A Study on Seismic Noise Variations at Colfiorito, Central Italy: Implications for the Use of H/V Spectral Ratios

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[1] Seismic noise recorded by broad-band stations in the middle of and around the Colfiorito plain is analyzed in the frequency band 0.1 to 10 Hz. Small daily variations in noise amplitude are found, on the order of 2 for $f > 1$ Hz. In contrast, long-term amplitude variations due to weather conditions are significant throughout the analyzed frequency band; for $f < 1$ Hz, the amplitude increase can be as large as a factor of 50. In the low-frequency band, horizontal components vary much more than the vertical at both firm and soft sites. However, these noise variations at low frequencies do not contaminate significantly the 0.9-Hz peak of the H/V spectral ratio that fits the fundamental eigenfrequency of the sedimentary fill of the basin, resonating during earthquakes. Correlating the long-term variations of noise with different meteorological parameters, we find that wind speed best matches the low-frequency noise disturbances. *INDEX TERMS:* 7200 Seismology; 7203 Seismology: Body wave propagation; 7212 Seismology: Earthquake ground motions and engineering. **Citation:** Cara, F., G. Di Giulio, and A. Rovelli, A Study on Seismic Noise Variations at Colfiorito, Central Italy: Implications for the Use of H/V Spectral Ratios, *Geophys. Res. Lett.*, *30*(18), 1972, doi:10.1029/2003GL017807, 2003.

1. Introduction

[2] Upper layers of soft sediments resonate during earthquakes. This effect can increase locally the level and duration of ground shaking with important implications for seismic hazard. *Nakamura* [1989] showed that the spectral ratio of the horizontal components to the vertical component of ambient noise measurements reproduces the fundamental resonance frequency of the uppermost soft layers. The evident advantages of his method are its low cost and short duration of measurements. Despite disagreement over its theoretical background, the Nakamura's technique is finding more extensive application in site effect and microzoning studies. But opinions on reliability of ambient noise still differ within the seismological community and, in the literature, successful and unsuccessful experiences alternate [see *Bard*, 1999, for a review]. Recently, *Faeh et al.* [2001] have proposed a promising interpretative model to explain this alternation, but further investigations are needed on the practical validity of ambient noise (see the web site of the SESAME Project: http://sesame-fp5.obs.ujf-grenoble.fr/).

[3] The present paper contributes to the debate by bringing new data and experimental results. We analyze seismic noise recorded at a 2D small-aperture (~200 m) array installed in the middle of the Colfiorito plain, central Italy (see Figure 1). The array recorded many aftershocks of the Umbria-Marche seismic sequence [see *Di Giulio et al.*, 2003]. Seismograms indicate a strong resonance of ground motion around 1 Hz at the array site (see Figure 1).

[4] A continuous 10-day noise record allows to: (i) check the precision of ambient noise in predicting the resonance frequency of the Colfiorito plain, and (ii) check the stability and reproducibility of H/V spectral ratios versus daily (human activity cycles) and long-term (meteorological) variations. Moreover, a meteorological observatory in Perugia, about 35 km away from Colfiorito, provides the sequence of the three parameters we are using: amount of precipitation, wind speed, and atmospheric pressure. We then investigate the correlation between the three meteorological parameters and simultaneous long-term noise disturbances.

2. Array Site and Data

[5] The Colfiorito plain is an approximately 3 km wide intermontane basin in the southern part of the northern Apennine arc (see Figure 1). The basin is filled with Quaternary alluvial deposits composed of lateral debris fans interfingering with the lacustrine sandy-clayey deposits. These soft sediments overlay a rock basement of limestones and marls of the Umbria-Marche Meso-Cenozoic Sequence. *Di Giulio et al.* [2003] reconstructed the bedrock topography, estimating a soft-sediment thickness of 70 m, approximately, beneath the array. They also estimated an empirical transfer function using conventional spectral ratios. The optimal shear velocity Vs that, in a 1D approach, fits the empirical transfer function is 210 m/s (see the inlet in Figure 2c). The shear velocity contrast between the low- and high-velocity layers at the bedrock interface is a factor of 6. Other details on the geological structure and effects of earthquakes can be found in *Di Giulio et al.* [2003].

