

# A Comparison of Sea-Floor and On-Land Seismic Ambient Noise in the Campi Flegrei Caldera, Southern Italy

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**Abstract** The Campi Flegrei (southern Italy) is one of the most active calderas in the world. This caldera is characterized by episodes of slow vertical ground movement, called bradyseism. With several hundred thousand people living within its borders, this area is in a high-risk category should there be an eruption. The seismological monitoring system in the Campi Flegrei is based on nine seismic stations, eight of which are equipped with short-period seismometers (1 Hz), and one with a broadband seismometer (60 sec–50 Hz). While all of the seismic stations are located on land, part of the seismic activity occurs in the undersea area of the Pozzuoli Gulf (Campi Flegrei), where there are no seismic stations. This gap in the data coverage produces a biased and incomplete image of the volcanic area. We carried out an experiment in the Pozzuoli Gulf with the installation of two broadband seismic stations on the seafloor with remote and continuous data acquisition for a duration of 31 days between January and March 2005. Using the data acquired, we have computed the power spectral density (PSD) to characterize the background seismic noise, and to evaluate the true noise variation, we have generated the seismic noise probability density functions from the computed PSD curves. The results of our analysis show that the broadband seismic noise is high when compared with the Peterson noise model (land model), but for periods less than 0.3 sec, the seismic noise on the seafloor is lower than the recordings on land over the same period range. The last bradyseismic crisis (1982–1984) highlights the importance of this frequency range, where most of the spectral content of the recorded earthquakes was observed. Finally, we evaluate the detection threshold of a new seismic station located on the seafloor of the Campi Flegrei caldera considering the characteristics of the local seismicity. This analysis shows that the detection threshold for the sea-floor stations ( $M_w \sim 0.2$ ) is less than that for land stations ( $M_w \sim 0.8$ ).

## Introduction

The Campi Flegrei volcanic area of approximately 80 km<sup>2</sup> is a densely populated urban area that makes up the western quarters of the city of Naples. The largest eruption in the area occurred 35,000 yr ago, with a massive eruption of alkali trachytic ignimbrites that caused a caldera collapse. Subsequent volcanic activity has taken place inside the caldera, with an overall migration of the eruptive vents from the extremities to the center of the caldera. The last historical eruption occurred in September 1538, producing Monte Nuovo, a pyroclastic cone built from phreatomagmatic and magmatic activity. At present, intense fumarolic activity is occurring at the Solfatara crater and in several zones both on land and off land. The main characteristic of

the present volcanic activity of Campi Flegrei is the bradyseism, that is, a slow vertical ground movement over a small well-defined area. This effect has been highlighted by the presence of many Roman edifices, which are at present submerged along the coastline in waters that are nearly 14 m deep (Rosi and Sbrana, 1987). In general, the bradyseism for the area is characterized by long periods of slow subsidence that are interrupted by short, rapid periods of uplift. In one case, a vertical displacement of 7 m preceded the Monte Nuovo eruption (Dvorak and Gasparini, 1991). The most recent bradyseismic episodes of particular intensity occurred in the years 1970–1972 and 1982–1984, with the initial episode of ground uplift of some 170 cm, followed about 10 yr later by a further 180 cm (Bianchi *et al.*, 1987). Since 1984, the ground has slowly but continuously subsided, with small episodes of further uplift (but always of only a few centi-

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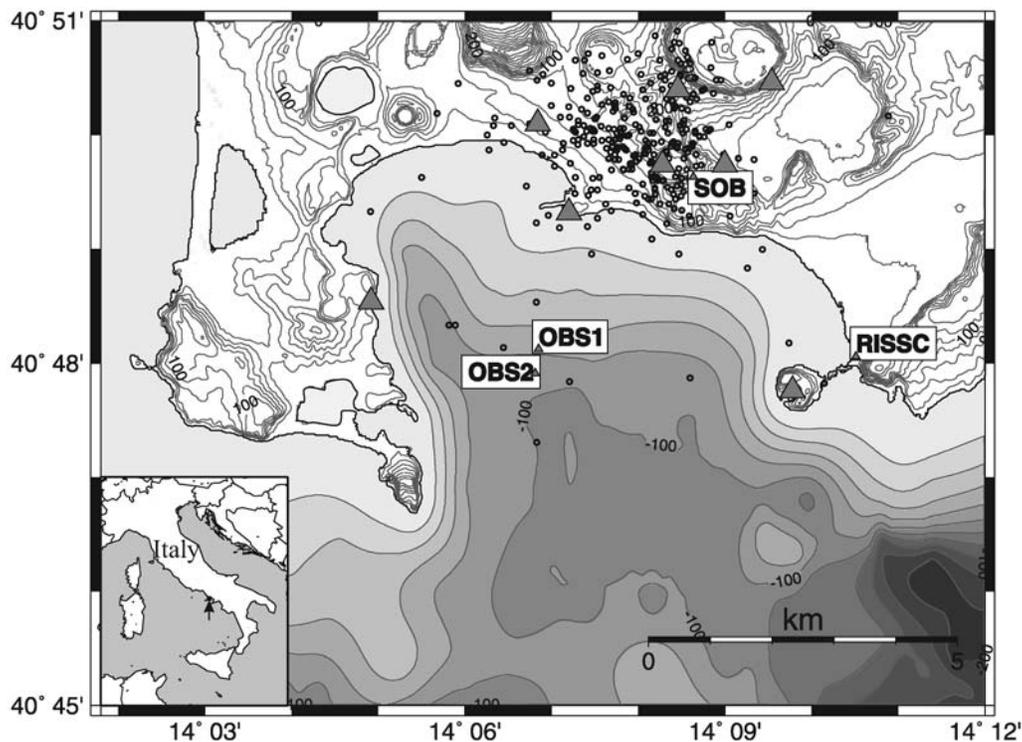
meters), the last of which occurred in 2006 (Troise *et al.*, 2007).

The Campi Flegrei volcanic area is monitored by a geophysical surveillance system that was established and is managed by the Osservatorio Vesuviano (Naples branch of the Istituto Nazionale di Geofisica e Vulcanologia). This system includes a seismic network, a continuous global positioning system (GPS) network, and a tide gauge monitoring and geochemical instrumentation network. Moreover, there are periodic collections of precise geodetic and microgravity measurements (Macedonio and Tammaro, 2006). The seismic network consists of nine stations (Fig. 1) that are mainly distributed along the coast, with a denser concentration around the Solfatara crater, where a large part of the seismicity occurs. The configuration of the seismic network allows the accurate location of earthquakes with epicenters on land and, in particular, in the Solfatara area, while the earthquakes with epicenters in the Pozzuoli Gulf (Fig. 1) are located with less precision; the accuracy of offshore earthquake location is hampered by the one-sided on-land station distribution. Moreover, due to the large levels of urbanization of the Campi Flegrei area with industrial plants, railway lines, and intense traffic, there is a high level of seismic noise that prevents the detection of lower energy seismic events, increasing the detection-threshold level of the seismic network, particularly for the earthquakes with epicenters in the sea.

