



## **SIBYL**

**(Seismic monitoring and vulnerability framework for civil protection)**

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Deliverable DC2: Guidelines for undertaking site-effect surveys

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## Table of contents

Table of contents	1
Summary	2
1. The SPatial AutoCorellation (SPAC) method	3
1.1 Test site configuration at the AUTH campus	4
• Correlation coefficients	6
• Phase velocity dispersion curve	7
• Shear-wave velocity profile	8
1.2 Test site Cologne	10
2. Horizontal to Vertical Spectral Ratio (HVSr) method	13
3. MPwise: Multi-Parameter Wlreless SEnsing system	15
4. Practical considerations when undertaking field activities	17
Acknowledgements	18
References	19

## SUMMARY

In the present report we present the most efficient and commonly used geophysical and geotechnical methods applied to assess the necessary parameters for site effects studies within the framework of programs relevant to the objectives of SIBYL.

After careful examination of the advantages and disadvantages of the different methods, it has been decided to present those that have been finally selected and were used in the different test sites within the framework of SIBYL in Greece, Germany and Italy. Moreover, instead of presenting these methods in an overly academic manner, it has been decided to present them through specific applications at the different sites. The selected methods are considered not only the most efficient for the purposes of SIBYL, but also the most cost-effective for multipurpose large scale surveys:

- (a) The SPatial Autocorellation Coefficient (SPAC) method, introduced by Aki (1957), has been applied to ambient noise vibrations recorded by a dense temporary array in the campus of the Aristotle University of Thessaloniki (AUTH), consisting of 38 geophones spatially distributed within an area of 50 x 80 m. The phase-velocity dispersion curve of Rayleigh waves was determined from the ambient noise data, which allowed the estimation of the shear-wave velocity structure of the investigated site.
- (b) The site response characteristics of the foundation soil, in terms of resonant frequency and amplification factor, were investigated using the well-known HVSR method (Nogoshi and Igarashi, 1971; Nakamura, 1989).
- (c) The Multi Parameter Wireless Sensor System (MPwise) is an innovative multi-hazard monitoring and early warning system designed for regional and on-site earthquake early warning, rapid response systems, structural health monitoring and site-effect estimation via 2D arrays. The software supporting this system was used to process the ambient noise measurements recorded in the temporary array at the AUTH and its results compared with the aforementioned techniques.

We will also provide a brief summary of the more “field orientated” factors what would need to be considered when undertaking such site assessments.

# 1. THE SPATIAL AUTOCORRELATION METHOD (SPAC)

Site effect studies based on ambient noise vibrations have enjoyed great popularity over the last decades. The ease and quickness of deployment and the low cost with which measurements can be obtained in the field have prompted a large number of studies on this subject. Many of those studies use the well-known HVSr technique, the horizontal-to-vertical spectral ratios (Nakamura, 1989; Lermo and Chavez-Garcia, 1994) to investigate site effects. In addition, the availability of a large number of instruments (acquired from the GFZ instrument pool) has led to the application of array techniques to microtremor measurements. The two methods used mostly to extract surface waves from microtremors by array measurements are the  $f-k$  (frequency–wavenumber) method (Capon, 1969) and the spatial autocorrelation method (SPAC method) introduced by Aki (1957). Although the  $f-k$  spectra have been frequently used (e.g., Horike, 1985; Kagawa, 1996, etc.), the larger number of papers over the last decades appear to use Aki's (1957) SPAC method (among others, Apostolidis et al., 2004; Roberts and Asten, 2004; Chavez-Garcia et al., 2004; Manakou et al., 2010; Claprod et al., 2011). With the SPAC method, a phase velocity using records of ambient vibration can be determined very easily with good accuracy. The recent applications of the SPAC method to station configurations quite different from the ideal station geometry for SPAC analysis (concentric circles with stations covering all azimuths regularly) has increase the number of applications for investigating the dynamic properties of the soil.

We assume that we record seismic noise by an array of stations on the free surface, and that we compute the crosscorrelation function between different pairs of stations, sampling different orientations on the free surface. If we assumed the seismic noise to be stationary in both time and space, and that the wave-field consists of dispersive waves propagating along the free surface, Aki (1957) shows that the ratio of the average of those different crosscorrelation functions and the autocorrelation function at a reference station (defined as the correlation coefficient) takes the form of a zero-order, first-kind Bessel function  $J_0$ , i.e.,

$$\rho(r, \omega_0) = J_0 \left( \frac{\omega_0}{c(\omega_0)} r \right) \quad (1)$$

This allows one to compute the phase velocity  $c(\omega_0)$  at a given frequency  $\omega_0$  when we can estimate an azimuthal average of the spatial autocorrelation  $\rho(r, \omega_0)$ , for a fixed distance  $r$ . This dispersion curve corresponds to the subsoil structure, assumed to be the same below all the stations of the array.

In recent applications of the SPAC method, the spatial distribution of the array is very far from the circular one. The seismographs have been distributed following different geometries: on non-perfect circular geometry (Bettig et al., 2001), irregular sensor distribution along the circle (Cho et al., 2004), non-circular geometry (DeLuca et al., 1997; Ohori et al., 2002) and even at couples of stations (Chavez-Garcia et al., 2005). Moreover, Aki (1957) already showed that the correlation computed in the frequency domain,

averaged for many time windows, was an adequate substitute for the azimuthal average required by the SPAC method.

Typically in the SPAC method, a fixed value of  $r$  is used. However, Okada (2003) and Ohori et al. (2002) showed that, since  $c(\omega)$  is a function of frequency  $\omega$ , better phase-velocity estimates are achieved by fitting the spatial-correlation function at each frequency to a Bessel function, which can use varying inter-station distances (extended spatial autocorrelation, ESAC). This idea has two main advantages; first, it is not required to obtain simultaneous recordings using an array of stations whose locations must obey a very rigid scheme; and second, it allows the ability to obtain results for a large number of closely-spaced distance intervals.