[6] Seismological stations were deployed in the study area from February 24 to March 19, 1998. For the last 10 days of the experiment, the continuous noise record is still available and has been analyzed here. The array was composed of three stations installed at the vertices of a triangle whose sides were 121, 126, and 141 m; a fourth station was installed in the center of the triangle. Another station was installed on a limestone outcrop on the eastern edge of the basin, about 1.5 km from the array (see Figure 1). Each station was instrumented with a triaxial Guralp CMG40T sensor connected to a Reftek 72A07 digital recorder. The sampling rate was 125 sps on each channel. Receivers were installed in free-field, buried in

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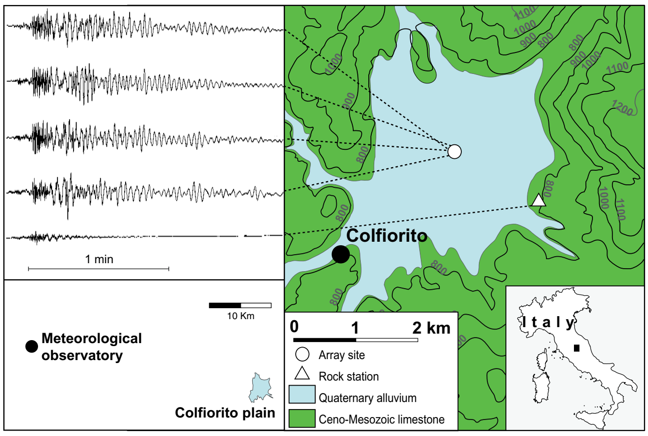

Figure 1. Map of the study area, indicating the position of the array (open circle) and a rock reference station (open triangle). The NS components of a M 3.6 earthquake are shown in the panel on the left hand side where seismograms indicate a long basin resonance around 1 Hz [redrawn from *Di Giulio et al.*, 2003].

~20-cm-deep holes in loose soil at the array site; the hole depth was around 5 cm at the rock site.

3. Analysis of Ambient Noise

[7] Among many studies on site response using ambient noise [e.g., *Aki*, 1957; *Field and Jacob*, 1995], Nakamura's technique is largely preferred nowadays since it requires only one triaxial station with no additional measurements at rock sites for comparison. Many authors [*Duval*, 1994; *Lermo and Chàvez-Garcìa*, 1993; among others] have stressed the significant stability of estimates deriving from this approach. A commonly accepted opinion is that the single components of ambient noise can show large spectral variations as a function of natural and cultural disturbances, but the H/V spectral ratio tends to remain invariant, preserving the peak at the site's fundamental resonance.

[8] The Colfiorito plain (Figure 1) is therefore an interesting test-site because we know so much about it. Many ambient noise properties can be checked as a function of local geology and weather conditions. Earthquake data characterize the basin seismic response, and seismic refraction profiles and geoelectrical measurements give detailed information on the interface between low- and high-velocity layers beneath the array [see *Di Giulio et al.*, 2003].

[9] During the array operation, ambient noise was characterized by large variations of amplitude and spectral content, independently of the daily cycle. Figures 2 and 3 are representative of the significant variations observed during the experiment. The three components of ambient noise recordings and the resulting H/V ratio are compared between time intervals characterized by daily and long-term variations. Fourier amplitude spectra shown in Figures 2 and 3 (panels a, b, c, and d) are the geometrical average over 30 consecutive 1-min-long time windows. In each time window, the signal is detrended and a 10% cosine taper is applied.

[10] In Figure 2, panels (a) and (b) show the typical range of daily variations as observed in the middle of the plain. The four array stations show consistent behavior; thus, only data from one of them will be shown hereonafter. The difference of spectral amplitude between day and night is small (a factor of 2 for $f > 2$ Hz, approximately). This difference is similar for horizontal and vertical components, and the H/V spectral ratio shows no significant change between day and night measurements (Figure 2c). The interval comprised between ±1 standard deviation around the mean (average over 30 H/V spectral ratios smoothed with a 0.03 Hz running frequency operator) maintains high stability throughout the analyzed frequency band. Time histories of Figures 2a and 2b show a nearly-harmonic character of the horizontal components around 1 Hz. The resonance frequency of conventional spectral ratios using

