Characteristics of ambient noise cross-correlations in northern Italy within the 0.1-0.6 Hz frequency range

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Abstract

In this note, we investigate the characteristics of ambient noise cross-correlations for station pairs in northern Italy, considering the secondary microseism bandwidth (0.1-0.6 Hz). The preliminary analysis that we performed exploiting the available continuous recording in the investigated area, agrees with the recent results of Pedersen et al. (2007): the directionality of the noise signal cannot be disregarded when the group velocity is estimated in the range 0.1-0.6 Hz and the selection of the path orientation for tomography must be carefully performed. In particular, while the favourable directions with respect to microseisms generated along the Atlantic coasts of France, Norway and British Islands cover a quite wide azimuthal range (from about 270N to 5N), allowing us to reliably estimate the fundamental mode Rayleigh group velocity for paths in the Alps (about 2.7 km/s), more care must be taken when the microseisms are generated in the Mediterranean Sea. In that case, different locations of the generating areas of microseisms could provide biased estimates of the group velocity due to differences between the true and the apparent velocity of propagation between the stations.
Introduction

In the last few years, many studies have exploited the seismic noise field for surface wave tomography (e.g. Sabra et al., 2005b; Shapiro et al., 2005; Gerstoft et al., 2006; Yao et al., 2006; Cho et al., 2007; Lin et al., 2007; Yang et al., 2007). These studies assume that the seismic noise wave-field is diffusive and they are based on the possibility of evaluating the Green’s function between two stations by computing the time derivative of the cross-correlation between noise recordings made at each site (Shapiro and Campillo, 2004; Sabra et al, 2005a). Despite the popularity of tomographic inversion using phase and group velocities derived from noise analysis, some questions still need to be addressed before the method can be generalized. One of the main questions is what happens when the noise wave-field is not completely diffusive and the directionality of the noise source cannot be disregarded. Concerning this topic, Pedersen et al. (2007), hereinafter referred to as PeKr07, studied the influence of the seismic noise field characteristics on noise correlations in the Baltic shield (northern Europe). They computed noise correlations in four frequency bands (FB1: 0.02-0.04 Hz; FB2: 0.04-0.1 Hz; FB3: 0.1-0.25 Hz; FB4: 0.25-1 Hz) using 38 broad-band stations of the SVEKALAPKO passive seismic experiments (Bock and SSTWGW, 2001). The primary and secondary microseism peaks (e.g. Webb, 1998) which, in Europe, are mainly generated along the north British coasts and the western coast of Norway (sectors SEC1 and SEC2 in Figure 1) (Friedrich et al., 1998; Essen et al., 2003; PeKr07) lie within the FB2 and FB3 intervals respectively. By considering profiles oriented along different azimuths, PeKr07 showed that the ocean-generated noise recorded in southern Finland cannot be considered completely diffusive and is better described as a mix of diffusive and subplane wave energy. For example, in the FB3 interval, reliable and stable estimates of the group velocity were obtained for azimuths of 240-360 degrees, corresponding to sources along the western cost of Norway and the northern British coast (Figure 1). At the margins of this range, the slowness decreases according to a cosine relationship that describes the link between the true and apparent velocities of propagation. PeKr07 suggested that the distance from the generating areas and the
scattering properties of the medium could play a role in determining the diffusive characteristics of
the wave field but their conclusions could not be applied to all areas of the world.

In this work, we investigate the characteristics of ambient noise cross-correlations within the
secondary microseism bandwidth for station pairs in northern Italy. The dependence of the noise
cross-correlations on the source location is investigated by considering azimuths towards the North
Atlantic Ocean and towards the Mediterranean Sea. The strong dependence of the estimated group
velocity on the location of the source area is demonstrated for microseisms generated in the
Mediterranean Sea.

**Study Area and Data Processing**

The study area (Figure 2) lies in the Alpine orogen, a zone between the Africa-Europe convergent
plate margin. It is composed of three main geomorphological features, namely the Alps, the
Apennines and the Po Plain. The Po Plain is a syntectonic sedimentary basin forming the infill of
the Pliocene-Pleistocene Apenninic foredeep, bounded by the Apennines to the south and the Alps
to the north (Amorosi et al., 1996). The maximum depth of Quaternary deposits ranges from 1000
to 1500 m (Pieri and Groppi, 1981) and covers the foreland of the two mountain chains.

