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APPLICATION OF THE SPATIAL AUTO-CORRELATION METHOD FOR SITE EFFECT EVALUATION USING AMBIENT NOISE

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Abstract

Natural vibrations on the surface of the Earth are termed ambient noise or microtremors. Such energy is generated by the various sources, such as wind, ocean waves at the seashore, traffic noise, heavy machinery, factories and household appliances. Because microtremors are generated by sources on the ground surface, the energy propagates mainly as surface waves. The vertical component of the microtremor energy is associated with Rayleigh waves which are primarily sensitive to the S-wave velocity-depth profile of the locality, and the phase velocity of such energy allows construction of a dispersion curve. Microtremors used in Spatial Auto-Correlation (SPAC) methods consist of a wide frequency range of surface waves from the frequency of about 0.1 Hz to several tens of Hz. The wavelengths (and hence depth sensitivity of such surface waves) allows determination of the site S-wave velocity model from a depth of one or two meters down to a maximum of several kilometers; it is a passive seismic method using only ambient noise as the energy source.

Ambient noise methods use a 2D seismic array with a small number of seismometers (generally between two and fifteen) to estimate the phase velocity dispersion curve and hence the S-wave depth profile for the site. A large number of methods have been proposed and used to estimate the dispersion curve; SPAC is the one of the oldest and the most commonly used methods due to its versatility and minimal instrumentation requirements. We show that direct fitting of observed and model SPAC spectra gives a superior bandwidth of useable data than does the more common inversión after the intermédiate step of constructing an observed dispersión curve.

Current case histories demonstrate the method with a range of array types including two-station arrays, L-shaped multi-station arrays, triangular and circular arrays. Array sizes from a few meters to several-km diameters have been successfully deployed in sites ranging from downtown urban settings to rural and remote desert sites.

A fundamental requirement of the method is the ability to average wave propagation over a range of azimuths; this can be achieved with either or both of the wave sources being widely distributed in azimuth, and the 2D array sampling the wave-field over a range of azimuths. Several variants of the method extend its applicability to under-sampled data from sparse arrays, the complexity of multiple-mode propagation of energy, and the problem of precise estimation where array geometry departs from an ideal regular array. We find that sparse nested triangular arrays are generally sufficient, and the use of high-density circular arrays is unlikely to be cost-effective in routine applications.

Passive seismic arrays should be the method of first choice when characterizing Vs30 and deeper, with active seismic methods being a complementary method for use if and when condition so require.

The use of computer inversion methodology allows estimation of not only the S-wave velocity profile but parameter uncertainties in terms of layer thickness and velocity. The coupling of SPAC methods with horizontal:vertical particle motion spectral ratio analysis generally allows use of lower frequency data with consequent resolution of deeper layers, than is possible with SPAC alone.

Considering its non-invasive methodology, logistical flexibility, simplicity, applicability, and stability, the SPAC method and its various modified extensions will play an increasingly important role in site effect evaluation. The paper summarizes the fundamental theory of the SPAC method, reviews recent developments, and offers recommendations for future blind studies.

Keywords: Passive seismic, active seismic, microtremor, ambient noise, surface wave, Rayleigh wave, Vs30, seismic array, HVSR, SPAC. V_{obs} V_{model}

1. Introduction

The microtremor method, often also named the ambient noise method involves study of spectra and phase velocity dispersion of surface waves to deduce properties of the Earth's surface at depths from a few meters to a few km. The frequencies in use are typically 1-30Hz, attributable mainly to anthropogenic sources, and 0.1 to 1 Hz, attributable to natural phenomena such as wave action at coastlines and wind action on vegetation.

The majority of surveys use vertical-component ground motion associated with Rayleigh waves, although surveys using three-component sensors have demonstrated that the properties of Love waves as well as Rayleigh waves can be used in the analysis.

The propagation velocity of surface waves is dispersive (frequency dependent) and in a vertically heterogeneous earth their sensitivity to properties of the earth at depth is a function of wavelength, where short wavelengths (high frequencies) are sensitive only to earth properties at shallow depths, and long wavelengths (low frequencies) are sensitive to earth properties at deep depths. In principle we seek to measure the dispersion curve of phase velocity versus frequency and by use of inversion modelling deliver a layered-earth model of acoustic properties. Foti et al (2011, Figure 1) [1] is a useful illustration of the process.

Of the three elastic properties compressional-wave velocity Vp, shear-wave velocity Vs and density rho, only the Vs has sufficient effect on surface-wave phase velocities to be generally resolvable in an inversion process. Vp and rho are usually fixed by assumption or by some empirical relation between the parameter and Vs.

The spatial autocorrelation method (SPAC – which can equally be termed spatially-averaged coherency) contains two key assumptions. Firstly, the surface waves observed are far-field waves with plane wave fronts, and secondly that sources are distributed in azimuth sufficiently to provide spatial averaging of observed inter-station coherencies.

The method can be illustrated beginning with the concept of a single plane wave observed at two stations, whereby the inter-station coherency may be written:

$$c_{ij}(f) = \exp\,[irk(f)\ \cos(\theta-\phi)] \qquad (1)$$

where cij(f) is the coherency frequency spectrum between stations i, j; r is the station separation, k is the wavenumber, θ is the angular displacement of the pair of stations, and ϕ is the propagation direction of the wave front.