With the aim of improving the performance of the seismic network in the Campi Flegrei, the installation of a seis-

mic station for real-time data acquisition was planned for the floor of the Pozzuoli Gulf, connected to a floating system. The general idea was to position a broadband seismic sensor with the recording system on the seafloor at a depth of about 100 m, with transmission of the data to a buoy by cable, followed by its radio transmission to the acquisition center of the Osservatorio Vesuviano. The floating system would be equipped with batteries charged by solar panels, an aeolic generator, and a GPS antenna. A radio bridge with an omnidirectional antenna would be used for data transmission to land. The cable would also function to supply power and to synchronize the data with a GPS antenna. To check on the feasibility of installing a seismic station on the seafloor of the Pozzuoli Gulf, experiments were carried out to measure the amplitude of the seismic noise near the site that could later be used for the installation of a permanent seismic station. The sea-floor seismic noise was studied, comparing it with the noise recorded by land stations. Finally, estimates were made of the improvements in the detection threshold of the seismic network that would be gained by a new seismic station on the seafloor.

There have been many observations and interpretations of sea-floor seismic noise levels, mainly connected with the wave motions at the sea surface and the interactions of the marine currents with the seismic instrumentation. Webb (1992) observed that the microseismic wave field is similar to the ocean surface wave field and that its generation was attributed to nonlinear interactions of ocean waves with the



**Figure 1.** Locations of Osservatorio Vesuviano seismic network (big gray triangles and SOB label), sea-floor stations (OBS1 and OBS2), and on-land stations (SOB and RISSC) used during the experimental period. The dots show the location of a selected set of well-located earthquake epicenters from 1982–1984.

seafloor. All of the previously reported measures and observations, however, refer to ocean floor measurements in a deep environment (Babcock *et al.*, 1994; Webb, 1998; Stephen *et al.*, 2003), and it is difficult to compare these with the situation within Pozzuoli Bay of the Campi Flegrei, with a water column of about 100 m, being close to the coast in a greatly urbanized area. Therefore, to study the seismic noise on the seafloor of the Pozzuoli Gulf, we conducted an *ad hoc* experiment, as described in this article.

### Seismic Network and Seismicity of Campi Flegrei Caldera

The seismic network managed by Osservatorio Vesuviano to monitor the Neapolitan volcanic areas (i.e., Vesuvio, Campi Flegrei, and Ischia Island) consists of 41 seismic stations, nine of which are in the Campi Flegrei area. Figure 1 illustrates the seismic network configuration. Most of the stations are equipped with short-period seismometers ( $T_0 = 1$  sec); four contain only vertical-component sensors, and four contain three-component sensors. One station is equipped with a broadband seismic sensor with a frequency response from 0.017 to 50 Hz. The data coming from short-period instruments are transmitted to the monitoring center in Naples by wired line at a rate of 100 samples/sec, while the broadband instruments are acquired locally at the same sampling rate and then transmitted in digital form (Saccorotti *et al.*, 2007).

The main feature of the Campi Flegrei seismicity is that earthquakes occur during the bradyseismic uplift phase and there is a lack of seismicity during periods of subsidence. The seismicity started about two months after the onset of an uplifting episode (De Natale *et al.*, 2006). The most recent seismic activity occurred during the 1982–1984 uplift episode, when more than 15,000 earthquakes were detected. During this period, a temporary digital seismic network was installed in the area in cooperation with the University of Wisconsin. The seismic stations were equipped with three-component short-period sensors (HS10-1 model, with natural frequency of 1 Hz) operating in trigger mode and sampled at 100 samples/sec (Aster *et al.*, 1992). Several detailed studies have been performed on the 1982–1984 seismic activity (De Natale and Zollo 1986; De Natale *et al.*, 1987; Aster *et al.*, 1992); in general, they have demonstrated that the seismic activity is characterized as:

- low-energy earthquakes ( $M \leq 4.2$ ),
- shallow hypocenters (less than 5 km),
- exhibiting swarm behavior (both spatially and temporally),
- centering mainly around the Solfatara crater area,
- having source mechanisms well explained by a double-couple model.

Figure 1 shows a selected set of well-located epicenters that occurred during the 1982–1984 episode, indicating that most of the events are located on land, with ~10% scattered throughout the Bay of Pozzuoli.

In the years following 1984, the Campi Flegrei area showed continuous subsidence of some millimeters per month, interrupted by four episodes of uplift in 1989, 1994, 2000, and 2006, each of which was no greater than 4 cm (Troise *et al.*, 2007). These later episodes of small uplift have been accompanied by weak seismic activity. Integrating the permanent seismic network with portable seismic stations equipped with broadband sensors, Saccorotti *et al.* (2001, 2007) analyzed the seismic activity following the bradyseismic crises that occurred in 2000 and 2006. They highlighted that the seismicity was clustered in swarms of low-energy events with hypocenters located around the Solfatara crater area at depths ranging from 0.5 to 5 km. In fact, the maximum observed magnitude during the summers of 2000 and 2006 was  $M \sim 2.2$  and  $M \sim 1.4$ , respectively. Furthermore, Saccorotti *et al.* (2001, 2007) pointed out that most of the recorded seismograms have spectral shapes that are typical of high-frequency microearthquakes and are similar to those seen during the bradyseismic crisis of 1982–1984. These events were shown to be related to shear fracture processes. Seismic signals that were characterized by a dominance of low-frequency (similar to weak monochromatic) oscillations were seen to accompany the July 2000 and October 2006 seismic swarms. Saccorotti *et al.* (2001, 2007) suggested that this is due to the presence of magmatic/hydrothermal fluid overpressure, which would induce fracturing orthogonal to the preexisting fluid-filled discontinuities.

After October 2006, no earthquakes were detected except for the single earthquake of 2007, which occurred on 8 February 2007 at 01:07:41 (universal coordinate time [UTC]) and was located in the Solfatara area with a magnitude ( $M_d$ ) of 0.5.

### Technical Description of the Experiment

Two seismic data-acquisition systems equipped with broadband sensors were installed on the Pozzuoli Gulf seafloor for about one month. These two ocean-bottom seismometers (OBS) were supplied by GeoPro GmbH (Hamburg, Germany) and were equipped with electronic-molecular seismometers (Abramovich *et al.*, 1997): a PMD-113 (0.03–30 Hz; Precision Measurement Devices (PMD) Scientific, Incorporated) and a CME-4011OBS (0.03–30 Hz; Center for Molecular Electronics, Moscow Institute of Physics and Technology). Electronic-molecular seismometers are characterized by the absence of moving mechanical parts and were chosen because of their particular properties: minimal dimension and weight, low power consumption, high-tilt tolerance, and no need to carry out recalibration of the mass center. These properties make this type of sensor particularly suited to undersea seismic applications (Pulliam *et al.*, 2003). The acquisition system used was SEDIS-IV of GeoPro, a light seismic-data-gathering system with a dynamic range of 120 dB, a 24-bit *A/D* converter, and six channels. The power for the instrumentation was supplied by *D*-type alkaline batteries, and together with the instrumenta-

tion, these were held in two different spherical containers of vitrovex, which is resistant to pressures equivalent to a water depth of 6000 m. Each system had two spheres fixed to the ballast through an acoustic release mechanism. The two OBSs were positioned by sinking them from a ship on 31 January 2005 at the points given in Figure 1; they were recovered on 2 March 2005, by activation of the ballast-release system through an acoustic command sent from the ship. For easier recovery, radio transmitters and luminous indicators were installed in the OBS.

The seafloor of the Pozzuoli Gulf is made up of soft sediment into which the two OBSs sank to about 20 cm, which we were able to verify from the deposits on the OBSs at the time of their recovery. This sinking into the sediment by the two OBSs provided good stability of the system with respect to the marine currents on the seafloor and a good seismic coupling between sensor and ground. Once installed, the two OBSs worked continually from 31 January 2005 to 2 March 2005. During this period, there were both regional earthquakes and teleseismic events (Table 1), although there was no recording of any local seismic event that could be attributed to the activity of Campi Flegrei.

