Seismic Ambient Noise Characterization of a New Permanent Broadband Ocean Bottom Seismometer Site offshore Catalonia (Northeastern Iberian Peninsula)

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INTRODUCTION

The scientific importance of long-term ocean-floor seismic observatories has been widely and internationally recognized by earth science communities. In addition to their usefulness in investigating global-scale geophysical processes, long-term ocean-floor observations are also required to better constrain regional tectonics. However, the implementation of ocean-floor seismic stations is a difficult task, and efforts have been made for more than two decades to resolve the technological and logistical issues associated with such deployments (Romanowicz *et al.* 2009; Suyehiro *et al.* 2006). Different programs in the United States and Canada (*e.g.*, NEPTUNE Project, `http://www.neptune.washington.edu`), Japan (*e.g.*, ARENA Project, Massion *et al.* (2004).), and in Europe (*e.g.*, ESONET Project, `http://www.oceanlab.abdn.ac.uk/research/esonet.php`) have promoted ocean-floor observatories, most of them multidisciplinary. A review of seafloor observatory science can be found in Favali and Beranzoli (2006).

The first initiative for long-term seafloor seismic monitoring in Spain was successfully realized on August 12, 2005, when a permanent broadband ocean-bottom seismometer (OBS) and a differential pressure gauge (DPG) were installed at about 50 km offshore of the region of Catalonia in the northeastern Iberian Peninsula (Figure 1). The ocean-floor station was completely integrated into the Catalan Seismic Network (CSN) in October 2007, when satellite transmission made it possible to have continuous and real-time data available at the network data center in Barcelona. The station, with geographical coordinates 40.71°N and 1.36°E, has the code COBS at the International Registry of Seismograph Stations of the International Seismological Centre.

The project was initially designed with the main goal of improving the understanding of the seismicity of the surrounding region, which is densely populated and industrially very active. The presence of nuclear power plants and chemical and oil industry facilities in the area has major implications on the seismic risk assessment of the region. Moreover, the fact that some earthquakes occur offshore leads to some difficulty in surveying seismic activity with the inland stations only. Thus, it was hoped that the installation of a broadband OBS for real-time data acquisition might improve the performance of the network.

The seismicity of the northeastern Iberian Peninsula is moderate within the context of the Mediterranean region, which is in agreement with its low rate of deformation (Goula *et al.* 1999). However, reliable historical macroseismic data prior to the 20th century confirms that great earthquakes have occurred during historical times and small events are continuously being recorded at present (Olivera *et al.* 1992). The Catalonia region can be divided into three structural units with different geotectonic characteristics (Figure 1): the Ebro basin, the Mediterranean system, and the Pyrenees. The Ebro basin is characterized by a thick sedimentary series greater than 3,000 m.. Seismicity in the basin is very low, in accordance with the low level of tectonic deformation. The Mediterranean system includes the Catalan coastal ranges, which are made of Paleozoic and Mesozoic materials, and the intermediate depressions, which are composed of neogene and quaternary sediments. These are bounded by a NE-SW fault system. In this area, several **M** > 4 earthquakes have occurred, most of them offshore. In particular, a series of earthquakes occurred in 1995, three of them with local magnitudes $M_L = 4.6$, 4.1, and 4.0, which were located close to the COBS station deployment site (Figure 1). Finally, the Pyrenees are composed of granitic massifs, gneiss, and Paleozoic series at the axial zone, and by Mesozoic and Paleogene series at the detached sedimentary cover. Some Neogene-Quaternary volcanic activity is present, and the highest seismicity rate of the region, with some earthquake magnitudes greater than 5, corresponds to this area.

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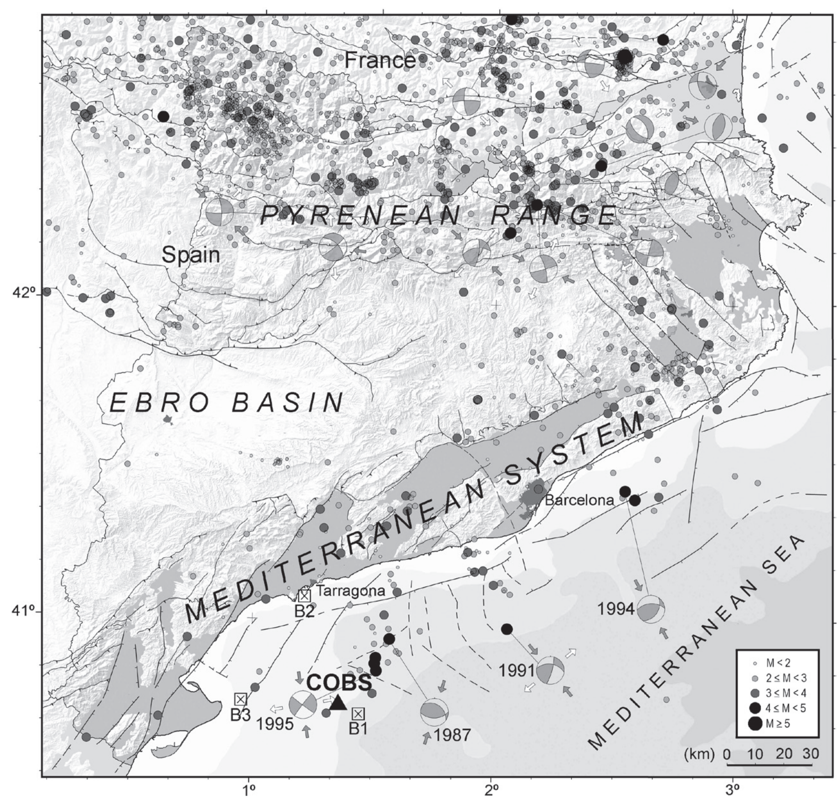


▲ **Figure 1.** Seismicity map of Catalonia region (northeastern Spain) for the period 1977–1997 (modified from Institut Cartogràfic de Catalunya 1999). The main geological features and the location of COBS station (solid triangle) are shown. The location of three oceanographic buoys used is plotted: B1 (Tarragona deep water buoy), B2 (Tarragona coastal buoy), and B3 (Tortosa coastal buoy).