Following [2] and [3], for a single noise-free wavefront observed by multiple station pairs distributed around a circle , equation (1) becomes a spatial average around the azimuth θ,

$$c\,(f) = Jo\,(rk) = Jo\,[2\pi\, fr/\, v(f)\,] \qquad (2)$$

where c(f) is the SPAC spectrum, Jo the Bessel function of zero order, and v(f) is the phase velocity dispersion curve of the observed wave. As shown by [4] the spatial averaging can equally be achieved by using a single pair of stations in the presence of an omnidirectional wavefield, ie the spatial average of equation (1) is achieved as an integration over a distribution of wave propagation directions ϕ.

In practice the spatial averaging necessary for SPAC methods to be useful is provided by both an angular distribution of stations in a seismic array, and by the usual angular distribution of propagating seismic noise. A series of studies exist attempting to quantify the effect of limited angular distribution of station azimuths and/or limited angular distribution of the wave field (eg [5],[3],[6] Asten et al, 2004; Asten, 2006; Cho et al, 2008). Extensive use of the SPAC methods over the past five years where multiple arrays have been employed and where ground truth is available lead us to the view that the demands of spatial averaging are not onerous and relatively simple arrays can be used without degrading the method; the point is illustrated in Section 7 of this paper.

2. Range of frequencies and detection depths

While Wathelet et al (2008) [7] defined upper and lower bounds on resolvable depths based on station spacings of an array, we prefer to define bounds based on wavelengths of signals alone. The reason is that in direct fitting of observed and model SPAC curves, useful upper frequencies are not defined by a Nyquist relation applied to station spacings, but only by the highest usable frequency on a Bessel curve having (in general) multiple peaks and troughs. Likewise it is the lowest usable frequency which defines the greatest depth of penetration, not the array diameter. Some authors such as Cho et al (2013) [8] claim useful estimates of phase velocity with a variant of the SPAC method for wavelengths up to 100 times the diameter of a miniature array. Such claims may be instrument and site dependent and we treat them with caution, but they do underline the fact that limits on useful data with SPAC methods are set by the maximum wavelength, not intrinsically by the array size.

Shallow resolution is defined here as $\lambda/3$ since Rayleigh wave modelling shows that the phase velocity of that wave is most sensitive to Vs near that depth. Maximum depth of useful interpretation is about half the wavelength of a fundamental-mode Rayleigh wave, so we propose the guidelines for maximum and minimum depths of investigation D_{min}, D_{max},

$$D_{min} = \lambda_{min}/a_{min} = V/(a_{min}.f_{max}), \text{ and}$$

$$D_{max} = \lambda_{max}/a_{max} = V/(a_{max}.f_{min}) \quad (3)$$

where V is the phase velocity of the Rayleigh wave, which is close to the harmonic average Vs over the depth range of interest, a_{min}, a_{max} are in the range 2 to 4 depending on site conditions and data quality. In this study we find values $a_{min} = 3$, and $a_{max} = 2$ to be useful guidelines.

Table 1 below provides some useful guidelines for common soil and rock types.

Table 1 - Examples of minimum shallow resolution D_{min} and maximum effective depth penetration D_{max} for fundamental-mode Rayleigh waves at selected frequencies and selected soil and rock types.

Minimum resolution (m) lamda/3=Vs/3fmax

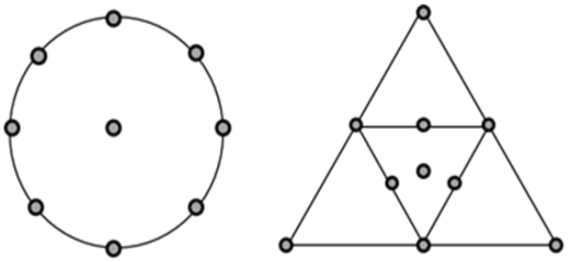
Material	Vs (m/s)	fmax=2 Hz	fmax=20 Hz
Soft Clay	80-200	13 -33	1 -3
Stiff Clay	200-600	33 -100	3 -10
Loose sand	100-250	17 -42	2 -4
Dense sand	200-500	33 -83	3 -8
Gravel	300-700	50 -117	5 -12
Weathered rock	600-900	100 -150	10 -15
Competent rock	800-2000	133 -333	13 -33

Maximum depth of investigation (m) lamda/2=Vs/2fmin

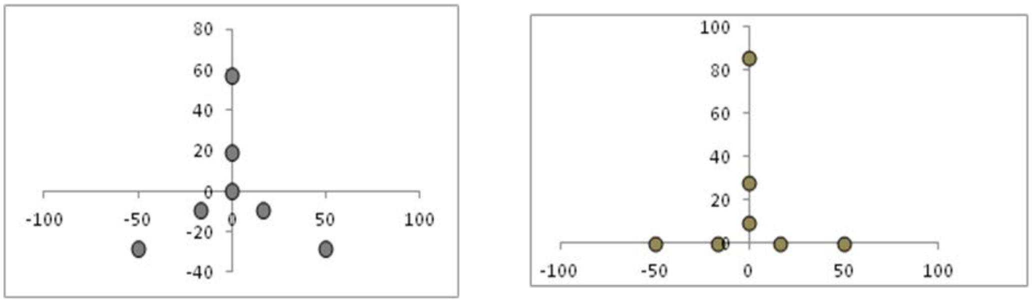
Material	average Vs (m/s)	fmin=0.2 Hz	fmin=2 Hz
Dense sand	200-500	500 -1250	50 -125
Gravel	300-700	750 -1750	75 -175
Weathered rock	600-900	1500 -2250	150 -225
Competent rock	800-2000	2000 -5000	200 -500

