# Microtremor Array Measurements and Three-component Microtremor Measurements in San Francisco Bay Area

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**SUMMARY:**
Microtremor array measurements and three-component microtremor measurements have been performed at several sites in the South Bay of the San Francisco Bay Area. Two seismographs with three-component accelerometers were used for data acquisition. The two accelerometers were separated by 5 to 4125m and several different separations were used at each site. The total record length of microtremor data for each separation was about 10 to 60 minutes and measurements at one site took several hours. A spatial autocorrelation was used for calculating phase velocity and clear dispersion curves were obtained in frequency range from 0.2 to 10 Hz. A joint inversion of H/V spectra and dispersion curves was applied to observed data and S-wave velocity models to a depth of about 2km were obtained.

*Keywords: S-wave velocity, Surface waves, Spatial autocorrelation, Microtremor, Array measurements*

## 1. INTRODUCTION

Most of us would accept that surface ground motion from earthquakes highly dependent on subsurface geological structure. The term “local site effect” can be defined as the effect of subsurface geological structure on surface ground motion. To estimate the local site effect, S-wave velocity to a depth of several tens of meters, such as $AV_S30$, is very popular all over the world. However, several recent severe earthquakes and subsequent research have revealed that much deeper (to a depth of several kilometers) and two- or three-dimensional structures also play important role on the local site effect. Seismic reflection and refraction methods have been applied to delineate deeper S-wave velocity structures over the last few decades. These conventional methods are expensive and time consuming so the development of less expensive and simpler methods are desired.

Active and passive surface wave methods have increased in popularity over the last 10 years. The passive method or microtremor array measurements (Okada, 2003) in which ambient noise is used as surface waves, is particularly attractive because the method does not require any artificial source and a depth of investigation can be easily increased. Large scale microtremor array measurements have been widely used in last 10 years in Japan for estimating S-wave velocity structures to a depth of several kilometers. In these investigations, triangle arrays with a size of several kilometers are used for calculating a phase velocity in the frequency range from 0.2 to 1Hz. These investigations using large scale microtremor measurements revealed that an abrupt change of the depth of deep bedrock caused a disaster concentration in the Kobe, Japan earthquake in 1995.

Most people use the spatial autocorrelation (SPAC) method (Aki, 1967) for calculating phase velocities from ambient noise; the method requires at least 4 or 7 sensors placed on center and the corners of triangles. Margaryan et al. (2009) showed that SPAC using only two sensors yields almost identical phase velocities compared to using triangle-shaped arrays with 4 or 7 sensors. SPAC using two sensors enables us to perform microtremor array measurements much more easily. We performed microtremor array measurements using two sensors at several sites in the South Bay of the San

Francisco Bay Area. The main purpose of the measurements was to evaluate the applicability of SPAC using two sensors and to estimate the deep S-wave velocity structures in the area. In addition, we recorded three-component ambient noise for horizontal to vertical spectral ratio (H/V) analysis, which was incorporated into the inversion of the dispersion curves obtained from SPAC.

## 2. DATA ACQUISITION AND PROCESSING

Microtremor array measurements and three-component microtremor measurements were performed at four sites in the South Bay of the San Francisco Bay Area (Fig. 2.1). At each site, one seismograph was fixed in one place and data was acquired at that location for the entire survey. Data was acquired by a second seismograph at larger separations ranging from 5 to 4125m from the fixed seismograph. Data acquisition was repeated at each new separation. In each measurement, 10 to 60 minutes of ambient noise was recorded. As the separations of seismographs increased, the record length of ambient noise was increased. The sampling interval used was 10msec. Fig. 2.2 shows an example of the array configuration from the Cupertino site. Data acquisition was performed in the day-time and the seismographs were placed in relatively quiet places such as in parks or residential areas.


**Figure 2.1.** Sites of investigation.

Two seismographs including three-component accelerometers (McSEIS-MT Neo) made by OYO Corporation were used for data acquisition. The seismographs include a GPS clock and two seismographs can be synchronized in any distance.

Recorded data was divided into several blocks with overwraps in data processing. Each block consists of 8192 samples with a data length of 81.92 seconds. Several blocks including nonstationary noise were rejected before following processing; FFT is applied to each block and time domain waveform data is transformed to the frequency domain; amplitude spectrum or coherence is calculated by each block then all blocks were averaged as spectra or coherences; ten to one hundred blocks are averaged for calculating final spectra or coherences.


**Figure 2.2.** Example of array configuration (Cupertino : 002).

## 3. CHARACTER OF AMBIENT NOISE IN BAY AREA

Several fundamental characters of ambient noise will be investigated in this section.

### 3.1. Amplitude spectra

Fig. 3.1 shows examples of amplitude spectra from the San Jose, Geometrics (001) and Cupertino (002) sites and how they compare with data recorded at a site in Tsukuba, Japan. We can see that the amplitude around 1Hz is relatively small in all components and at all sites. The amplitude at the Tsukuba site is larger than the Bay Area sites in the frequency range of 0.3 to 1Hz.