The cross-correlations are computed for station pairs belong in the Italian Seismic network (RSNC,
seismo.ethz.ch/networks/SDSNet/SDSNet.html). The locations of the stations are shown in Figure
2. Each station is equipped with broad-band sensors (with response flat from 40 second for RSNC
and 120 second for SDSN) connected to a 24-bit analog-to-digital converter. Data from RSNC and
SDSN are sampled at rates of 100 and 120 Hz, respectively.

Vertical-component recordings, corrected for the instrumental response, are re-sampled at 10 Hz
and filtered using a fourth-order Butterworth filter with corner frequencies 0.1 and 0.6 Hz. We
selected this bandwidth because the corresponding wavelengths of the fundamental mode Rayleigh
waves predominantly sample depths corresponding to the alluvial cover of the Po Plain.
Ambient noise within this bandwidth is dominated by the secondary microseisms (e.g. Longuet-Higgins, 1950; Bromirski and Duennebier, 2002; McNamara and Buland, 2004). Friedrich et al. (1998) identified five main source areas of secondary microseisms in Europe by analyzing broadband continuous recordings at the Gräfenberg array (southern Germany, about 500 km north of the Po Plain). The strongest sources are located near the western Norwegian and northern British coasts (sectors SEC1 and SEC2 in Figure 1), while a minor source region lies in the Mediterranean Sea (sector SEC5 shown in Figure 1). Figure 3 shows the power spectral densities, computed following McNamara and Buland (2004) and Marzorati and Bindi (2006), for station SALO during March 2006. Most of the spectral content is between 0.15 and 0.35 Hz, and the strongest microseisms occurred during the first two and the last week of the month.

The cross-correlations are computed considering windows with a length of 1 day. Before computing the cross-correlations, we clip the signal to reduce the influence of any earthquakes represented in the data. We clip the amplitude when it exceeds two times the standard deviation of the amplitude values for the station in question (Sabra et al 2005b; Gerstoft et al., 2006). Very similar results (here not shown) are obtained when the one-bit clipping procedure is applied. A detailed discussion about the data processing scheme for ambient noise tomography can be found in Bensen et al. (2007). Finally, the time derivative of the noise cross-correlation is computed. Following Sabra et al. (2005b), the quality of the cross-correlation function is estimated by computing the signal-to-noise ratio (SNR) defined as the ratio between the maximum of the cross-correlation envelope and the standard deviation of the cross-correlation computed for lags between -200 and -150 s (Figure 4). Cross-correlations having SNR <15 dB are not considered further in the analysis.

Results

We estimated the group velocity of the fundamental mode Rayleigh wave considering pairs of stations in central and western sectors of the Alps. Figure 2 shows in black the paths between the station pairs that provided cross-correlations with signal-to-noise ratio greater than 15 dB, while the paths corresponding to lower signal-to-noise values are shown in white. The azimuths of favourable
(i.e. high SNR) directions span the range from 270 to 5 degrees, which corresponds to paths towards the Atlantic coast of France, the northern British coast and the western coast of Norway (Figure 1). The cross-correlations obtained for different distances are shown in Figure 5. The maxima of the cross-correlation envelopes correspond to a group velocity of \( (2.7\pm0.2) \) km/s.

The results of this analysis agree with those of PeKr07: in the secondary microseism bandwidth, the noise directionality cannot be ignored since only the black paths in Figure 2 were favourably oriented. This result suggests that the wave-field is not completely diffusive. The range of azimuths encompassing favourable directions is quite broad and this could be due to both source characteristics (e.g. the size of the microseisms generating area) and scattering effects.

Secondary microseisms are also generated in the Mediterranean Sea (e.g. sector SEC5 in Figure 1). To study the directionality of noise generated in the Mediterranean Sea, we considered two station pairs, namely SALO-MUGIO (120 km) and SALO-BOB (126 km) (dashed lines in Figure 2): the angle between the two pairs is approximately equal to 65 degrees. The former pair is oriented towards the North Atlantic Ocean while the latter is oriented towards the western Mediterranean Sea. Furthermore, while the path between SALO-MUGIO is in the Alps, the SALO-BOB path crosses the Po Plain, where the group velocity of the fundamental mode Rayleigh wave in the analyzed frequency range is expected to be significantly lower than in the Alps, due to the presence of a deep alluvial basin. The cross-correlations for days of March 2006 computed for these two station pairs are shown in Figure 6. The results for the SALO-MUGIO pair (“Atlantic direction”) are in good agreement with the results previously obtained for the Alps: when strong microseisms are generated in the North Atlantic Ocean, the cross-correlations show a high signal-to-noise ratio. The lag of the cross-correlation peak is about 45 s, corresponding to a group velocity of 2.7 km/s.