3. Choice of array

A very large number of array shapes are reported in case histories, illustrated in Fig. 1, with comments on attributes of the different shapes in [12]. The circular array gives the most effective azimuthal averaging; examples using 5,6,7 and 9 stations on the ring appear in for example [8-11]. It is our experience that the sparse nested or common-base triangles are the most efficient geometry, since these give sufficient azimuthal averaging in most cases, and logistical effort can be applied to a range of triangle sizes rather than a density of stations. In areas of restricted access the common-base triangle or the L-shaped array are useful. In many cases useful SPAC data can be obtained with a linear array, at its most simple being a two-station array, with examples in [13, 14].



(a) Circular shape (b) Nested Triangular shape (c) L-shape



(d) Sparse nested triangles (sizes increase x3) (e) Common-base nested triangles (sizes increase x3)

Fig.1 – Five arrray geometries which have been used for microtremor studies (from Fig.6 of [12]).

4. Alternative processing methodologies

Following estimation of SPAC coefficients $c(f)$ from equation (2) the inverse solution to extract phase velocity $v(f)$ can be done using estimates at multiple values of r for each frequency (the extended SPAC method, ESAC [15]) or at multiple values of frequency for a single value of r (the modified SPAC method, MSPAC [16]). The MSPAC method was generalized to allow use of moderately irregular array geometries and is probably the most popular method in use due to an accessible software implementation [17].

An alternative approach [5,3] utilizes direct fitting of observed and model SPAC curves, called the multiple-mode SPAC (MMSPAC) method due to its facility in identifying the presence of multiple modes of Rayleigh-wave propagation, if present. The technique has improved stability in that it employs only one inversion step whereas ESAC and MSPAC use two. Fig.2 illustrates the processing stream for the alternative methods, applied to a triangular array.

A fourth variant of the SPAC method is krSPAC, where direct fitting of SPAC spectra is carried out in the wavenumber domain instead of frequency [18]. It has strong advantages in retaining high-frequency data (and hence depth resolution) when array geometry is grossly irregular.

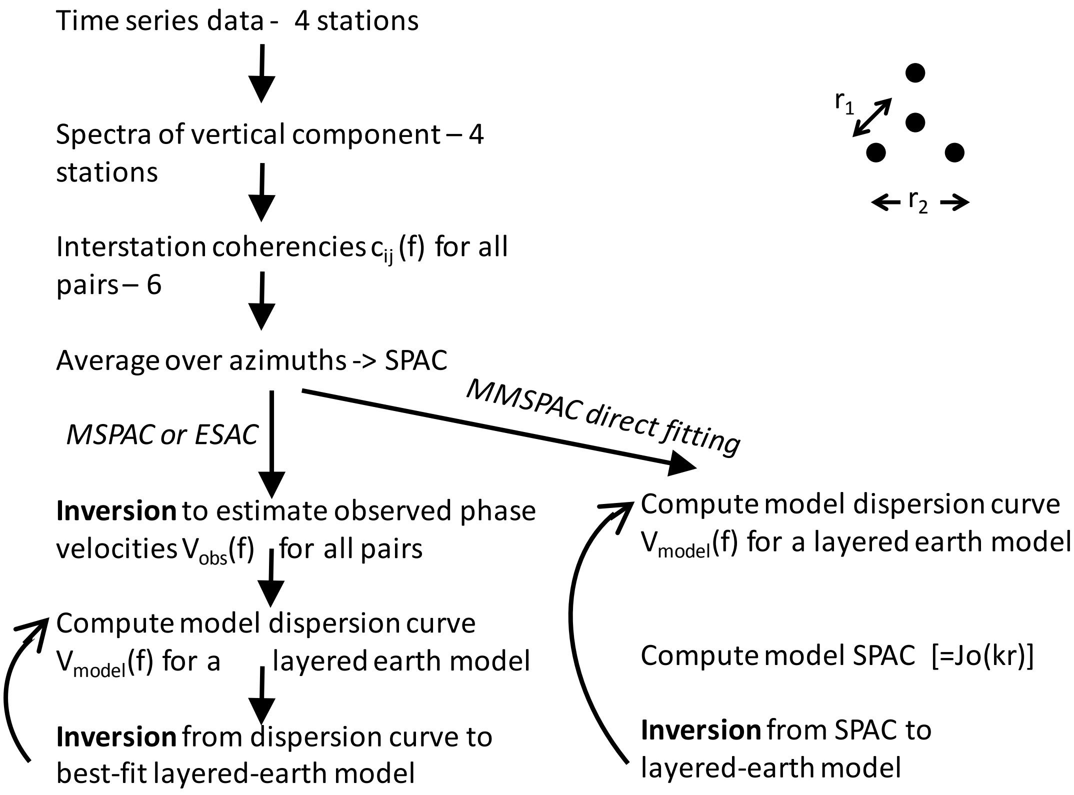


Fig.2 - Processing streams (at left) for ESAC, MSPAC and (at right) for MMSPAC (direct fitting) methodologies. A triangular array (top right) provides SPAC spectra for two station separations r_1, r_2, which can be inverted or fitted simultaneously.