The data acquired from the seafloor were compared with those measured at two seismic stations on land, which were also equipped with broadband sensors. The positions of these stations, RISSC and SOB, are shown in Figure 1. The RISSC temporary seismic station is equipped with a Trillium broadband sensor (40 sec, 30 Hz; Nanometrics seismological instruments) and an Osiris-6 Agecodagis data logger. The data recorded at the RISSC station relate to the period between 17 February 2005 and 2 March 2005. The SOB seismic station of the Osservatorio Vesuviano (Fig. 1) is equipped with a Guralp-CMG40 broadband sensor and with a Kinematics K2 data-acquisition system. For this station, the data available are only the recordings of earthquakes and not of seismic noise data. The comparison between the waveforms of the events recorded on the seafloor and on land provides information on the quality of the seismic signal acquired on the seafloor. In Figures 2 and 3, we show examples of recordings at the OBSs and RISSC stations of a regional and of a teleseismic event. Figure 2 shows the vertical and horizontal components for a regional event at about 600 km in distance. The signals recorded were low-pass filtered at 0.3 Hz. The

essential characteristics of the recordings are similar for the different stations, even if the signals recorded by the OBS have a greater high-frequency content. Figure 3 shows 700 sec of recording of a teleseismic event (Philippines; Table 1) at an epicentral distance of 55°. The signals recorded were filtered with a Butterworth filter with a band pass of angular frequencies of 0.03 and 0.15 Hz. The seismic recordings at the different stations are similar and the body waves were well recorded in the vertical components of the different sensors.

## Characteristics of the Recorded Seismic Noise

### General Overview

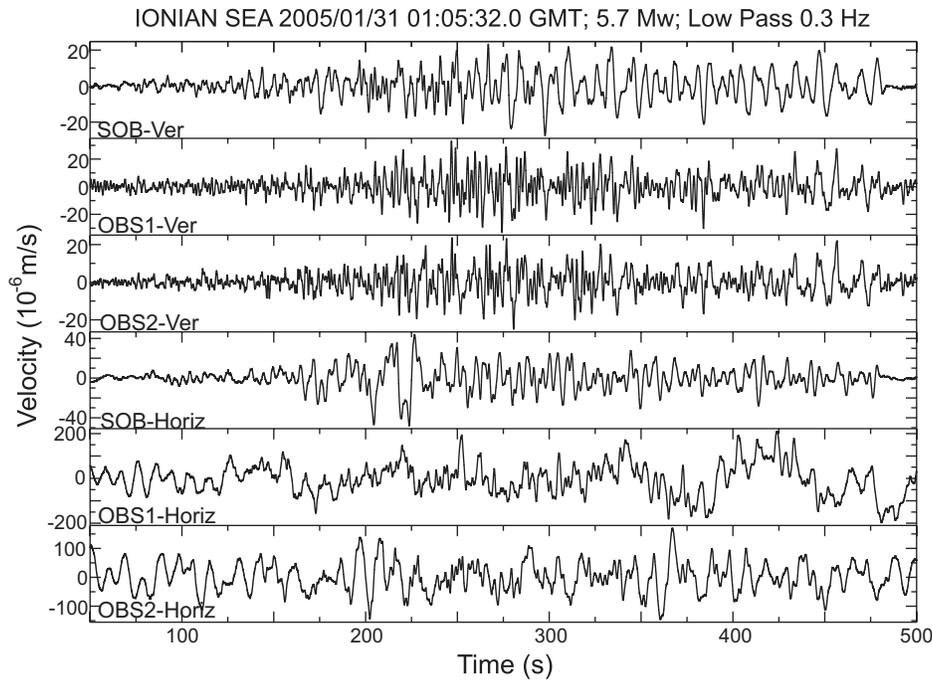
We used spectral analysis to characterize the seismic noise recorded at the two OBS systems and the land reference stations. For this, we divided the continuous one month acquisition period into one-hour time segments. The mean values of each segment were removed, as was the long-term trend, and finally a cosine taper was applied to reduce the truncation effects of the time series. Signal amplitudes were converted from counts into velocity (m/sec). The power spectral density (PSD) of each segment was calculated using the method of Welch (1967) using the programs of the generic mapping tools package (Wessel and Smith, 1991). The PSD values were converted into dB [referred on a velocity of  $1(\text{m/sec})^2/\text{Hz}$ ] to compare them with the curves of the new low-noise model (NLNM) and new high-noise model (NHNM) of Peterson (1993), used as a reference for the definition of the quality of a seismic recording site.

Figure 4 shows the PSD curves from 24 hr of recording. In the different panels, each curve refers to a different hour during the day; the dashed curves, instead, show the NLNM and NHNM levels (Peterson, 1993). Generally, for most of the period bands analyzed, the calculated PSD values are greater than the NHNM values, demonstrating that both the land and sea-floor stations are very noisy due to both the high level of anthropogenic noise and proximity to the coast, where weather and microseism noise effects are greater.

In particular, as can be seen from Figure 4, which shows the PSD calculated for vertical components of the RISSC land station and for the two OBSs, at periods less than 0.3 sec, the two sea sites show PSD levels lower than those

Table 1  
Earthquakes Recorded during the Experimental Period

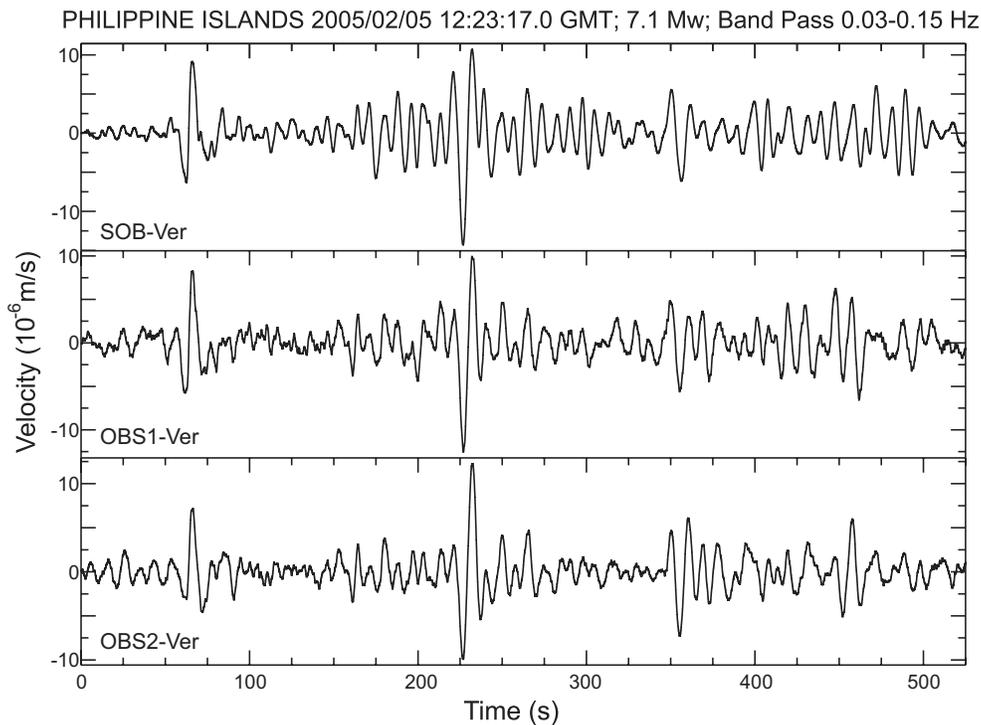
Date (yyyy/mm/dd)	Magnitude	Location	Origin time (UTC)	Latitude (°)	Longitude (°)	Depth (km)
2005/31/01	$M_w \sim 5.7$	Ionian Sea	01:05:32.0	37.65	20.10	25
2005/02/05	$M_w \sim 7.1$	Philippine Islands	12:23:17.0	5.33	123.36	510
2005/02/07	$M_b \sim 5.1$	Tunisia	20:46:26.0	36.20	10.87	34
2005/02/08	$M_w \sim 6.7$	Vanuatu	14:48:21.0	-14.30	167.25	204
2005/02/22	$M_w \sim 6.4$	Iran	02:25:26.0	30.75	56.80	42
2005/03/01	$M_d \sim 3.5$	Southern Italy	05:41:37.0	41.70	14.88	10
2005/03/02	$M_w \sim 7.1$	Banda Sea	10:42:10.5	-6.61	130.01	200