### 3.2. Horizontal to vertical spectral ration (H/V)

Fig. 3.2 shows the horizontal to vertical spectral ratio (H/V) from the four sites in the Bay Area and how they compare with the one from Tsukuba. We can see that the H/V for the Tsukuba site has a relatively clear peak frequency compared with the Bay Area sites. At the Bay Area sites, there are two peak frequencies of H/V spectra. Higher peaks vary from 1 to 2Hz and lower peaks vary from 0.2 to 1Hz. The peak frequencies of H/V spectra are relatively clear at the Cupertino (002) and the Palo Alto (004) sites. Peak frequencies are 0.2Hz at Cupertino (002) and 0.4Hz at Palo Alto (004). There is another vague peak of 1Hz at the Cupertino site. At the San Jose, Geometrics (001) and the San Jose, Williams Street Park (006) sites, peak frequencies of H/V spectra are not clear. The San Jose, Geometrics (001) site has vague peaks at 0.2 Hz and 0.8Hz, the San Jose, Williams Street Park (006) site has vague peaks at 0.3 and 1Hz.

### 3.3. Coherence

In order to evaluate the accuracy of seismographs, we performed a so-called huddle test in which two seismographs are placed at same place and the observed data are compared. Ideally, waveform data must be identical. For microtremor array measurements, phase similarity of vertical component is particularly important. Coherence of two seismographs as a function of frequency is generally used as an indicator of similarity. Fig. 3.3 shows an example of coherences at two sites compare with the Tsukuba site. Coherences are relatively small around a frequency of 1Hz at all sites. It may be due to the small amplitude of ambient noise around 1Hz as shown in Fig. 3.1. Coherences are close to one between a frequency range of 0.2 to 0.8Hz the frequency range of interest for this study.

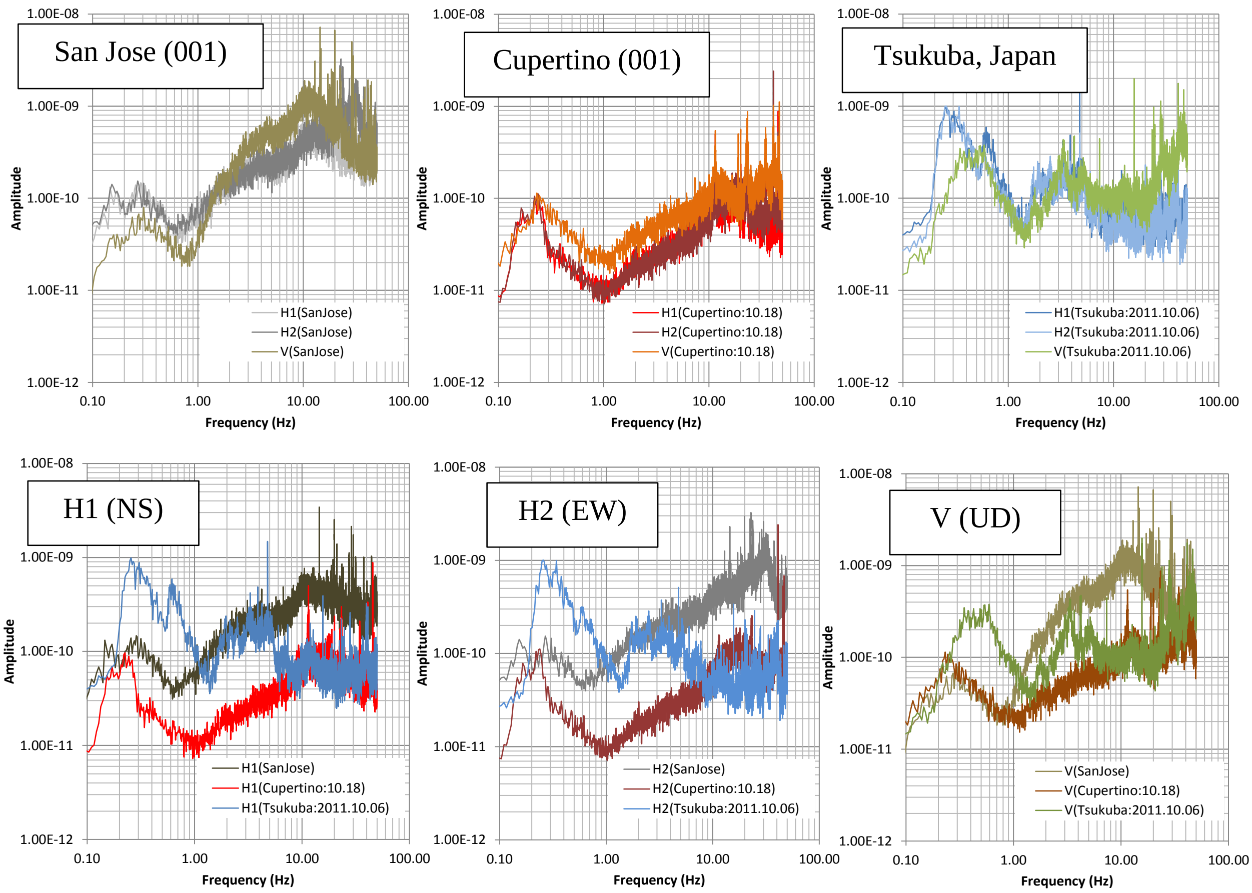



**Figure 3.1.** Examples of amplitude spectra at the San Jose, Geometrics (001) and Cupertino (002) compare with Tsukuba, Japan.