Fig.3 shows an example of MMSPAC direct fitting on data from Mirandola, Italy. The site is described in [10]. The direct fitting method allows use of frequencies 2 Hz to 30 Hz for this small triangle. By contrast, use of MSPAC is unable to use frequencies above 10 Hz (see Fig.12 of [12]), thus losing resolution of upper layers in the geological section. Use of MMSPAC direct fitting doubles the usable bandwidth and largely removes the need for complementary active surface-wave studies to provide shallow resolution. The point is emphasized by Fig.4 of [10] which shows the usable frequency ranges as assessed by 12 independent groups who studied this data as part of the InterPACIFIC comparison project. That figure shows that Team 1, using MMSPAC achieved the same useful frequency range with passive methods, as did the majority of other teams who used combined active and passive methods.

Fig.3 also shows the presence of higher-mode energy in the band 10-13 Hz. The blue model curve represents the Rayleigh effective mode R_e, constructed as a superposition of modes where energy partition between modes is computed on the assumption that the wave-field is generated by ideal surface point sources [19]. This band of higher-mode energy is associated with the interpreted shallow, strong velocity contrast at depth 14m in Fig. 3d.

SPAC methods benefit from simultaneous comparison of observed and model spectra of the horizontal:vertical particle motion ratio (HVSR) as determined from at least one 3-component recorder in the seismic array. The peak in HVSR at 0.8 Hz is associated with the velocity contrast at basement depth 116m. In this instance the HVSR data is interpreted only by qualitative fitting of observed and model spectral shapes, but [20-23] provide examples where formal inversion fitting is employed. A separate paper [23] reviews HVSR methods in passive seismic studies. Where identifiable low-frequency peaks in HVSR exist, it is a general rule that the frequency of the peak provides information complementary to SPAC methods, and allows improved characterization of deep interfaces in some situations; two examples in [25] illustrate the point. Thus combined use of SPAC and HVSR in routine surveys is highly desirable.

