Long-term Seafloor Experiment with the CUMAS Module: Performance, Noise Analysis of Geophysical Signals, and Suggestions about the Design of a Permanent Network

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INTRODUCTION

The Campi Flegrei caldera (southern Italy) is one of the most hazardous areas in the world because it is home to several hundred thousand people live there and an important center of socio-economic activities. The caldera includes the westernmost part of the city of Naples and extends into the Gulf of Pozzuoli (eastern Tyrrhenian basin; Figure 1). The main feature of the present volcanic activity of the caldera is the episodic slow and high-amplitude soil movement (bradyseism) accompanied by intense and shallow seismic activity that only occurs during the uplift phase.

The most recent strong bradyseismic episode occurred between 1982 and 1984, when there was a maximum ground uplift of more than 170 cm, which was followed by slow and continuous subsidence, accompanied by rare low-amplitude uplifts (of a few centimeters). The maximum uplift was observed in the center of the caldera, in the town of Pozzuoli, while toward the caldera margins the uplift decreased gradually. The amplitude and the areal distribution of the vertical soil displacement that occurred over time in the marine sector, which covers more than one third of the caldera area, is completely unknown. During this 1982–84 bradyseismic episode, there were more than 10,000 shallow earthquakes (<4 km) with a maximum recorded magnitude of 4.2 (Aster et al. 1992). The space distribution of the earthquake hypocenters was denser on land, where the monitoring network had been deployed (Figure 1). In contrast, only a small number of the earthquakes were located in the marine sector. This can be explained primarily by a probable lesser level of seismic activity in the marine sector than on land, and secondly by the inadequate coverage of the sea area by the monitoring network configuration in place at the time.

The present geophysical surveillance system that operates in the Campi Flegrei volcanic area is managed by the Osservatorio Vesuviano (Vesuvius Observatory), a branch of the Istituto Nazionale di Geofisica e Vulcanologia (National Institute of Geophysics and Volcanology, INGV). This system consists of several permanent networks that provide continuous seismological, geodetic (global-positioning system, GPS), mareographic, and geochemical data, which is managed by a centralized monitoring center in Naples that operates 24 hours a day. In particular, the seismological network includes eleven stations that are located on land (see Figure 1), nine of which are equipped with short-period seismometers (1 Hz) and two that have broadband seismometers (60 s; 50 Hz).

Future enhancement of the surveillance system is aimed at improving the hypocenter location of earthquakes that occur in the marine sector, lowering the detection threshold of this seismicity, and revealing low-frequency seismic events related to the specific volcanic activity of this area. In addition, the acquisition of ground movement measurements at the seafloor is necessary to correctly model the deformation pattern of the whole of the Campi Flegrei caldera. A first step toward these objectives has been the extension to the seafloor of the existing monitoring network through the development and operation of a marine multisensor platform that was specifically designed for real-time monitoring.

This platform was named CUMAS, for “cabled underwater multidisciplinary acquisition system,” and it was deployed in the Pozzuoli Gulf (Figure 1) and operated for about one year. A detailed description was given by Iannaccone et al. (2009). The core of CUMAS was the seafloor module that contained the geophysical and oceanographic sensors, hereafter referred to as the Campi Flegrei sea bottom (CFSB) station. The sensors

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acquired seismic signals (three-component, broadband seismometer), low-frequency acoustic signals (hydrophone), and water current velocities (single-point three-axial current meter). A sea-bottom pressure recorder (SBPR) was installed to test the feasibility of detection of the seafloor vertical ground displacement during bradyseismic episodes. A buoy was connected by cable to the CFSB station and equipped with auxiliary sensors (meteorological station) and a radio communication device that allowed real-time data transmission to the monitoring center. After installation of the CFSB station in the Gulf of Pozzuoli on 25 January 2008 (about 2.4 km from the shore and at 97 m water depth; Figure 2) and a test period lasting three months, CUMAS operated in real time until July 2009, acquiring data for the marine sector of the caldera for the first time. The data of the seismometer and the SBPR span three and four months, respectively, due to some failures in the CFSB station housing, while for the current-meter, although it provided data for the whole of the CUMAS working period, these data have since been shown to be incorrect. In spite of these technical problems, which limited the data availability with respect to the original plan, CUMAS has provided valuable data.

We performed an analysis of the seismic, acoustic, and bottom-pressure data to obtain relevant indications for the design of a permanent seafloor network in the area. In addition, we analyzed and processed the SBPR signal to validate this system for detection of seafloor uplift and to assess the detection thresholds for this specific application. This report provides the seismic and acoustic background noise and event recordings analyses in comparison to the equivalent land data. In this paper we conclude by discussing some practical aspects relating to seafloor monitoring installations.