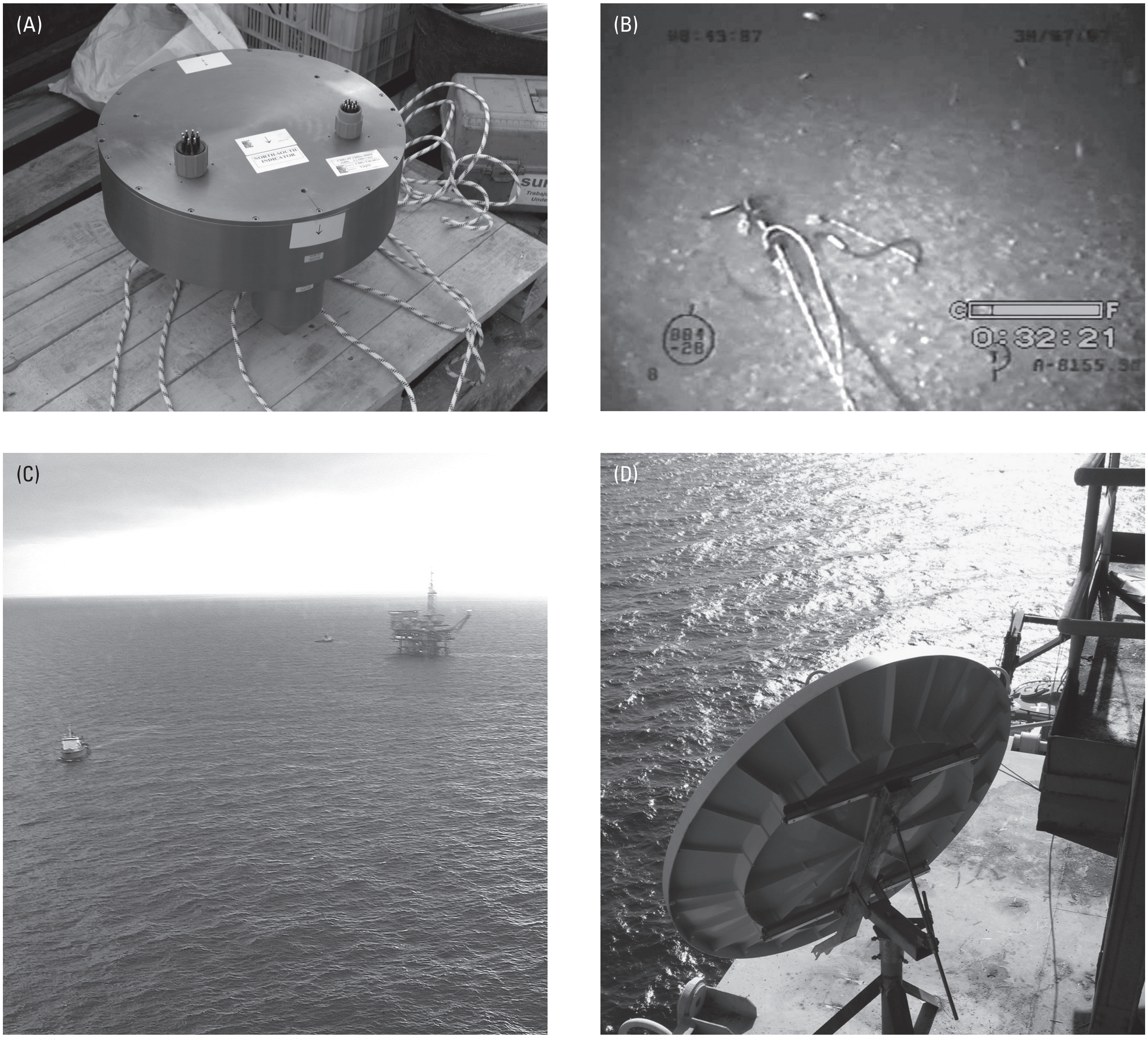
In this paper, we summarize the results of the operation of COBS station in terms of the site ambient noise conditions and quality of the data acquired. There have been many studies on seismic seafloor noise levels, and it has been observed that, in general, they are higher than for land-based seismic stations. The general sources of the seafloor noise levels are well understood; they are mainly related to the wave motions at the sea surface and the interactions of the marine currents with seismic instrumentation (Webb 1998). Unlike most of the reported results from seismic noise studies, which refer to deep environment ocean-floor measurements, this study presents the results for a shallow deployment (with a water column of about 150 m) at 50 km from the coast and 400 m from the Casablanca oil platform (REPSOL-YPF), which constitutes the infrastructure that supplies power to the sensors and hosts the satellite communications equipment. Finally, we analyze the improvement in offshore earthquake locations gained by the CSN due to the availability of almost real-time COBS data.

Seismic data from the OBS station as well from the other broadband stations of the Catalan Seismic Network are accessible to the public by request (http://www.igc.cat) and will be made available through the ORFEUS data center.