The substitution of temporal averaging for azimuthal averaging (an idea that was mentioned in Aki, 1957), allowed Chavez-Garcia et al. (2005) to compute average correlation values for many different distances, and to obtain a phase velocity dispersion curve that compared well with other results. The basic hypothesis is that, given long enough records of ambient vibration, the average spatial cross correlation between any given pair of stations is an adequate estimate of the azimuthal average of the same cross correlation functions. Aki (1957) observed that cross correlation along different directions did not differ significantly, a fact that allowed him to conclude that “we may regard the microtremor as being propagated in every direction, each with almost uniform power”. If microtremors propagate homogeneously in all directions, measurements along a single direction are equivalent to an azimuthal average. Similarly, Scherbaum et al. (2003) and Arai and Tokimatsu (2004) showed that Horizontal-to-Vertical Spectral Ratio (HVSr) curves from seismic noise recordings, originally proposed by Nogoshi and Igarashi (1970, 1971), are sensitive to the shallow S-wave velocity structure of a site, and can be profitably inverted to obtain the structure.

Once the surface wave dispersion or HVSr curves of a site are available, from their inversion, the S-wave velocity profile of a site can be obtained. In order to overcome the difficulties related to the non-linear nature of this inverse problem, several inversion approaches have been tested over the last few years. Scherbaum et al. (2003) showed that the independent inversions of Rayleigh wave dispersion and HVSr curves are inexorably affected by the trade-off between S-wave velocity and the thickness of the sedimentary cover. For this reason, Parolai et al. (2005) and Arai and Tokimatsu (2005) proposed the joint inversion of Rayleigh wave dispersion and HVSr curves, where in each case surface wave higher modes are included in the analysis.

To investigate soil conditions using seismic noise, a dense temporary array of geophones has been installed at two test sites at the Aristotle University of Thessaloniki (Greece) and in Cologne (Germany).

## **1.1 Test site configuration at the AUTH campus**

Within the framework of the SYBIL project, a temporary 2D array of 38 geophones were spatially distributed between the two investigated buildings,

the Administration and the New Philosophy buildings, within the campus of the Aristotle University of Thessaloniki - AUTH (Figure 1). Each station consisted of a 4.5Hz three-component geophone coupled to a CUBE digitizer<sup>1</sup> and a GPS receiver. The distance between the stations ranged between 2 and 73m (Fig. 1). About 2 hours of noise measurements were recorded with a sampling rate of 400sps. We analyzed only the vertical component of the noise records in order to get the Rayleigh wave dispersion curve.

The scope of the array was to determine the shear-wave velocity ( $V_s$ ) and the site response characteristics of the foundation soil. The shear-wave velocities are used to classify the foundation soil into EC8 soil categories and subsequently for the numerical and structural modeling of the two investigated buildings in other tasks of the project. In addition, the  $V_s$  velocities will be used for the definition of the reference input motion acceleration spectrum to be used as the input motion for the dynamic analyses of the buildings. Further details on these issues may be found in DC4: Reports on the case studies.

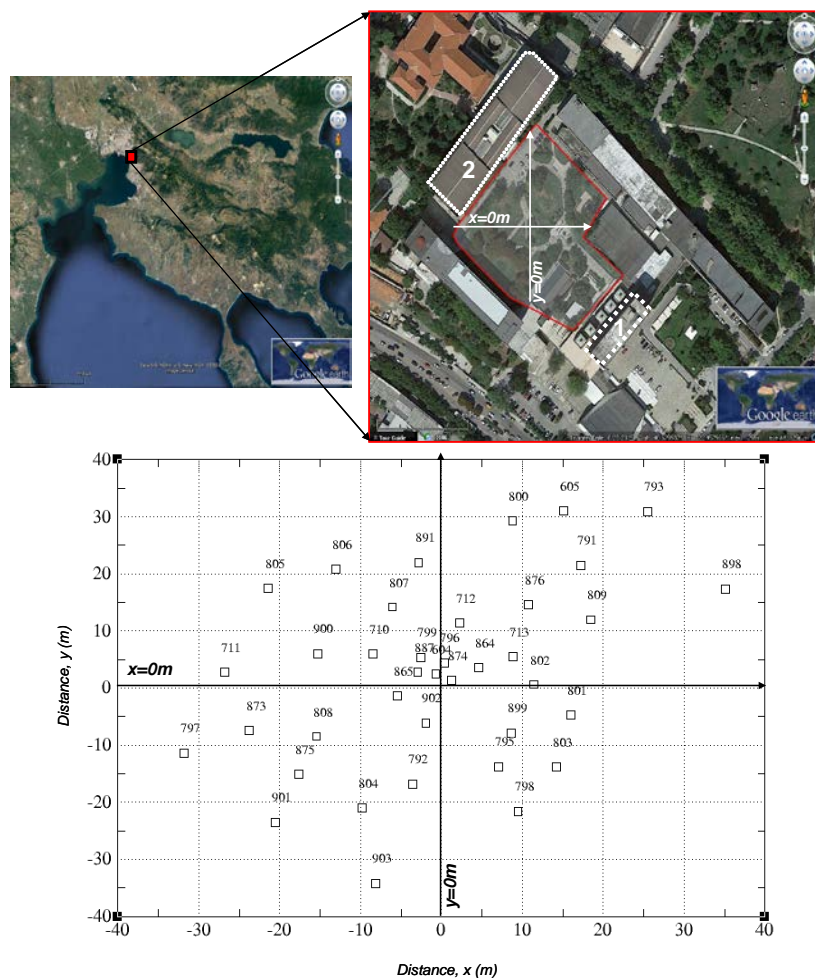


Figure 1. The location of the 2D array within the university campus (within the red polygon) and the spatial distribution (squares) of the 38 geophones in the field. The numbers close to squares indicate the code of each station. Numbers 1 & 2 (buildings outlined by white dotted lines) correspond to the Administration building and the New Philosophy faculty respectively.