**SHORT DESCRIPTION OF THE CUMAS SYSTEM**

The CUMAS system consisted of a seafloor module that was connected by cable to a buoy equipped with the power supply and data-transmission devices. The seafloor module of the CFSB station included the geophysical and oceanographic sensors; in particular, a three-component broadband seismometer (CMG-40TBS; Güralp Systems Ltd.), a low-frequency hydrophone (SQ03; Sensor Technology), and an SBPR (8000 Series; Paroscientific). A single-point, three-component, water-current meter and a water-temperature sensor were also installed on the CFSB station to monitor the marine environment. The status sensors, which included a digital compass and a two-component digital tilt-meter, were added to track the attitude of the module over the course of the experiment. Control sensors for water intrusion detection and vessel internal temperature and power consumption were installed to monitor the acquisition system itself.

The acquisition of the data streams of the seismometer and the hydrophone was performed at a sampling rate of 100 sps by a Quanterra Q330 digitizer. The data acquisition system for the physical-oceanographic digital sensors and for the status sensors that have a lower sampling rate was performed by an embedded computer (MOXA UC-7408, with a Linux
operating system) that was equipped with a storage memory of 4 Gbytes for data back-up. The sampling rates of the SBPR, current meter, and status sensors were set to 10 sps, 2 sps, and 1 sps, respectively. A detailed description of the scientific and status sensors can be found in Iannaccone et al. (2009).

The CFSB station was connected to the buoy by an electromechanical cable, for use in the deployment/recovery operations and for the power supply and data transmission (Figure 2). The buoy was an elastic-beacon type and it was equipped with solar panels, a wind generator, data transmission devices, a meteorological station, and a GPS antenna that provided an absolute time reference for the scientific and status data from the marine module and the buoy. The communication system installed on the buoy allowed the data transmission and the remote control and modification of the acquisition parameters of all of the devices in the sea. The scientific data acquired by the Q330 data logger of the CFSB station were sent as continuous streams directly to the monitoring center, where they were managed by the existing Earthworm-based system (Johnson et al. 1995). This allowed a seamless integration of CUMAS data into the data management system of the geophysical monitoring network and the leveraging of several Earthworm-based software applications that are widely used in seismology. Conversely, the low-frequency data, such as those related to the health of the CUMAS and the buoy hardware (e.g., water intrusion, internal temperature and pressure, voltages, and currents) and the meteorological station data on the buoy, were acquired as text files in custom formats and sent to the monitoring center every hour. There, procedures developed in-house converted the files into Earthworm-compatible data packets that were integrated into the system in a near real-time fashion. Winston software (Cervelli et al. 2004; Winston 2009) was used to store the various data channels flowing into Earthworm (i.e., scientific sensors and status channels) in a MySQL database (http://www.mysql.com).
The winston software can implement some useful features, such as compressed data retrieval and data display either as static images (for Web publishing) or through the interactive Swarm software (Cervelli et al. 2004). An original Web application was developed (Elia et al. 2009) to provide a graphical user interface to Earthworm and Winston; this can display hours to days of data as a virtual “helicorder” and let users download the recorded data as files in SAC format (Seismic Analysis Code; http://www.iris.edu/software/sac) by selecting a time span and the channel settings. An additional Web page provided the meteorological data in the format used by the U.S. National Oceanic and Atmospheric Administration (NOAA).

ANALYSIS OF THE SEA-BOTTOM PRESSURE-RECORDER DATA

The SBPR detected the pressure variations produced by waves, tides, atmospheric pressure, and water-column height variations. The SBPR was installed in the CFSB station to explore the feasibility of monitoring slow seafloor vertical movements related to bradyseismic episodes as variations in water-column height.

Similar SBPRs are used in NOAA’s DART (Deep-ocean Assessment and Reporting of Tsunamis; http://nctr.pmel.noaa.gov/Dart/) systems (Meinig et al. 2005) and sometimes to detect seafloor deformation. Recently, Sohn et al. (2009) found a periodic variation in the seafloor pressure near a geothermal field of the mid-Atlantic ridge, at a depth of about 3,600 m, which they interpreted as displacement of the ocean bottom. A displacement of 13 mm was ascribed to small flow-induced pressure fluctuations in the very shallow hydrothermal field.

During the CUMAS experiment, the land-based geodetic monitoring systems of the Campi Flegrei (continuous tide gauges and GPS data and periodic SAR images and high-precision leveling measurements) did not detect any bradyseismic ground movement. This would suggest that seafloor movements were not expected at the CUMAS site either. However, long-term and continuous vertical movements of the seafloor are difficult to detect, as the resolution of the sensor is influenced by the local ambient noise and the sensor electronics noise. Polster et al. (2009) performed an extensive study on the effective resolution and drift of SBPRs (Paroscientific) by analyzing long-term data from 118 sensors deployed in the Pacific and Atlantic oceans over the last 20 years, and making use of the theoretical tide signals. For sensors installed on the sea floor, they estimated a mean pressure noise level corresponding to 1.78±0.04 mm, thus indicating this as the minimum detection threshold.