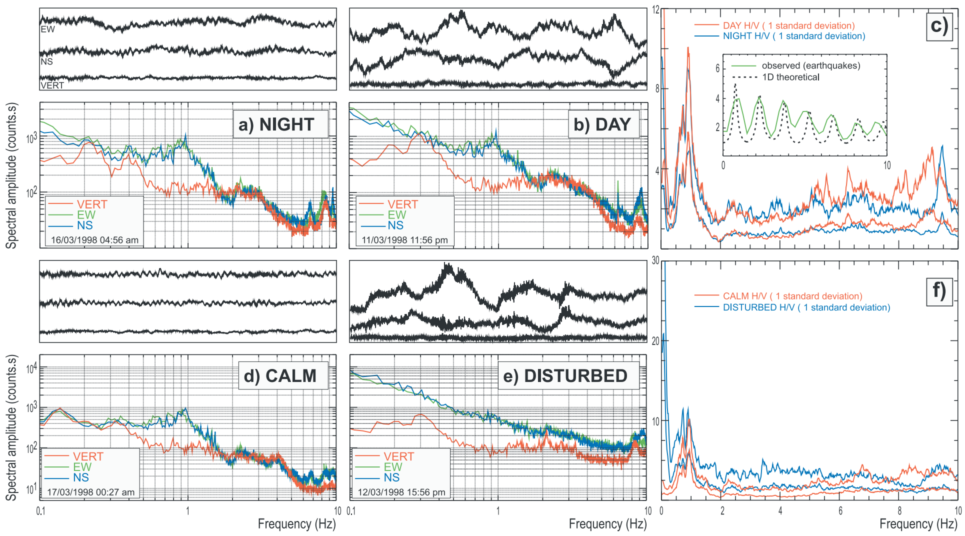

Figure 2. Daily (panels a and b) and long-term (panels d and e) spectral variations in the ambient noise measurements at the array site. The time histories of ambient noise are 1-min long. In (c), the H/V ratios of day and night records are compared; in the inlet, conventional spectral ratios estimated through earthquake data and the 1D theoretical transfer function [after *Di Giulio et al.*, 2003] are shown. In (f), long-term variations of the H/V spectral ratios are compared.

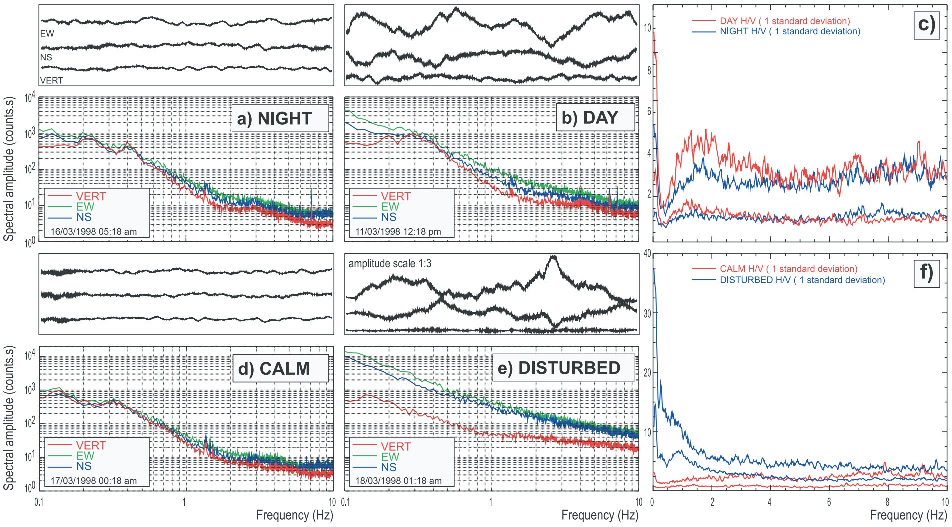

Figure 3. As Figure 2, using the ambient noise record of the rock station. Note that in (e) the amplitude scale is compressed by a factor of 3.

earthquake data peaks at 0.9 Hz (see the inlet in Figure 2c, where the results of *Di Giulio et al.*, 2003, are redrawn). We find exactly the same value here in the noise H/V spectral ratios. Although overtones are significantly amplified in the conventional spectral ratios using earthquake data, according to the theoretical 1D transfer function, they completely disappear from the ambient noise H/V spectral ratios. This result confirms a well-known tendency of microtremors [see *Lachet and Bard*, 1994; *Faeh et al.*, 2001].