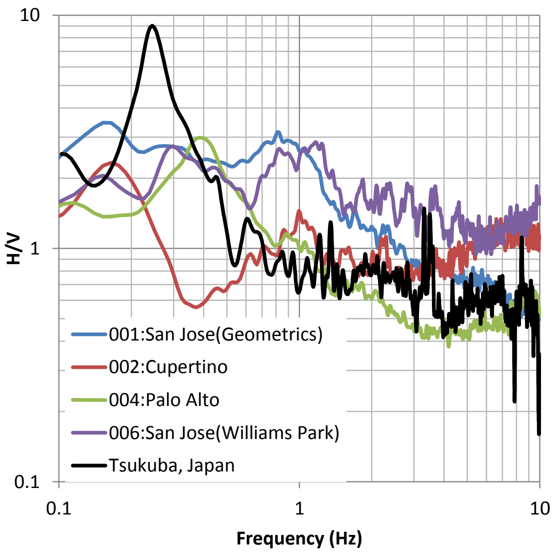



**Figure 3.2.** Comparison of horizontal to vertical spectral ration (H/V) at four sites in Bat Area and Tsukuba, Japan.

## 3.4 Repeatability

Repeatability of H/V spectra is examined at two sites by recording ambient noise on four different days. Fig. 3.4a shows a comparison of amplitude spectra obtained on two different days and Fig. 3.4b shows comparison of the H/V spectra obtained in four different days. Both shape and absolute

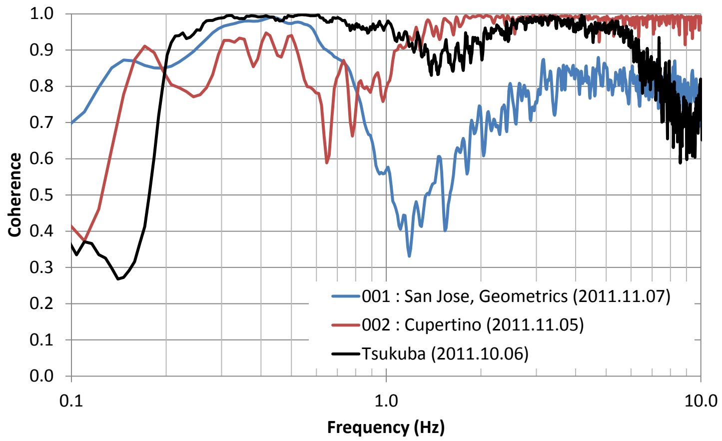
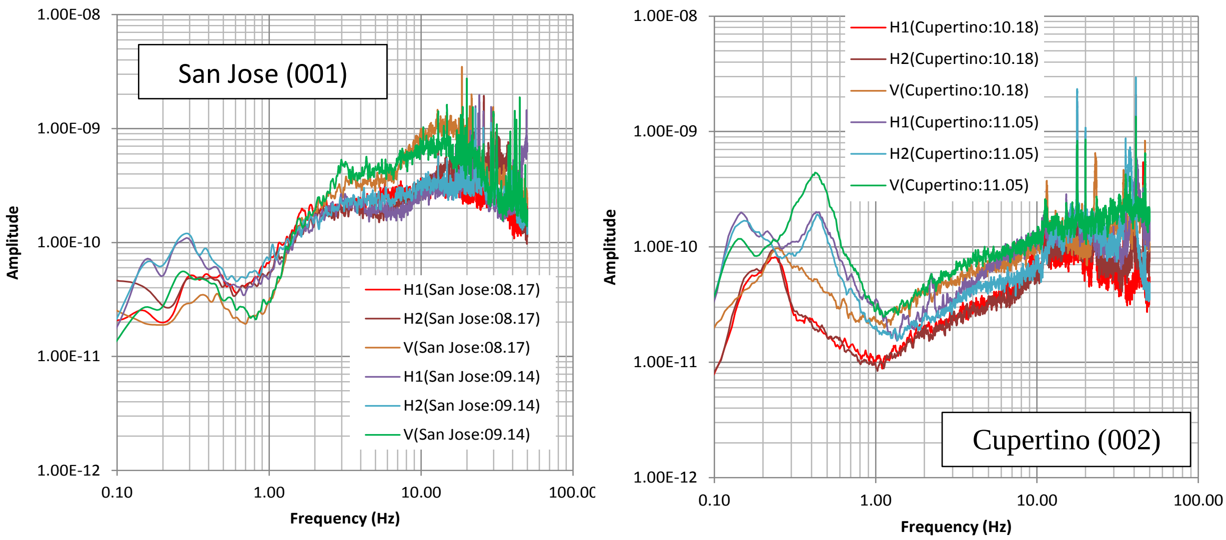
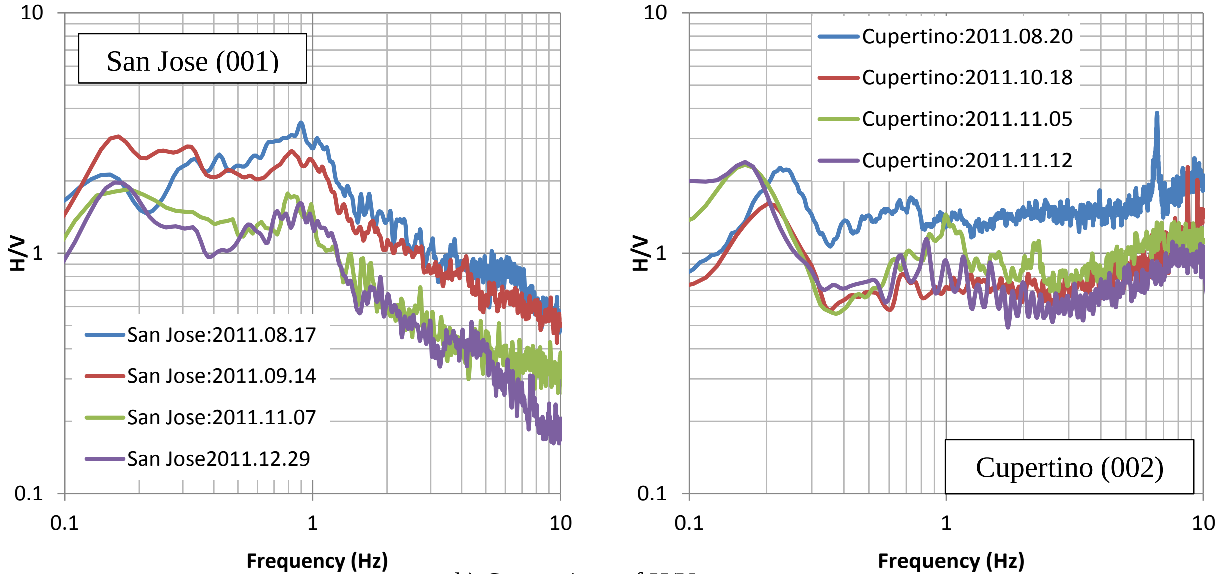