Days with good signal to noise ratios are 9, 10, 11, 26, 18, 27, 28, 30, 31 March and the surface pressure maps provided by the MetOffice (see electronic online materials) confirm the presence of North Atlantic storms able to generate secondary microseisms within some of the source regions previously detected by Friedrich et al. (1998).
The cross-correlations for the SALO-BOB pair (“Mediterranean direction”) show a more complex behaviour. The time lag for 1, 2, 3, 5, 9, 10, 11, 19, 29 March is about 110 s while it reduces to 91 s for 6, 7, 12 March. The lag difference could be related to a decrease of the apparent velocity for a wave-field sufficiently close to a plane wave propagating along a direction not aligned with the station pair direction (PeKr07). The meteo-marine observations (see online materials) suggest that the microseisms corresponding to different lags were generated in different locations. For example, during 6 March 2006 a strong perturbation is located in the western Mediterranean Sea, being the sea wave directions oriented towards the northern coast of Africa (Figure 8, top panel), where the microseisms are probably generated (sector SEC5 in Figure 1). The lag for this day is 91 s. On the contrary, during 10 March 2006, the sea state (Figure 8, bottom panel) suggests that the microseisms are probably generated in front of the eastern coast of Liguria region and along the northern coast of Corsica Island. The power spectral densities in Figure 3 also suggest that the 6 March microseisms are generated farther away from BOB than those recorded on 10 March, since the former are characterized by a spectral content at lower frequencies (Stephen et al., 2003; Bromirski et al., 2005). The time lag for the 10 March cross-correlation is about 110 s. A different direction of the incoming energy for microseisms recorded on 6 and 10 March is confirmed by the azimuthal analysis shown in Figure 9. Figure 9 shows the direction of incoming energy at station BOB as determined by performing a rotation of the complex Fourier spectra of the horizontal components in order to maximize the horizontal energy, following the procedure outlined by Tanimoto et al. 2006. The results confirm that on 6 March the microseisms recorded at BOB arrived from a direction between 180N and 210N while on 10 March the direction of the incoming energy lies between 125N and 160N.

If we assume that the 6 March microseisms propagate approximately along the BOB-SALO direction, the time lag of 91 s corresponds to a group velocity of 1.4 km/s. If we assume, following the indications of Figures 8 and 9, that the microseisms generated on 10 March propagate along a
direction that deviates by about 30 degrees from the SALO-BOB direction (corresponding to the
direction of the path between SALO and the north-western coast of the Corsica Island) the time lag
of 110 s correspond to a group velocity of about 1.3 km/s, in good agreement with the previous
estimate. It is worth noting that the stack of the cross-correlations over one month (top panels of
Figure 6) is dominated by the peak at 110 s and then it could provide a biased estimate of the group
velocity. Preliminary analysis computed over the period January-August 2006 (Figure 7) confirms
this result.

Finally, the time lag of cross-correlations for SALO-MUGIO during 4 and 5 March 2006 is
approximately zero, suggesting a contemporaneous arrival of the signal at both stations. Figure 10
compares the 5 March 2006 cross-correlations for both SALO-MUGIO and SALO-BOB station
pair. The sea charts (electronic supplements) suggest that more than one microseism source is active
during those days. In particular, a strong perturbation is located in the Ligurian Sea but the sea state
is also favourable for generation of microseisms within sectors SEC4 and SEC5 in Figure 1 and
also along the portion of the African coast between them. Without a control of the location of the
generating areas, any discussion about the origin of the signals that generated the features of the
cross-correlations shown in Figure 10 is highly speculative and we do not proceed further on these
analyses.

Conclusions

Fundamental mode Rayleigh and Love wave tomography from cross-correlations of ambient noise
recordings is a promising and powerful tool for describing lithospheric properties without, for
example, the limitations in resolution imposed by earthquake and station locations. As pointed out
by PeKr07, the analyses have to be performed with care especially when the hypotheses on which
the theory is based are not completely fulfilled. One of the main problems is related to the
characteristics of the noise field which could be only approximately diffusive, depending on the
frequency range of interest, the scattering properties of the medium and the source-to-station
distance. We have analysed cross-correlations computed for pairs of stations in northern Italy in the secondary microseism frequency band (about 0.1-0.6 Hz). While the favourable directions for microseisms generated along the Atlantic coasts of France, north British Islands and Norway span quite a wide range (from 270°N to 5°N), in agreement with PeKr07, microseisms generated in different areas of the Mediterranean Sea can introduce significant apparent velocities for small differences between the direction of propagation and the direction between the stations (less than 30 degrees).