<sup>1</sup> <http://www.gfz-potsdam.de/sektion/geophysikalische-tiefensondierung/infrastruktur/geophysikalischer-geraetepool-potsdam-gipp/instrumente/seismik-pool/recorder-dss-cube/>

## Data analysis

- *Correlation coefficients*

Cross correlation coefficients were calculated using each pair of stations (in total 703 station pairs). The computations were carried out using 34 time windows of 300 sec duration each (with an overlap of 50%), using a series of narrow bandpass Butterworth filters. The average crosscorrelation coefficient for a specific distance was determined as a function of frequency from the time windows used and resembles a  $J_0$  Bessel function.

Figure 2 shows the average correlation coefficients with their associated standard deviations for 17 representative inter-station distances. The correlation coefficients that do not tend to unity at low values of the argument indicate that the two stations involved are affected by different sources of ambient vibration. This was verified when, going back to the time signals, we observed transients at one station that were not recorded at the second one. For all station pairs, the correlation coefficients at frequencies lower than 3-4Hz were very low. We explain this as being due to field-conditions and the limitation of the geophones to record below their natural frequency response. The frequency of the first-zero-crossing of the correlation coefficients was shifted to lower values with increasing distance between stations. The larger distances constrain the dispersion curve at lower frequencies, while the smaller interstation distances contribute information in the higher frequency range. Generally, the results at smaller inter-station distances are stable over a larger frequency range, while the scatter of the individual estimates for larger inter-station distances becomes greater than the average values.

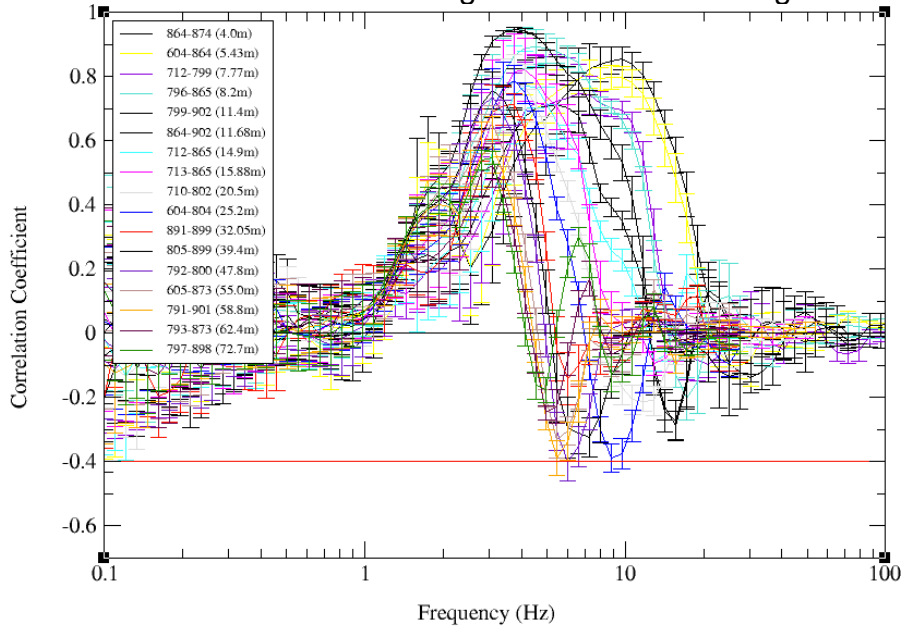


Figure 2. Average cross correlation coefficients as a function of frequency for 17 different station pairs. The codes of the stations used are the same as those in Fig. 1. The distance of each station pair is given within the parenthesis. Each line corresponds to the average cross correlation computed for 34 time windows of 300 sec duration of ambient vibration for the corresponding pair of stations. The vertical bars indicate their associated standard deviation values computed at each frequency, assuming normal distribution.

- *Phase velocity dispersion curve*

Once we had estimates of the correlation coefficients as a function of frequency and distance, we used equation (1) as the basis for an inversion procedure to compute  $c(\omega_0)$ . The aim was to determine the  $c(\omega_0)$  values that minimize the difference between our correlation coefficients  $\rho(r, \omega_0)$  and  $J_0(\omega_0/c(\omega_0)r)$ . This non-linear problem can be substituted by the linear transformation  $d_0 = g(p)$ , where  $d_0$  is the dataset (our correlation coefficients for all distances and frequencies),  $p$  is the set of parameters we are inverting for (the values of the phase velocity for all frequencies), and  $g(p)$  is the function that relates the observations with the parameters we are inverting for (it is the zero-order, first-kind Bessel function). This procedure was proposed by Tarantola and Valette (1982) and later described in detail by Menke (1984). The last equation is nothing more than the restatement of equation (1), describing the relationship between the data we measure  $\rho(r, \omega_0)$  and the parameters we wish to obtain  $c(\omega_0)$  and assumes that our model (the  $J_0$  function) represents, the cross correlation coefficients as demonstrated by Aki (1957).