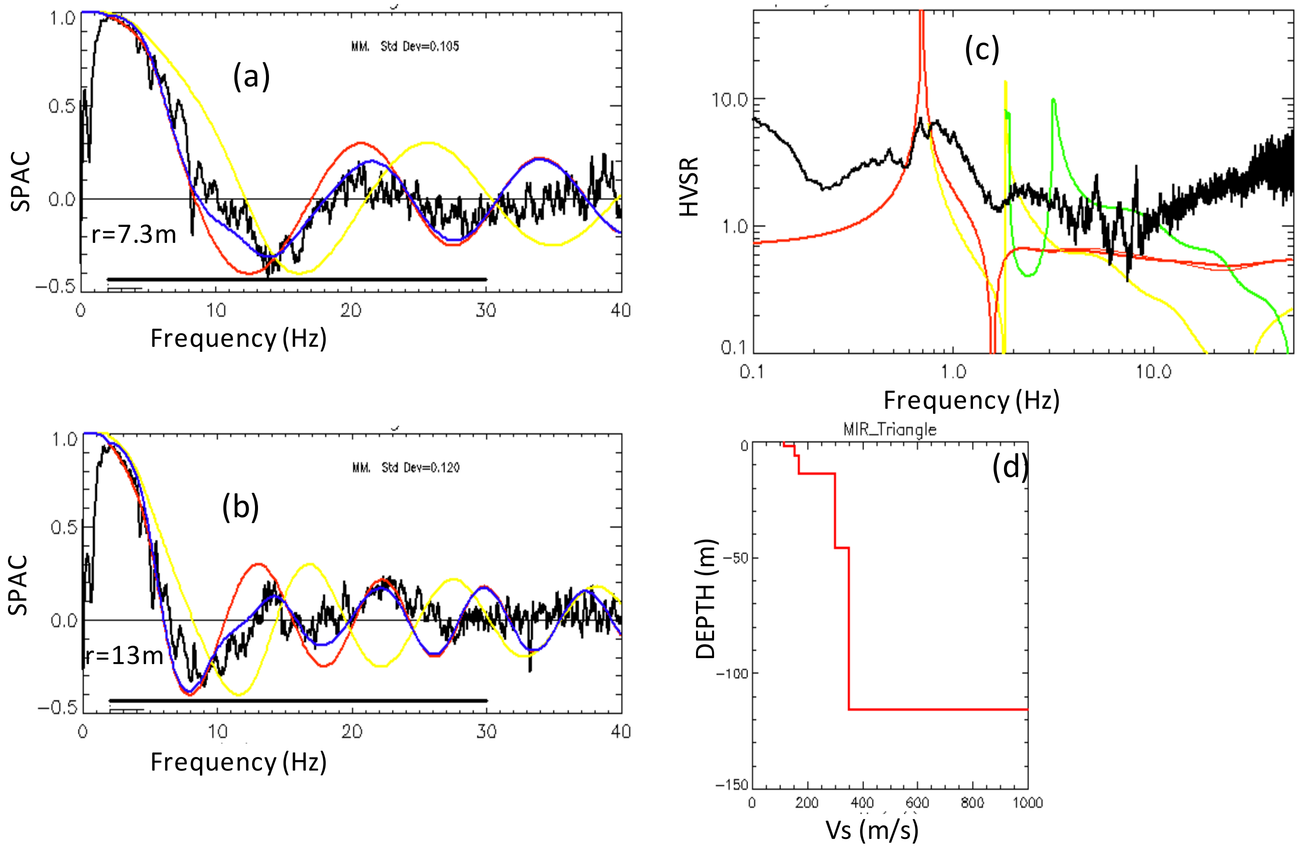


Fig.3 - MMSPAC method applied to a triangular array side length 12.7m, Mirandola, Italy.
Black: observed SPAC and HVSR spectra.
Red, yellow: model curves for Rayleigh fundamental R_0 and 1st higher modes.
Blue: model curve for Rayleigh effective mode (overwrites the plotted R_0 mode for most frequencies) .
(a), (b) SPAC for r=7.3m (radii) and r=12.7m (sides).
(c) HVSR at array center. (d) Vs profile from fitted SPAC (including larger triangles not shown here) and from HVSR fit.

5. Integration of passive and active surface-wave methods

A surface wave method using active sources has become increasingly popular during the last several decades, for estimation of S-wave velocity to a depth of several tens of meters. Spectral analysis of surface waves (SASW) has been used for the determination of one-dimensional (1D) Vs profiles down to a depth of 100 m [26]. SASW surveys employ a shaker or a vibrator as sources, and calculate phase differences between two receivers via cross-correlation. Park et al. [27] proposed a multichannel analysis of surface waves (MASW) method, which determines phase velocities directly from multichannel surface wave data after transforming waveform data from the time-distance domain into the phase velocity–frequency domain. MASW enables us to perform surface wave analysis using relatively inexpensive equipment, such as a sledge hammer, geophones, and an engineering seismograph, so that the method has been widely used for many engineering site investigations globally. A clear limitation of the active surface wave methods is its penetration depth. Active sources, sledge hammers, weight drops, and shakers generally penetrate to a depth of 15 to 30 m depending on the site and source energy, and the depth of penetration is often not enough for investigation purposes. However Stephenson (pers. comm. 2016) reports using a 220kg weight drop to achieve 100m depth penetration in the San Francisco Bay area. Integrating passive and active surface wave method is getting popular. The passive method is mainly used to supplement the penetration depth or low frequency phase velocities of the active method. SPAC is an ideal supplement to the active surface wave method since same equipment can be used for data acquisition and irregular shape arrays, such as L-shaped or linear, works in many cases.

Fig. 4 shows a typical example of integration of passive and active surface-wave methods. We can see that maximum wave length obtained from the active method (MASW) was approximately 30 m whereas one obtained from the passive method (SPAC, linear array) was approximately 150 m although the same geometry and equipment were used for both methods. It clearly shows the advantage of the passive methods over active methods in terms of the penetration depth.

