Joint observation of coherent coda waves at surface and underground arrays

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SUMMARY
Local and regional seismicity jointly recorded by two dense small aperture arrays, one installed at surface and one at 1.3 km depth, constitutes an interesting data set useful for coda observations. Applying array techniques to earthquakes recorded at the two arrays we measure slowness, backazimuth and correlation coefficient of the coherent coda wave signals in five frequency bands in the range 1–10 Hz. Slowness distributions show marked differences between surface and underground, with slow signals at surface (slowness greater than 1.0 s km$^{-1}$) that are not observed underground. We interpret these coherent signals as surface waves produced by the interaction of body waves with the free surface characterized by rough topography. The backazimuth values measured in the frequency bands centred at 1.5 and 3 Hz are almost uniformly distributed between 0 and 360$^\circ$, while those measured at higher frequencies show different distributions between surface and underground. On the contrary, the earthquake envelopes show very similar coda shapes between surface and underground recordings, with an almost constant coda-amplitude ratio (between 4 and 8) in a wide frequency range.

Key words: Coda waves; Wave scattering and diffraction; Wave propagation.

1 INTRODUCTION
Since the pioneering work of Aki & Tsujura (1959) seismologists are aware that most of short period seismic energy is distributed inside the S-coda, that is believed to be generated by scattering processes in the crust and in the upper mantle. An important question arising from the bulk of the experimental and theoretical studies carried out in this field (for a comprehensive general review see Sato et al. 2012) is where effectively the scattering processes occur. Being the upper crust much more heterogeneous than lower crust and upper mantle, researchers assume that most of scattering processes occur in the shallowest layers. Experimental validation of this assumption can be obtained using frequency-wavenumber analysis applied to the coda radiation recorded at small-aperture seismic arrays. The results from arrays located at surface show that P-coda of local and regional earthquakes is composed by almost coherent waves with a persistent azimuth toward the source and constant slowness, while the S-coda is almost incoherent soon after the direct arrival (Kuwahara et al. 1997). Important progresses have been obtained using joint measurements at borehole and surface arrays, which allow for a correct measurement of the scatterer spatial distribution. These measurements show that the propagation in the shallowest layers distorts the wavefronts of secondary waves (Vernon et al. 1998), while the presence of strong velocity gradients between surface and borehole recorders modifies the energy partition between body and surface waves in the S-coda (Margerin et al. 2009; Nakahara & Margerin 2011). Since few measurements from borehole arrays are available, the question of where the scattering processes responsible for the generation of coda waves actually originate is not completely addressed yet.

In this paper, we show the observations from two small-aperture short period seismic arrays set up in the region of Mt. Gran Sasso, central Italy (Figs 1 and 2), near the epicentre of the $M_c$ 6.3 earthquake that struck the town of L’Aquila on 2009 April 6. The first array was installed inside the massif, in a system of tunnels excavated about 1.3 km below the surface, while the second array was operating on the surface, laterally displaced by about 1.5 km. We apply array techniques to 30 earthquakes recorded both at surface and inside the gallery, and observe the pattern of array parameters (backazimuth and slowness) calculated in short duration time windows sliding along the coda. Even though the coda decay rate is the same at surface and in the underground laboratory, the comparison between the slowness distributions at the two arrays shows that codas recorded at the surface are more rich of surface waves as the frequency increases.
Figure 1. (a) Topography of Mt. Gran Sasso with the positions of UND and FON arrays. (b) Vertical SW–NE section along the line shown in (a). (c) FON array configuration. (d) UND array configuration. Full symbols represent the stations used in this work.

Figure 2. Location of UNDERSEIS array and epicentres of the earthquakes analysed in this work. Symbol size is proportional to the event magnitude.

