the circumference for practical survey problem. The number of sensors and the spatial arrangement is required detailed consideration in the future. If the observation that the sensor number has been enriched can be implemented, if it also can be applied is FK method collapse circular arrangement, which is required by the SPAC method is somewhat in the future, be applied case is to increase the phase velocity of Love waves it is expected.

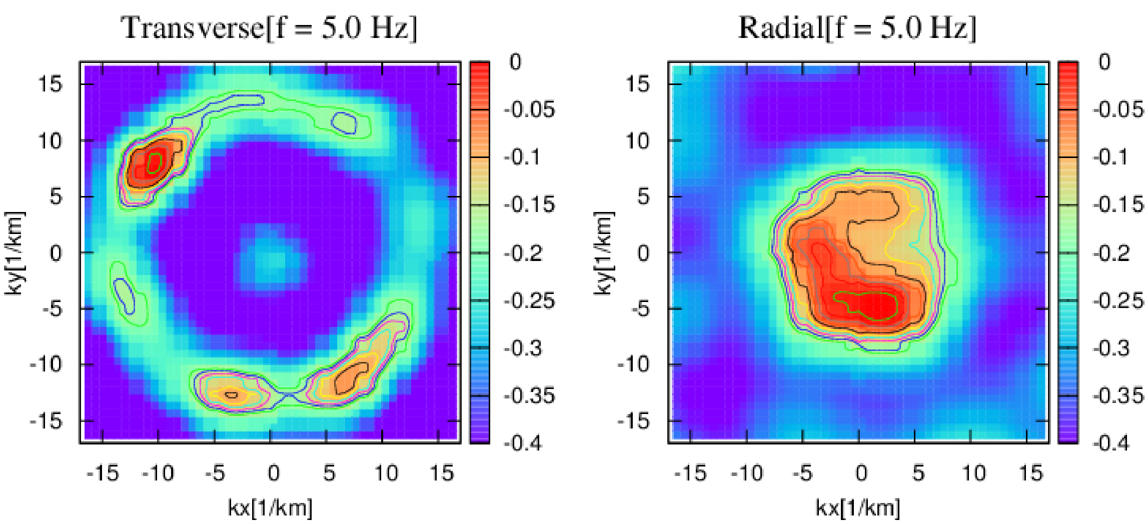

Fig. 7 F-K power spectra of horizontal microtremors at a frequency of 5.0 Hz. A left figure shows transverse FK power spectrum and a right figure shows a radial FK power spectrum. FK Powers are normalized by a maximim value. The peak shows the arrival azimuth and the wavenumber of microtremors. A phase velocities is calculated from the frequency devided by the wavenumber. For transvers component we can see ring-like FK power spectrum distribution. The figure suggests that microtremor azimuthal coverage is wide.