INSTRUMENT DESCRIPTION AND DATA

The seafloor seismic station COBS is equipped with a CMG-3T sensor and an integrated 24-bit resolution CMG-DM24 digitizer from Güralp Systems Ltd. and a differential pressure gauge (DPG) manufactured by the Scripps Institution of Oceanography. The seismic sensors and the digitizer are housed in a 50-cm-diameter, 12-cm-height titanium cylinder (Figure 2) with a total weight around 80 kg in air. The seismic sensors have a flat instrument velocity response from 50 Hz to 120 s. The system automatically compensates tilt up to 10 degrees. The DPG has a pass band between 2 Hz to 500 s and it weighs 5 kg in air. The digitizer acquires eight data streams of the three-component seismic sensor and the DPG at sampling rates of 100 samples per second (sps) and 1 sps, together with eight additional streams with system status information and environmental data. COBS site is located at 150-m water depth in the Mediterranean Sea, approximately 50 km offshore Tarragona (northeastern Iberian Peninsula). The OBS is completely buried into the sediments and the DPG is deployed 10 m away from the seismic sensor. The system is linked by a 750-m-long, 26-mm-diameter electromechanical cable with the Casablanca oil platform, which hosts the power supply, the GPS, and the communications equipment for Very small aperture terminal (VSAT) satellite data transmission (Figure 2). This ensures the availability of continuous, almost real-time seafloor seismic data at the Catalan Seismic Network data center in Barcelona (http://www.igc.cat). COBS data is integrated into the monitoring and data management system of the CSN using Earthworm.

As for the instrument orientation, the north axis of the OBS has an azimuth of 196±4° with respect to the geo-

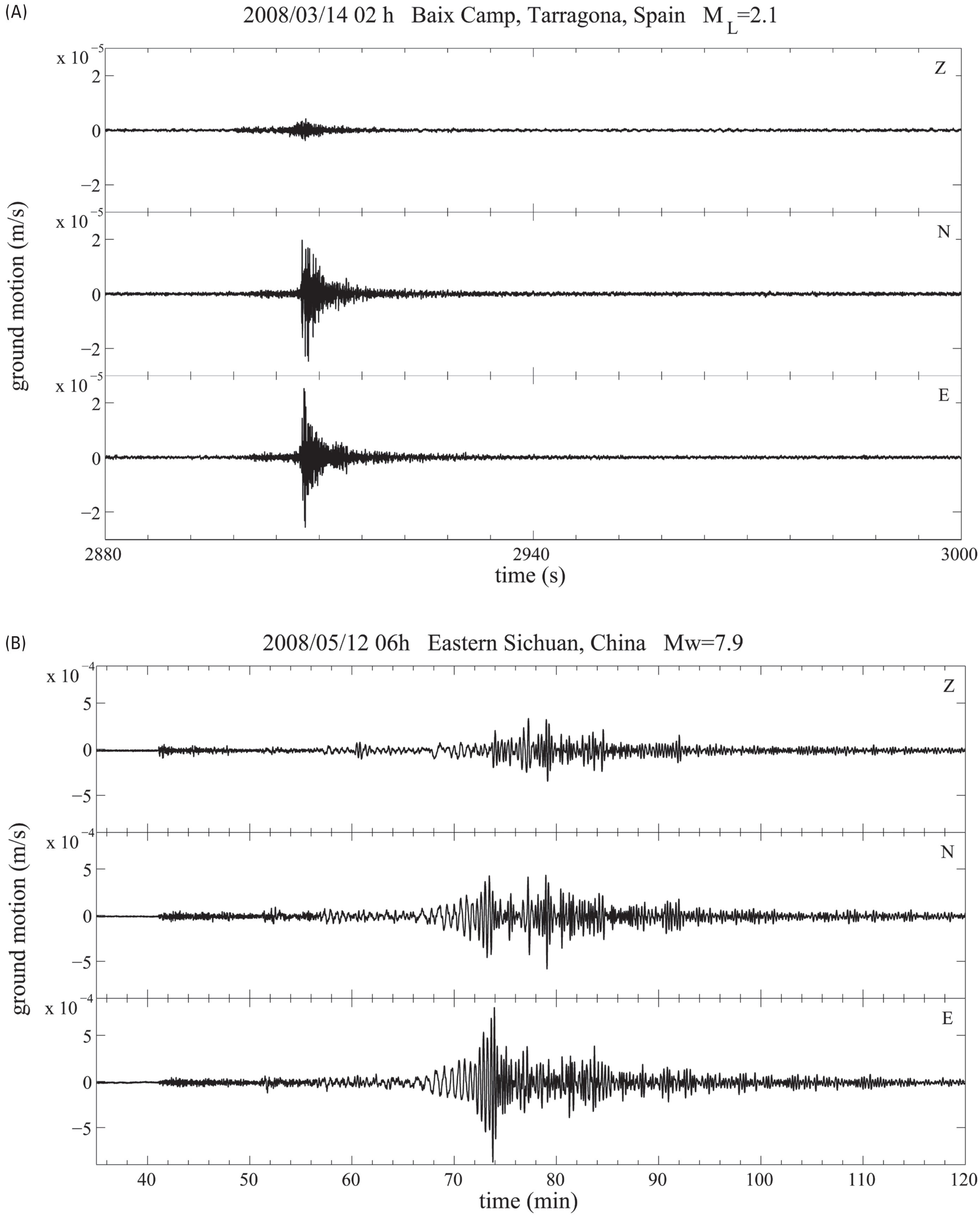


▲ **Figure 2.** Images of the seafloor deployment: A) ocean-bottom seismometer; B) image of the seabed after the deployment; C) aerial view of the deployment operations; and D) satellite antenna at the Casablanca platform.