**Figure 3.3.** Examples of coherences at Bay Area in Comparison of Tsukuba, Japan.




a) Comparison of amplitude spectra.




b) Comparison of H/V spectra.

**Figure 3.4.** Comparison of amplitude spectra (a) and H/V spectra at the San Jose (001) and the Cupertino (002).

amplitude have a clear difference in amplitude spectra shown in Fig. 3.4a. In contrast, shapes of the H/V spectra are almost identical at both sites even if the absolute value of H/V has a difference. At the San Jose, Geometrics (001) site, peaks around 0.2Hz and 1Hz are consistent although both peaks are vague. At the Cupertino (002) site, a peak around 0.2Hz is clear in all measurements.

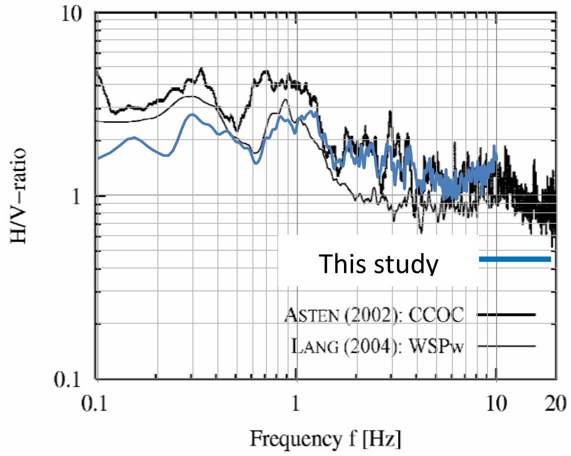



**Figure 3.5.** Comparison of H/V spectra (modified Lang and Schwarz (2005)).

Fig 3.5 shows a comparison of the H/V spectra at San Jose, Williams Street Park (006) site with results presented by other researchers (Lang and Schwarz, 2005). We can see that two peaks at 0.3 and 1 Hz and the shape of the spectra are almost identical in three different measurements.

All of these results show that the H/V spectra of ambient noise are very stable and they relate to subsurface velocity structure of sites. It also implies that the H/V spectra may be used to estimate velocity structures of sites.