2 ARRAYS SET UP AND GEOMETRY, DATA AND METHOD

A small aperture short period seismic array, named UNDERSEIS (UND hereafter) was set up in the underground nuclear physics laboratory located beneath Gran Sasso massif, Central Italy, at an average depth of 1.3 km below the surface. This underground array recorded continuous data from 2003 to 2010. The UND array was composed of 20 short period Mark L4-C 3D 1 Hz seismometers, with 24 bit digital acquisition recording continuously at 100 sps (Saccorotti et al. 2006). A second array located at surface (hereafter FON) was operated for 6 months in 2007. The surface array consisted of six stations equipped with 1 Hz 3-D sensors (Lennartz LE3D-lite) acquired continuously at 125 sps with 20 bit dynamic range (Lennartz Marslite data loggers). Fig. 1 shows position and configuration of the two arrays, the topography of Mt. Gran Sasso and a SW–NE vertical profile of the mountain. FON array was displaced by about 1.5 km SSW of UND array, at elevation of about 1 km higher. In 2007, while FON array was operative, some stations of UND array were not working and some others were affected by local sources of noise (engines, pumps, machines, etc., located inside the laboratory). On average, the selected earthquakes were recorded with good signal to noise ratio by 11 stations of UND array, as shown in Fig. 1.

2.1 Data

We selected 30 local and near regional earthquakes of magnitude in the range [1.7, 4.2] contemporaneously recorded at the two arrays with good signal-to-noise ratio. Location and magnitude of these earthquakes are taken from the Italian Seismic Catalog ISIDE (http://iside.rm.ingv.it/iside/standard). Hypocentres are all crustal and epicentres are shown in Fig. 2 (Table with detailed information in the on-line material). Seismogram examples are reported in the top panels of Figs 3 and 4.

2.2 Method

We used the ‘Zero Lag Cross-Correlation’ (ZLCC) technique to analyze the selected earthquakes. The technique was first described by Frankel et al. (1991) and subsequently by Del Pezzo et al. (1997). The signal recorded at the generic \( i \)th and \( j \)th array stations in a time window containing \( M \) samples, after bandpass filtering in a given
were filtered in the following frequency bands: 1–2 Hz, 2–4 Hz, 3–6 Hz, 4–8 Hz, 6–12 Hz, centred, respectively at 1.5, 3, 4.5, 6 and 9 Hz. In each frequency band the ZLCC technique was applied to time windows of 1.5, 0.8, 0.6, 0.5 and 0.4 s, respectively, with 25 per cent sliding.

3 RESULTS

3.1 Backazimuth and slowness along the coda

Backazimuth, slowness and $c_k$ coefficient were calculated for each time window, and their distribution along the coda was plotted for the time windows characterized by $c_k > 0.80$. We set the threshold value of $c_k$ at 0.80 to select results characterized by correlation values above the maximum value of $c_k$ in the noise (as one can observe in the seismograms before the P-wave arrival). Examples of such analysis are reported in Figs 3 and 4 for FON and UND arrays, respectively. In the first panel we plot three component filtered seismograms. The second plot shows the rms of the filtered seismograms averaged over the event window. The following three panels show the values of $<c_k>$, and finally the estimated backazimuth and slowness values when their associated $<c_k>$ exceed the threshold value of 0.80. Figs 3 and 4 show that direct body waves are characterized by very high correlation at both arrays. On the contrary, along the coda the number of windows with correlation above the threshold (hereafter ‘coherent windows’, CW) is much higher at UND than at FON. We examined the distributions of slowness and backazimuth values in the CW along the coda for each analyzed frequency band. Slowness distributions (Fig. 5) at FON array are characterized by a narrow peak at 0.2 s km$^{-1}$ at frequency of 1.5 Hz with very few values greater than 0.5 s km$^{-1}$. As the frequency increases, the peak at 0.2 s km$^{-1}$ decreases while more and more measures appear at higher values. At frequency of 4.5 Hz and greater, the values greater than 1 s km$^{-1}$ are more populated than smaller values. The apparent velocity smaller than 1 km s$^{-1}$, and even smaller than 0.5 km s$^{-1}$ in some cases, indicates that surface waves constitute an important part of the coherent coda waves at surface. This result is completely different from UND array, where the slowness distributions are extremely similar each other at any frequency bands, with the highest peak between 0.1 and 0.2 s km$^{-1}$ and absence of measures for values greater than 0.6 s km$^{-1}$. The corresponding apparent velocity between 5 and 10 km s$^{-1}$ demonstrates that the most of coherent signals in the earthquake coda recorded underground consists of body waves. The backazimuth distributions are roughly uniform only at low frequency (1.5 Hz at FON, 1.5 and 3 Hz at UND), while at higher frequency they show irregular patterns, different between the two arrays (Fig. 6). The backazimuth distributions reflect the fact that in the higher frequency bands the number of coherent signals along the coda is much smaller than at lower frequency. However, the different backazimuth distributions suggest that the coherent signals found in the earthquake coda are not the same at surface and underground. The smaller number of CW at FON array compared with UND array (Figs 3 and 4) is interpreted as a combination of surface effects. Shallowest rock layers below FON array are much more geologically heterogeneous than those surrounding UND array. The presence of loose material produced by erosion and rock falls at surface is well evident in the area of FON array. In addition, the signals recorded at surface are strongly affected by the irregular topography (Formisano et al. 2012). Therefore, local site effects and a scattering coefficient much higher in the layers below FON than below UND array produce a general decrease of coherence at surface. In other words,
the wavefield is strongly distorted in its interaction with the irregular surface, and this contributes to produce very local site effects which mark the different array stations. This interaction contributes to reduce the number of coherent signals observed at the surface array.