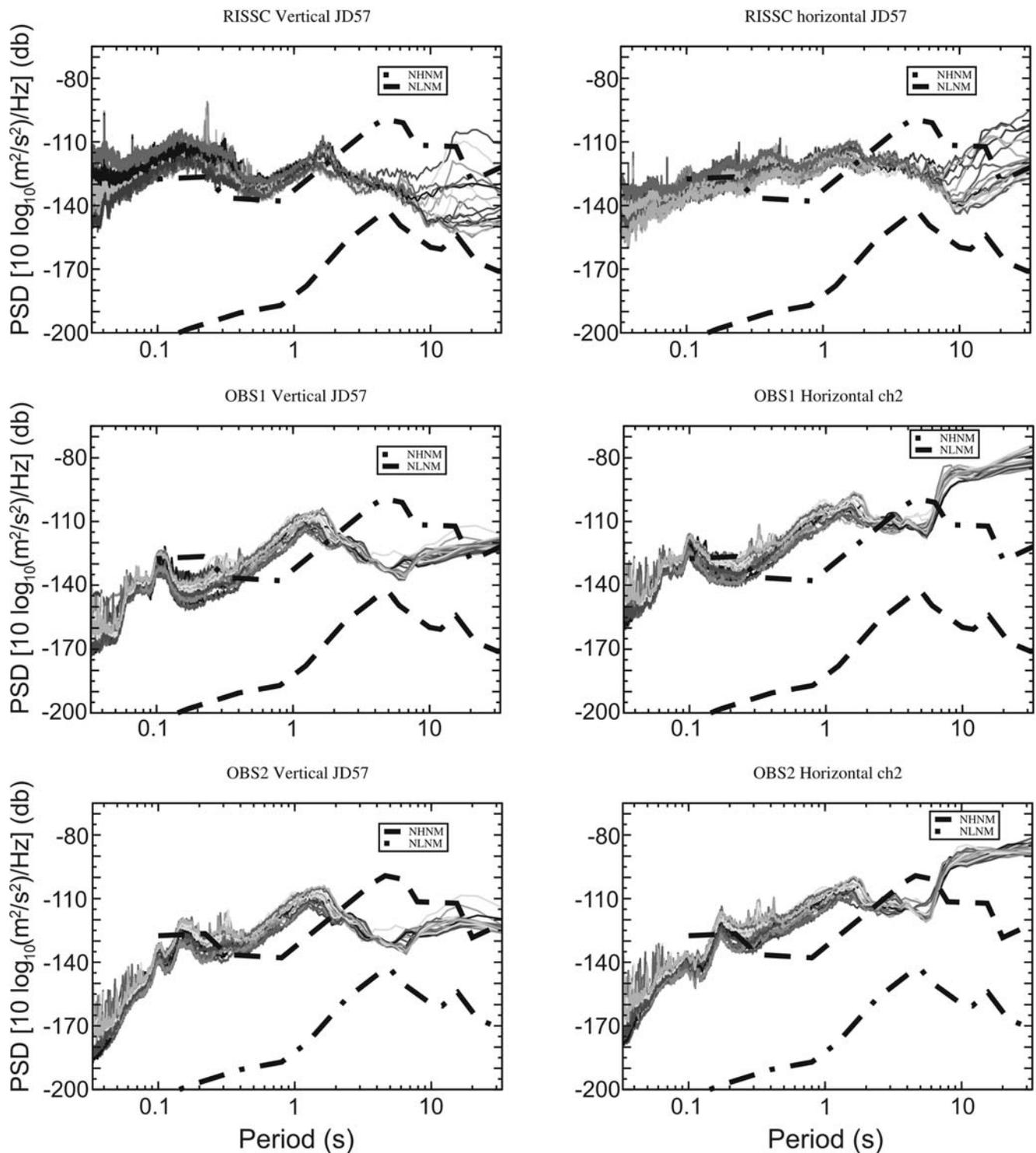
**Figure 2.** Regional event (Ionian Sea, Table 1): vertical and horizontal components for the SOB, OBS1, and OBS2 stations. The data were filtered with a low-pass filter with a corner frequency of 0.3 Hz.

for the land stations; for periods greater than 0.3 sec, the spectral shapes are similar between the sites. It can be seen, however, that the peak of OBSs PSD in the range [1.5 sec; 2 sec] is about 10 dB greater than that of the stations on land. Moreover, for periods near 6 sec, the PSD levels of the hor-

izontal components of the OBSs undergo rapid variations, going from values of  $-120$  dB to around  $-90$  dB for periods greater than 6 sec. In this same band ( $> 6$  sec), the horizontal components of the RISSC land station are less noisy by about 40 dB.



**Figure 3.** Teleseismic event (Philippine Islands, Table 1): vertical components recorded at the SOB (top), OBS1 (center), and OBS2 (bottom) stations. The data were filtered with a Butterworth band-pass filter with corner frequencies of 0.03 and 0.15 Hz.