## 4. DISPERSION CURVE ANALYSIS IN TERMS OF SPATIAL AUTOCORRELATION

### 4.1. Applicability of spatial autocorrelation using two sensors

As mentioned before, most people use at least four seismographs in a triangular array for calculating phase velocities using the SPAC. For the sake of simple and quick operation, we used only two seismographs for the analysis. Fig. 4.1 shows an example of coherences with same distance but different direction and recording time. We can see that the two coherences are almost identical. This implies that low frequency (0.2 to 1Hz) ambient noise in the Bay Area does not have particular direction of propagation and two-sensor SPAC surveys can be applied to deep velocity structure investigations.

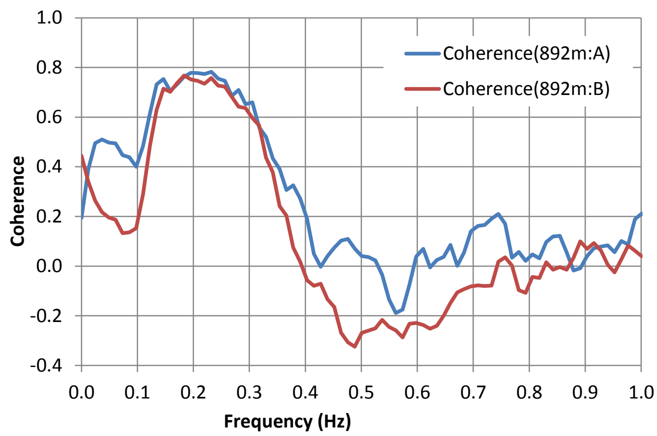
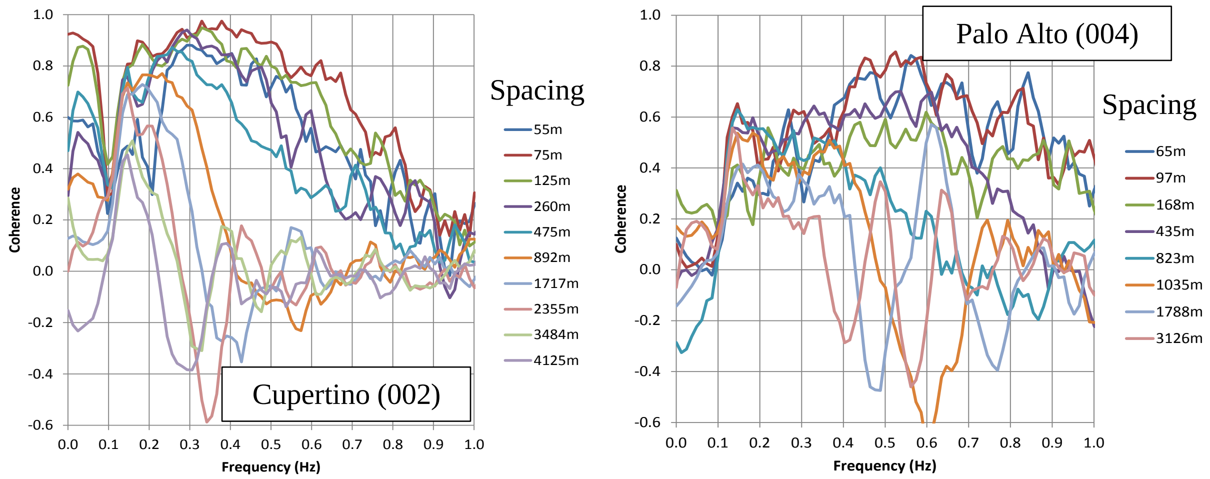



**Figure 4.1.** Example of coherences with same distance obtained at the Cupertino. Configuration of sensors is shown in Fig. 2.2.

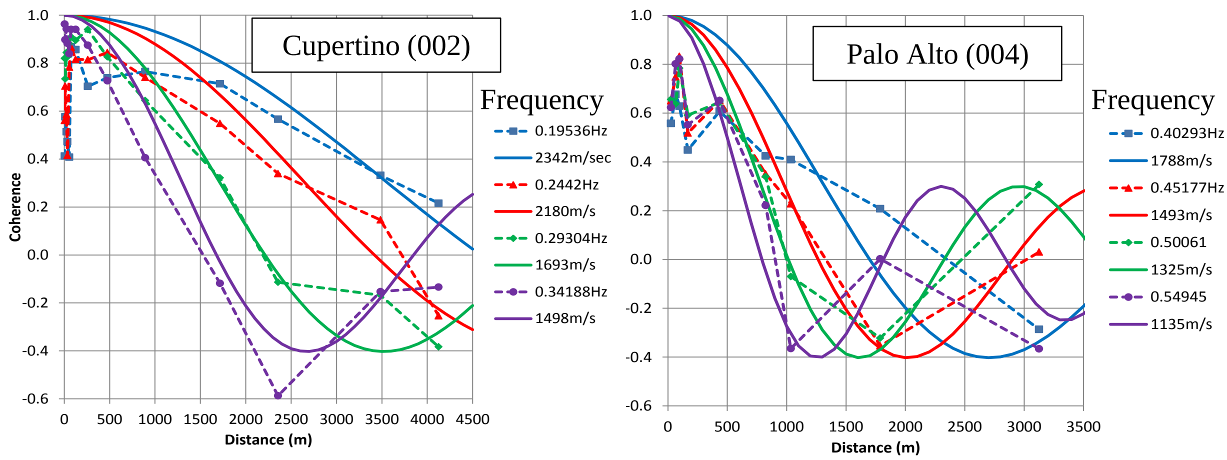
## 4.2. Example of spatial autocorrelation

Fig. 4.2 shows example of spatial autocorrelations at the Cupertino (002) and the Palo Alto (004) sites. Fig. 4.2a shows coherences whose spacing is larger than 55m as a function of frequency. We can see that coherences have a clear difference associated with the spacing of seismographs.