### 3.2 Coda envelopes

We compared coda amplitude decay pattern between FON and UND arrays. For each array station we filtered the seismograms in frequency bands centred at $f_c = 1.5, 3, 6, 12$ and $18$ Hz with bandwidths spanning from $0.5f_c$ to $2f_c$, typical of coda decay analysis. We calculated the rms of the three components separately, and finally the three component log average coda envelopes for each station. Then the ratio between the average rms computed at surface and underground was computed for any analyzed frequency bands. One example is shown in Fig. 7. We observe that the coda ratio between FON and UND arrays is about five for frequencies smaller than $3$ Hz, with an increase to about eight for higher frequency. This means that the amplitude of coda waves recorded at surface is amplified by a factor between 5 and 8 if compared with the underground recordings.

The slowness distributions show that surface waves enrich the coda energy for surface stations, while the high similarity between the coda shapes at surface and underground stations indicates that seismic total attenuation is poorly affected by the uppermost layers composing the structure of Mt. Gran Sasso.

### 4 Discussion and Conclusions

Three important evidence can be deduced from the results of our array measurements. First, in the frequency bands centred at $4.5$, $6$ and $9$ Hz the coherent wave packets inside the S-coda recorded at surface show a high percentage of slow waves, which are absent in the coda recorded underground. This result suggests that coherent surface waves are produced more efficiently as the frequency increases, at least in presence of highly irregular topography as the case of our experimental setup. Secondly, the backazimuth values measured in the frequency bands centred at $1.5$ and $3$ Hz are distributed almost uniformly between 0 and 360°, while those measured at higher frequencies show different directions between surface and underground. This result indicates that coherent phases observed at surface and underground are substantially different signals. The roughness of the topographical surface corresponding to short wavelength may contribute to this effect. Thirdly, the earthquake coda envelopes calculated at the surface stations are very similar to those calculated at the underground stations, although array analysis shows slow coherent signals in the coda at surface which are not observed in the data from the underground array. Our interpretation is that slow coherent signals are composed by...
Observation of coherent coda waves

Figure 7. Amplitude of the earthquake 20070816135 signal (rms) computed in four different frequency bands at the two arrays. The rms have been averaged among the three components of ground motion at stations FON2 (blue line) and U01 (red line). The ratio between surface and underground amplitude is also shown in each plot (black line).

surface waves generated by the interaction of the coherent body-wave packets (characterized by smaller slowness) with the free surface. The similarity between the coda decay rate, computed at surface and underground, indicates that coherent surface wave energy is insufficient to significantly change the overall coda decay pattern at surface with respect to that recorded underground, at least at Gran Sasso site. Although this observation should be more carefully investigated together with a comparison of direct S-wave attenuation estimates carried out both underground and at surface (see e.g. Hauksson & Teng 1987; Abercrombie 1998), this result seems to strengthen the common assumption that the coda-based estimates of seismic quality factor are reliable and robust measurements of seismic attenuation.

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REFERENCES


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