Using a priori values for the parameters  $p$  and the whole set of the correlation coefficients for different distances, an expected value of the phase velocity dispersion curve plus a variance associated at that data point, was calculated. The inversion was repeated several times using different values for the parameters  $p$ , and verified that the final results were very similar. The phase velocity dispersion curve that was determined following this iterative inversion procedure using 680 out of the 703 correlation coefficients is plotted in Figure 3. For the range of validity of the results from the SPAC method, the criterion of Henstridge (1979) was used. This dispersion curve corresponds to fundamental mode of Rayleigh waves.

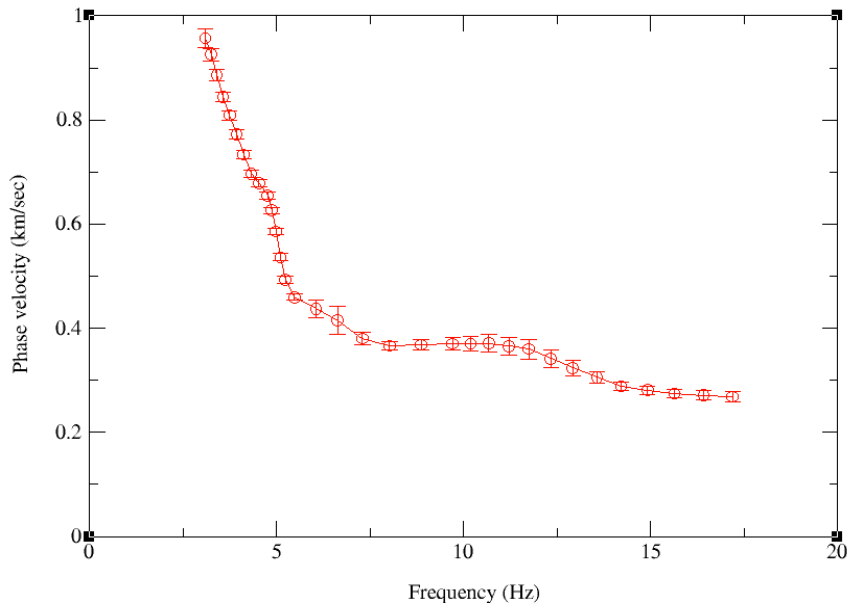


Figure 3. Solid circles indicate phase-velocity dispersion curve inverted from the data shown in Figure 1. The vertical bars indicate their associated standard deviation values computed at each frequency, assuming a normal distribution.



- *Shear-wave velocity profile*

As discussed before, the dispersion curve can provide the necessary information for S-wave velocity estimation. However, the relationship between surface wave and S-wave velocities with the sediment thickness is highly non-linear. Nonetheless, we expect that the obtained final models will lie close to the global minimum of the solution. Picozzi and Albarello (2007) showed that in such cases, a linear inversion can be carried out to refine the velocity models. Here, we only take advantage of the linearization of the problem to study how the procedure and data can be reliably constrained through the analysis of the model and data resolution matrices. By focusing on the diagonal elements of the resolution matrixes, we can see how much each of the model parameters is resolved by the experimental observations.

The phase velocity dispersion curve shown in Figure 3 was inverted to obtain the 1D shear-wave velocity profile below the 2D array, using Herrmann's iterative inversion programs (Herrmann, 1987 and 2013). The linear inversion of surface-wave dispersion requires an initial model which contains a priori knowledge about the geological and geophysical properties of the investigated structure in terms of shear and longitudinal wave velocities, soil thickness, density and damping. Based on this initial model and the experimental dispersion curve, the theoretical phase (and/or group) velocity curve is calculated. The initial model  $x_0$ , is progressively refined in an iteration procedure until a proper fit is achieved between the theoretical ( $V_{the}$ ) and experimental ( $V_{exp}$ ) dispersion curves.

$$b = V_{the} - V_{exp} = A(n.m)x \quad (2)$$

where  $x$  is the vector of the parameters determined through each iteration that should be replaced in the initial model  $x_0$  in order to minimize the term  $b$ . Since the inversion problem has infinite solutions, the procedure stops when a good converge between the theoretical and experimental dispersion curve is obtained. The estimated model obtained at this step represents the most probable geological structure of the investigated site.

Figure 4 displays the final model together with the resolving kernels of the inversion procedure. The resolving kernels should manifest a single peak at the depth of the layer they correspond to. A resolving kernel that shows this single peak is an indication that the  $V_s$  value inverted for the corresponding layer has been well resolved. The shear-wave velocity profile determined from the inversion of the phase velocity dispersion curve of Figure 3, shows a surficial layer with velocities of around 250 m/sec. This layer has a thickness of 8-9m and corresponds to surface materials. Below this layer, a stiffer stratum exists with velocities greater than 400-500m/sec. This layer is actually the well-known red clay layer that dominates the subsoil conditions in the campus and generally in the city of Thessaloniki. It is actually a well-documented soil stratum according to past detailed geotechnical information (Anastasiadis et al., 2001) and geophysical cross-hole measurements (site XIM in Figure 5) in the vicinity (Raptakis et al., 2001). The comparison is very satisfactory, proving the accuracy of the deployed SPAC method.