[11] Panels (d) and (e) of Figure 2 compare the three components of ambient noise between recordings representative of the lowest and highest observed amplitudes. Figure 2e shows a huge increase of spectral amplitude throughout the analyzed frequency band. The difference between horizontal and vertical components is particularly large for $f < 1$ Hz; however, this difference does not affect significantly the shape of the spectral peak at 0.9 Hz in the H/V ratio (Figure 2f).

[12] Figure 3 shows the spectral variations of ambient noise at the rock station. Also for the rock site, a minor difference is observed between day and night measurements (see Figures 3a and 3b). In contrast, the difference between the lowest and the largest amplitude is significant in the long term (compare Figures 3d and 3e). Again, variations on the horizontal components are larger than on the vertical component, mostly at low frequencies. Such an effect is so strong that the ±1 s.d. intervals of the H/V spectral ratios of Figure 3f do not overlap, up to ~7 Hz.

4. Investigating the Role of Meteorological Parameters

[13] In the literature [*Longuet-Higgins*, 1950; *Hasselmann*, 1963; *Friedrich et al.*, 1998] there is an unanimous consensus on the meteorological origin of long-term ambient noise disturbances. *Withers et al.* [1996] show a significant correlation between wind speed and high-frequency seismic noise at borehole stations, up to 43-m depth.

[14] In the study area (see Figure 1), the closest meteorological observatory is operating in Perugia and belongs to Italian National Meteorological Service, Servizio Meteorologico. The observatory distance from Colfiorito is about 35 km. Even though this distance is not small enough to consider the values of meteorological parameters in Perugia to be valid for the array site, we can assume that the shape of the long-period trend of these parameters in the Colfiorito plain does not differ substantially from that recorded at the meteorological observatory of Perugia. Therefore, we have tentatively correlated the variations of ambient noise amplitude with three of the meteorological parameters measured in Perugia: wind speed, atmospheric pressure, and amount of precipitation. The measurement rate is 8 samples per day.

[15] In Figure 4, the trend of the three meteorological parameters is compared with the running amplitude of the H/V ratio in the frequency band 0.1–3 Hz. The coloured panels are composed of 48 H/V spectral ratios per day (results of the rock site and the array station are shown in a and b, respectively). Among the meteorological parameters, wind speed matches fairly well the variations of low-frequency H/V amplitude at both the firm and soft sites. It seems that the effect of wind on seismic noise becomes significant as soon as the wind velocity exceeds 10 knots, i.e., 5 m/s, approximately. This value agrees with a threshold of 3 m/s found by *Withers et al.* [1996], at Datil borehole site, west central New Mexico. However, we have to take into account distance and difference in elevation between the Perugia meteorological observatory (208 m a.s.l.) and the area of the array experiment: the plain of Colfiorito is more than 800 m a.s.l. and mountains exceed 1000 m all around the basin (see the topography isolines in Figure 1). Due to this difference in elevation and the irregular morphology of the study area, a small increase of the wind intensity at 208 m a.s.l. can correspond to a stronger effect on the top of mountains and in intermontane basins. Unfortunately, the values of the meteorological observatory cannot be easily extrapolated. Even in presence of this uncertainty, Figure 4 suggests a primary effect of wind on ambient noise. In the literature, there is a tendency to attribute the increase of low-frequency noise to a marine or oceanic origin [e.g., *Friedrich et al.*, 1998]. Of course, this hypothesis cannot be excluded in our study case, as a concomitant effect. Since peninsular Italy is surrounded by