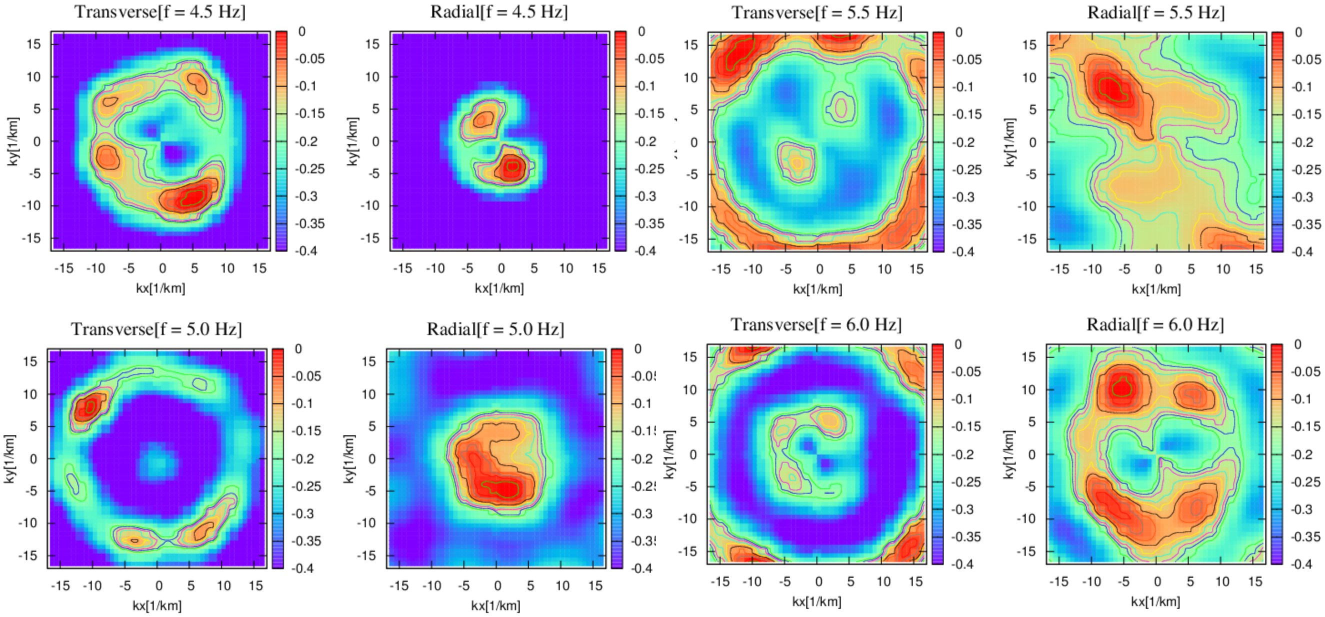

Fig. 8 F-K power spectra of horizontal microtremors at frequencies of 4.5, 5.0, 5.5 and 6.0 Hz. We can see that transverse FK power shows strong powers on a circumstance. This suggests transverse-type microtremor arrive from various orientations.