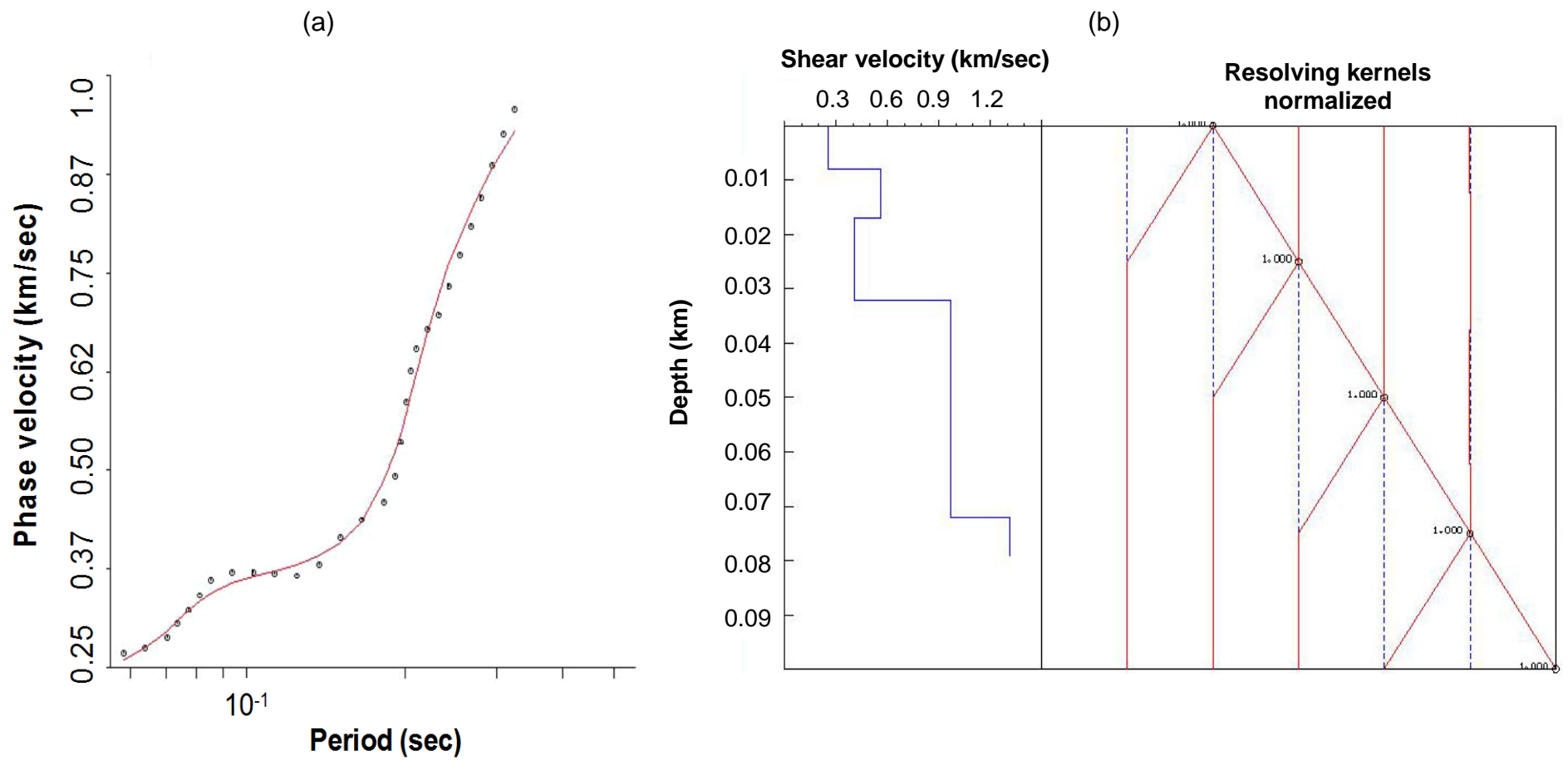


Figure 4. a) The circles show the final estimate of the phase velocity dispersion curve (see also Fig. 3). The solid line shows the predicted phase velocity dispersion curve computed for the best-fitting model through the inversion procedure. b) The shear-wave velocity profile obtained from the inversion of the dispersion curve, together with the resolving kernels for each layer in the model.

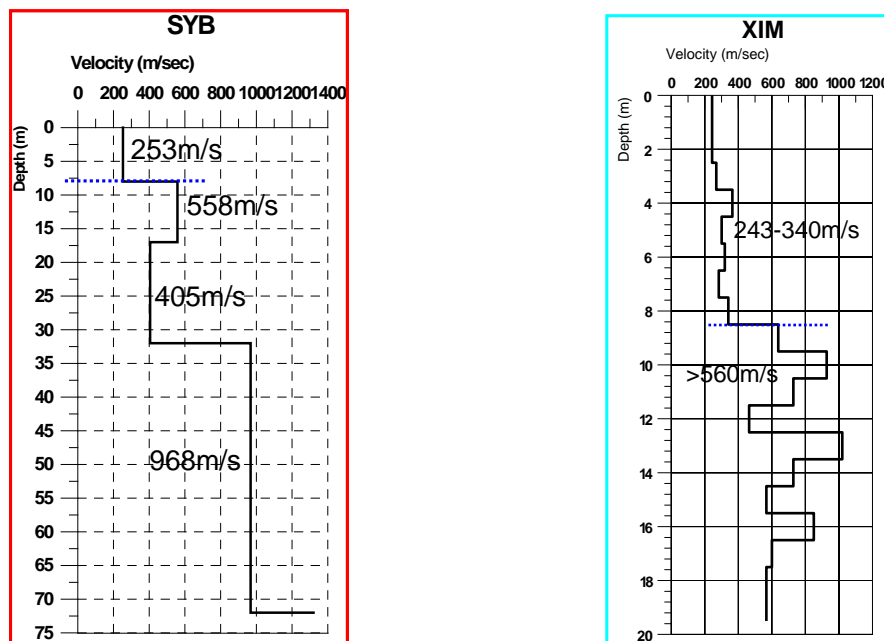


Figure 5. Shear-wave velocity profile determined at the investigated area (SYB profile). For comparison, the 1D Vs profile of the neighbor cross-hole at site XIM is also shown.