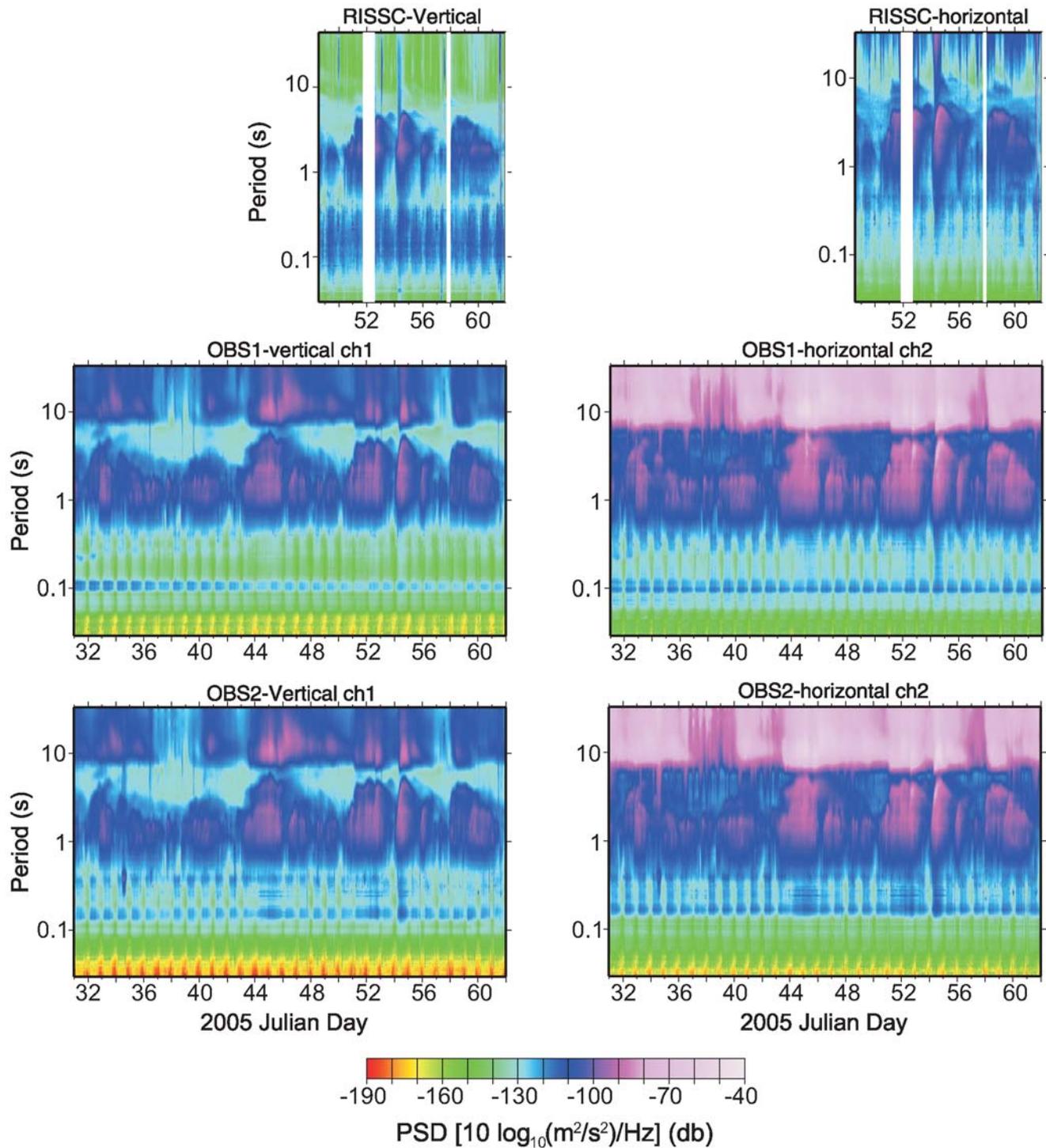


**Figure 4.** Comparison of the noise spectra of the OBS stations (OBS1, top; OBS2, center) and the RISSC station (bottom) for 26 February 2005 (57th Julian day). Each individual curve was calculated using an hour of seismic data, starting from 00:00. The dashed curves show the levels of N1HM and N1NM (Peterson, 1993) (obtained using the seismic data acquired by continental seismic stations).

#### Temporal Behavior of the Sea-Floor Seismic Noise

The spectrograms calculated for the entire recording period (about 31 days) for the two OBSs and the RISSC station are shown in Figure 5. The panels in Figure 5 show that for periods between 0.7 and 7.0 sec, the noise has great varia-

bility in amplitude and in the period of the maximum peak for both the OBS and RISSC stations. Also, between 0.03 and 0.3 sec, the noise shows large temporal variations that are mainly linked to diurnal changes. The horizontal components are on average noisier than the vertical components,



**Figure 5.** Spectrograms for the vertical (right-hand panels) and the horizontal (left-hand panels) components of the RISSC (top), OBS1 (center), and OBS2 (bottom) stations.

which is particularly true for the periods longer than 7.0 sec, for which the noise recorded on the seafloor is greater than that recorded on land and is greater in the horizontal components than the vertical. For the OBS1 and OBS2 stations, it is possible to pick out some clear PSD peaks confined to very narrow period intervals, as shown by the thin blue line in

the spectrogram at around 0.1 sec. This noise was probably caused by a resonance phenomenon in the incoherent sediment layer in which the instrument was buried (Zeldenrust and Stephen, 2000). The characteristic resonance period depends on the physical properties of the layer in terms of the velocity of the  $S$  waves and the thickness of the layer. Such

variation may be responsible for the shift between the resonance period observed at OBS1 (0.1 sec) and that at OBS2 (about 0.2 sec).

Figure 6 shows the temporal trend of the mean PSD in the band between 0.06 and 0.3 sec. In this interval, the noise undergoes a rapid decrease during the night hours, with the minimum noise level recorded around midnight. In this band, the RISSC station is noisier by about 20 dB with respect to the OBS1 and OBS2 stations. The large variability between day and night and the frequency interval considered (3 to 17 Hz) suggest that in this band the noise is anthropogenic (Webb, 1992; Mc Namara and Buland, 2004). Following this hypothesis, the stations on the seafloor are less noisy than those on land because they are at a greater distance from the noise sources.

#### Correlation with Meteorological Factors

It is well known that the meteorological conditions and, in particular, the wind velocity, have an important role in the generation of seismic noise on the seafloor (Wilcock *et al.*, 1999). A detailed investigation of this interaction was reported by Babcock *et al.* (1994), where the authors used data from an experiment carried out in the North Atlantic with concomitant measures of meteorological parameters and of seismic noise on the ocean floor. In this work, a clear correlation was seen in the frequency band of 0.16 to 0.3 Hz between the amplitude of the seismic noise and the meteorological conditions.

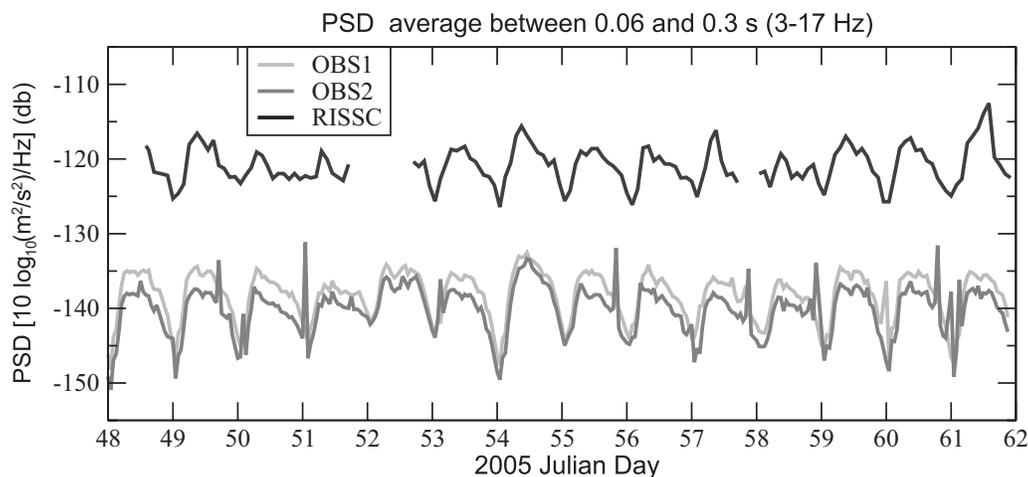
We studied the correlation between seismic noise and atmospheric factors using meteorological data recorded by a station in the investigated area. Figure 7 shows the trend of wind velocity versus time over the duration of the experiment. In the same figure are also shown the spectral amplitudes of the [1.7 sec; 5 sec] short-period bands and of the [5 sec; 30 sec] long-period bands versus time for OBSs and

RISSC station. Table 2 reports the values of the correlation coefficients,  $r$ , calculated to quantify the similarities between the trend of the noise levels and the wind velocities. The spectral amplitude in the short-period band strongly correlates with the wind velocity for both the sea stations and the land station for both the horizontal and vertical components (Fig. 7, top; Table 2). In this interval, the values of the correlation coefficients for the horizontal and vertical components vary between 0.49 and 0.66, indicating that the wind is a common source of the seismic noise observed on land and on seafloor. In fact, as suggested by some authors (Webb, 1998; Wilcock *et al.*, 1999) in this band the wind-driven gravity waves on the sea surface are the dominant source of seismic noise. This noise is more evident on the sea-floor station as shown by the noise-wind correlation value that for the OBSs is greater than for land stations (Table 2).