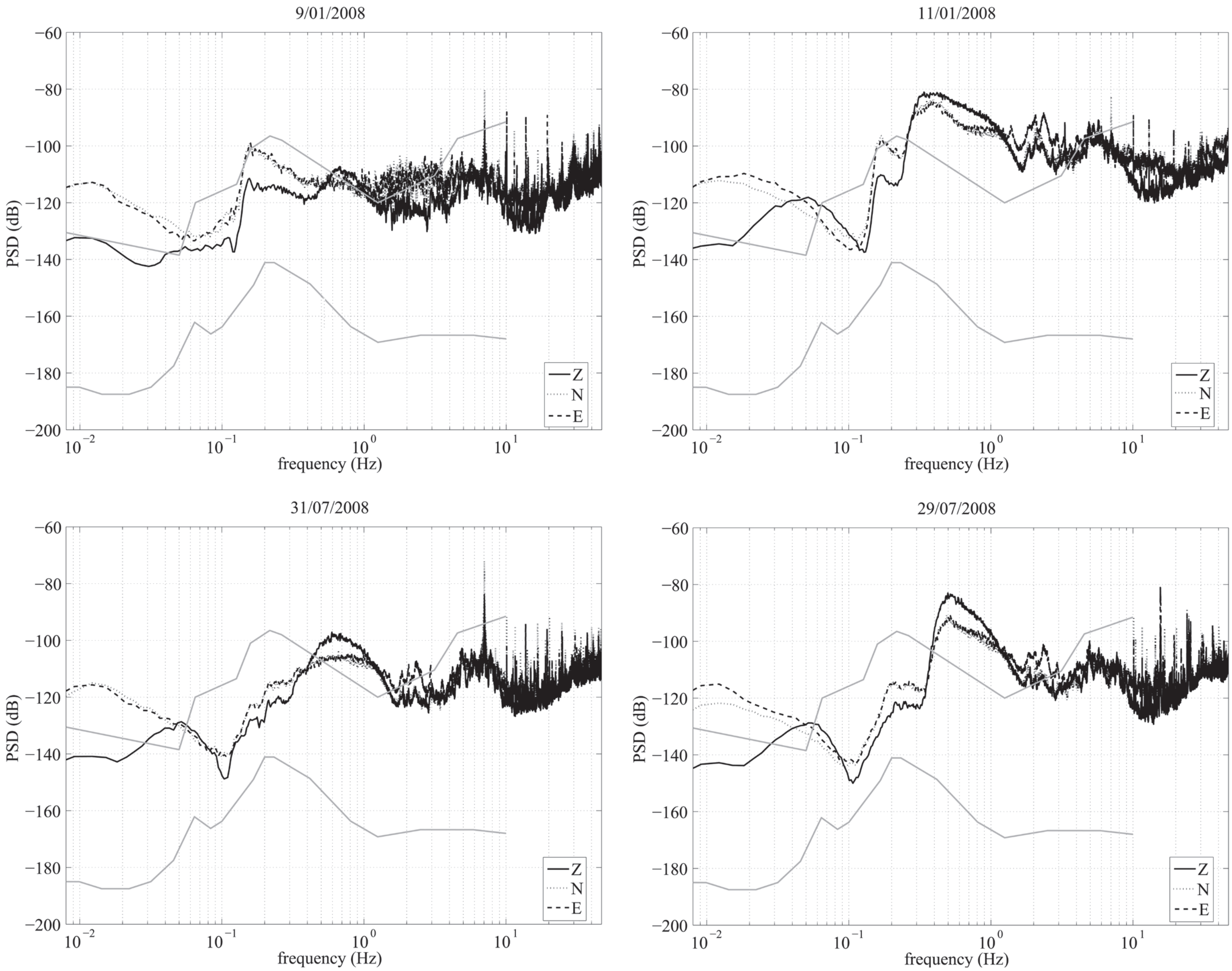
graphic north. This angle was first measured using a remotely operated vehicle (ROV) from a ship and later confirmed by means of polarization diagrams using data from several teleseismic earthquakes. Figure 3 shows two examples of seismic data recorded by COBS station from a local and a teleseismic event.

SEISMIC AMBIENT NOISE ANALYSIS

For the purposes of this work, three-component continuous digital recordings from January 1 to December 31, 2008 were monitored in order to reveal noise level variations at different frequency bands. Noise samples (each 60 minutes long) were taken from the continuous twelve months' data recordings, which were acquired at a sampling rate of 100 samples per second. Earthquakes, explosions, and other transient signals were excluded from all noise samples by visual inspection of the record sections. The smoothed power spectral density (PSD) was calculated for a number of 50% overlapping record segments with a length of 2^{15} samples, corresponding to individual segment lengths of 327.68 s. The PSD was calculated for each segment, after removing the linear trend and tapering with a Hanning window, and then averaged over all segments. The PSD was finally corrected for the instrumental response and presented in units of dB 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 3.** Examples of recordings of a local and teleseismic event at COBS station.



▲ **Figure 4.** Comparison of the noise levels for quiet and stormy days of January and July, 2008. The PSD for three hours of three-component data is plotted together with the NHNM and NLNM of Peterson (1993).

Figure 4 shows power density spectra for two different time periods. Each curve refers to a different component and monthly average noise levels, and the dashed curves show the NLNM and NHNM levels based on land stations (Peterson 1993). Figure 4 shows that January data is, in general, noisier than July data, although the behavior is similar for frequencies higher than 6 Hz. In fact, the ocean-floor seismic-noise spectrum depends on the wind, and therefore it varies with location and season (Webb 1998). In this work, we refer to the following band sections (Webb 1998) for the interpretation of the noise levels: the long-period noise, from 120 s to 0.1 Hz; the microseism band, from 0.1 to 5 Hz; and the very low frequency (VLF) ocean acoustics band, from 5 to 50 Hz.

Below the microseism band, the primary or single-frequency peak around 0.07 Hz is a permanent feature of seafloor or land spectra. Its origin is associated with the conversion of water waves into seismic energy in shallow waters in coastal regions. The increased noise level with respect to the reference noise models observed in Figure 4 for the long-period band is related to ocean currents and infragravity waves (Webb 1998). The noise peak observed in the vertical channel below 0.1 Hz comes from the seafloor compliance, which is defined as the seafloor deformation under pressure forcing from linear surface gravity waves (Crawford and Webb 2000). The pressure signal from these waves, which is stronger at a sedimented site than at a hard-rock site, is only significant at frequencies corresponding to wavelengths longer than the water depth (150 m at this site), and it can be removed (Webb and Crawford 1999), as will be shown later. Stronger long-period noise on the horizontal components is due to tilt (Araki *et al.* 2004).

