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Using Ellipticity Information for Site Characterisation

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Responsible activity leader: Donat Fäh
Responsible participant: ETH Zürich
Authors: Donat Fäh, Marc Wathelet, Miriam Kristekova, Hans Havenith, Brigitte Endrun, Gabriela Stamm, Valerio Poggi, Jan Burjanek, Cécile Cornou

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Using Ellipticity Information for Site Characterisation


(1) Swiss Seismological Service ETH Zurich
(2) IRD-LGIT, University Joseph Fourier, Grenoble
(3) Geophysical Institute. Slovak Academy of Sciences, Bratislava
(4) University of Potsdam
(5) University of Liege

Summary

The H/V technique has proven very convenient for estimating the fundamental frequency of soft deposits. In one-dimensional structures, average H/V spectral ratios can also be used to estimate the ellipticity of the fundamental mode Rayleigh wave. Ellipticity information can then be applied to constrain an inversion using surface-waves' phase velocity curves.

The dual goals of the NERIES project JRA4-Task B2 are to implement a new method that allows retrieval of Rayleigh wave ellipticity from H/V spectral ratios, and use of ellipticity information for structural inversion. The method for retrieving ellipticity is based on time-frequency analysis with continuous wavelet transform. It has been integrated in the software package of the JRA4 working group (http://www.geopsy.org). This software was initiated during the SESAME project and further developed in JRA4. The software also includes an inversion procedure using both phase velocity curves and ellipticity information.

A large series of tests were performed with synthetic and observed datasets of ambient noise. The aim was to compare automatic and manual procedures for interpreting ellipticity results. We tested a number of processing parameters and established these parameters for robust results. In general, good results are obtained for the right flank of the H/V spectral ratios. When using an optimum choice of the processing parameters, the results from fully automatic processing of synthetic noise for different models are satisfactory. In some cases, it is possible to slightly improve automatic results by manual picking – mainly in the vicinity of the peak and trough. For some models also the left flank of the ellipticity curve can be retrieved. Finally, we establish rules for the reliable extraction of ellipticity curves. The combined inversion of dispersion phase velocity curves and ellipticity are fully implemented and successfully tested.

For real cases, we presently cannot validate the derived ellipticity curves from single-station recordings. This drawback might be improved by future development of two array-based methods. One method to obtain ellipticity curves uses a reduction factor applied to the classical H/V curve, accounting for the correct Rayleigh/Love ratio. This ratio is derived from 3C SPAC analysis. The second array method derives H/V curves from high-resolution frequency-wavenumber array analysis of the three components of motion. Applying all the methods to the same real cases is our plan and will better validate the single-station wavelet-based method.
1. Introduction

Among several proposed microtremor methods, the H/V technique (e.g. Nakamura, 1989) has proven very convenient for estimating the fundamental frequency of soft deposits (e.g. Tokimatsu, 1997; Bard, 1998; Bonnefoy-Claudet et al., 2006a). This method allows detailed mapping of this frequency within urban areas. In one-dimensional structures, average H/V spectral ratios can also be used to estimate the ellipticity of the fundamental mode Rayleigh wave (e.g. Yamanaka et al., 1994). In the P-SV case, the ellipticity of the ground motion at the free surface is defined as the ratio between the horizontal and vertical displacement eigen-functions at each frequency. Ellipticity is detectable in H/V spectral ratios between the peak at the fundamental frequency of resonance and the first minimum at higher frequency (e.g. Fäh et al., 2001). The shape of the H/V ratio around its maximum peak can thus be used to estimate a shear-wave velocity profile. Yamanaka et al. (1994), Satoh et al. (2001), and Parolai et al. (2006) applied this approach to deep sedimentary basins, while Fäh et al. (2001, 2003) used it for shallow sites. This ellipticity-based method applies only to sites presenting a strong S-wave velocity between sediments and bedrock and when sources are near (4 to 50 times the layer thickness) and close to the surface (Bonnefoy-Claudet et al., 2006b). At such sites, the H/V spectral ratio shows a strong peak.

Combining surface wave dispersion curves with the ellipticity of the fundamental mode Rayleigh waves has the advantage of defining the total depth of the soft sediments (Fäh et al., 2008). The principal problem of retrieving ellipticity from H/V spectral ratios is to correct for the energy of body and Love waves present in the ambient vibration recordings. Two types of methods can be applied to correct H/V ratios from single stations (e.g. Fäh et al., 2001). The first is classical polarization analysis in the frequency domain, where polarization is defined as ‘the ratio between the Fourier spectrum of the horizontal components and the spectrum of the vertical component.’ In this method we assume that the vertical component in the frequency band of interest, close to the H/V peak, is dominated by Rayleigh waves. The SH part of the wavefield contributes only to the horizontal component of motion. If this part could be removed, the H/V ratios would better represent the ellipticity of the fundamental mode Rayleigh wave. Such removal requires some assumptions concerning the spectral content of SH-waves. Generally, we assume that the radial component (Rayleigh waves) equals in amplitude the transverse (Love waves). The amplitude of the H/V spectral ratio can then be reduced by log10(sqrt(2)) when the H/V amplitude is given in a logarithmic scale. However, this assumption is often incorrect.

The second method for H/V ratios tries to reduce the SH-wave influence by identifying P-SV-wavelets along the signal and computing the spectral ratio from these wavelets only. This can be done by time-frequency analysis on each of the three components of ambient vibrations. In a time-frequency representation of the vertical signal, the most energetic sections are identified in time for each frequency. We assume that this maximum is related to a single Rayleigh wave wavelet for which the H/V ratio is computed. The average over all wavelets defines the H/V spectral ratio. Since we assume strongly excited fundamental mode Rayleigh waves, this curve will also measure the ellipticity curve.

Figure 1.1 compares the theoretical ellipticity of a model composed of one layer over bedrock with the classical H/V curve (the model M2.1 given in Appendix A). The classical H/V spectral ratio is corrected by considering an equal contribution of SH and P-SV waves. The H/V ratio computed by classical time-frequency-analysis is presented as well (grey curve). Both classical H/V spectral ratios and H/V ratios computed with classical time-frequency analysis exceed ellipticity over a wide range of frequencies. In this example, the synthetic signals are dominated by Love waves (Bonnefoy-Claudet et al, 2006b), whose effect could not be removed from the H/V curves by the classical time-frequency method.
Figure 1.1. (modified Figure 3a in Fäh et al., 2008) H/V spectral ratio obtained for a synthetic ambient vibrations signal in a model with one layer over bedrock (Model M2.1 is explained later in this report.). The black line is the result from classical polarization analysis in the frequency domain and is corrected for SH waves. We assumed equal amplitude of SH and P-SV waves on the horizontal components. The grey line was obtained from time-frequency analysis. The blue curve is the ellipticity of the fundamental model Rayleigh wave of model M2.1. The red curve corresponds to the H/V curve with the new method proposed here and verified in JRA4 Task B2.

There is room for improving the above methods, an issue addressed in JRA4 of the NERIES project. The first "direct" strategy aiming at detecting "pure" Rayleigh wavelets in the time histories can be improved by time-frequency analysis with Continuous Wavelet Transform (CWT) using the modified Morlet wavelet (see Figure 1.1, red curve). The development, implementation and testing of this method are presented in the following chapters. The method was originally proposed during the SESAME project (http://sesame-fp5.obs.ujf-grenoble.fr/); its theoretical background is provided in Chapter 2. A specific post-processing has now been developed (Chapter 3). The method is implemented in the SESARRAY/geopsy package (Chapter 4) and extensively tested with synthetics and real signals (Chapter 5). The combined inversions of dispersion phase velocity curves, ellipticity curves and peak frequency are also fully implemented and successfully tested (Chapter 6).

A second and third strategy are outlined in Chapter 7. They are based on ambient vibration array measurements. The second method of deriving ellipticity curves applies a reduction factor to the classical H/V curve, accounting for the correct Rayleigh/Love ratio which may be derived from 3C SPAC analysis. Finally, the third method derives H/V curves by using high-resolution frequency-wavenumber array analysis on the three components of motion.
2. Theoretical background

Early in this section we briefly explain the basic principles of the Continuous Wavelet Transform and then we define a modified Morlet wavelet and its time and frequency resolutions.

2.1. Continuous Wavelet Transform

A Continuous Wavelet Transform (CWT) of a real function $x(t)$ with respect to an analyzing wavelet $\psi(t)$ is defined as

\[
CWT \{x\}(a,b) = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{\infty} x(t) \psi^* \left( \frac{t-b}{a} \right) dt
\]  

(2.1)

Parameter $a$ is the dilatation (scaling) parameter and $b$ is the translation parameter. If $t$ is a time, then scale $a$ is inversely proportional to frequency and $b$ is a translation in time. Functions \( \{ \psi(t)(a,b) = \frac{1}{\sqrt{|a|}} \psi \left( \frac{t-b}{a} \right) \), where \( a, b \in \mathbb{R} \), \( a \neq 0 \), generated by scaling and translating the mother wavelet $\psi(t)$, form a set of analyzing wavelets (Figure 2.1), while the width of an analyzing wavelet in the time or spectral domain is proportional to $a$. Such a set of functions is called a wavelet family, or more simply wavelets.