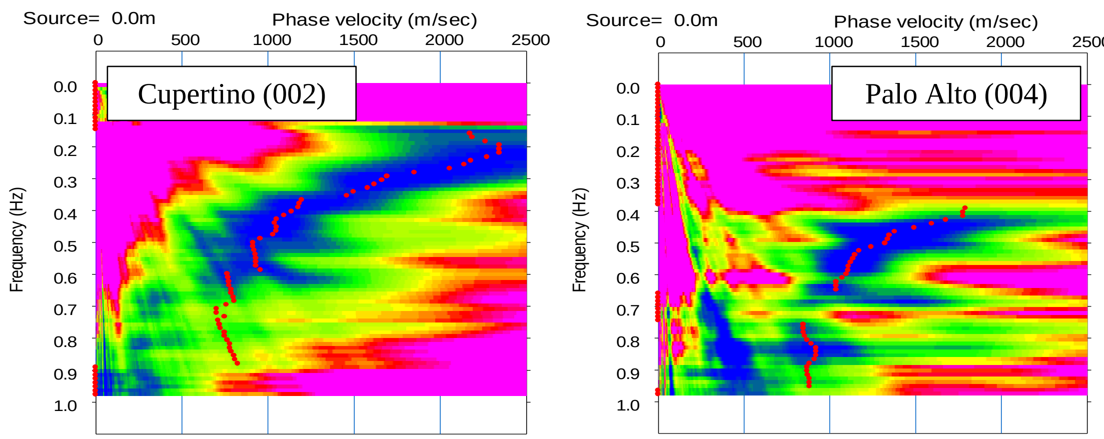
Fig. 4.2b shows typical coherences as a function of distance (spacing of seismographs) with theoretical Bessel functions calculated for phase velocities that yield minimum error between the observed




a) Coherences as a function of frequency.




b) Coherences as a function of distance.




c) Error between observed coherences and theoretical Bessel functions.

**Figure 4.2.** Example of spatial autocorrelation at the Cupertino (left) and the Palo Alto (right).

coherence and the theoretical Bessel function. In Fig. 4.2b, broken lines and symbols indicate observed coherences and solid lines indicate theoretical Bessel functions. We can see that observed coherences and the theoretical Bessel functions agree well.

Fig. 4.2c shows error between observed coherences and theoretical Bessel functions. The red color indicates large error and the blue color indicates small error. Red dots indicate minimum error phase velocities at each frequency and they can be considered as observed dispersion curves. Clear dispersion curves can be recognized in frequency range from 0.1 to 0.7 Hz at the Cupertino (002) and from 0.4 to 1Hz at the Palo Alto (004) sites.

**4.3. Dispersion curve inversion and estimated S-wave velocity models.**

Fig. 4.3 shows comparison of dispersion curves. At the San Jose, Geometrics (001) and the Cupertino (002) sites, the longest wave length is about 10 km and it may include information on the S-wave velocity structures to a depth of 2 to 3km. At the Palo Alto (004) and the San Jose, Williams Street Park (006) sites, the longest wave length is about 4km and it may include the information of S-wave velocity structure down to a depth of 1km. If we pay attention to the frequency range from 0.4 to 0.8Hz, the phase velocities of the San Jose, Geometrics (001) and the Cupertino (002) sites are much slower than those of the Palo Alto and San Jose (004), Williams Street Park (006) sites.

A joint inversion (Suzuki and Yamanaka, 2010) was applied to the observed dispersion curves, and H/V spectra, and S-wave velocity models were analysed for four sites. In the inversion, phase velocities of the dispersion curves and the absolute value and peak frequencies of the H/V spectra were used as observation data. The unknown parameters were layer thickness and S-wave velocity. A Genetic Algorithm (Yamanaka and Ishida, 1995) was used for optimization. Search area of the inversion were determined from initial velocity models created by a simple wavelength transformation in which wavelength calculated from phase velocity and frequency is divided by three and plotted at depth. Theoretical H/V spectra and phase velocities are generated by calculating the weighted average of the fundamental mode and higher modes (up to the 5th mode) based on medium response.

Fig. 4.4 shows comparison of S-wave velocity models obtained by the inversion. We can see that a low velocity layer with S-wave velocity lower than 400m/s exists between depths of 50 to 100m at all sites. Intermediate bedrock with S-wave velocity higher than 1000m/s exists between depths of 500 to 1000m. Deepest bedrock with S-wave velocity higher than 2500m/s seems to exist at a depth of at least 1500m. It seems that the lower peak frequency of 0.2 to 0.4Hz in the H/V spectra is mainly due to the deepest bedrock.