The microseism band is characterized by oceanic microseisms related to the dominant spectral peak between 0.15 and 0.2 Hz. This large peak is called the secondary or double-frequency peak and was explained by Longuet-Higgins (1950) as being generated by non-linear pressure perturbations in the ocean bottom caused by the coupling of ocean waves of equal wavelengths traveling in opposite directions. Using Longuet-Higgins's theory, Kedar *et al.* (2008) have recently demonstrated the existence of a dominant source of microseism generation in the north Atlantic Ocean, which is identified in a region extending from the Labrador Sea to the south of Iceland. Figure 4 also shows that the calculated mean PSD values present a wide noise peak in the microseismic band around 0.6 Hz. As explained by Webb (1998), the seafloor is usually noisy at these frequencies because of the microseisms caused by 0.5 Hz ocean waves that can be quickly produced by even a moderate breeze. But energetic microseisms driven by local ocean waves can be present in ocean floor spectra at frequencies as high as 5 Hz (Webb 1998).

The noise levels at the COBS site are below the NHNM for the VLF acoustics band. Noise level between 10 and 50 Hz is mostly controlled by man-made sources (Webb 1998). In this sense, the spectral lines observed in Figure 4 above 7 Hz might be due to the oil platform activity and/or ship machinery. Although the oil platform is a potential source of high-frequency seismic noise, it constituted an essential infrastructure for the success of the present project, since the cost and the logistics involved would have been unaffordable otherwise. The existence of the platform eliminates, on the one hand, the need for periodic exchange of batteries and data packages using ROV and ship, and allows, on the other hand, available real-time data at reasonable cost. This is not the first deployment of a permanent ocean-floor seismic station near an oil platform. The ocean-floor seismic station at Oseberg (OSG) (*e.g.*, Atakan and Havskov 1996) was installed 2 km away from an oil platform at 160-m depth. It was operative from 1989 to 2003 and provided data to the Norwegian national seismic network. It was recognized as an important element of the network, which provided information critical to the monitoring of the seismicity offshore of Norway.

We discuss the ambient noise levels at the COBS site, their possible sources for different frequency bands, and the contribution of the seafloor seismic station to the CSN performance in the next section.

DISCUSSION

Temporal Variations of the Noise Levels at COBS

It has been observed at COBS that the PSD values do not show diurnal changes for any component, probably due to the absence of anthropogenic noise sources near the sensor. As for the oil platform, it does not change the activity rate during the day.

All of the data for the 12-month interval can be summarized in spectrogram displays of the PSD as a function of time and frequency. This representation may help to check for seasonal variations of the noise levels. Figure 5 shows the daily average three-component spectrograms for one year of continuous recording. The maximum noise levels occur in winter and the minimum in summer, as expected, because the intensity of storms is higher in winter than in summer and there are, on average, a greater number of noise sources (low-pressure areas) in winter than in summer (Romanowicz *et al.* 2006). From Figure 5 it can be seen that the COBS noise shows large temporal changes, especially in the microseism band, that are linked to seasonal variations. It is observed that around 0.1 Hz, the vertical-component PSD is up to 40 dB lower in summer than in winter. For the horizontal components, Figure 5 shows a reduction of up to 20 dB of the noise amplitudes during the summer season.

Correlation with Meteorological Data

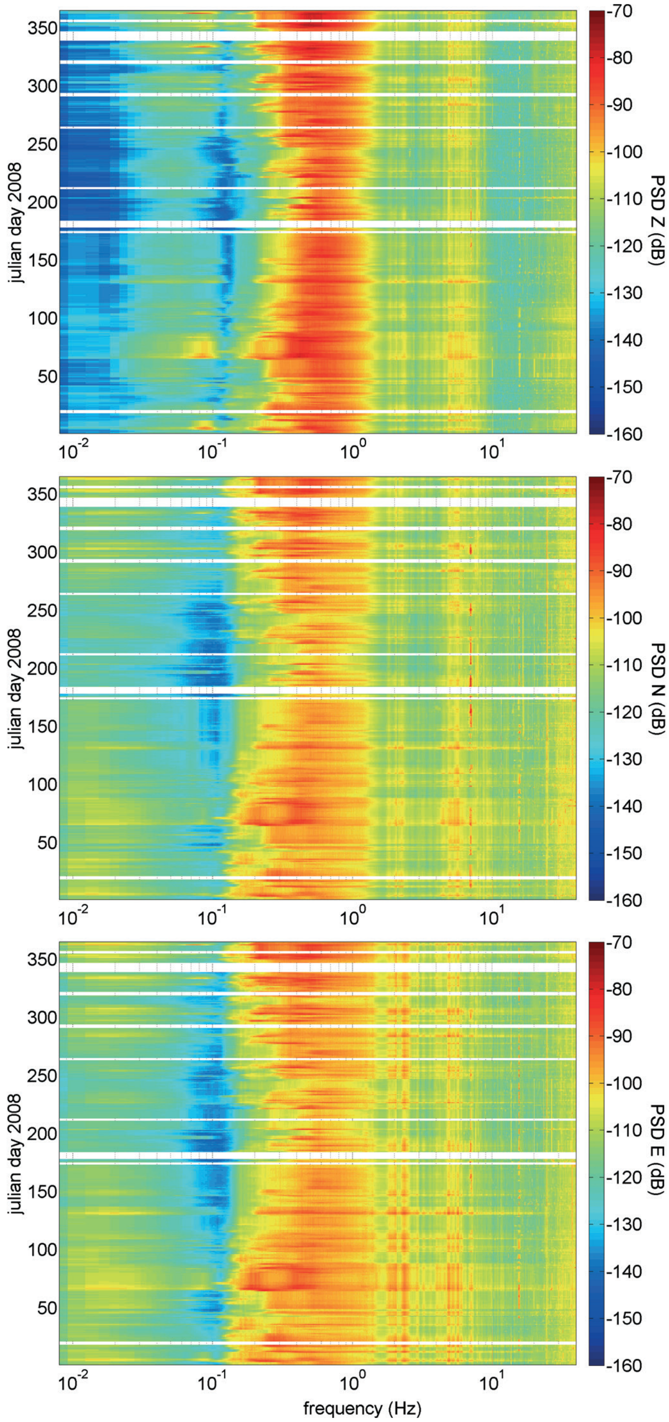
It is well known that meteorological conditions play an important role in the generation of seafloor seismic noise, in particular due to the influence of wind speed. In this study we use data from three oceanographic buoys located near the OBS (Figure 1) to compare the power density spectra calculated under different meteorological and oceanographic conditions. Figure 6 shows the trend of the significant wave height measured at the three nearby buoys compared to the calculated spectrogram for the first 15 days of the recorded data. It is observed that the noise levels change considerably with the weather in a broad frequency range and that high noise levels correlate well with significant wave height peaks, which correspond to high wind speed recordings. The compliance peak below 0.1 Hz at this site, visible primarily on the vertical component, becomes stronger and wider in frequency for high significant wave height values. Comparing the arrival times at buoys Dolenc *et al.* (2008) demonstrated that the infragravity waves are generated when the short-period ocean waves reach the coast and not when they pass directly above the station. On the other hand, the significant wave height has a great influence in the calculated noise levels for the microseism band. This indicates that, as suggested in other studies (*e.g.*, Webb 1998), wind-driven gravity waves are important sources of seismic noise in these frequency bands.