![Figure 2.1. Example of the mother wavelet and of the analyzing wavelets.](image1)

![Figure 2.2. H/V computed with common modified Morlet wavelet from fundamental mode Rayleigh wave synthetics.](image2)

The value of the coefficient of the wavelet transform $CWT \{x\}(a,b)$ (so called wavelet coefficient) measures how the wavelet function at scale $a$ and in time position $b$ is similar to the time-frequency structure of the signal (large values – large similarity).

In general, the wavelet function $\psi(t)$ has to satisfy the admissibility condition (Daubechies 1992)

\[
C_\psi = 2\pi \int_{-\infty}^{\infty} \frac{\left| \Psi(\omega) \right|^2}{|\omega|} d\omega < \infty
\]

(2.2)
where $\Psi(\omega)$ is the Fourier transform of $\psi(t)$. For most practical purposes $\psi(t) \in L^1(\mathbb{R})$ (i.e., $\int_{-\infty}^{\infty} \psi(t) \, dt < \infty$). Then $\Psi(\omega)$ is continuous and the condition can only be satisfied if
\[ \int_{-\infty}^{\infty} \psi(t) \, dt = 0. \] (2.3)

The signal $f(t)$ can be reconstructed from its continuous wavelet transform by
\[ x(t) = C^{-1}_\psi \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} CWT(x)(a,b) \psi(t)(a,b) \, \frac{da \, db}{a^2}. \] (2.4)

With respect to the definition of CWT (formula 2.1), the name ‘time-scale representation’ is more suitable for the wavelet transform than ‘time-frequency representation.’ However, if the frequency characteristic of an analyzing wavelet is localized to a small neighborhood of a nonzero frequency $\omega_0$ (central angular frequency of the wavelet), one can find an equivalent time-frequency interpretation for the results of CWT. Angular frequency $\omega$ can then be estimated by
\[ \omega = \omega_0 / a, \] (2.5)
and the corresponding frequency in [Hz] by
\[ f = \frac{\omega_0}{2\pi a} = \frac{f_0}{a}. \] (2.6)

Continuous wavelet transform can be defined and implemented also in the Fourier domain as a set of convolutions with a ‘constant Q filter bank’.

### 2.2. Morlet wavelet

A common choice of the analyzing wavelet for CWT analysis is a Morlet, thanks to its good properties (e.g., well defined central frequency, lowest product of time and frequency uncertainties, and extractable information about signal phase). A Morlet wavelet is a complex wavelet. In the time domain it is defined by
\[ \psi(t) = \pi^{-1/4} e^{j\omega_0 t} e^{-t^2 / 2} \] (2.7)
for $\omega_0 \geq 5.3364$ (Daubechies 1992) or $\omega_0 \geq 5.4285$ (Flandrin 1999) to satisfy the admissibility condition. Usually, $\omega_0 = 6$ is used.

A common Morlet wavelet with $\omega_0 = 6$ did not work well for time-frequency computation of H/V nor for very simple synthetic data (the blue curve in Figure 2.2 compared to the theoretical light-green one). Therefore, we use a modified Morlet wavelet, which is narrower in the frequency domain (We increase the frequency resolution in the wavelet representation of the noise signal.). This is, of course, at the expense of lowering time resolution because of the Heisenberg-Gabor principle of uncertainty, but it seems that the frequency resolution is more substantial for the time-frequency technique of H/V computation from noise data. Results are much better with this modified wavelet than with the original Morlet wavelet.
The higher the \( m \) value in the figure legend, the narrower is the modified Morlet wavelet in the frequency domain.

### 2.2.1. Modified Morlet wavelet

Modifying the Morlet wavelet is done as described in Lardies & Gouttebroze (2002) or Yan et al (2006). Because the CWT can be implemented in the Fourier domain like a set of convolutions (Torrence & Compo, 1998) we introduce the relation for spectral representation of the modified Morlet wavelet as

\[
\Psi(\omega) = \frac{1}{\sqrt{4\pi}} \exp\left(-\left(a\omega - \omega_0\right)^2 m\right), \quad \text{for} \quad \omega > 0
\]  

(2.8)

where parameter \( m \) controls the wavelet's width in the spectral domain and \( \omega_0 \) has the meaning of a central angular frequency of the modified Morlet wavelet at the scale \( a = 1 \). The higher value of parameter \( m \), the narrower is the wavelet in the spectral domain. Hence it has better frequency resolution. The choice \( m = 1/2 \) corresponds to the original Morlet wavelet. How the choice of parameter \( m \) influences the quality of results is described in Chapter 5. The choice \( m = 1/2 \) often produces biased results.

### 2.2.2. Time-frequency resolutions of modified Morlet wavelet

The resolution of CWT is determined locally in time \( t \) and in frequency \( f \) (or scale \( a \)) by the duration of the analyzing wavelets in the time domain \( \Delta t_a \) and by their bandwidth in the frequency domain \( \Delta f_a \). Time and frequency resolutions are given by \( \Delta t_a = a \Delta t_\psi \) and \( \Delta f_a = \Delta f_\psi / a \), where \( \Delta t_\psi \) and \( \Delta f_\psi \) are the duration and bandwidth of the mother wavelet function \( \psi \). From the above formula we see that the resolution of the wavelet analysis is better for high dilatation \( a \) (low frequencies \( f \)) in the frequency domain and for low dilatation (high frequencies) in the time domain. The Morlet wavelet is based on the Gaussian function and hence the time and frequency resolutions of the mother wavelet are \( \Delta t_\psi = 1/\sqrt{2} \) and \( \Delta f_\psi = 1/(2\sqrt{2}) \) (Chui, 1992). Therefore, the time-frequency resolution rectangle \( \Delta t \Delta f \) in the Heisenberg-Gabor uncertainty principle \( \Delta t \Delta f \geq \frac{1}{4\pi} \) reaches its minimum, i.e. the time-frequency resolution defined by \( \Delta t \Delta f \) is the best possible. According to Yan et al (2006) time and frequency resolutions for the modified Morlet wavelet are defined by are \( \Delta t_\psi = \sqrt{m} \) and \( \Delta f_\psi = 1/(4\pi \sqrt{m}) \).

We note that the modified Morlet wavelet also has the desirable property of the best possible time-frequency resolution \( \Delta t \Delta f \). Frequency (scale) dependent time and frequency resolutions of the family of analyzed, modified Morlet wavelets are then given by

\[
\Delta t_a(f) = a \Delta t_\psi = \frac{\omega_0}{\omega} \sqrt{m} = \frac{\omega_0}{2\pi f} \sqrt{m}
\]

(2.9)

\[
\Delta f_a = \Delta f_\psi / a = \frac{1}{4\pi \sqrt{m}} \frac{\omega}{\omega_0} = \frac{2\pi f}{4\pi \omega_0 \sqrt{m}} = \frac{f}{2\omega_0 \sqrt{m}}
\]

(2.10)

These formulas can be used for tuning the modification of the wavelet according to a particular application (e.g. the frequency range of interest, separation in frequency or in time.
of the analyzed signal’s components). The \( m \) parameter is modifying the Morlet wavelet. The expression \( m = 1/2 \) corresponds to the commonly used Morlet wavelet. When \( m > 1/2 \), we analyze wavelets that are narrower in frequency: the frequency resolution is improved but the time resolution is reduced.

Another very important application of these formulas is to estimate the region (in a time-frequency sense) where the end effect in the wavelet analysis can affect the results. This topic was addressed in Kijewski and Kareem (2002). If we consider the definition of CWT and the properties of wavelets, it is clear that the wavelet centered at some frequency represents a window that extends both into the past and future before the exact time being analyzed. The width of this time window depends on the choice of the mother wavelet and also the scale (frequency) being analyzed. At both ends of the signal, the analyzing wavelet extends beyond the data length. Wavelet coefficients in these regions are then computed not only on the basis of the signal values. The quantitative accuracy of the value of these coefficients is therefore questionable. Kijewski and Kareem (2002) showed that integer multiple \( \beta \) of the time resolution of the analyzing wavelets (defined for a modified Morlet wavelet) can be imposed to quantify the usable region of time samples \( t_i \) within which the wavelet representation is without significant end effects. It is given by \( \beta \Delta t_a(f) \leq \Delta t_i \leq -\beta \Delta t_a(f) \). They numerically demonstrated that in most cases a choice of \( \beta = 3 \) is sufficient for estimating the region with significant end effects. Note that the size of the region increases with decreasing frequency: the portion of data influenced by the end effects is larger at low frequencies than at higher. If the length of data allows it, the simplest way to reduce the influence of the end effects on the results is to remove the affected regions of wavelet representation from the next processing.
3. Computation of H/V ratio with Continuous Wavelet Transform

3.1. Basic principle

In the time-frequency method of H/V computation, the H/V ratio is not computed from the whole spectra for vertical and horizontal components of the ambient noise signal as in the classical spectral ratio method. Instead, the TF representations of the vertical and both horizontal components are computed using CWT. Then the wavelet representations of both horizontal components are merged into the one (\(CWT_H\)) by:

\[
|CWT_H| = \sqrt{|CWT_{NS}|^2 + |CWT_{EW}|^2},
\]

where \(CWT_{NS}\) and \(CWT_{EW}\) are complex representations of the CWT for all horizontal components. In contrast to Love waves, Rayleigh waves will have an energy maximum on the vertical component. Therefore, to extract mostly Rayleigh waves, the absolute value of the CWT for the vertical component (\(CWT_v\)) is scanned for all maxima. For each maximum identified on the time axis, the value of \(|CWT_H|\) is picked with a delay of one quarter of period (Figure 3.1). That is the theoretical delay between vertical and horizontal components for a Rayleigh wave. It can be positive (prograde particle motion) or negative (retrograde particle motion). The ratio between horizontal and vertical values is saved for each maximum found on the vertical component. This process is repeated for all frequencies \(f_i\).