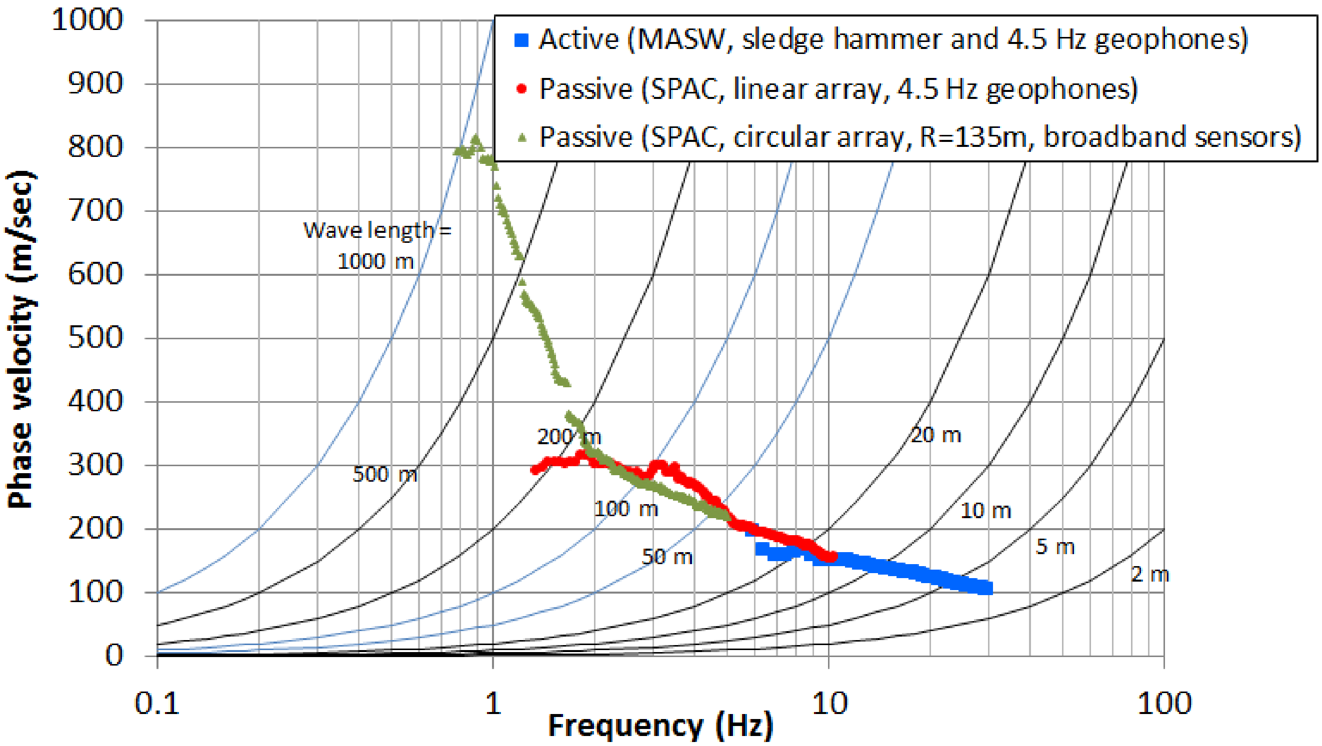


Fig.4 – Comparison of dispersion curves obtained from active (MASW) and passive (SPAC with linear and circular arrays) surface wave methods at Mirandola, Italy.

The zone of overlap between active and passive data is usually several Hz as shown in Fig. 4. A recent study [14] shows that SPAC provides phase velocities up to 20~40 Hz with wavelength of 2 to 3 m at most sites. The active methods require much more effort of field work compared with the passive method. If the passive methods provide phase velocities up to several tens of Hz, the active method might not need to be performed and the effort of field work could be dramatically reduced. It is needless to say performing both active and passive methods is the best for estimating the Vs profile to a standard 30m depth (Vs30). The recent studies imply that performing SPAC may be better than performing MASW if we are restricted to performing only one of these methods.

6. The challenges of low-velocity layers (LVL) and multiple modes

A series of very detailed passive and active surface-wave surveys are available from the Christchurch area, New Zealand [11]. Four points in particular can be deduced from Fig. 5 (supported by other plots not shown).

a) The high frequency limit with MMSPAC at this site is 14 Hz, giving D_{min}=2.2m. This compares with a high frequency limit obtained using MSPAC and inversion of dispersion curves, of 3Hz [11]. (That study was also able to extract useful frequencies up to 10 Hz from the passive data, by an alternative method of frequency-wavenumber filtering). Complementary active surface wave data in [11] obtained useful frequencies up to 25 Hz).

b) The variable frequency separation of peaks in the MMSPAC direct fitting allows resolution of a probable LVL at 2m depth.

c) Frequencies 0.5-1 Hz allow resolution of a basement interface at 472m. Data at 0.5 Hz allows an estimate of D_{max} to be 1400m.

d) A band of frequencies 1-1.8Hz (Fig. 5b) show that the observed SPAC follows neither the R_0 mode nor the effective mode R_e . Furthermore as shown in Fig. 6 the positioning of the observed SPAC relative to R_0 and R_e is not constant, thus we conclude that while multiple modes clearly exist at this site, their composition cannot be estimated by the simple power partition ratio based on an assumption of vertically-acting point sources.

This last point underlines the challenge posed by higher modes; while their presence can usually be recognised they cannot be quantitatively modelled with confidence. A higher mode incorrectly interpreted as a fundamental mode will yield estimates of Vs biased to high values, which is undesirable when correct estimation of Vs for earthquake hazard studies is demanded. The problem is lessened when low frequency (long wavelength) data is available, which increases the importance of survey design to gain such data.