## 1.2 TEST SITE COLOGNE

In the project, field measurements were undertaken at one of the SIBYL test sites, Cologne, Germany, from Monday 30th November to Friday 4th December 2016. A total of 7 schools were inspected (see Figure 6). The array measurements were done in a park on grass in front of the schools of interest, within the schools themselves (e.g., paved recreational areas) or on paved areas in front of the school. The instruments consisted of 10 MPwise (Multi-Parameter Wireless SEismic array instruments (see Picozzi et al., 2010 and Section 3 of this report) connected to 4.5 Hz geophones, and a standard 17 Ah battery. The sampling rate was set to 400 samples per second (Nyquist at 200 Hz). Measurements were carried out usually for around 1 hour. In order to avoid loss of data and biased results due to sensor malfunctions, a software platform that allows the analysis of the data in real time was developed. To

this regard, a graphical user interface allows the user to facilitate details on the array measurement through the provision of comprehensive information about the array layout, the quality of the data acquired at each individual station, as well as the possibility to discard unusable data from, for example, malfunctioning stations, while analyzing the reliable data. The ESAC method is applied to derive the dispersion curves for Rayleigh waves (see Figure 7). From these curves, applying the method proposed by Albarello and Gargani (2010), the so-called  $V_{s30}$  parameter was estimated at each location.



Figure 6. Map showing the relative locations of the schools inspected in Cologne, Germany.

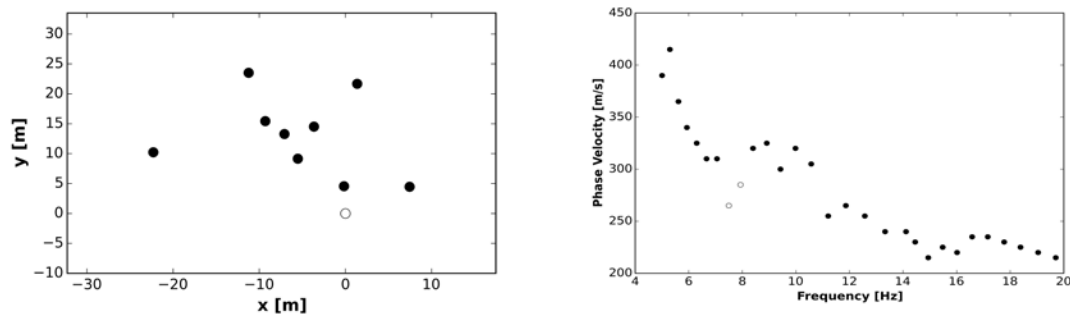


Figure 7. Left) Array geometry of the measurements at the Gymnasium Kreuzgasse. Right) Dispersion curve for Rayleigh waves obtained with the ESAC method.

$V_{s30}$  is the average shear wave velocity in the upper-most 30 m of the surface, and is a commonly used proxy that provides a measure of potential site amplification (Borcherdt, 1994). Albarello and Gargani (2010) estimated the uncertainties associated with these values to be of the order of 10%. The results of the linear inversion for the test site at the Gymnasium Kreuzgasse in Cologne (Figure 7) are shown in Figure 8, in particular, the shear wave velocity model, the Jacobian matrix, the data resolution matrix, the model resolution matrix, dispersion curves and the misfit. The Jacobian matrix indicates the sensitivity of the Rayleigh waves for the model parameter. The model resolution matrix shows that the model parameter describing the shallow layers can be better resolved. The data resolution matrix is a measure of how good the predicted/synthetic data agree with the observed data.

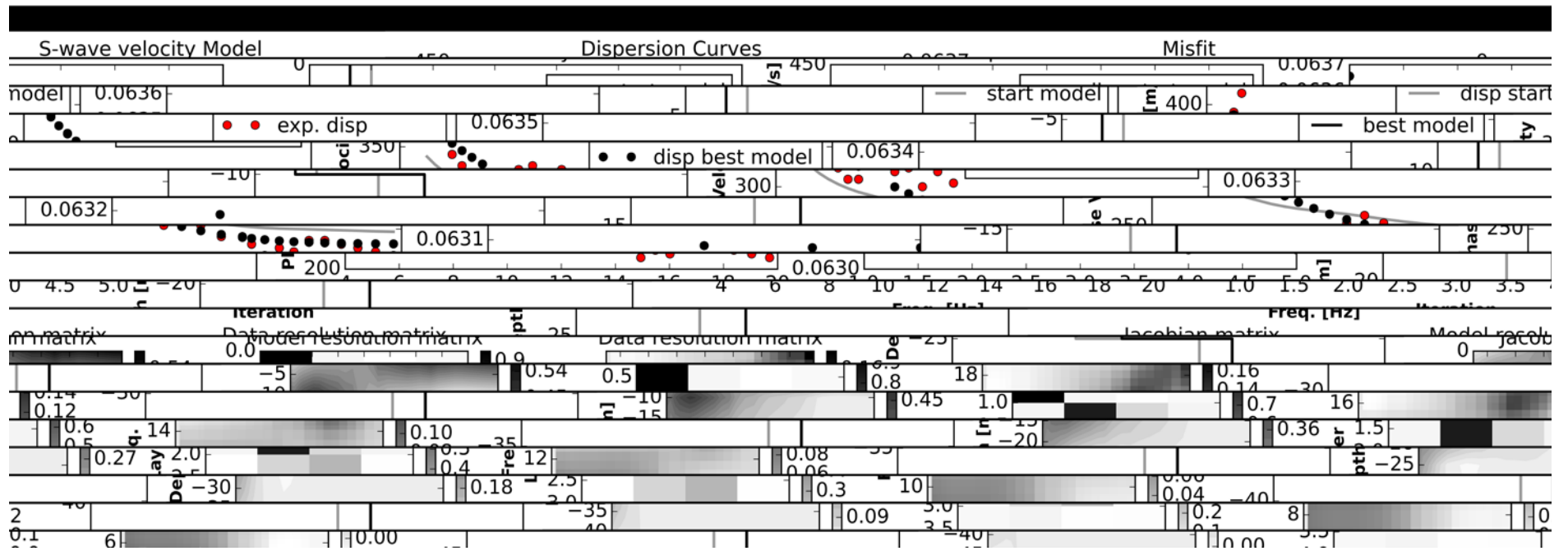


Figure 8. Results of the linear inversion for the test site at the Gymnasium Kreuzgasse in Cologne. In particular, the shear wave velocity model, the Jacobian matrix, the data resolution matrix, the model resolution matrix, dispersion curves and misfit.