For each frequency, the saved ratios are analyzed statistically. A histogram is drawn for each frequency (Figure 3.2) with a log scale. From all synthetic cases processed during this project, we note that the distribution of ratios is log-normal. In an ideal case of separated modes of Rayleigh waves, the 2D histogram should exhibit a well defined ridge, with its crest corresponding to the ellipticity.

![Figure 3.1. Principle of time-frequency computation.](image1)

![Figure 3.2. Simplified scheme histogram.](image2)

Figure 3.3 shows an example of clearly identified Rayleigh wave ellipticity (for fundamental and higher modes) in synthetic data for a model of one layer over half space and distant sources all located in the same direction.
Figure 3.3. Model M2.2 (layer over half space, distant sources all located in approximately the same direction). The analyzed synthetic noise seismograms were produced during the SESAME project. The green curve is the ellipticity of the fundamental mode Rayleigh wave. The black curves are ellipticity curves of higher modes. Note the very good agreement between the results and theoretical ellipticity when using both horizontal components. Further improvement occurs by omitting the NS component where the contributions of waves other than Rayleigh are likely.

For complex models and/or configuration of noise sources and for real data, the analysis often becomes more complicated due to an increased contribution of waves other than Rayleigh waves within the same frequency band and time window. This complexity will be discussed in more detail in Chapter 3.4.

3.2. Selection of wavelets

To use energy maxima well distributed over the signal so that the influence of a single time window is reduced and cannot produce higher amplitudes than the other data, we introduced an additional parameter. For the histogram computation we add $nppm$: number of maxima used per minute. Specific time windows with higher amplitudes can be affected by temporary near sources with particular spectral properties. The parameter $nppm$ insures that the obtained statistics in the histogram better represent the average characteristics of all data. Using small values of $nppm$ makes the selection more stringent: only the most energetic time-frequency maxima per minute are used for the histogram computation.

3.3. End effects

The CWT is affected by the ends of the signal. To exclude such end effects on the CWT and the related estimation of ellipticity, the CWT is not computed within the region influenced by end effects as it is described in the Section 2.2.2. The part of the data that has to be removed is reduced by computation of CWT for the whole available data length. In this way, the analysis at low frequencies is also improved.

3.4. Extracting the ellipticity curve from the 2D histogram

Two options were considered for extracting the ellipticity curve from the histogram: first, ellipticity is estimated from the average (geometrical mean) of the histogram values (the...
probability density function, PDF) for a certain frequency; second, it is assessed by manual picks.

Parts of the histogram are influenced by the Rayleigh wave contribution only. The highest values of the PDF at a certain frequency (represented by colors of the histogram) correspond to ellipticity at this frequency. Reliable picking of these values is easy. However, other parts of the histogram may be influenced by contributions from other waves on the horizontal component with frequency content and arrival times similar to those of Rayleigh waves on the vertical component. These other waves can only be partly separated out by the wavelet method. In such cases, contributions from Love and SH waves will generate higher H/V amplitudes than the Rayleigh ellipticity we want to identify, and contributions from SV waves will lead to lower H/V values. Both contributions are reduced for small values of \( nppm \). Generally, with decreasing \( nppm \), the crest formed by maximum values of the PDFs at neighbouring frequencies is shifted to lower H/V amplitudes. Gradual removal of biased values should theoretically converge to the stable lower values – not affected by a changing \( nppm \) parameter and only influenced by Rayleigh waves. In some cases, these stable lower values can be identified; however, simple objective criteria for reliable detection are still missing.
4. Software Implementation

The H/V technique was widely studied during a previous European project (SESAME, 2001-2004), which indirectly gave birth to the new software “Geopsy” (http://www.geopsy.org), distributed under a GPL license. Since its first open release in 2005, it has been adopted by a continuously growing, global community. Over a few years, it has become a standard tool for ambient vibration analysis. Its purpose is not only H/V processing but extends also to all aspects of ambient vibration processing. Built upon a modular structure, its capabilities can be extended without limits, offering at the same time an object-oriented, easy to use, free and open source environment for developing new signal processing tools. The new module for Geopsy developed in this project is called “hvtfa”: computation of H/V curves with a time-frequency analysis using wavelet transform. Details about mathematics were presented in the previous chapter. Here we present the implementation.

Time-frequency analysis is based on a modified Morlet wavelet. On input, 3-component signals (for one or several stations) must be provided in a Geopsy viewer (table, graphic or map; see Geopsy online manual). If the signals of one station are split into various time segments, they are automatically merged together since they share the same station name and coordinates.

4.1. Internal processing steps

1. For all three components, the average value is subtracted (DC removal) and the Fourier spectra are calculated.
2. The modified Morlet wavelet in the frequency domain centered around the frequency \( f_c \) is given by
   \[
   \frac{1}{\sqrt{\pi}} \exp \left( - \left( \frac{f}{f_c} \omega_0 - \omega_0 \right)^2 m \right)
   \]
   Where, \( f \) is the frequency, \( \omega_0 \) is the first Morlet parameter (> 5.5), and \( m \) is the second Morlet parameter. This function is convoluted with the three components and then transformed back into the time domain, providing a complex signal there; \( \omega_0 \) is set to 6 and only \( m \) is kept as a varying parameter.
3. The complex signals for horizontal components are grouped together with a vectorial combination:
   \[
   \sqrt{\text{North}^2 + \text{East}^2}
   \]
4. The absolute values of the complex vertical and the complex, combined horizontal components are calculated.
5. For all maxima (including the local) on the vertical component, the time and amplitude are kept. Amplitudes on the horizontal component are measured at times shifted by +/-90° relative to the vertical peaks. For all vertically heterogeneous ground structure, the horizontal Rayleigh component is always in advance or delayed by 90° relative to the vertical component. As defined by equation 3.42 in Wathelet (2005), the ellipticity ratio is an imaginary number for all frequencies.
6. All amplitudes and the ratio of the horizontal over vertical amplitudes are output to a .max file (see below for detailed format).
7. The points 2 to 6 are repeated for all frequencies \( f_c \) chosen by the user.

The .max file can be analyzed by max2curve software. The median (or mean) and the median (or mean) deviation can be extracted after selection of the most energetic peaks. If all events are selected, the computed curve approaches a classical H/V curve. To select the most energetic events and provide a quasi-uniform distribution of events along the time axis, the best option is to limit the number of selected high energy events to a given standard per
time unit (called here \textit{nppm}, for Number of Peaks Per Minute). The Geopsy module and max2curve can be used through a graphical user interface or via a command line interface. They are both described below.

\textbf{4.2. Geopsy module \textit{hvtfa}: graphical tool}

To start the "\textit{hvtfa}" module, first launch the Geopsy mainframe. Three-component signals must be provided with consistent station names and coordinates. Gather all signals to process in a viewer (table, graphic or map) and click on the \textit{hvtfa} icon in the toolbar or select the corresponding item in the 'Tools' menu option. If the signals are cut into small sections (e.g. files of one hour length), there is no need to merge them. All sections are automatically merged by the \textit{hvtfa} module.

Figure 4.1 shows an exemplar station with three components and the \textit{hvtfa} toolbox. Below is a parameter description:

- **Time limits**: select start and end time of signal to process
- **Wavelet**: define the wavelet parameter \( m \) (see above). \( f_i \) is not a processing parameter. It helps in estimating the time and frequency resolution displayed just below.
- **Frequency range**: define the frequency range to compute. The default and recommended setting is a log scale. The range and the number of samples are case-dependent. The minimum frequency must be less than the resonance frequency observed with the classical H/V curve.
- **Output**: define a directory to save .max files. One .max and .log file each is saved per station. Names are automatically set to the station name. The .max file contains the H/V ratio for all events detected on the vertical component and for a phase shift of +90° as well as -90° of the horizontals relative to the vertical. The .log file contains the parameter values used during the processing.

With the 'Load parameters' button, you can load an existing .log file to restore parameters. Use 'Start' and eventually 'Stop' buttons to begin/end computation. The produced .max files have the format shown in Figure 4.2. Comment lines begin with '#'. There must be at least one comment line at the beginning of the file that describes the columns. This line is used by max2curve to identify the processing type. In fact max2curve can deal with .max files produced by \textit{hvtfa}, \textit{fk}, and \textit{spac} tool (see option -h for more information). For \textit{hvtfa} format the description line must start with:

\begin{verbatim}
# seconds from start | cfreq | H/V | AmpZ | AmpH | Delay
\end{verbatim}

cfreq is the central frequency of the Morlet wavelet. Delay is expressed in a period fraction of either -0.25 or 0.25 (corresponds respectively to -90° and +90° phase shift). Various .max files can be merged together by a cat command. However, you must note the time in the case of maximum selection with \textit{nppm} (Number of Peaks Per Minute). If you want to merge .max files generated for different stations and if the structure can be assumed as 1D, use the following command (replace DT by the correct time length of the recordings):

\begin{verbatim}
cat S*.max | awk 'BEGIN{t=0}{if ($1=="#") {if($2=="File" && NR>50) t+=DT; print $0} else print $1+t "$2 "$3 "$4 "$5 "$6 "$7;}' > all.max
\end{verbatim}
Figure 4.1. Geopsy graphical interface. Selected signals are displayed together with the parameter needed for the hvtfa module.