Fig. 4.5 shows comparison of observed and theoretical data. Fig. 4.5a shows comparison of dispersion curves and we can see that the theoretical dispersion curves almost agree with observed data. Fig. 4.5b shows comparison of H/V spectra. Although there is difference in absolute H/V value, we can see that a peak frequency and shape of H/V spectra are almost identical.

## 5. CONCLUSIONS

Large scale microtremor array measurements and three-component microtremor measurements were performed in the South Bay of the San Francisco Bay Area in order to delineate deep S-wave velocity structures of the area. Investigation results imply that SPAC using two sensors can detect accurate phase velocities down to a frequency of 0.2Hz and a maximum penetration depth as deep as 2 to 3km. The deepest bedrock with an S-wave velocity higher than 2500m/s seems to be at least 1500m depth at the investigation area.

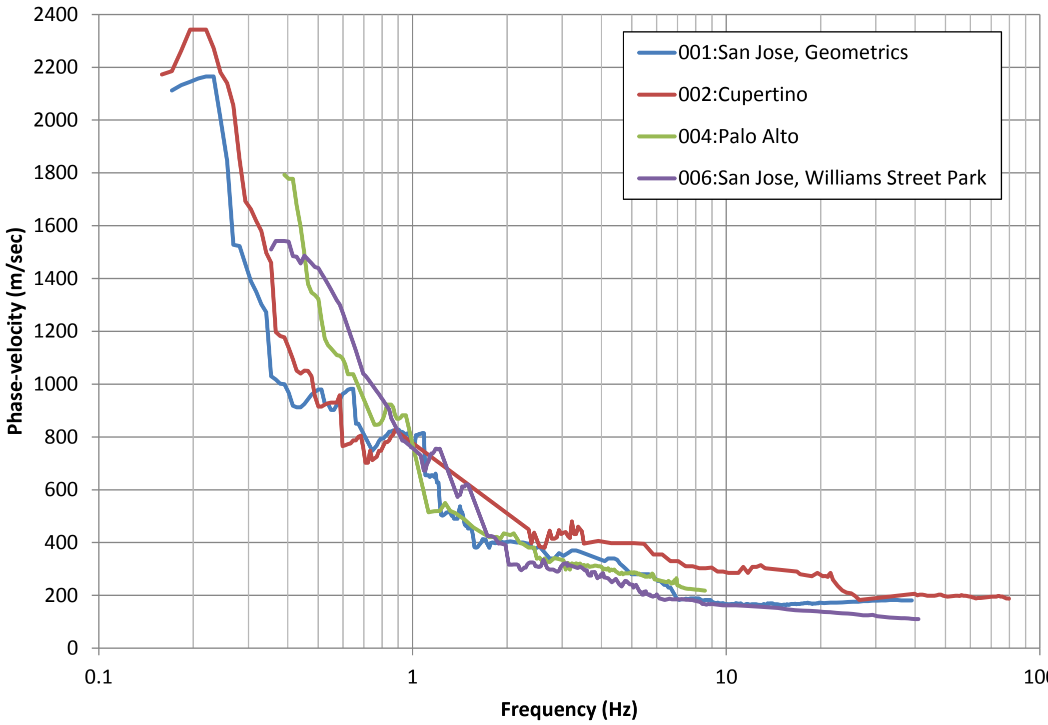



**Figure 4.3.** Comparison of observed dispersion curves.

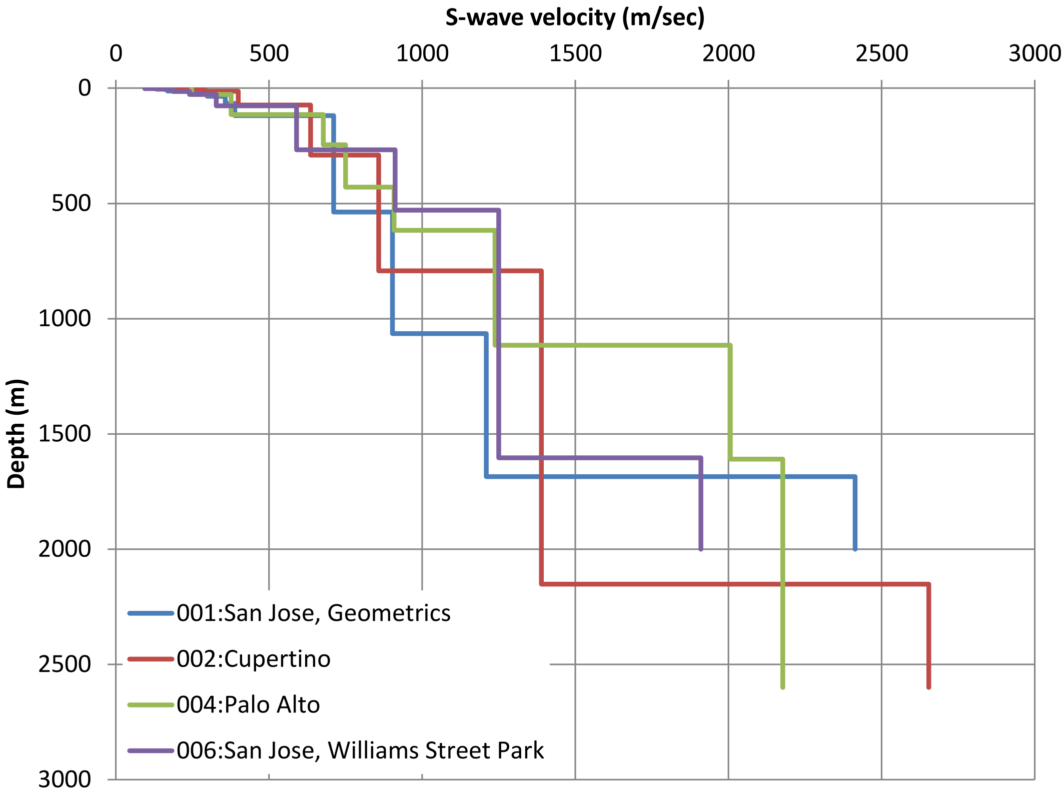
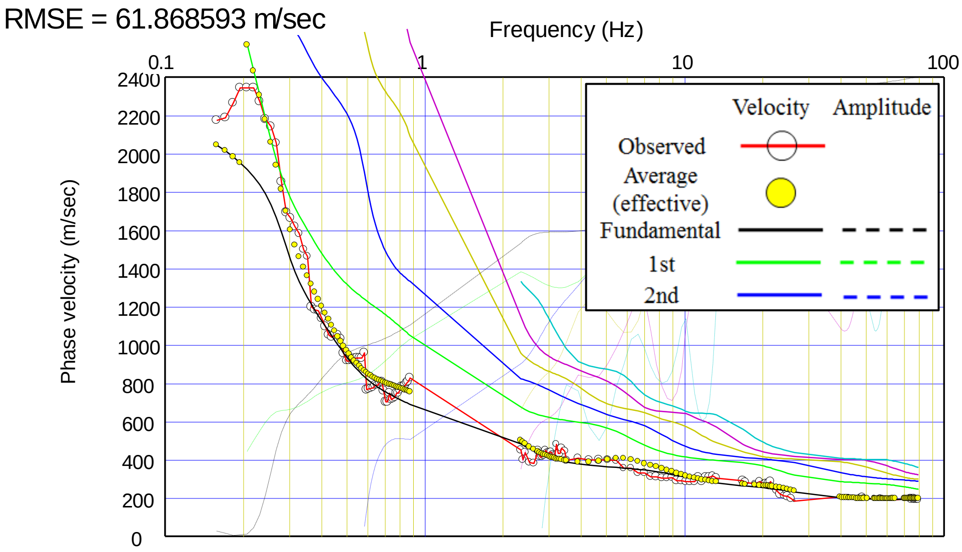
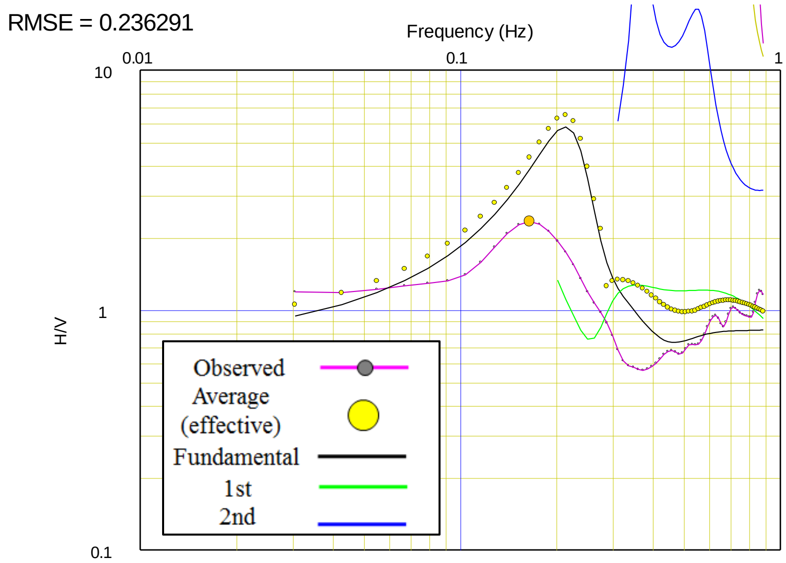



**Figure 4.4.** Comparison of S-wave velocity models obtained by inversion.




a) Comparison of dispersion curves. A red line indicates observed data and yellow circles indicate theoretical data.




b) Comparison of dispersion H/V spectra. A pink line indicates observed data and yellow circles indicate theoretical data.

**Figure 4.5.** Comparison of observed and theoretical data (Cupertino).

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