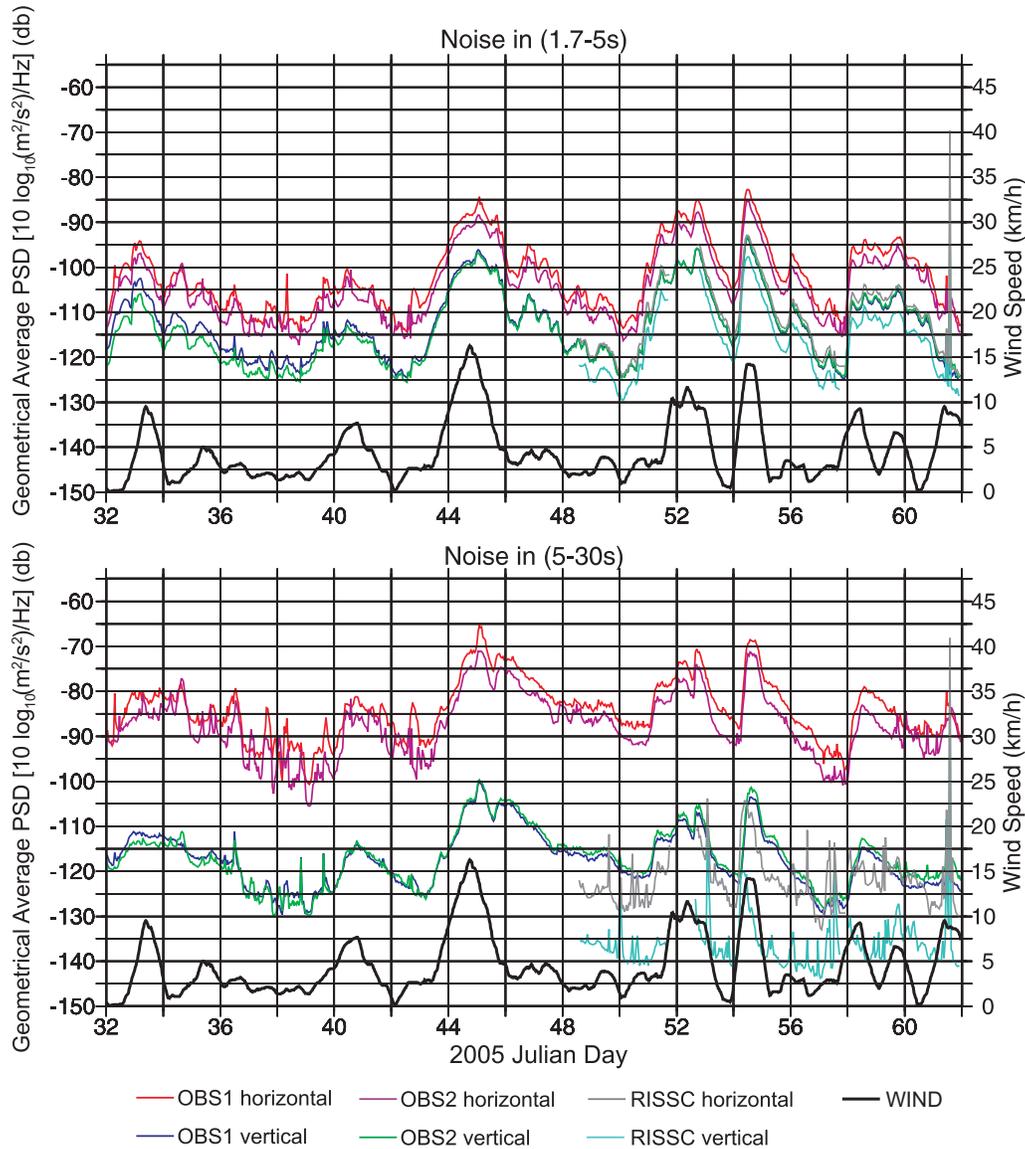
For the longer period, in the [5 sec; 30 sec] band, the noise recorded at sea shows differences from the corresponding noise recorded on land (bottom of Fig. 7). In this band, the noise of the vertical components is on average at the same levels observed for the short-period band both for the OBSs and the RISSC. The noise of the horizontal components, however, increases by about 20 dB for the OBSs and decreases by about 15 dB for the RISSC station, compared to short-period levels. In the long-period band, the influence of the wind on the noise is still present, but the correlation coefficients are lower than those for the short-period band (Table 2). The correlation coefficient is on average greater in the horizontal recordings than for those in the vertical recordings.

#### Statistical Analysis of the Seismic Noise

To define the noise levels characteristic of the OBSs and the land station, we carried out a statistical analysis



**Figure 6.** Temporal variations of the average PSD levels in the bands between 0.06 and 0.3 sec relative to the vertical components of the recordings at the RISSC, OBS1, and OBS2 stations.



**Figure 7.** Correlation with the wind velocity. Temporal variation of the PSD average levels for the horizontal and vertical components recorded at the RISSC, OBS1, and OBS2 stations. The average curves are computed in the [1.5 sec; 5.0 sec] (top) and [5.0 sec; 30 sec] (bottom) bands.

of the spectral curves calculated for each hour of the signal. This analysis followed the method proposed by McNamara and Buland (2004). All of the PSD curves were used to define a probability density function (PDF) of the seismic noise. This function was calculated through the following procedure:

- each PSD curve was smoothed in full octave averages at  $1/8$  octave intervals,
- the PSD values obtained for each interval of  $1/8$  were organized in 1.0 dB intervals to define the distribution frequency for each period,
- for a fixed period,  $T_c$ , the PDF was estimated as the ratio between the number of spectral estimates that fall to a 1 dB power bin and the total number of spectral estimates over all of the powers with a central period  $T_c$ .

Figure 8 shows the calculated PDF starting from the estimates of the spectral levels relative to the horizontal and vertical components of the OBS1, OBS2, and RISSC stations. It can be seen that for periods of less than 1 sec, the PDF function presents a marked peak and its value returns rapidly to zero. For periods greater than 1 sec, however, the PDF function shows high background levels, and secondary peaks can be seen arising from transient systems or from variability in the natural sources of noise.

Using the PDF values, we have calculated for each period and for each component the eightieth percentile levels of PSD. The curves given in Figure 9 show the levels of the eightieth percentiles relative to the horizontal and vertical components. From these, it can be noted that for the vertical components for periods less than 0.3 sec, the noise recorded

Table 2  
Correlation Coefficient Values,  $r$ , between the Wind Velocity and the PSD Levels

Period Band (sec)	Station Name	Component	Correlation ( $r$ )
(1.6–5)	RISSC	Vertical	0.53
(1.6–5)	RISSC	Horizontal	0.49
(1.6–5)	OBS1	Vertical	0.63
(1.6–5)	OBS1	Horizontal	0.66
(1.6–5)	OBS2	Vertical	0.66
(1.6–5)	OBS2	Horizontal	0.66
(5–30)	RISSC	Vertical	0.42
(5–30)	RISSC	Horizontal	0.57
(5–30)	OBS1	Vertical	0.51
(5–30)	OBS1	Horizontal	0.58
(5–30)	OBS2	Vertical	0.55
(5–30)	OBS2	Horizontal	0.54

at the OBSs is about 10 to 20 dB lower than that recorded on land. At long periods (greater than 7 sec), the RISSC station is quieter than the OBS by about 20 to 30 dB for the vertical component and about 50 dB for the horizontal component. For other periods, the noise levels of the land and of the sea-floor sites appear to be comparable.