Figure 4.2. Structure of output files and format of .max files.
4.3. max2curve: graphical user interface

Max2curve basically computes one histogram per frequency. It lets you filter statistics with some automatic processes or by manually discarding data points. Average and standard deviations are then easily extracted.
Max2curve can be started without arguments or directly from the menus (double click on a desktop icon or 'Start menu' for Windows). In this case, you will be prompted to give the .max file to open. Next, you must define the histogram sampling and eventually the filter parameters can be adjusted. Figure 4.3 shows the dialog box displayed on startup.

![TFA Options](image)

Figure 4.3. Dialog displayer at max2curve startup with event filtering parameter and histogram sampling.

Then you enter max2curve environment which contains two windows: the main histogram window shows a colored grid with one histogram per frequency and the 'Grid Statistics' window shows the individual histograms one frequency at a time.
For hvtfa post-processing, the “best” filter is *nppm* (Number of Peaks Per Minute). Manual filtering is generally not used. By default, the mean and mean deviations are computed from the histogram. Use 'Curve' button from 'Grid Statistics' window to generate median and median deviation. The left side of the main histogram plot is a common curve handler where curves can be cut, resampled, averaged and saved.
The 'Save' button saves the filtered samples. In other words, it generates another .max file with an additional column that takes values 0 or 1, to select or exclude a sample. To save an average curve, scroll to the desired curve with the 'Curve data' scroll bar. To identify curves on the plot, you can setup a legend or play with the 'Visible' button.
4.4. Geopsy module hvtfa: command line interface

The same task can be achieved directly from a command line which is rather handy for sensitivity analysis or huge datasets. Here is an example of the command line usage:

geopsy -db testing.gpy -tool hvtfa -group “M2.1” -param param.log -progress

All parameters are read from file param.log.

### Parameters ###
FROM TIME TYPE = 1
TO TIME TYPE = 1
MINIMUM FREQUENCY = 0.1
MAXIMUM FREQUENCY = 15
INVERSED FREQUENCY = n
SAMPLES NUMBER FREQUENCY = 200
SAMPLING TYPE FREQUENCY (0=log, 1=linear)= 0
MORLET M = 1
OUTPUT DIRECTORY = /home/mwathele/projets/ellipticity/
### End Parameters ###
All stations that belong to group 'M2.1' inside database 'testing.gpy' are processed. See option '-h' for more details about these options and how to access signal files (not necessarily through a database).

4.5. Max2curve: command line interface

Max2curve can be launched from command line to obtain the mean or median curve after filtering without opening the graphical user interface. Here is an example:

```
max2curve S001.max -tfaNppm 1 -min 0.1 -max 10 -n 200 -median
```

It produces three text columns: frequency, median and median deviation.

4.6. Dinver: graphical user interface

Dinver is a general environment for inversion with Monte-Carlo based methods. Currently Neighborhood Algorithm (Sambridge 1999) modified after Wathelet (2008) is implemented. A plugin for the inversion of surface wave dispersion curve has been extended during the NERIES project to invert ellipticity and dispersion curves jointly. Figure 4.5 shows an example of Dinver interface running the surface wave plugin. From a practical point of view, inverting an ellipticity curve resembles the inversion of a single dispersion curve. The only difference is the definition of the 'target' which includes a supplementary curve. For more information, you can browse Dinver documentation online.

![Figure 4.5. Dinver graphical user interface. On the left the list of runs is shown with their tuning parameters; just below statistics about the run progress are found (e.g. minimum misfit). At the bottom is the definition of the parameter space (Vp and Vs profiles). In the center, the target definition is shown (ellipticity curve to invert) together with the results in terms of Vs and Vp profiles (Ground profiles) and their corresponding ellipticity (window on the right).](image)
5. Validation of the ellipticity curve extraction

A large series of tests were performed with synthetic and observed datasets of ambient noise. The aim was to compare automatic and manual procedures for interpreting the Continuous Wavelet Transform (CWT) results. We tested a number of processing parameters and established these parameters for robust results. Recommendations can be found in the summary of Chapter 5.2.

5.1. Tests with synthetic data

The implemented method is based on time-frequency analysis with Continuous Wavelet Transform (CWT) described above. The first tests were performed with 13 synthetic datasets of ambient noise provided by the SESAME project (http://sesame-fp5.obs.ujf-grenoble.fr/ Deliverable D12.09 “Report in parameter studies” available at the internet site) and the ESG2006 microtremor blindtest experiment (Comou et al., 2007). The models are M2.1, M2.2, M2.3, M2.4, M10.1, M10.2, M10.3, M11.1, M11.2, N101, N102, N103, N104 and are described in Appendix A. Some are simple one- or two-layer over bedrock models; others are complex and multi-layered. The synthetics were computed with Hisada’s technique based on wavenumber (1994, 1995). Noise sources were approximated by surface forces and randomly distributed in space and time with random direction and amplitude. The time function was either a frequency-band limited, delta-like signal (impulsive sources) or a pseudo-monochromatic signal (a harmonic carrier with a Gaussian envelope) (RANSOURCE program by Moczo and Kristek (2002)).

The aim here is to compare automatic and manual procedures. First, we tested a number of processing parameters with the goal of constraining parameter values for reliable and robust results. For each dataset, tests with at least 54 combinations of parameter values were performed (see Table 5.1).

The parameters used for wavelet H/V computation were (Table 5.1):
- The Morlet wavelet parameter, \( m \), with the following values: 0.5, 1, 2, 4, 8, 16.
- The length of the signal, \( d \) (s.): 600 (10 min), 1800 (30 min), 3600 (1 hour) and 7200 (2 hours)
- The number of peaks selected per minute, \( nppm \): 1, 5, 10, 20.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m ): Morelet wavelet parameter</td>
<td>0.5</td>
</tr>
<tr>
<td>Length of the signal (s)</td>
<td>600</td>
</tr>
<tr>
<td>( nppm )</td>
<td>1</td>
</tr>
</tbody>
</table>

*Table 5.1. Parameters used for the automatic computation. For a detailed description of the parameters, see Chapters 2 and 3.*

5.1.1. Automatic processing

For each synthetic model, average curves for different parameter selections were computed (6 \( \times \) 4 \( \times \) 4 = 96 combinations). In Figure 5.1, the influence of the Morlet parameter \( m \) is shown, keeping \( nppm \) fixed equal to 1 and the length of analyzed signals to 2 hours. The red curves correspond to the highest values and the blue curve to the lowest. These results are systematically compared to the theoretical fundamental Rayleigh ellipticity (thin black curve). Considering the right flank of the ellipticity main peak, experimental curves are quite close to the correct ellipticity for all cases, especially for all models with an ellipticity having a classical peak and trough shape. High values for Morlet parameter \( m \) (4-16) generally give better results than lower ones do (0.5-2). However, for most cases the difference is rather small. For N103, the deepest site, a strong bias is observed. In fact, \( nppm \) must be adapted to the
period of the considered waves. In this case, better results are obtained with a \textit{nppm} of 0.1 (Figure 5.3).

In Figure 5.2, the durational influence of the processed signal is measured with constant $m=8$ and constant \textit{nppm}. For all cases, all durations (d) give almost the same results. For longer time series, the obtained curves are smoother than for shorter ones. In each case, a long time window is preferred.

In Figure 5.3, the influence of the number of Rayleigh events selected per minute (\textit{nppm}) is checked with constant $m=8$ and $d=7200s$. With a low number of events per minute, the algorithm selects only the strongest events detected on the vertical component: those likely to contain most of their energy as Rayleigh waves. With high \textit{nppm}, the estimated curve naturally tends to the classical H/V spectral ratio. The contribution of other wave types (e.g. Love or SH waves) therefore affects the H/V curve. For \textit{nppm}=5, the fit is acceptable for many cases. For \textit{nppm}=1, the fit is acceptable for all cases except for site N103, the case with the lowest resonance frequency. In this latter case, a \textit{nppm}=0.1 gives the best results. Lower \textit{nppm} values require longer signals to avoid scattered curves. For N103, 23000 s. (6 hours 39 min.) were not sufficient.

Automatic processing provides good results only for the right flank of the fundamental mode’s first maximum of the ellipticity curve. For these datasets, longer signals generally produce better results (a duration of 30-40 minutes is sufficient if the analyzed frequency band is above 1Hz). The best parameter selection for $m$ is in the range of 4-16 with preference to $m=8$, for \textit{nppm} in the range of 1-5 or lower, with preference to lower values, even as low as 1 when the recording time is sufficiently large to obtain good statistics. The case of \textit{nppm}=1 is also included in Figure 5.3. With \textit{nppm}=1, $m=8$ and length=7200s, we get a nice fit for all cases except N103, which has the deepest layer of sediments. For N103 and \textit{nppm} >=5 we obtain all the same curves. Only for \textit{nppm}=1 the curve tends to go down towards true ellipticity. If we apply \textit{nppm}=0.5 to model N103, with 6 hours of signal, the results are better but not perfect. For \textit{nppm}=0.1 (1 peak every 10 minutes), with 6 hours of signal, the fit is good. This result for \textit{nppm} is not surprising because the use of small \textit{nppm} favors the selection of only the very strong Rayleigh wavelets: those are less disturbed by other wave types. Will this be valid for real cases too?