Low-frequency Correction of the Vertical Component

It has been shown (*e.g.*, Crawford and Webb, 2000) that most of the low-frequency (< 0.1 Hz) noise at a seafloor site comes from instrument tilting under fluid flow and the seafloor displacement under ocean-surface gravity waves. This noise can be reduced on the vertical channel by removing the part that is coherent with noise on the horizontal seismometer channels and the pressure channel (Crawford *et al.* 2006). Therefore, a differential pressure gauge is an essential part of any broadband ocean-floor seismic station (Webb and Crawford 1999).

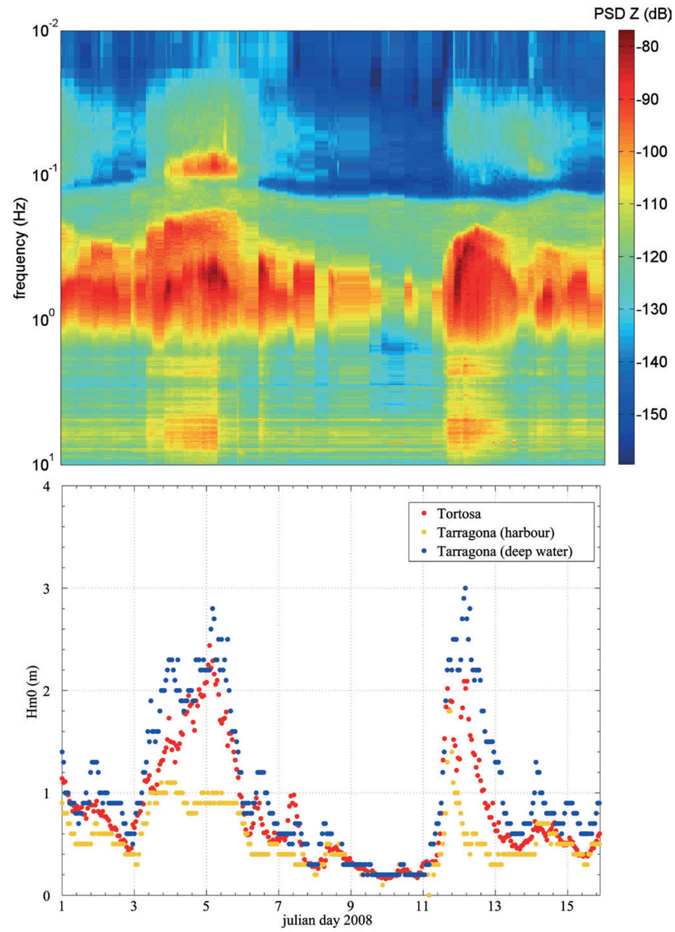
The tilt-generated seismic background noise can be removed following Crawford and Webb (2000) and Crawford *et al.* (2006) by calculating the so-named transfer function from the spectral ratio and coherence between the horizontal and vertical channels and then subtracting the coherent horizontal energy from the vertical channel. The same technique can be used to remove the pressure signal from the vertical component (Webb and Crawford 1999). This technique assumes that the horizontal channels are mostly controlled by tilt below 0.1 Hz and that the infragravity signal is only on the pressure and vertical channels.

Figure 7 shows an example of the coherence calculated between the vertical and horizontal components and between the vertical component and pressure measurements for a seismologically quiet day. In all cases, the coherence is high in



▲ **Figure 5.** One-year spectrograms for the vertical and horizontal components of the OBS.

the frequency band between 0.02 and 0.1 Hz. We remove the coherent data by first calculating the frequency-domain transfer functions between the different components and then using the algorithms of Crawford and Webb (2000). The corrected spectra, plotted in Figure 7, show that the new noise floor is up to 40 dB lower that in the original data below 0.1 Hz, so the noise levels are now between the NHNM and NLNM of Peterson (1993).