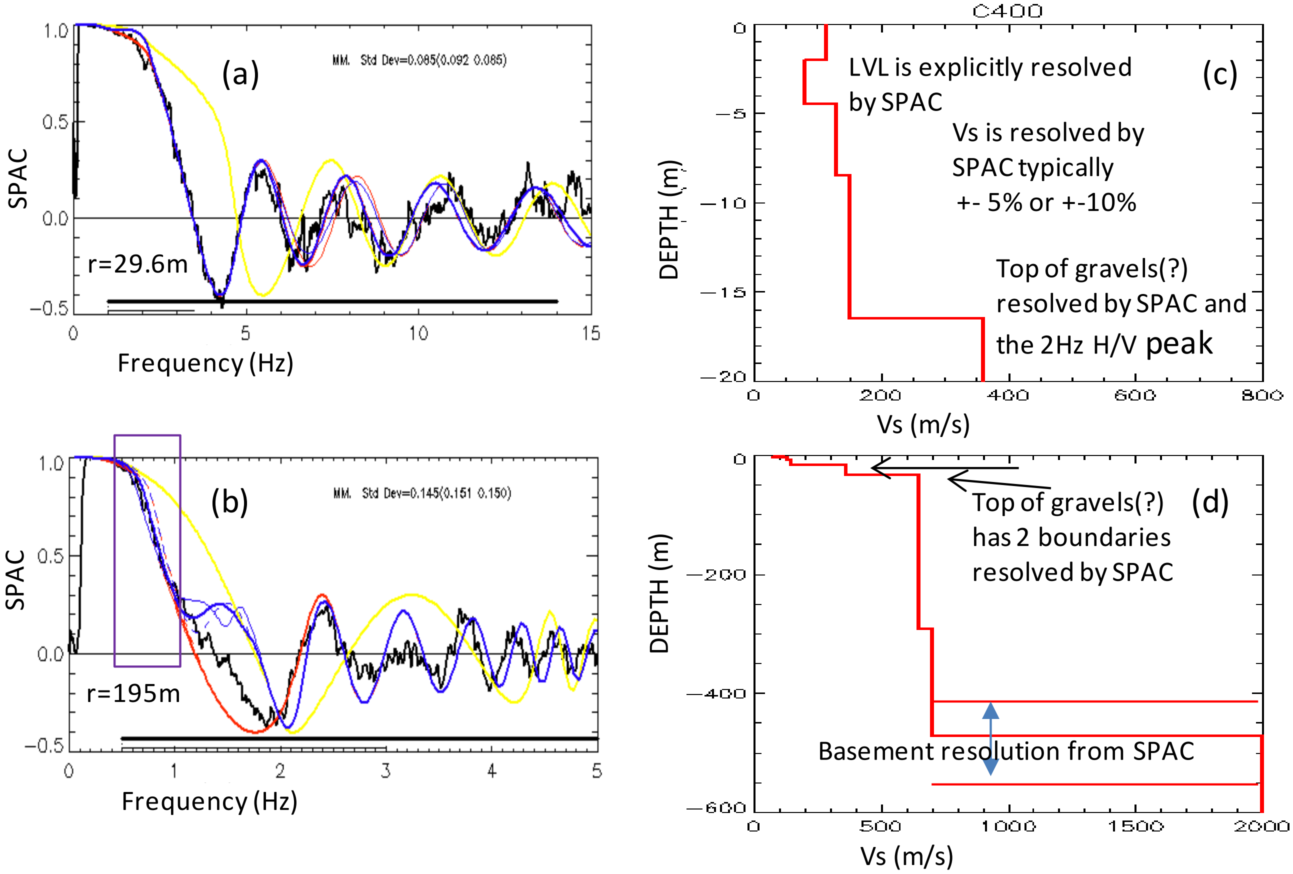


Fig.5 - MMSPAC method applied to two 6-stn circular arrays, Hagley Park, New Zealand.
Colors as for Fig. 3. Array geometry is shown in Fig. 6d.
(a) SPAC for r=29.6m. Thick blue line: best fit model including LVL at 2m depth. Thin blue: model without LVL; the fit is degraded in the frequency band 7-10Hz.
(b) SPAC for r=195m. Thick, thin and dashed blue lines: best fit model with basement at 472m, 550m, and 420m. The frequency band 0.5-1 Hz (purple box) clearly shows resolution of the basement in this depth range.
(c), (d) Vs profiles for a single model from all fitted SPAC data.

The first point adds to the finding of Sections 4 and 5, where we note that when passive seismic processing is optimized to retain high-frequency data, the need for complementary active seismic surveys is reduced.

A similar overlap of passive and active seismic data was observed in [28].

A comparison of layered-earth model interpretations for the Hagley Park site as shown in Fig. 5 and in [11] shows that while the former used a minimum number of eight layers, with high-contrast boundaries, the latter used a large number of 25 layers with gradational boundaries and monotonically increasing Vs. When the latter model is used in Fig. 6, the quality of the fit is insignificantly different.

The comparison of interpretation methods in [11] also shows a model with multiple LVLs which in terms of fitting SPAC, frequency-wavenumber and active-source data is not distinguishable from the monotonically increasing Vs model.

These last two observations illustrate a well-known limitation of surface-wave methods, and show that all geological constraints in terms of known high and low velocity strata, and basement type, should be included as constraints in interpretations.

7. Practical choice of array

The high quality and high redundancy of the Hagley Park data allows an assessment of how simpler arrays may perform at the site. Fig. 6 shows MMSPAC data fitted with the same model as was Fig. 5, for a semicircular array of six stations, for a simple triangular array, and for a single pair of stations.