A summary of how the tests perform with different synthetic data sets is shown in Table 5.2. A further improvement of the method would include making \textit{nppm} variable, depending on the frequency band that is considered in the analysis.
Figure 5.1. Influence of Morlet wavelet parameter “m” on determining Rayleigh ellipticity for synthetic datasets.
Figure 5.2. Influence of signal length “d” on determining Rayleigh ellipticity for synthetic datasets.
Figure 5.3. Influence of the selection of Rayleigh events on determining Rayleigh ellipticity for a synthetic dataset with constant $m=8$ and $d=7200s$. For N103 the cases with $nppm$ equal to 0.5 and 0.1 are shown, for a duration $d$ of 6h.
5.1.2. Manual Picking without common strategy

In a second step, the different participants of the project applied manual picking in the histograms for \( m=0.5-16, \ d=800-7200 \) and \( \text{nppm}=5-20 \). The overview of the individual participant reports are given in Appendix B. Good results for all cases can be obtained only...
for the right flank of the H/V spectral ratios. For some models also the left flank of the ellipticity curve can be retrieved. Compared to the best automatically determined ellipticity values, manually picked values take larger values and often lie above the theoretical ellipticity curve. The best parameter selection for \( m \) is again in the range 4-16 with preference to \( m = 8 \), lower values for \( nppm \), and a long duration of the signals (A duration of 30-40 minutes is in general sufficient; however, it should be selected in view of the frequency band that is analyzed.).

From the models tested, M10.1 and M2.3 were the most difficult. Model M10.1 has a fundamental frequency of resonance \( f_0 \) below 1Hz, and its ellipticity values as a function of frequency are changing very fast. M2.3 is a model without large velocity contrast. Such cases are also difficult when searching the peak in the H/V spectral ratio for the determination of \( f_0 \). Many participants preferred manual analysis at this stage. However, since manual picking was performed with the knowledge of the theoretical ellipticity curve, a blind test was set up to verify if manual processing improves the results compared to a fully automatic assessment. This issue is discussed in the next chapter.

5.1.3. Manual Picking with a common strategy

According to the theoretical considerations described in Chapter 3.4, we developed a common strategy for manual picks. This method is based on the choice of high probability density values that are stable throughout processing with different \( nppm \). As described above, these stable values are either along the ‘crest’ of the probability density functions or below it.

Participants of JR4 B2 were trained in this method using the same synthetic data as those used for automatic analysis. At the final meeting in Zurich in June 2008, a blind test was organized, where synthetic data from 10 of the 13 models were distributed with different names among 5 participants. All 10 data sets were processed with fixed \( m \)-value (the preferred value \( m = 8 \)) and signal length (40.5 min). Only the \( nppm \)-parameter was varied between 5 and 20.

The results of the manual picks are presented in Figure 5.4. It compares theoretical ellipticities and curves picked from histograms. For each data set, the ellipticity was estimated independently by two participants. The results show that for the following data sets at least one very good estimate of the ellipticity was made over a large frequency range from below the fundamental frequency to beyond the trough: M10.2, M11.1, M2.4, N101, N104. For two additional sets, M10.3 and M11.2, at least the right flank of the ellipticity was correctly estimated. The position of the peak and trough were clearly identified for all data. However, the estimates of the entire ellipticity curve were not satisfactory for N102, N103 and M2.3 data.

Disregarding the influence of the experience of the investigator, the varying performance for the different models can partly be attributed to their type. This aspect is discussed below in the summary of all manual and automatic tests with synthetic data.

5.2. Summary of tests with synthetic data

Table 5.2 summarizes the results obtained for all 13 synthetic data sets. For the 10 datasets that were analyzed during the blind test, only the ‘manual’ results obtained were taken into consideration. For the three other sets, ‘manual’ results were obtained by individual tests described in Chapter 5.1.2.

The table presents a qualitative evaluation of how the estimated ellipticity of the fundamental Rayleigh mode performs over a selected frequency range. This includes the left and right flank of the fundamental peak and trough and part of the curve at higher frequency (referred to as the tail in Table 5.2). The analysis shows that on average both automatic and manual picking perform well in identifying theoretical ellipticity.
### Table 5.2. Qualitative summary of the results by automatic (mean over PDF) and manual (picking) processing.

The results can be summarized as follows:

1) The best outcome is obtained for the right flank of the ellipticity and for data produced from relatively simple models with shallow surface layers and strong velocity contrasts: M2.1, M2.4, M11.1, N104.

2) For N101 the analysis also performs well; however, due to the weak gradient of Vs over depth in N101, the ellipticity curve is quite flat and manual picking may miss the general trend of the curve.

3) For M2.2, M2.3, M10.2, M10.3, M11.2 and N102, mixed results were obtained, which are generally satisfactory in the relevant frequency range between peak and trough.

<table>
<thead>
<tr>
<th>Models</th>
<th>Left flank mean</th>
<th>Left flank manual</th>
<th>Peak mean</th>
<th>Peak manual</th>
<th>Right flank mean</th>
<th>Right flank manual</th>
<th>Trough mean</th>
<th>Trough manual</th>
<th>Tail mean</th>
<th>Tail manual</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>M2.1</td>
<td>Good</td>
<td>Very good</td>
<td>Very good</td>
<td>Very good</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Very good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Very good results both for mean and picking of the entire curve.</td>
</tr>
<tr>
<td>M2.2</td>
<td>Poor</td>
<td>Poor</td>
<td>Good</td>
<td>Very good</td>
<td>Very good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good results for the right flank of the ellipticity peak.</td>
</tr>
<tr>
<td>M2.3</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Poor</td>
<td>Poor</td>
<td>Good</td>
<td>Poor</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>No clear recommendations. The ellipticity curve has no clear peak and m-value of 8 may be too high for manual picking.</td>
</tr>
<tr>
<td>M2.4</td>
<td>Good</td>
<td>Good</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Very good</td>
<td>Good</td>
<td>Excellent</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>M10.1</td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>No good match for any selection. Very low frequency peak with steep right flank.</td>
</tr>
<tr>
<td>M10.2</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Very good</td>
<td>Very good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Best results for the right flank of the H/V peak, and a weak overestimation in the left flank.</td>
</tr>
<tr>
<td>M10.3</td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
<td>Good</td>
<td>Very poor</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Best results for the right flank of the H/V peak.</td>
</tr>
<tr>
<td>M11.1</td>
<td>Good</td>
<td>Very good</td>
<td>Good</td>
<td>Very good</td>
<td>Excellent</td>
<td>Very good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Poor</td>
<td>Best results for the right flank of the H/V peak. Too high values for the ellipticity.</td>
</tr>
<tr>
<td>M11.2</td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
<td>Good</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Very good</td>
<td>Very good</td>
<td>Good</td>
<td>Poor</td>
<td>Best results for the right flank of the H/V peak.</td>
</tr>
<tr>
<td>N101</td>
<td>Very good</td>
<td>Very good</td>
<td>Very good</td>
<td>Very good</td>
<td>Very good</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>For the best fitting parameter selection, the automatic curve cannot be improved by manual picking.</td>
</tr>
<tr>
<td>N102</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Very good</td>
<td>Poor</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Mixed results obtained by different persons – some with excellent, some with good fit.</td>
</tr>
<tr>
<td>N103</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Poor</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Poor</td>
<td>For the best fitting parameter selection, the automatic curve cannot be improved by manual picking.</td>
</tr>
<tr>
<td>N104</td>
<td>Excellent</td>
<td>Very good</td>
<td>Good</td>
<td>Excellent</td>
<td>Good</td>
<td>Excellent</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>For the best fitting parameter selection, the automatic curve cannot be improved by manual picking.</td>
</tr>
</tbody>
</table>

On average: Good Good Good Good Very good Very good Good Good Good Good
4) Both automatic and manual processing did not perform well for data from model M10.1 with deep layers, even though a strong velocity contrast exists between bedrock and upper layers. Reasons might be that the ellipticity curve is very steep or that the energy content of the waves is low at smaller frequencies.

5) Model N103 is a special case that requires a low value of npm, due to its very thick sediments.

Comparing automatic and manual processing shows that manual picking may help in better identifying the peak and trough of the ellipticity. In particular, the form of the trough can be improved by manual picking. Therefore, since the present results show only a slight improvement by manual picking, automatic processing is recommended for general application.

5.3. Tests with real data

5.3.1 Description of selected field test sites

To test the applicability and investigate the advantages of the wavelet-transform method, we applied it to data from 5 field sites. These sites were selected among the 19 European test sites, where ambient vibration array measurements and active seismic studies were carried out within NERIES JRA4, task C, in autumn 2007 and spring 2008, respectively. A summary of the available previous information (before NERIES measurement campaigns) for all 19 test sites, e.g. excerpts from geological maps, SPT and CPT logs, down-hole and cross-hole measurements and results of previous ambient vibration recordings, is given by Picozzi et al. (2007). Table 5.3 below shows the main characteristics of the 5 field sites that may influence the measured Rayleigh wave ellipticity.