### Detection Thresholds for Local Earthquakes

These results allow us to estimate the improvement of the local earthquake detection we can expect from installing a new seismic station on the seafloor of the Pozzuoli Gulf.

Most of the earthquakes occurring in the Campi Flegrei caldera area are of the tectonic type, that is, they show a spectral content and seismic source parameters consistent with a shear fault mechanism; a detailed study performed on a subset of earthquakes from the strong uplift episode of 1982–1984 showed that the radiation patterns of all events were well interpreted in terms of double-couple source models (De Natale *et al.*, 1987). Thus, to evaluate the detection threshold of a seismic station on the seafloor, we compared the seismic noise amplitude levels at the two OBSs with the theoretical spectral curves described by the seismic source model proposed by Brune (1970). In particular, the spectral amplitude was estimated by:

$$A(f) = 2\pi f M_0 \frac{R_{\vartheta\varphi} F_s}{4\pi\rho R c^3} \frac{1}{1 + \left(\frac{f}{f_c}\right)^2} e^{-\pi f T/Q}, \quad (1)$$

where  $M_0$  is the seismic moment,  $R_{\vartheta\varphi}$  is the radiation pattern coefficient,  $F_s$  represents the free surface and reflection/transmission corrections,  $R$  is the hypocentral distance,  $c$  is the wave velocity,  $f_c$  represents the corner frequency,  $\rho$  is mean rock density,  $Q$  is a quality factor, and  $T$  is the wave travel time. We have computed the  $P$ -wave spectra by (1), assuming  $R_{\vartheta\varphi} = 0.6$ ,  $F_s = 1.7$  and using the following values valid for the Campi Flegrei area (Del Pezzo *et al.*, 1987):  $\rho = 2.2 \text{ g/cm}^3$ ,  $c = 3 \text{ km/sec}$ ,  $Q = 120$ ,

$\Delta\sigma = 1 \text{ MPa}$ . The conversion from magnitude scale to seismic moment was performed using the classical relation proposed by Hanks and Kanamori (1979):

$$M_w = \frac{\log M_0 - 16.1}{1.5}. \quad (2)$$

The comparison of the predicted signal amplitude using Brune's (1970) model with the background seismic noise was performed considering the mean value in 1/3 of an octave band, assuming  $\Delta f = (2^{1/6} - 2^{-1/6})f_0$ , as suggested by Melton (1976). In particular, using equation (1) and assuming a mean hypocentral distance of 5 km, the spectral amplitude of seismic waves generated by earthquakes of magnitude 0.2 to 2 have been calculated from  $S(f_0) = |A(f_0)|\Delta f$ . The seismic noise amplitude was obtained from  $N(f_0) = \sqrt{P(f_0)\Delta f}$ , where  $P(f_0)$  is the eightieth percentile PSD curve as described in the previous paragraph and reported in Figure 9.

Figure 10 shows the calculated theoretical spectral amplitudes in 1/3 octave bands starting from the Brune model (1970), corrected for the response curves of the Trillium broadband used during the experiment and the curves relative to the eightieth percentile of the PSD for the vertical components of the RISSC and OBS stations.

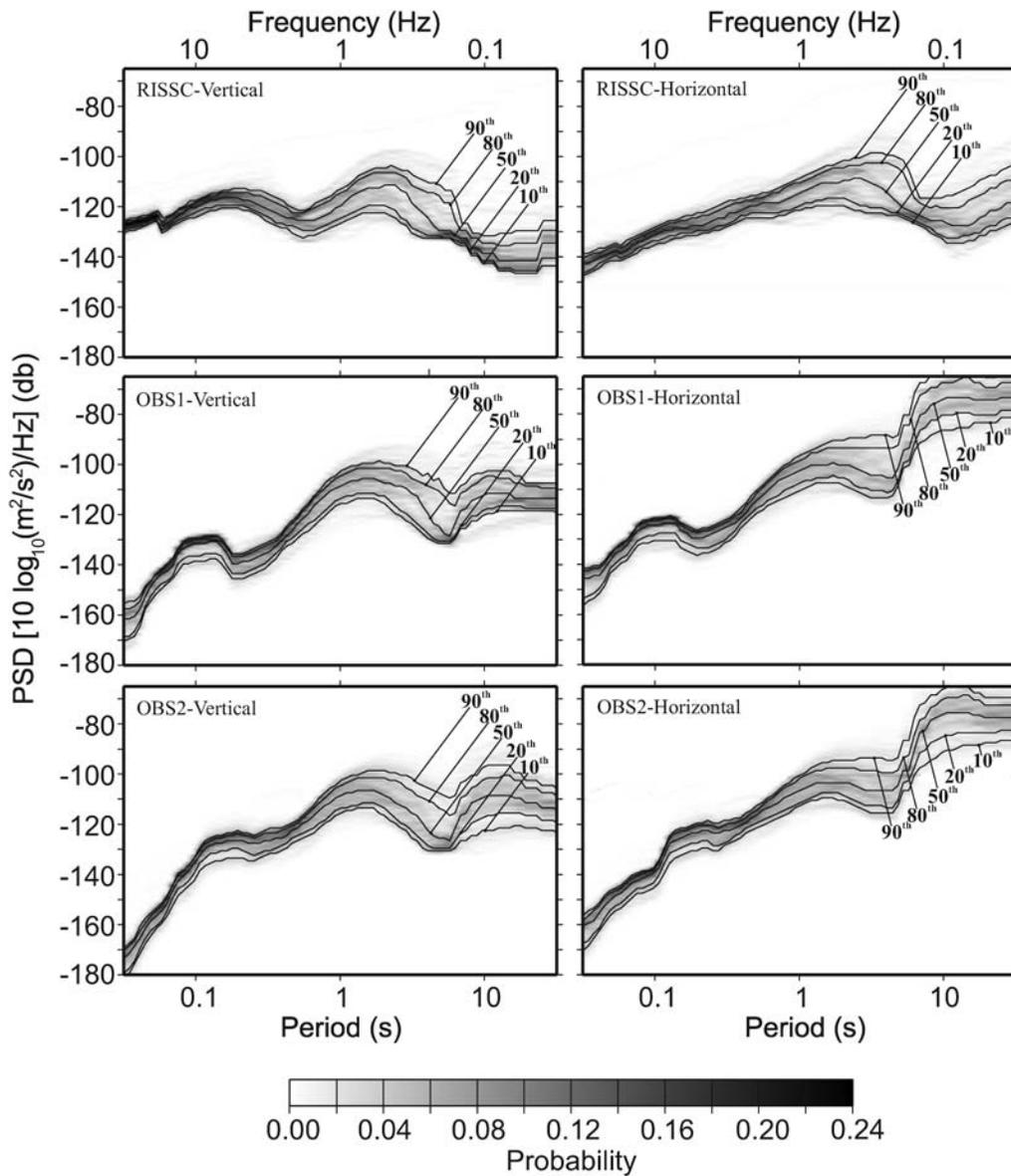
For small magnitude earthquakes ( $M_w \sim 0.2$ – $2.0$ ), the signal-to-noise ratio is better for the OBS1 sea-floor station than for the RISSC station on land. We assumed that an earthquake can be detected when its amplitude is at least twice the noise level. From the curves in Figure 10, it can be seen that the detection threshold for the sea-floor stations, at  $M_w \sim 0.2$ , is less than that on land at  $M_w \sim 0.8$ .