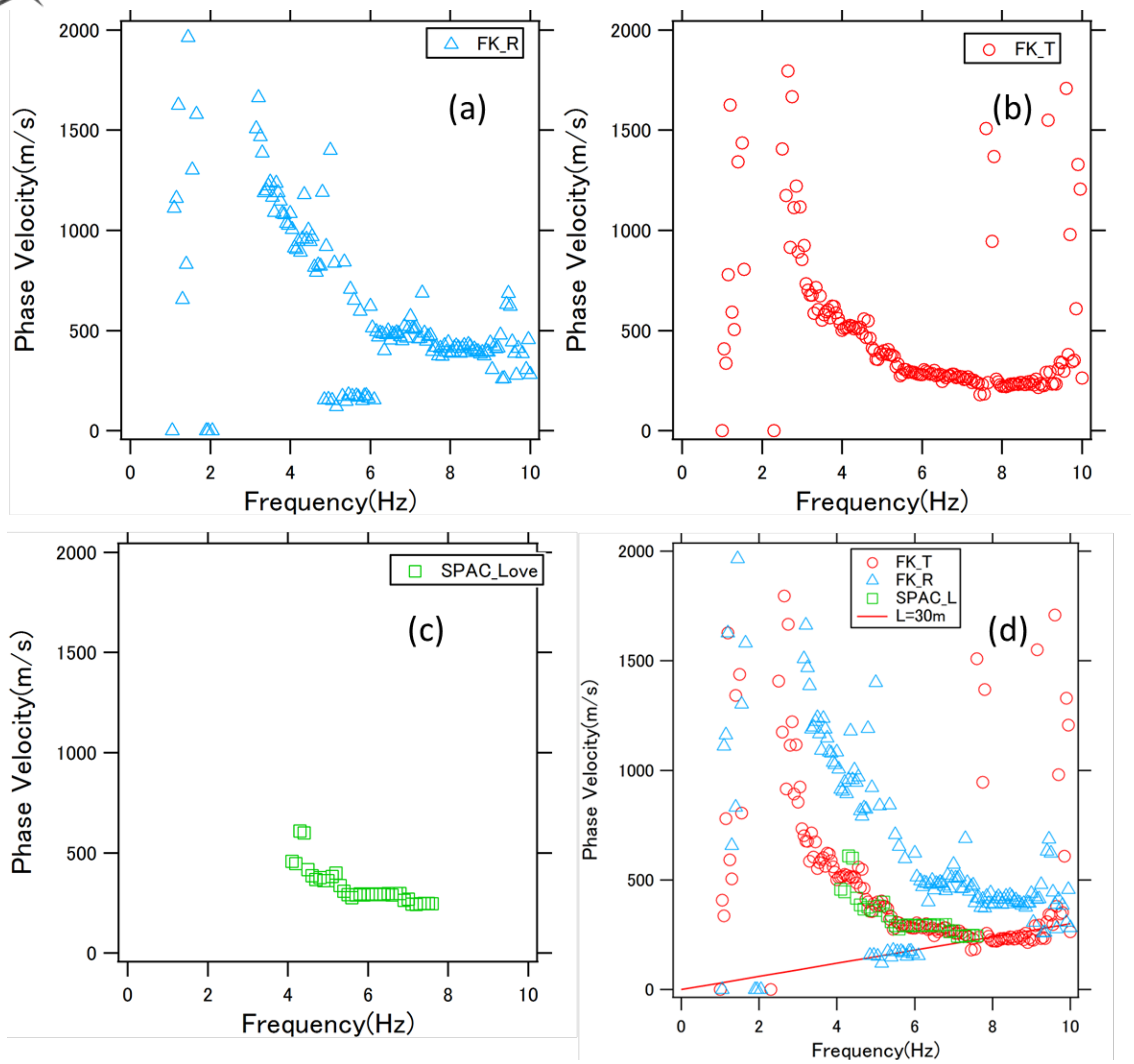

Fig.9 Phase velocities of Rayleigh and Love waves by FK and SPAC method. (a) Phase velocities of Rayleigh waves estimated from radial FK spectra. (b) phase velocities of Love waves from transverse FK spectra, (c) phase velocities of Love waves from horizontal SPAC method. (d) All phase velocities. Phase velocities of Love waves from transverse FK spectra are almost equal to those from horizontal SPAC method. We can see that stimated Raleigh phase velocities are larger than Love phase velocities.

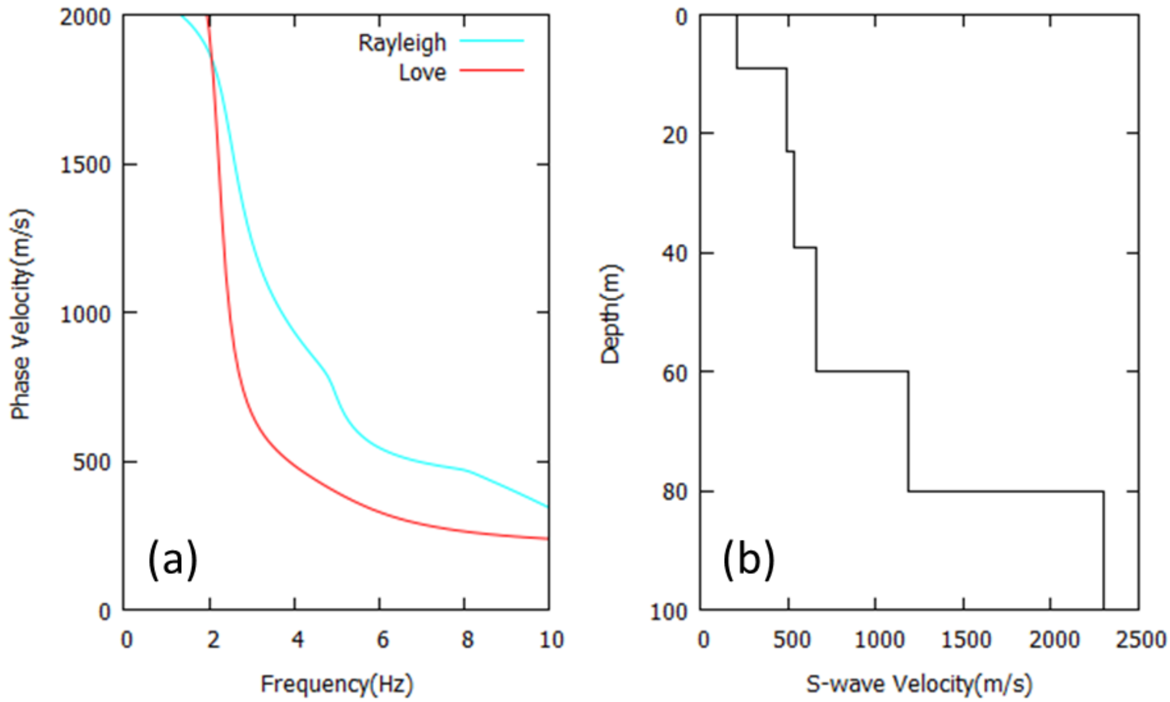

Fig.10 Phase velocities of Rayleigh and Love waves calculated from S-wave velocity structures. (a) Calculated phase velocities of Rayleigh waves. (b) S-wave velocity structure used for the calculation. S-wave velocity structure were estimated from previous studies and bore hole data in this site. It is expected that phase velocitites are not the same at the frequency range in this site.

5. Conclusions

We carried out microtremor array observations using the nonagon array consisting of 10 sensors with a radius of 44m at the ground of Faculty of Science and Engineering, Iwate University in Morioka City at the northern Honshu, Japan in order to reduce the non-uniqueness for the inversion process by using both phase velocities of Rayleigh and Love waves for microtremor array survey. We were able to determine the same phase velocities from different orientation triangular array records using SPAC method and FK method. In the analysis with the nonagon array records we were able to obtain good dispersion curves of continuity in a wide range of frequency band. The horizontal FK spectra shows that the transverse and radial microtremor arrival orientations were uniformly distributed and the radial wavenumbers were larger than transverse ones at the estimated frequency range. In the horizontal microtremor analysis it was possible to obtain phase velocities of Love waves in a wide frequency band by both FK and SPAC method.

4. Acknowledgements

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