## **2. HORIZONTAL TO VERTICAL SPECTRAL RATIO (HVSr) METHOD**

The Horizontal to Vertical Spectral Ratio (HVSr) method is a quick, reliable and low-cost technique for site-effect characterization widely used in engineering seismology (Lermo and Chávez-García, 1993; Bard, 1998). It was originally introduced by Nogoshi and Igarashi (1971) and revised by Nakamura (1989). The technique is based on the idea that frequency dependent ellipticity of surface wave motion can explain the H/V spectral ratio shape. In areas characterized by sediment over hard rock, the H/V spectral ratio peak is strongly associated with the soil resonance frequency (Nogoshi and Igarashi, 1970).

The ambient noise records from the 38 stations used during the AUTH field measurements were divided into 29 windows of 20 sec each with 50% overlapping. For each 20sec window, the ratio of the Fourier amplitude spectra of the horizontal to vertical components was calculated and the average HVSr corresponding to two horizontal components for each station determined (Figure 9). The first predominant peak observed between 2.2 and 2.7 Hz corresponds to the resonant frequency of the foundation soil. The associated amplification of the resonance ranges between 3 and 6. The large value of the resonant frequency corresponds to a stiff formation, while the large peak is a good indicator of a significant impedance contrast existing in the subsoil structure (Lermo and Chavez Garcia, 1994). The two smaller peaks observed at frequencies 5 and 10 Hz are probably due to other minor interfaces with smaller impedance contrast. Using the shear-wave velocity profile determined by the inversion procedure, the theoretical 1D transfer function, assuming a vertical incidence of shear waves, was calculated and superimposed to the H/V ratios of Figure 9. The agreement in terms of resonance between the theoretical and experimental H/V ratios is very good, showing that the inverted Vs profile describes well the sediments existing in the area.

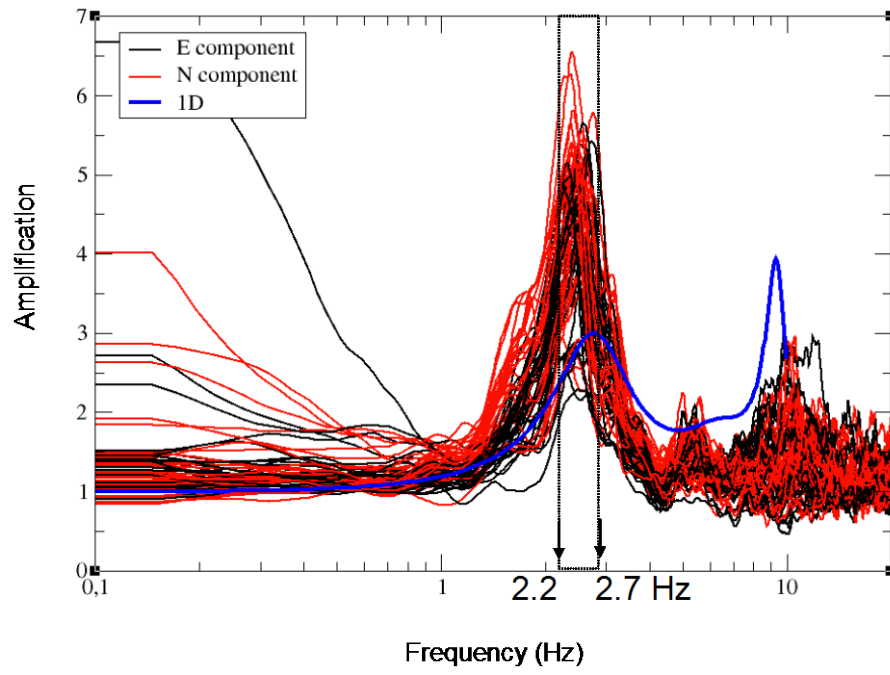


Figure 9. Average H/V ratios of the two horizontal components for the 38 stations used in the 2D array and 1D theoretical transfer function calculated from the SYB Vs profile.