### Discussions and Conclusions

To evaluate the performance of a new seismic station that could be deployed in the Pozzuoli Gulf and to determine the strategies that would lead to a reduction in the ambient noise, we installed two temporary broadband OBS seismic stations in the center of the Pozzuoli Gulf equipped with electronic-molecular broadband sensors. During the acquisition period, some teleseismic and regional events were recorded but no local earthquakes were detected; we therefore focused our analysis on seismic noise, calculating its characteristic levels and highlighting its properties over one month of continuous acquisition.

The whole period band analyzed (0.03 to 30 sec) can be divided into three main intervals:

1. Periods between 0.03 and 0.3 sec: the seismic noise both on land and on the seafloor shows strong diurnal variations, with maximum values in the daylight hours and minimum values during the night. The main source of seismic noise is anthropogenic, producing strong seismic signals mainly propagating as high-frequency surface waves. These signals attenuate within several kilometers



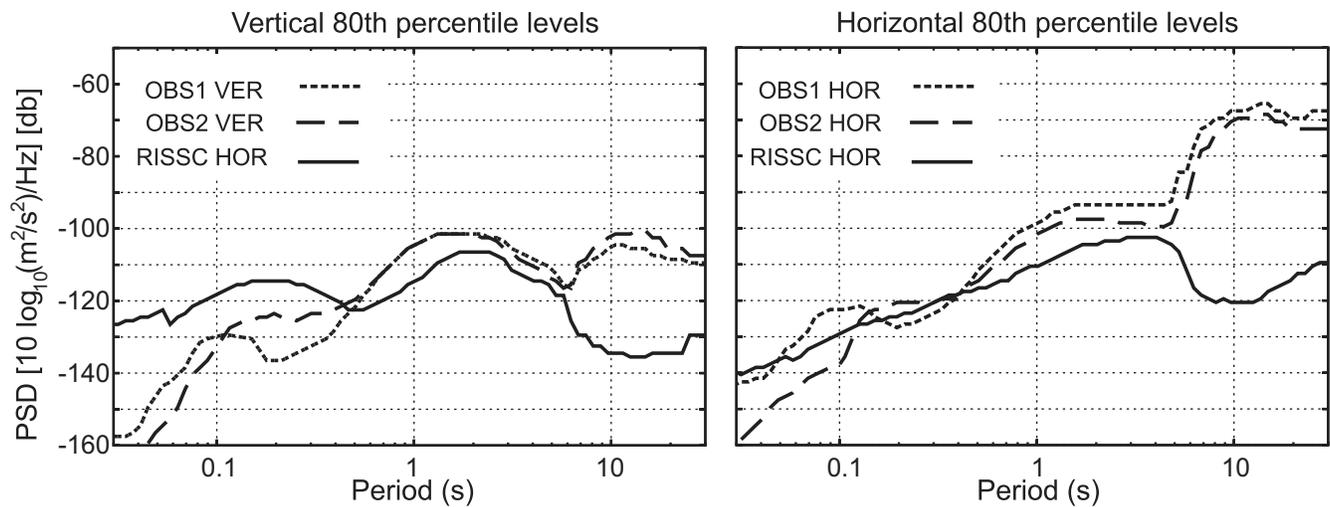
**Figure 8.** PDF and percentile curves for the vertical (left-hand panel) and horizontal (right-hand panel) components of the RISSC (top), OBS1 (center), and OBS2 (bottom) stations. Each panel was constructed using 277 PSD curves relative to the data acquired between 17 February 2005 and 3 March 2005.

from the sources. As a consequence, the stations on the seafloor that are further away from the cultural noise sources are quieter than the land stations in the vertical components. The seismic noise on the seafloor shows levels of around 20 dB less than those on the land.

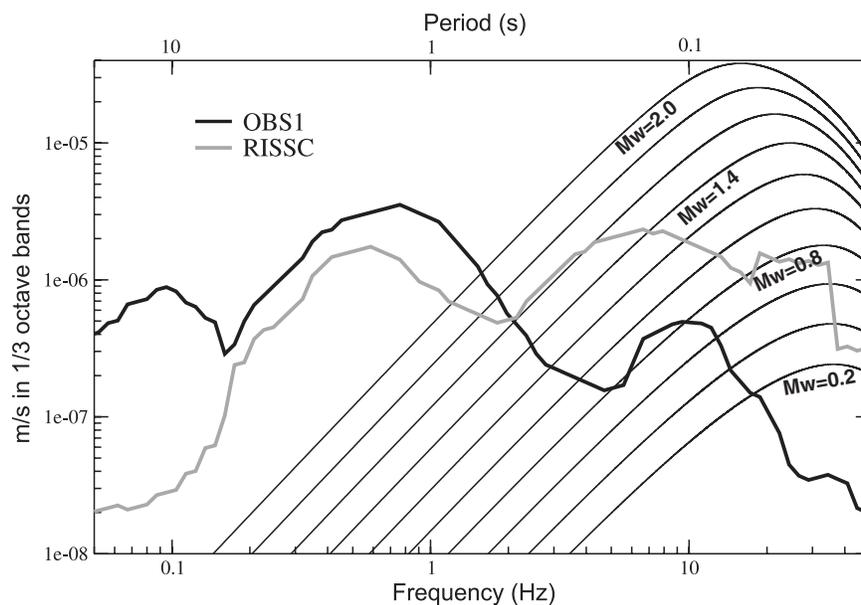
2. Periods between 0.3 and 5.0 sec: the seismic noise both on land and on the seafloor strongly correlates to the wind velocity. The noise level on the seafloor is greater (by about 10 dB) with respect to that on land, with differences that are smaller on days that are less windy. In this period band, the wind-driven gravity waves on the sea surface are the dominant source of the sea-floor seismic noise (Webb, 1998). The seabed noise levels observed suggest that seismic waves in this frequency band will only be

well recorded for very large earthquakes or during periods of calm.

3. Periods between 5 and 30 sec: the sites on the seafloor are noisier than those on land. The differences are of about 30 dB for the vertical components and about 50 dB for the horizontal components. The sea-floor noise correlates well with the wind velocity and could be caused by the presence of marine currents on the seafloor induced by the action of the wind at the surface (Romanowicz *et al.*, 1998). To reduce this effect, we propose burying the seismic sensors in the seabed for future installation. A less expensive alternative could be the installation of a vectorial current meter on the seafloor to decorrelate the current effects from the seismic recordings.



**Figure 9.** Curves illustrating the levels of the 80th percentile PSD calculated starting from the values of the PDF function (Fig. 8) for the vertical (left-hand panel) and horizontal (right-hand panel) components of the seismic recordings at the RISSC, OBS1, and OBS2 stations.



**Figure 10.** Spectral amplitude curves (Brune, 1970) for different values of magnitude computed at hypocentral distance of 5 km and 80th percentile PSD vertical components (thick lines) computed for the OBS1 and RISSC stations.

The comparison between the theoretical and experimental spectra shows that the installation of a seismic station on the seafloor provides advantages for the detection of local seismic events because it shifts the present detection threshold of on-land stations from  $M_w \sim 0.8$  to a lower value of  $M_w \sim 0.2$ .

#### Data and Resources

All data used in this article come from the widely described experiment performed in the Campi Flegrei area and from the Osservatorio Vesuviano waveforms database. These data can be released upon request to [vassallo@na.infn.it](mailto:vassallo@na.infn.it).

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