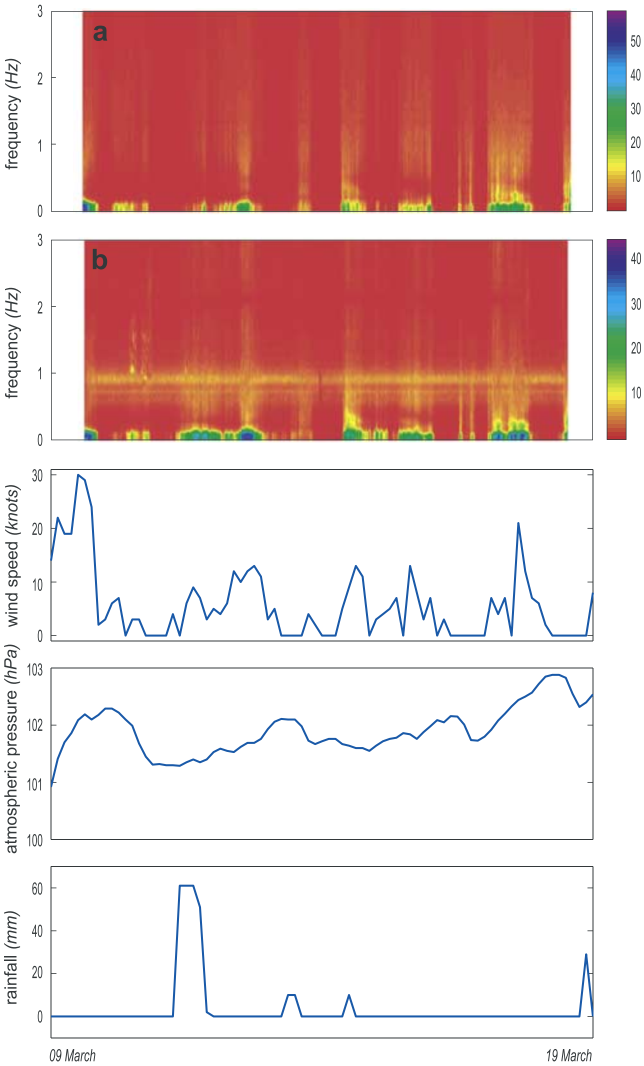

Figure 4. The time histories of three meteorological parameters are compared with the running amplitude of the H/V spectral ratios in the frequency band 0.1–3 Hz (rock site and array station are in a and b, respectively). The low-frequency disturbances are fairly well correlated with the maxima of wind speed. Despite this effect, the peak at 0.9 Hz in (b) does not show a significant variation throughout all the record.

sea, as soon as the intensity of wind increases the amplitude of sea waves is expected to increase too. The results of Figure 4 confirm the role of wind in exciting noise disturbances [*Withers et al.*, 1996] and indicate that the H/V ratios increase moderately at high frequencies ($f > 1$ Hz) whereas the amplification of the horizontal components is orders of magnitude higher than the vertical component at low frequencies.

5. Concluding Remarks

[16] Seismic noise recorded in the Colfiorito area is analyzed to check the microtremor reliability in fitting the resonance frequency observed during earthquakes. Daily and long-term meteorological variations are investigated as well.

[17] Comparing results from earthquake data and ambient noise, we have found that the fundamental frequency of the basin (0.9 Hz) is precisely fit in the noise H/V spectral ratio. In contrast, overtones peaked both in the theoretical 1D transfer function and in conventional earthquake spectral ratios (see Figure 2c) are not found in the ambient noise H/V spectral ratios. Given the agricultural nature of the Colfiorito area, daily variations of the H/V spectral ratios show a minor extent whereas long-term (meteorological) variations can be very strong, reaching a factor of 50 at low frequencies and affecting both firm and soft sites. The H/V spectral ratios show a flat increase (up to a factor of 4 for $f > 2$ Hz, approximately) whereas they increase up to more than one order of magnitude for lower frequencies. Even in the most disturbed days, this effect does not contaminate significantly the peak at 0.9 Hz in the H/V spectral ratio. The opportunity of having a meteorological observatory in Perugia, about 35 km away from the Colfiorito plain, allowed us to correlate the low-frequency variations of ambient noise with the long-term trend of meteorological parameters. The low-frequency ambient noise disturbances are concomitant with the maxima of the time history of wind speed.

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