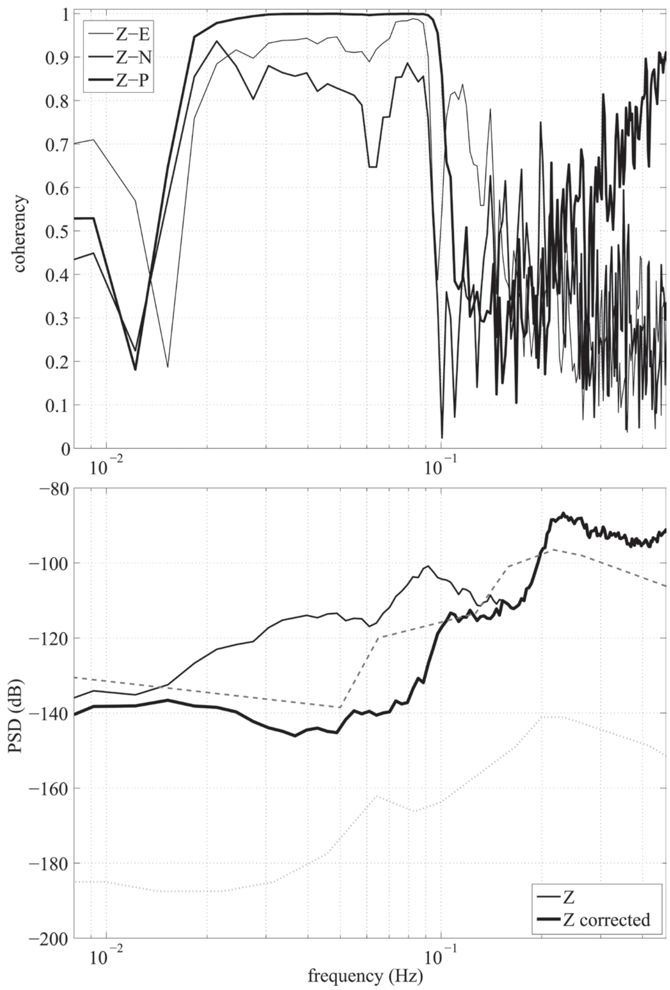


▲ **Figure 6.** Vertical-component spectrogram for two weeks of COBS data together with the variation of the spectral significant wave height measured at buoys B1 (Tarragona deep water), B2 (Tarragona harbor), and B3 (Tortosa).

Comparison with other OBS and Land Sites

Apart from other temporary deployments (*e.g.*, Dahm *et al.* 2006), some permanent seafloor seismic stations exist in the Mediterranean region in addition to COBS. SN1 (Favali and Beranzoli 2008) was the first real-time seafloor observatory in Europe and has been operating since 2005. It was deployed 25 km offshore of the eastern coast of Sicily (southern Italy) at a depth of 2,060 m. Using data from an initial experiment, Monna *et al.* (2005) reported noise levels at SN1 comparable to a nearby land station above 0.1 Hz. In comparison with COBS, SN1 shows lower noise levels at all frequencies. However, we note the presence of a peak around 0.8 Hz due to local wind-driven sea waves, also observed at COBS. As for the noise peak produced by infragravity waves that is observed at COBS below 0.1 Hz, it is reported at SN1 for frequencies lower than 0.02 Hz (Monna *et al.* 2005).

In 2008, a multidisciplinary marine module, which was named CUMAS and included a broadband OBS, was deployed in the Campi Flegrei caldera (southern Italy) (Iannaccone *et al.* 2009). Because noise measurements at this permanent site have not been reported yet, we compare here the background seismic noise of two broadband ocean-bottom seismometers that