<table>
<thead>
<tr>
<th>site</th>
<th>latitude</th>
<th>longitude</th>
<th>environment</th>
<th>surface geological</th>
<th>EC8 class</th>
<th>depth to bedrock</th>
<th>v_s bedrock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Athens</td>
<td>37.9722°</td>
<td>23.7051°</td>
<td>urban</td>
<td>stiff</td>
<td>B</td>
<td>15 m</td>
<td>590 m/s</td>
</tr>
<tr>
<td>Bolu</td>
<td>40.7462°</td>
<td>31.6073°</td>
<td>urban</td>
<td>stiff</td>
<td>C</td>
<td>n/a (&gt; 30m)</td>
<td>n/a</td>
</tr>
<tr>
<td>Colfiorito</td>
<td>43.0382°</td>
<td>12.9219°</td>
<td>rural</td>
<td>soft</td>
<td>D</td>
<td>55 m</td>
<td>1500 m/s</td>
</tr>
<tr>
<td>Edessa</td>
<td>40.8043°</td>
<td>22.0500°</td>
<td>urban</td>
<td>stiff</td>
<td>E</td>
<td>18 m</td>
<td>1100 m/s</td>
</tr>
<tr>
<td>Nestos</td>
<td>41.0709°</td>
<td>24.7636°</td>
<td>rural</td>
<td>soft</td>
<td>C/D</td>
<td>52 m</td>
<td>1000 m/s</td>
</tr>
</tbody>
</table>

Table 5.3. Information for the 5 selected sites including surface geology and EC8 class. Bedrock depth and velocity are taken from the site monographs compiled in Task A. (Note that bedrock refers to the geological bedrock here, i.e. see bedrock velocity for site Athens). The bedrock depth and velocity is unknown at Bolu, since bedrock was not reached by the 30.45 m deep borehole at this location. The coordinates listed here are those measured for the central station during the measurements of Task C. Two different coordinate pairs are given for the site Colfiorito, since measurements were performed in two different locations there (see below).

A report on the field measurements during task C (geometries and locations of ambient vibration arrays and active measurements, timing and duration of the individual measurements, equipment used, in-field processing etc.) is given by Endrun & Renalier (2008). For the 5 sites mentioned above, the recordings of the central station of the ambient vibration arrays (generally shaped in a circle of varying diameter with a central station) were used to test the performance of the wavelet-transform approach and compare its results to classical H/V processing. The central station consists of a three-component Lennartz 5 s
sensor connected to an EarthData digitizer. Recordings were done with a sampling rate of 100 Hz and a sensitivity of 2.5 \(\mu\text{V}/\text{bit}\).

At two of the locations in Greece, Edessa and Nestos, previous ambient vibration H/V measurements were performed within the framework of the European program SESAME (SESAME group 2004a). At the selected Italian site, Colfiorito, ambient vibration array measurements were performed within SESAME (SESAME group 2004b, Di Giulio et al. 2006). No previous ambient vibration measurements are reported for Athens and Bolu. Below we briefly describe the geology and measurement conditions at each site and report preliminary results of the array processing of NERIES data, as far as they are available.

**Athens**
The site in Athens is located on a yard of the Research Center for Public Works (K.E.D.E.) in the Kallithea area or center of the metropolitan region of greater Athens. A busy road and a railroad track are close-by noise sources. However, measurements were conducted on a Sunday during the election weekend in Greece, so a substantially reduced amount of traffic was expected. An accelerometric station has been installed on the premises since August 1981, after Athens was affected by an earthquake series in the eastern Gulf of Corinth, and recorded a maximum PGA of 0.3 g during the 1999 Athens earthquake \(M_S = 5.9\).

The geological basement for the eastern part of Attiki, where the K.E.D.E. site is located, consists of the Athens schist series up to considerable depth (Koukis & Sabatakis 2000) mostly covered by younger (Tertiary to Recent) deposits. This series represents a flysch phase of delta-type deposits of Upper Cretaceous age and consists of various lithological types, from low-grade metamorphic schists via metasedimentary sandstones to bodies of mostly decomposed meta-igneous rocks (Koukis & Sabatakis 2000). Intense tectonism during the Lower Tertiary and various degrees of weathering and alteration have additionally contributed to the development of a highly heterogeneous material. A geotechnical classification groups different types of the schist into 7 classes, ranging from stiff soil-like material to strong rock-like material. The complicated composition of the geological basement at this site can explain the low S-velocity value given in Table 5.3.

At the K.E.D.E. site, the sedimentary cover consists of fine-grained Quaternary deposits, with a maximum thickness of 30 m (Koukis & Sabatakis 2000). Isolines of the recent deposits follow the NNE-SSW direction of the Kifissos and Illisos Rivers, in between which the site is situated.

From the ambient vibration array measurements, dispersion curves for Rayleigh (via frequency-wavenumber analysis) and Love waves (via horizontal components of the spatial autocorrelation functions) were derived as well as the vertical component spatial autocorrelation function. The dispersion curves show a good general correspondence to the theoretical curves for the reference downhole data, but agreement with the reference cross-hole data is not as good. Considering all curves as a fundamental mode, a joint inversion results in models that show a gradual increase in S-velocities, with velocities above 1200 m/s reached between 40 and 70 m depth and a possible additional jump to higher velocities below 350 m depth. The Rayleigh wave ellipticities for these models show a small (amplitude of 2 or less) peak below 1 Hz, which does not agree with the H/V processing results of the measured data. Further array analysis (determination of propagation direction, polarization analysis and three-component MSPAC processing) indicates that there is a significant amount of Love energy present in the frequency band of the observed H/V peak (contribution of Rayleigh waves less than 20% in the frequency range of the H/V peak according to three-component MSPAC). That makes this site an interesting case for testing the wavelet-transform-based method.

**Bolu**
The site in Bolu is located at the Public Works and Settlements Branch Office within the city. Measurements were carried out in front of (on a parking lot) and around the buildings, avoiding a busy street. The accelerometric station was installed in Bolu in 1997 and recorded a maximum PGA of 0.82 g during the Düzcè earthquake of November 1999 \(M_W = 7.1\), while
a maximum PGA of 0.74 g was recorded during the previous Kocaeli earthquake of August 1999 (Mw = 7.4). Damaged and uninhabitable buildings can still be seen around the site. Bolu is situated at a distance of less than 10 km off the main branch of the North Anatolian Fault and at about twice that distance from the eastern termination of the Düzcê fault: a major northern strand of the North Anatolian Fault (Faccioli et al. 2002). The town is located in one of a number of fault-bounded basins extending eastward from the Marmara Sea on Holocene unconsolidated alluvium (Aydin & Kalafat 2002). The site location is near the lowest point in a NS cross-section of the valley and likely sits on the softest, deepest, small-grain sediments of Bolu valley (Akkar & Gülkan 2002), overlaying Pliocene deposits and a probably rather complex basement of metamorphic and crystalline rocks. The soil at the surface is silty clay, and sandy or silty clay or clayey sand was also found to the maximum depth of 30.45 m of a recent geotechnical borehole (Picozzi et al. 2007).

From the ambient vibration array measurements, dispersion curves for Rayleigh (via frequency-wavenumber analysis) and Love waves (via horizontal components of the spatial autocorrelation functions) were derived as well as the vertical component spatial autocorrelation function. The dispersion curves show good agreement with the MASW results and the reference data (which, for this site, were not derived from borehole measurements, but from MASW processing by TUBITAK). Accordingly, for the inversion, the combined Love wave information from ambient vibrations and NERIES MASW measurements was used to extend the frequency range of the Love wave dispersion curve. For Rayleigh waves, the MASW data offer no additional information at high frequencies and were not considered. A joint inversion, interpreting all data as a fundamental mode, results in models with a gradual increase in S-velocity but no large velocity jumps. Velocities above 1000 m/s are only reached beneath 160 m depth. The Rayleigh wave ellipticities for these models show a small (amplitude of 2 or less) peak below 2 Hz that agrees with the high frequency limit of the H/V amplitude increase of the measured data.

Colfiorito

At Colfiorito, measurements were carried out at two locations within the premises of a farm. Interruption by an angry land-owner made relocation of the measurements necessary after the first two arrays. A local noise source during the measurements in the otherwise very quiet countryside might have come from motocross races taking place at the northern boundary of the valley. An accelerometric station was installed in the Colfiorito Valley in 1991 and recorded a maximum PGA of 0.47 g during the Umbria-Marce sequence of September 1997 (Ml = 5.6 & 5.8). The Colfiorito plain is an approximately 3 km wide intramountain basin in the southern part of the Apennine arc. The structural depression of Colfiorito is filled with Quaternary alluvial deposits composed of lateral debris fans interfingering with lacustrine sandy-clayey deposits that constitute the main body of the fill. The basement below these soft sediments consists of limestone and marl rocks of the Umbria-Marche Meso-Cenozoic sequence (Di Giulio et al. 2006). The sediment-basement interface has been mapped by Di Giulio et al. (2003) and shows a quite irregular topography. Several deep and narrow sub-basins within the plain feature sedimentary thicknesses of up to 180 m, with the largest depths found in the NW corner of the area. In the center of the basin, the sediment-basement contact is relatively flat at a depth of about 60-70 m. The complex lateral variations in the thickness of the deposits have been attributed to recent karstic or tectonic activity, as outlined by sink-holes and dolines as well as normal faults on the NE wall of the basin (Di Giulio et al. 2003). Both sets of measurements were located more or less in this central part of the valley, with the second location being closer to the borehole from which the previous downhole velocity information (Picozzi et al. 2007) was gathered. From the ambient vibration array measurements, dispersion curves for Rayleigh (via frequency-wavenumber analysis) and Love waves (via horizontal components of the spatial autocorrelation functions) were derived as well as the vertical component spatial autocorrelation function. The dispersion curves for the second location show good agreement with both the MASW results for this location and the borehole reference data. The variations between the results for the two locations agree with previous ambient vibration
array measurements in the area (Di Giulio et al. 2006). Data for this site have not been inverted yet.