In conclusion, given the significant upper crust lateral contrast between the group velocity estimated for paths travelling in the Alps (2.7 km/s) and paths crossing the Po Plain (1.4 km/s), the investigated area is certainly interesting for a tomographic experiment at a regional scale. Better control knowledge of the generating areas of microseisms in the Mediterranean Sea obtained with small scale arrays is important to avoid the bias introduced by the apparent velocity of propagation. Moreover, since the microseism activity shows a significant annual trend (e.g. Figures 5 and 6 in Marzorati and Bindi, 2006), any future survey should last long enough to sample all the seasonal variability of the noise wave-field.

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References


Figure captions

**Figure 1.** PeKr07: the grey lines delinate the range of azimuths that provided stable estimates of the fundamental Rayleigh group velocity in the range 0.1-0.25 Hz in southern Finland (for details, see Figure 10 of Pedersen et al., 2007); GRF: the five sectors from SEC1 to SEC5 indicate the back-azimuths of main source areas for microseisms recorded at Gräfenberg array (for details, see Figure 6 in Friedrich et al., 1998); thick black lines: sector corresponding to azimuth for station pair in the Alps (see black and white paths in Figure 2); dashed lines: the 222N degrees direction corresponds to SALO-BOB station pair (Figure 2) while the direction 196N degrees corresponds to the direction perpendicular to SALO-MUGIO station pair (Figure 2).

**Figure 2.** Study area. The stations considered belong to the RSNC-Italian Seismic network (white triangles), and to the SDSN-Swiss Seismological Service network (black triangles). The black lines are relevant to favourable directions in the Alps while unreliable cross correlations were obtained along the white lines (see text for details). The dashed line connects the BOB and SALO stations, crossing the Po Plain. Stations SALO, BOB, and MUGIO are installed in Salò (Garda lake), Bobbio (Northern Apennines) and Muggio (Central Alps), respectively.

**Figure 3.** Power spectral densities (PSDs) computed for station SALO during March 2006 (vertical component). The PSDs are computed considering windows of 60 minutes at hour 00:00 UTC of each day.

**Figure 4.** Example of daily noise cross-correlation function (DNCF) computed for the SALO-BOB station pair. The black dot indicates the maximum of the cross-correlation envelope while the signal-to-noise ratio (SNR) is computed with respect to the standard deviation of the cross-correlation between -200 and -150 s (dashed line).

**Figure 5.** Distance versus time cross-correlations computed for stations in the Alps (black paths of Figure 2). The maxima of the cross-correlations describe the coherent propagation of a wave with a group velocity of (2.7 ± 0.2) km/s.

**Figure 6.** Daily cross-correlations computed during March 2006 for the station pairs SALO-BOB (left) and SALO-MUGIO (right). The stacks over the entire month are displayed at the top of each panel.

**Figure 7.** Monthly cross-correlations computed over the period January-August 2006 for the SALO-BOB (black) and SALO-MUGIO (white) pairs. The stacks over 8 months are displayed in the top panel.

**Figure 8.** Wave forecast (significant wave heights and directions) for the Mediterranean and Black seas provided by the University of Athens ([http://www.oc.phys.uoa.gr/](http://www.oc.phys.uoa.gr/)) from the WAVEWATCH-III model (Tolman, 1991). The top panel shows the prediction for 6 March 2006 at 12:00 UTC while the bottom panel show the model outcome for 10 March 2006 at 21:00 UTC. LS: Ligurian sea; CI: Corsica Island. A coloured version of the figure is available in the electronic supplements.

**Figure 9.** Direction of the incoming energy at station BOB, computed by rotating the complex Fourier spectra of the horizontal components in order to maximize the energy (Tanimoto et al. 2006). Left panel: analysis for March 06; the signal has been filtered over the band 0.15-0.20 Hz. Right panel: analysis for March 10; the signal has been filtered over the band 0.25-0.30 Hz.
Figure 10. Noise cross-correlations computed for stations pairs SALO-MUGIO (white) and SALO-BOB (black) on 5 March 2006.
FIGURES

Figure 1

Figure 2
Figure 3

Figure 4
Figure 7
Figure 8

06/03/06 12:00 UTC: Significant wave height (m) and direction

10/03/06 21:00 UTC: Significant wave height (m) and direction
Figure 9

Figure 10