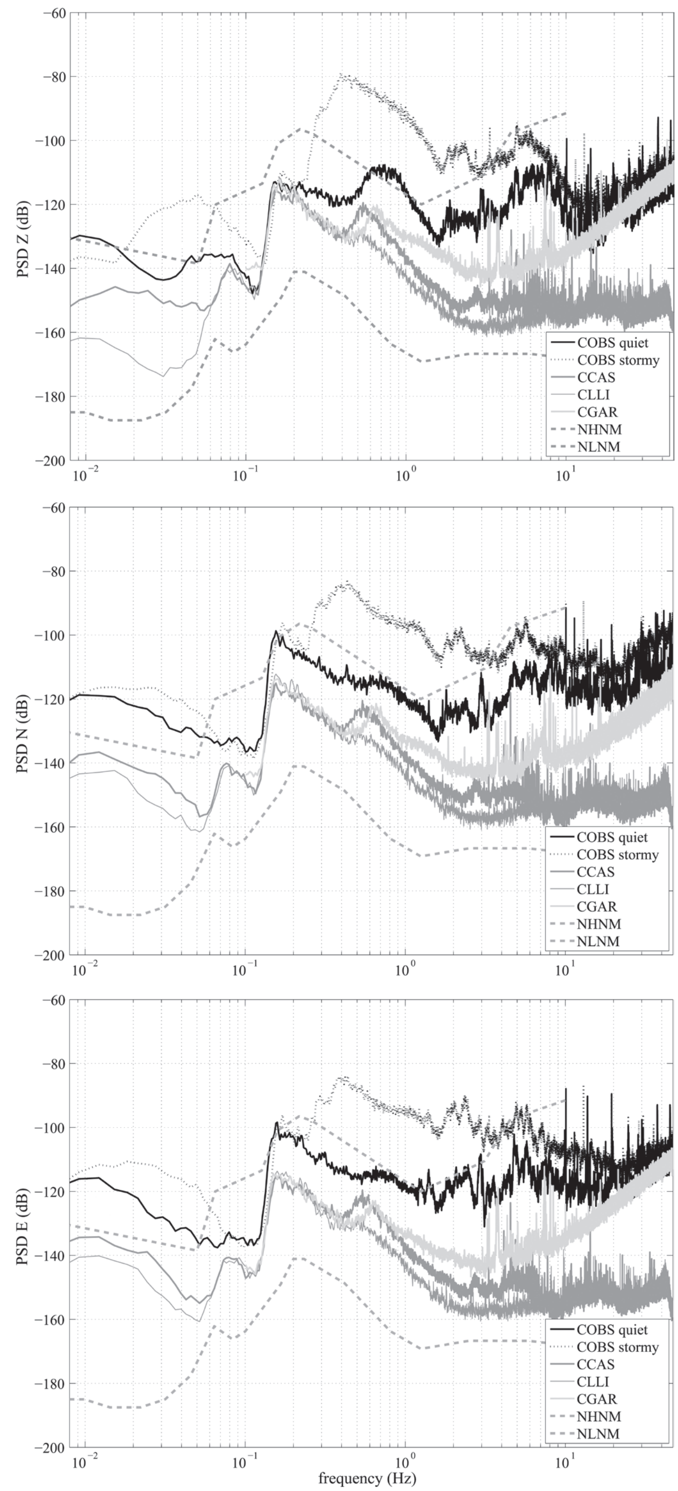


▲ **Figure 7.** (Top) Coherence between horizontal and vertical components and pressure data calculated for the time period between 1:00 h and 1:59 h 4 January 2008, and (bottom) vertical-component PSD before and after low-frequency data removal.

were deployed in the seafloor of the caldera at a previous date (Vassallo *et al*. 2008). In contrast to SN1, these OBS were sunk at a depth of about 100 m, close to the coast, under conditions similar to COBS station. From the experiment at the Campi Flegrei site, which is in general noisier than the COBS site, we want to point out the similarity of the noise peak caused by local sea waves observed at both the COBS site and the Campi Flegrei caldera between 0.5 and 1 Hz.

In the Mediterranean region (Ligurian Sea), the Antares OBS has been operating at a depth of 2,550 m since 2005 (Deschamps *et al*. 2005). This permanent seafloor observatory has similar seismic instrumentation as the one presented here. A seismic noise analysis at the Antares site and a comparison with the noise levels at COBS are in progress.

Among other recorded ocean floor measurements in deep environments (*e.g.*, Stephen *et al*. 2003) we will highlight here a comparison of the noise characteristics between the COBS site and MOBB, which is a successful permanent ocean-bottom seismometer installation located 40 km offshore Monterey Bay, California, at a water depth of 1,000 m



▲ **Figure 8.** Comparison of noise levels recorded at COBS (for a quiet and a stormy day) and three land stations of the Catalan Seismic Network.

(Romanowicz *et al*. 2009). The noise characteristics at MOBB and the quality of data acquired have been extensively studied (*e.g.*, Dolenc *et al*. 2005, 2007; Romanowicz *et al*. 2006, 2009). MOBB is significantly quieter than COBS for all frequencies. In this case, the noise "hump" produced by infragravity waves, which is observed at MOBB for frequencies lower than 0.05 Hz (Dolenc *et al.* 2008), is recorded at COBS below 0.1 Hz. Since only linear waves with wavelengths comparable or larger than the water depth can generate a detectable pressure signal at the seafloor (Webb 1998), the additional water column at SN1, Antares, and MOBB results in a higher value of the high-frequency cutoff of the long-period noise peak at COBS.

Finally, we show in Figure 8 the noise levels for a meteorologically quiet day at COBS station and three land-based stations of the CSN. CGAR is a coastal station, CCAS is a 32-m-depth borehole station at less than 20 km from the coast, and CLLI is located at the Pyrenean range, at about 90 km from the sea. We observe that whereas the horizontal components are noisier, the vertical component noise at COBS is comparable to the three land stations around the microseismic peaks. As for the noise peak observed in this figure at COBS around 0.7 Hz, caused by the influence of wind-driven ocean waves, it also exists at CGAR and CCAS and it almost disappears at CLLI. The peak is shifted toward lower frequencies for stations located farther from the sea.

Contribution to the Catalan Seismic Network

COBS data is integrated into the monitoring center data management system of the CSN through Earthworm. COBS station is at present in a configuration testing period and is thus not contributing to the CSN automatic location system yet. However, when an event is detected by the automatic system, COBS recordings are also analyzed manually, together with the other stations of the network, thus contributing to the final locations. This information is published at the Institut Geològic de Catalunya (IGC) Web site (http:// www.igc.cat).

In spite of the seafloor noise levels, which can be high under severe meteorological conditions, some improvements of the hypocenter location accuracy have been achieved from the integration of land and COBS data. The hypocenter locations of some low-magnitude ($M_L < 2$) offshore seismic events by the integration of land and offshore (COBS) data in comparison with locations estimated from land data only show that the COBS data reduced the azimuthal gap and better constrained the hypocenter depth. The earthquake location tests performed to date show up to a 37% and 25% reduction of the horizontal and depth location errors, respectively, with COBS station. Nevertheless, these results are not significant, since only a small number of low-magnitude offshore local events have occurred during COBS operation period. New data will help to validate these results.

CONCLUSIONS

In August 2005 a permanent ocean bottom seismometer (OBS) and a differential pressure gauge (DPG) were installed inside the security perimeter of the Casablanca oil platform (50 km offshore Tarragona, northeastern Spain), within the framework of a project that has the aim of improving knowledge of the seismicity and seismic risk in the region. The sensors were submerged at about 400 m to the southwest of the oil platform and were deposited at about 150 m in depth. In July 2007 the OBS station (international seismic station code COBS) was integrated into the Catalan Seismic Network (CSN) through a VSAT platform that is transmitting continuously almost real-time seismic data via satellite to the IGC hub. Once at the seismic data center, data are continuously archived and processed with an automatic system.

We have conducted a study of the OBS signal in terms of noise and compared the levels to the ambient noise levels of other OBS and some land-based Catalan Seismic Network sites. We find that COBS, like most ocean floor stations, has quite noisy behavior in comparison to land stations. Nevertheless, COBS has recorded a number of teleseismic, regional, and local events since it became operational. At present, the data provided by the seafloor sensor are used to perform manual locations, which can be improved for local offshore events that would have a larger station gap without these data.

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