Edessa
The accelerometric station in Edessa is located in the basement of the prefecture building of the town. Array measurements were performed in front of the building and on the parking lot, and for the larger arrays also in near-by streets. Accordingly, many pedestrians and a lot of traffic were passing around and through the arrays. The accelerometric station was installed in 1982 and recorded a maximum PGA of 0.1 g during the Griva/Goumenissa earthquake of December 1990 ($M_W = 6.1$).

The geology near Edessa, which is located on a hill with a steep cliff to its east, is quite complex. Ophiolitic formations, flysch, limestones and schists are found around the area (Pitilakis et al. 1992). The most striking geological characteristic is a layer of travertine with a maximum thickness of 100 m underlying the city. The soil on top of this layer is classified into three categories by Pitilakis et al. (1992). The relevant one for the array location in between the two rivers that cross Edessa is loose silty sands, sandy silts and locally gravelly silts interbeded by thick and extended turf strata of very low shear strength. The top of the travertine is located at about 17 m depth beneath the accelerometric station (Pitilakis et al. 1992). The borehole from which a cross-hole velocity profile was available is located on the opposite site of the building from the array measurements, at a distance of at least 100 m to the central station.

Dispersion curves from ambient vibrations as well as from active seismics turned out to be quite complex for this site, showing a tendency of increasing velocities with increasing frequency. That pattern can be interpreted as superposition of different modes. The vertical spatial autocorrelation functions look very complex, another indication for the presence of higher modes. They could not be used in the inversion. Modeling of MASW results as well as inversion of the ambient vibration dispersion curves leads to models with a low velocity layer between a high-velocity, very thin surface layer and the bedrock below approximately 15 m depth, a depth that agrees very well with prior information. The Rayleigh wave ellipticities for these models show a pronounced peak near 2.5 Hz, well within the range of some observed H/V peaks.

Nestos
The site Nestos does not house an accelerometric station, but is located within the construction area of a highway bridge across the Nestos River north of its delta. Local noise sources were heavy trucks passing by the array site due to continuing construction activities. Several boreholes had been drilled in a pre-investigation for the highway bridge, with crosshole velocity information available for 5 locations in the area. As expected near a sizeable river, the site geology consists of fluvial deposits of clean sand and silty sand in a loose to medium-dense state overlaying weathered gneiss (SESAME group 2004a). Borehole stratigraphy also infers some lens-shaped inclusions (Picozzi et al. 2007). Between the different cross-hole measurements, the depth to the bedrock varies between 35 and 52 m, increasing in the direction of the river. The array measurements were carried out closest to crosshole 3, at about 100 m distance to the central station of the array.

From the ambient vibration array measurements, dispersion curves for Rayleigh (via frequency-wavenumber analysis) and Love waves (via horizontal components of the spatial autocorrelation functions) were derived as well as the vertical component spatial autocorrelation function. The dispersion curves show perfect agreement with the MASW results, but do not agree as well with the data from the reference cross-hole. That difference might indicate the lateral variability of subsurface conditions in the area. A joint inversion of the ambient vibration array data results in models with nearly constant velocities around 250 m/s, with a jump to velocities above 700 m/s around 40 m depth and an additional increase to velocities above 1000 m/s between 60 and 100 m depth. The Rayleigh wave ellipticities for these models show a strong peak at about 1.35 Hz in very good agreement with the H/V ratio of the measured data. Further array analysis (frequency dependent propagation and polarization directions and three-component MSPAC) indicate that at this site, Love and
Rayleigh waves both contribute to the H/V peak (fraction of Rayleigh waves about 60%), while in several other frequency bands, e.g. between 2 and 2.5 Hz, the fraction of Rayleigh waves is very small (20% or less).

Figure 5.5 summarizes the inversion results using only the measured dispersion curves of Love and Rayleigh waves and the vertical spatial autocorrelation functions. In the figure observed H/V ratios are compared with the ellipticity curves of the inverted models. For Nestos and Edessa the right flanks of the ellipticity curve compare well with the observed H/V ratios above the fundamental frequency of resonance. For the sites Athens and Bolu, the theoretical ellipticity curves do not agree with observed H/V ratios. A combined inversion of ellipticity and dispersion curves might improve the comparison. Further work is needed to show the usefulness of ellipticity information for the 5 sites.
Figure 5.5. Left: Ensembles of best S-wave velocity models found from joint inversion of ambient vibration data sets (as described above) for four of the five test sites, using the Neighbourhood Algorithm (Wathelet 2005, Wathelet 2008). Also shown are the reference models from cross-hole (black) and down-hole (grey) measurements. Right: Forward calculated Rayleigh wave ellipticities (black curves) for the models shown, together with the measured classical H/V ratios from all deployments of the eight array stations at each site, which gives an indication of lateral heterogeneity at the sites. Colors from dark to light green show increasing diameter of the arrays.
As outlined in Figure 5.6, H/V ratios for some sites vary in time, mostly due to the variable presence of near sources (pedestrians, traffic). This might affect also the analysis, and a careful pre-selection of “valid” time windows might further improve the results. Figures 5.7, 5.8, and 5.9 show the results obtained with H/V time-frequency analysis, applied to the recordings from the array’s central station. Two selections of the parameter \( \text{nppm} \) have been applied (\( \text{nppm} = 20 \) and 5). From the analysis of the synthetic signals, we would expect the curve for \( \text{nppm}=5 \) to be closer to the «real» ellipticity. Presently, however, we have no means to validate the derived ellipticity curves. The array methods that are under development and described in Chapter 7 will improve this situation in the near future. The combined inversion of the derived ellipticity and dispersion curves will then illustrate if we can improve the comparison between the observed H/V ratios and Rayleigh waves ellipticity that is shown in Figure 5.5.
Figure 5.7. H/V time-frequency analysis (nppm 20,5) compared with classical HV ratios (dotted) for Athens and Edessa.

Figure 5.8. H/V time-frequency analysis (nppm 20, 5) compared with classical HV ratios (dotted) for Nestos and Bolu.
6. Inversion using Ellipticity information

The ground structure parameters (mainly Vs(z), shear wave velocity as a function of depth) cannot be estimated by considering only the resonance frequency. Unfortunately, inverting the raw amplitude of the H/V curve has proven to be an unreliable alternative, mainly because the shape of the spectral curve is controlled by the ambient vibration wavefield, a complex mix of different types of waves. The proposed time-frequency analysis tries to extract time windows that contain a majority of Rayleigh waves. Rayleigh waves are dominating vertical components of ambient vibrations. Hence this component is scanned for Rayleigh wavelets. The H/V ratios are computed for dominant wavelets, assuming dominant Rayleigh wave arrivals. H/V ratios for a pure Rayleigh wave can be compared to the theoretical ellipticity curves. The retrieved curves are used to invert Vs(z) profiles.

<table>
<thead>
<tr>
<th>Model</th>
<th>Min. Freq.[Hz]</th>
<th>Max. Freq.[Hz]</th>
<th>Misfit</th>
</tr>
</thead>
<tbody>
<tr>
<td>M10.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>M10.2</td>
<td>2.45</td>
<td>4.10</td>
<td>0.244</td>
</tr>
<tr>
<td>M10.3</td>
<td>2.34</td>
<td>3.50</td>
<td>0.214</td>
</tr>
<tr>
<td>M11.1</td>
<td>3.24</td>
<td>4.50</td>
<td>0.115</td>
</tr>
<tr>
<td>M11.2</td>
<td>2.27</td>
<td>3.35</td>
<td>0.359</td>
</tr>
<tr>
<td>M2.1</td>
<td>2.17</td>
<td>3.80</td>
<td>0.304</td>
</tr>
<tr>
<td>M2.2</td>
<td>2.13</td>
<td>3.90</td>
<td>0.194</td>
</tr>
<tr>
<td>M2.3</td>
<td>2.38</td>
<td>3.30</td>
<td>0.104</td>
</tr>
<tr>
<td>M2.4</td>
<td>5.50</td>
<td>10.30</td>
<td>0.393</td>
</tr>
<tr>
<td>N101</td>
<td>1.00</td>
<td>10.00</td>
<td>0.150</td>
</tr>
<tr>
<td>N102</td>
<td>1.40</td>
<td>3.05</td>
<td>0.330</td>
</tr>
<tr>
<td>N103</td>
<td>0.20</td>
<td>0.38</td>
<td>0.395</td>
</tr>
<tr>
<td>N104</td>
<td>0.92</td>
<td>1.37</td>
<td>0.297</td>
</tr>
</tbody>
</table>

Table 6.1. Frequency limits for inverted ellipticity curves. The last column is the misfit computed with respect to the true theoretical ellipticity curve. It gives an idea of the error level for determining ellipticity curves. The misfits are computed along the amplitude axis, which is probably not suitable for the ellipticity curve. Using the frequency axis is expected in a future release of the software.
Synthetic datasets were intensively analyzed to check the reliability of the computed curve as a measure of Rayleigh ellipticity. Tested parameters are $d$ (the total length of the time window), $m$ (Morlet wavelet number), and $nppm$ (number of peaks per minute). For most cases, the best choice is an $nppm$ as low as possible and $m$ around 8. The ellipticity curve can be correctly retrieved for all cases except M10.1 (See Chapter 4). The curves are used for the inversion when amplitudes are between 5 and 0.4 (see also previous chapters). If a maximum and minimum are observed inside the previous limits, the range is reduced to include only the steep part of the curve. The frequency range that we consider useful for each case is shown in Table 6.1.