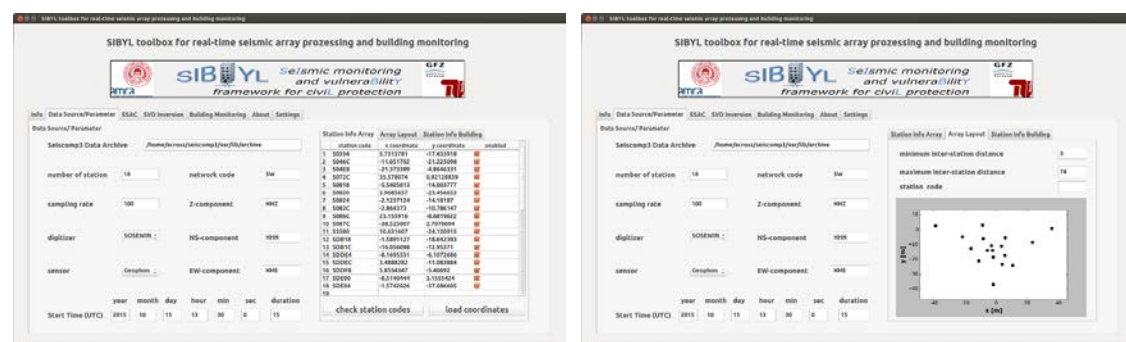


### 3 MPWISE: MULTI PARAMETER WIRELESS SENSING SYSTEM

The MP-wise is an innovative system manufactured by Helmholtz-Centre Potsdam - GFZ that allows several types of sensors to be combined with a high-performance computing system able to implement complex information integration and processing tasks at the node (sensor) level, and therefore suitable for a wide range of possible applications. The aim of the new multi hazard monitoring and early warning system is to fulfill the needs for different types of application, mainly regional and on-site earthquake early warning and rapid response systems, structural health monitoring and site-effect estimation of 2D arrays. However, it might be useful also for geotechnical problems like landslides monitoring, or other geohazards like tsunamis. The system is designed in a modular way, allowing one to easily implement different configurations with respect to the required sensors and the communication interfaces depending on the application of interest. Referring to the possible sensors, the prototype has been tested and is able to be combined with standard strong motion, weak motion, and broadband sensors, MEMS sensors, including accelerometers and gyroscopes, cameras, temperature and humidity sensors and a low cost GNSS system.

The main advantages of the embedded and joint processing system are 1) the system would be more resilient to external disturbances, 2) useful information will be available already at the node level for undertaking automatic (unsupervised) emergency measures, 3) potentially no raw-data will have to be transmitted across the network, which would only circulate the resulting (higher-level) information, leading to the need for a narrower communication band and prompter response of the system.

The MP-wise system was applied to the data of the 2D array. In particular, ad-hoc software for the real time data acquisition in the field was developed (see Figure 10). The software allows the recordings to be selected on a laptop and the calculation of the autocorrelation coefficients is automatically done in the field. The derived dispersion curve (Figure 10 bottom left) can then be inverted by using a linearized approach and the shear wave velocity profile (Figure 10 bottom right) as well an estimate of the  $V_{s30}$  value based on the Albarello and Gargani (2010) approach is performed.





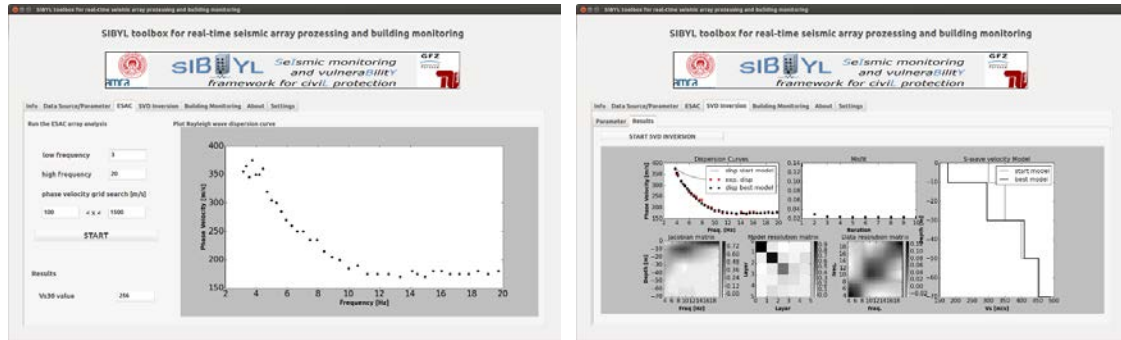


Figure 10. Output from the MPwise processing of seismic array data for site assessment (note, this is the Graphical User Interface (GUI) developed for the SIBYL project). Top left) The data source and parameter menu allow the user to configure different parameters, such as the number of stations, network code, sampling rate, channel identifier, digitizer and sensor specific constants. Top right) Overview of the array geometry. Bottom left) Real-time processing of the array measurements using the ESAC method to obtain a Rayleigh wave dispersion curve. Bottom right) SVD inversion to obtain a 1D shear wave velocity model, as well as a quality control provided by Jacobian, model and data resolution matrices.

## 4 PRACTICAL CONSIDERATIONS WHEN UNDERTAKING FIELD ACTIVITIES

The following (Table 1) is a series of more practical points regarding the undertaking of field activities related to site effects assessment. Obviously, provision would need to be made to best deal with the site at hand, hence one should consider the following as being more general in nature.

*Table 1: Some considerations when undertaking seismic site assessments.*

Factor	Considerations	Outline/response
Sampling rate	Dependent upon frequency range of interest (generally 0.5 – 20 Hz), data storage/communication.	100 – 400 s.p.s.
Maximum and minimum distances between senses	Strongly dependent upon investigation depth of interest (e.g., 30m for $V_{s30}$ ), the underlying material, and how much detail is required.	2 – 40 m
Number of sensors	Dependent upon the resolution required, and the available time for recording.	10 – 20 individual units
Time required	Dependent upon the number of available sensors and local noise conditions.	30 minutes to 1.5 hour

Other factors include:

- Ensure the best coupling between the sensors and the ground. For example, softer material (i.e., such as on a sports field, public park) is preferred, however, sometimes paved surfaces are all that is available.
- For these sorts of activities, noisier environments are not such an issue as it is this signal that is in fact being used. However, factors such as larger transients at specific sensors but not the whole array will need to be considered during the processing.
- Coordinate estimation (of the individual sensors relative to each other and of the network as a whole) will need to be as accurate as possible (e.g., use surveying equipment such as theodolites is recommended).
- The distribution of inter-station distances should be such as to allow the even depth resolution of the underlying subsurface. Likewise, the stations must be distributed to ensure the best azimuth coverage.

## **ACKNOWLEDGEMENTS**

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