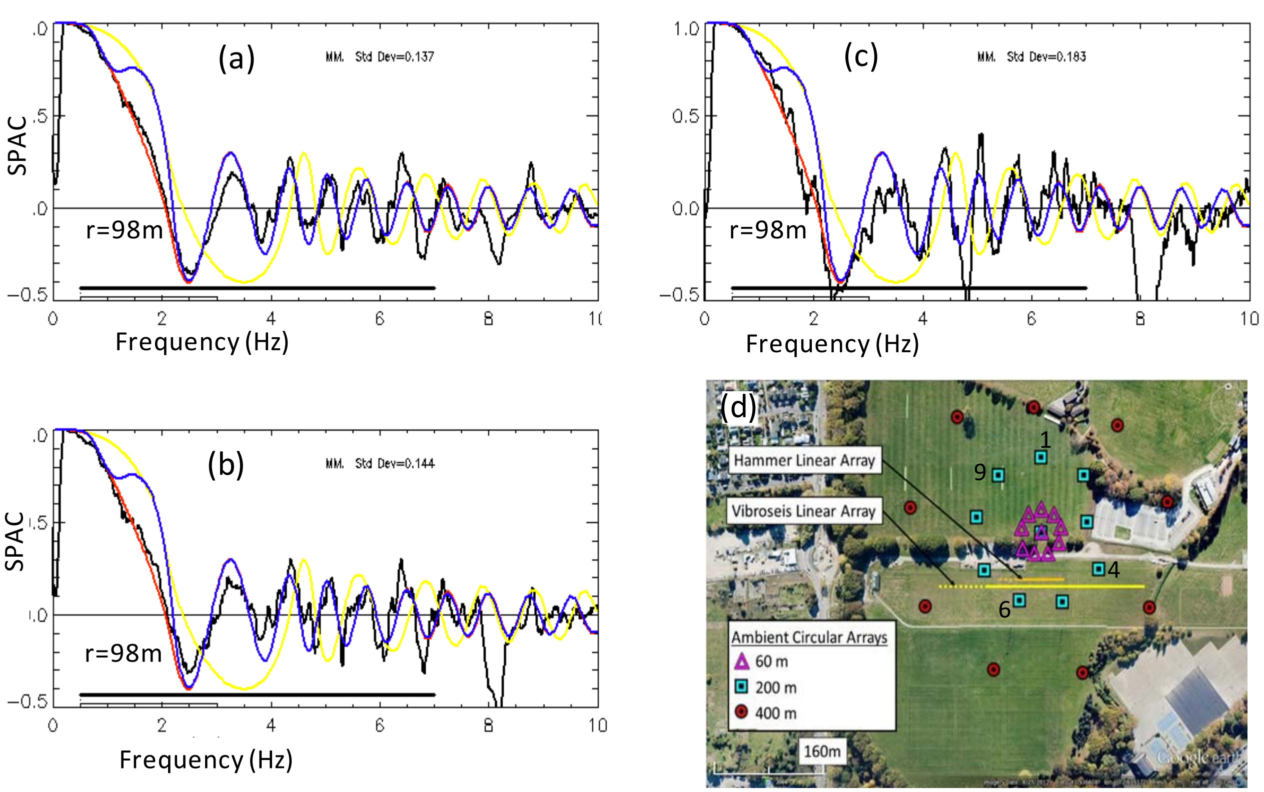


Fig. 6 – (a) MMSPAC for the 200m diameter array of Fig. 6d (blue squares), using six radial pairs to stations 4-9. Data length 50 min.The fitted model is same as Fig. 5c-d. Colors are as for Fig. 3.
(b) MMSPAC using a simple triangle array, with three radial pairs to stations 4, 6 & 9.
(c) MMSPAC using one pair only, stations center & 4. Same data length and smoothing as (a) and (b).
(d) Map of layout of three circular arrays at Hagley Park (from [11]).

It is arguable that the triangular array presents no loss of information relative to the circular array, while the single pair (or 2-station array) retains the essential shape of the SPAC spectrum although obviously degraded.

We conclude that triangular arrays present sufficient spatial averaging on such a site, and thus where layout time is important, sparse nested triangles are likely to be a cost-effective technical solution than the use of dense circular arrays. The fact that the single pair provides useful data with a data length of 50 minutes is encouraging. The additional effort of using two rather than one only station for HVSR surveys is not large, and the return on effort is likely to be high in terms of providing Vs information to supplement the more qualitative HVSR measurement.

8. Major comparisons of passive and active seismic interpretation methodologies

Two recent studies at three European sites [10] and the QEII site, Christchurch, New Zealand [29,30] quantify some of the uncertainties in Vs models when data is interpreted by different groups and/or with different methodologies. A strength and a limitation of these studies is that a large amount of data allows much redundancy, and analysts were able to interpret as much or as little of the data provided as they chose. This process facilitates maximum resolution of the Vs profile, but does not define benefits or limitations of different field arrays for routine efficient use.

The preceding section finds evidence for the adequacy of sparse triangular arrays in passive seismic methods, but objective proof of this will require further blind tests on new sites, where minimal array data is supplied in a staged process in order to determine comparative performance of interpretation methodologies on data from efficient field arrays.

9. Recommendations

Passive source methods should be the first method of choice for Vs30 and deeper studies. Joint use of passive and active-source methods is recommended for gaining maximum resolution near surface, but use of MMSPAC direct fitting methods reduces the high frequency advantage of active methods to the degree where the additional cost of active methods may not be justifiable.

Sparse nested triangles are the most efficient use of instrumentation, except where strongly directional noise sources are expected. Supplementary use of at least one 3-component receiver usually provides additional depth information where strong velocity contrasts exist at basement.

Where HVSR surveys are used as single stations for reconnaissance purposes, the use of a synchronized second station allows interpretation by 2-station SPAC, with advantages for quantitative estimation of Vs values.

The use of SPAC interpretation by direct fitting of observed and model SPAC spectra allows a wider frequency range in interpretation than do the more conventional methods requiring estimation of dispersion curves prior to inversion to a layered-earth model. This facilitates detection of near-surface low-velocity layers if present.

Guidance from geological logs on types of strata and of basement is essential for accurate interpretation of a Vs depth profile, especially if LVLs are suspected or frequency bands exist where multiple modes dominate.

Multiple modes are a frequent occurrence, generally restricted to frequency bands of an octave width or less. The use of effective mode modelling with its theoretical assumption of perfect vertically-directed sources is not a perfect solution since power-partition between modes is source dependent and may also be time dependent. However it is recommended to take steps to recognize multiple modes during processing, and assess the likely validity of effective-mode modelling on a case-by-case basis.

Blind comparative studies on interpretation methodologies using data from limited arrays such as sparse triangles, L-shaped arrays, and 2-station arrays, should be a goal during ongoing characterization of passive seismic methods.

10. Acknowledgments

Brady Cox and David Teague of the University of Texas contributed the Hagley Park data. Cox, Teague and Bill Stephenson of the US Geological Survey provided many helpful points of discussion.

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