In the following figures, all inversion results are displayed in the same way. Vs and Vp profiles are always shown on the left. The corresponding dispersion curves and ellipticities are given on the right. The thin curves are the true curves (Vp and Vs profiles, dispersion and ellipticity curves); they are not used during the inversion. The thick curves are the “experimental” ones used during the inversion: ellipticity computed from synthetic signals and/or the theoretical dispersion curve for frequencies above 10 Hz. Table 6.1 shows that the experimental ellipticity fits the true ellipticity curve with a misfit between 0.20 and 0.40. Hence the ellipticity curve is expected to have a maximum error of about 40%. For the inversion results, only models fitting the ellipticity curve within 40% and/or the dispersion curve within 10% are kept.

In Figure 6.1, the ellipticity of model M10.2 is inverted alone with a three-layer model. Inverting only ellipticity amplitude is not a well resolved problem. As with inverting resonance frequency, there is a major trade-off between depths and velocities (Fäh et al. 2003, Scherbaum et al. 2003). But knowing the velocity profile over the shallow part of the ground structure might partially solve the problem (see Figure 6.1, top-left). Alternatively, with classical techniques like MASW, the dispersion curve can be obtained at high frequencies (generally above 10 Hz), a finding which gives information about only the upper part of the ground structure (about 10 to 25 m). Hence, the same case is inverted with the same parameterization but the dispersion curve above 10 Hz has been added as an additional constraint (Figure 6.2). To check that the ellipticity curve provides some complementary information, Figure 6.3 shows the inversion of the dispersion curve only.
Figure 6.1. Inversion of ellipticity only (case M10.2). See text for legend.

Figure 6.2. Inversion of ellipticity and dispersion curve (case M10.2). See text for legend.
For all other cases, only the joint inversion is shown. Parameterization is left unchanged except for models N101 to N104 where a deeper structure is expected. Results are shown in Figures 6.4 to 6.14. For all cases except M2.4, N102 and N104, a reasonable fit of the ellipticity is obtained. In those cases the inverted Vs profiles (grayed area) always include the true solution. The other cases are revised in Figures 6.15 to 6.17.

For M2.4 (Figure 6.15), the frequency range for the "experimental" ellipticity was too big. The higher frequency part of the ellipticity is incorrect in Figure 6.10. It is cut now at 8Hz in Figure 6.15, which keeps the same 3-layer parameterization. For N102 (Figure 6.16), a spectacular improvement of the solution is found by inserting a gradient in the intermediate layer. For N104 (Figure 6.17), a correct Vs profile is obtained if the depths of the layers are constrained (first layer between 1 and 50m, second layer between 200 and 500m).
Figure 6.4. Inversion of ellipticity and dispersion curve (case M10.3). See text for legend.

Figure 6.5. Inversion of ellipticity and dispersion curve (case M11.1). See text for legend.
Figure 6.6. Inversion of ellipticity and dispersion curve (case M11.2). See text for legend.

Figure 6.7. Inversion of ellipticity and dispersion curve (case M2.1). See text for legend.
Figure 6.8. Inversion of ellipticity and dispersion curve (case M2.2). See text for legend.

Figure 6.9. Inversion of ellipticity and dispersion curve (case M2.3). See text for legend.
Figure 6.10. Inversion of ellipticity and dispersion curve (case M2.4). See text for legend.

Figure 6.11: Inversion of ellipticity and dispersion curve (case N101). See text for legend.
Figure 6.12. Inversion of ellipticity and dispersion curve (case N102). See text for legend.

Figure 6.13. Inversion of ellipticity and dispersion curve (case N103). See text for legend.
Figure 6.14: Inversion of ellipticity and dispersion curve (case N104). See text for legend.

Figure 6.15. Inversion of ellipticity and dispersion curve (case M2.4). See text for legend.
Figure 6.16. Inversion of ellipticity and dispersion curve (case N102). See text for legend.

Figure 6.17. Inversion of ellipticity and dispersion curve (case N104). See text for legend.
7. Deriving ellipticity information from array recordings

For array recordings of ambient vibrations, there are two ways to retrieve ellipticity information. Such techniques were further developed within the NERIES project. The first strategy to derive ellipticity curves considers a reduction factor that accounts for the correct Rayleigh/Love ratio. That ratio on horizontal components can be derived from three-component SPAC analysis (Köhler et al., 2007) as a function of frequency. A combination with the H/V curve computed by the classical method (simple spectral ratios) should produce a good estimated ellipticity of Rayleigh waves. The reliability of such a method is still to be proved.

The second strategy proposed by Poggi and Fäh (2008) is using high-resolution frequency-wavenumber array analysis. The technique is applied to the three components of motion and is based on the assumption that amplitude maxima in the f-k cross-spectrum must represent the true power amplitude of the corresponding signal. In the case of Rayleigh waves, therefore, the ratio between maxima obtained from the horizontal (radial-polarized) and vertical components of motion will also represent the frequency-dependent ellipticity function. Consequently, if the Rayleigh dispersion curves of the different modes can be identified on the f-k plane, then the corresponding modal ellipticity patterns can also be separated and extracted. This second method also offers the possibility of estimating the Rayleigh/Love ratio. This is presently implemented and will be part of future work.

These array techniques have been developed over the past few years and work is still in progress. Applying all the methods to the same real cases is part of future research, which will help validate the single-station wavelet-based method.

8. Conclusions and Recommendations

The dual goal of the NERIES project JRA4-Task B2 is to implement a new method that retrieves Rayleigh wave ellipticity from H/V spectral ratios, and to use ellipticity information for structural inversion. The method for retrieving ellipticity is based on time-frequency analysis with continuous wavelet transform. It has been integrated into the software package of the JRA4 working group (http://www.geopsy.org). From analyzing synthetic ambient vibration data for a large number of models, we show that parts of the fundamental mode ellipticity curve are reliably retrieved from H/V spectral ratios using the new technique. After considering all models, we obtained reliable results only for the right flank of the H/V curve, between the first peak at the fundamental frequency of resonance and the first trough at higher frequency. Automatic processing is very successful and is recommended. Longer signals produce better results. A recording duration of 30-40 minutes is generally sufficient if the analyzed frequency band is above 1Hz. For the frequency band below 1 Hz, we recommend using longer time windows up to several hours of ambient vibration recordings.

The best parameter selection for the Morlet wavelet parameter $m$ is in the range of 4-16 with preference given to $m=8$. For the number of selected wavelets per minute, $n_{ppm}$, we recommend using the range 5 or lower, with preference to lower values as low as 1 when the recording time is sufficiently large to obtain good statistics. It is also advisable to process the data with different values of $n_{ppm}$ to identify the stable parts of the fundamental mode ellipticity curve. Our result for synthetic signals is not surprising because the use of small $n_{ppm}$ favors the selection of only very strong Rayleigh wavelets: those less disturbed by other wave types. Future investigation will show if this is also valid for real cases. The results from our analysis show only a slight improvement by manual picking. Automatic processing is therefore recommended. Manual picking may help in better identifying the peak and trough of the ellipticity curve. However, manual picking requires an experienced analyst. For real cases, we presently have no means of validating the derived ellipticity curves. The array methods that are under development within project NERIES JRA4 will soon improve this situation. One method of obtaining ellipticity curves is to apply a reduction factor to the classical H/V curve, using the correct Rayleigh/Love ratio. This ratio is derived from 3C.
SPAC analysis. The second array method derives H/V curves using high-resolution frequency-wavenumber array analysis of the three components of motion. Applying all methods to the same real cases is part of future research and will help validate the single-station wavelet-based method.

The software includes an inversion procedure using both phase velocity curves and successfully implemented ellipticity information. Results from synthetic data show that combining ellipticity information with the high-frequency branch of the dispersion curve leads to good results in velocity profile inversion.
8. References


Daubechies, I., 1992. Ten lectures on wavelets. SIAM.


Appendix A: Description of the models

The models and synthetics used here are the products of two previous studies:
2) The ESG2006 microtremor blindtest experiment (Cornou et al., 2007).
Details regarding the models and the synthetics can be taken from the above references.
M10.3

Depth (km)

Vp (km/s)

Vs (km/s)

Poisson's ratio

M11.1

Depth (km)

Vp (km/s)

Vs (km/s)

Poisson's ratio

M11.2

Depth (km)

Vp (km/s)

Vs (km/s)

Poisson's ratio
Appendix B: Test results from automatic and manual picking

(Appendix B.1: Test of the FTAN ellipticity method with automatic procedures (G. Stamm, V. Poggi, D. Fäh, ETHZ)
Appendix B.2: Comments on synthetic tests of new wavelet tool to calculate Rayleigh wave ellipticity in GEOPSY (B. Endrun, UP)
Appendix B.3: Comments on synthetic tests of new wavelet tool to calculate Rayleigh wave ellipticity in GEOPSY (H.-B. Havenith, ETHZ and ULg)
Appendix B.4: Parametric tests on synthetic noise - M2.1, M2.3 and N102 models (M. Kristekova, FMPI-CU)
Appendix B.5: Statistical evaluation of parameter's combination influence in the FTAN manual analysis of the synthetic datasets M10.1, M10.2 and M10.3 (V. Poggi, ETHZ)
Appendix B.6: Manual testing models M10.3, M11.1 and M11.2 (G. Stamm, ETHZ)