We performed a comparative analysis to evaluate the use of the CUMAS SBPR data for detecting seafloor deformation associated with bradyseismic uplift events. For this analysis, we assumed the signal from the MISE coastal mareographic station (see Figure 1) as the reference signal, because it is positioned at the caldera edge where ground uplift is usually minimal. We converted the SBPR signal acquired by CUMAS into water-column height by removing the atmospheric pressure, measured by the barometer of the meteorological station of the buoy, and considering the physical properties of the seawater in the area (Stabile et al. 2007). The resulting signal was compared to the sea-level measurements of MISE. Figures 3A and B show the time-series of the CUMAS SBPR as converted to water-column height, and of the MISE over a period of seven days. These two signals are very similar and show a low-frequency oscillation that is associated with the daily tide, with a period of 12.4 hours. Figure 3C shows the differences between the CUMAS SBPR and the MISE signal. As we can reasonably assume that no ground uplift events occurred during the observation period (20–27 May 2008), we can consider this residual signal of the CUMAS SBPR as the noise resulting from the combination of the instruments and the site noise, for the data analysis performed. Figure 3D shows the spectrum of the SBPR residual signal. The spectrum is typical of white noise except for two narrow-band peaks that correspond to periods of 21 min and 26 min. These peaks can be interpreted as stationary waves (seiches) in the nearly circular Gulf of Pozzuoli (Capuano et al. 2004). The spectrum of the SBPR residual signal was almost flat over the frequency range 1–8×10⁻³ Hz, with a maximum level almost constant at around 1.4 cm. Given the types of tidal and SBPR sensors installed in the area, we can thus consider...
this value as the present threshold for detection of an event of ground uplift at the seafloor.

**ANALYSIS OF THE SEISMIC AND ACOUSTIC SENSOR DATA**

Vast scientific literature exists on seismic noise recorded on the seafloor and acoustic noise in the ocean at frequencies of seismological interest (e.g. Brocher *et al.* 1981; Webb 1998; Babcock 1994; Bromirski *et al.* 2005). Nearly all of these studies have dealt with measurements acquired at great depth, in oceans and far from the coast. Only a few seismological data analyses have been carried out in shallow waters and near the shore, which conversely are of particular interest for the coastal monitoring of volcanic and seismic areas that extend both on land and at sea. The CUMAS experiment enabled a comparative analysis of earthquake and noise recordings from the hydrophone and the seismometer in these shallow waters. This analysis provides useful indications for the design of a future local seafloor network in the Campi Flegrei and for a first assessment of its detection power.

**Seismic and Acoustic Background Noise**

The background seismic noise recorded by the CUMAS seismometer of the CFSB station showed a power spectral density (PSD) with a different pattern compared to the reference new high noise model (NHNM) and the new low noise model (NLNM) curves defined by Peterson (1993). In particular, the PSD computed for the vertical component (Figure 4A, black curves) had a sharp and narrow peak at around 0.1 s (10 Hz) inside the NHNM and NLNM curves, while for periods higher than 0.3 s, the PSD increased to reach a maximum at around 1.5 s, with a broad bell shape exceeding the NHNM. Starting from the period value of 2 s, the PSD again fell inside the NHNM–NLNM range of up to 10 s. The PSD computed for the horizontal components was similar to that obtained for the vertical component, but it was noisier in the 0.1–0.5 s range of periods. However, the microseismic peak at 5 s appeared more visible in the PSD of the horizontal components (Figures 4B, C).

The seismic noise PSDs obtained for CUMAS had a similar pattern with respect to the PSDs computed for the ocean bottom seismometers (OBSs) previously deployed in the same area during an experiment carried out in 2005 (Figure 4, gray curves; Vassallo *et al.* 2008). In addition, the PSD amplitudes of CUMAS and the OBSs significantly agreed for periods greater than 0.2 s, while below this value the OBSs showed larger amplitudes of seismic noise PSD, especially for the horizontal components. It is worth noting that in contrast to CUMAS, the OBSs were installed through a free-fall deployment, with no control during the descent and touch-down. Therefore, despite the different sensor-hosting structures, types of deployment, periods of operation, and locations of CUMAS and the OBSs, the comparison of the PSDs of the seismological signals indicates considerable persistence of the main features of the background seismic noise.

Background noise analysis was also performed for the hydrophone signal in the same interval as the seismometer (0.03–30 s). For this instrument (SQ03 model; Sensor Technology), the response function was supplied for the 20 Hz to 60 kHz frequency range, while it was not provided for lower frequencies. The PSDs obtained from the hydrophone signals (Figure 5, gray curves) had an almost constant amplitude for periods below 0.4 s; a broad bell shape from 0.4 s to 5 s, with the maximum value higher than –20 dB around 1 s; and a sharp peak around 10 s with a maximum value of about
-40 dB. Although it is unusual to compare background noise recorded by a hydrophone and a seismometer, we note the general resemblance of the PSDs of the CUMAS hydrophone with those for the components of the seismometer (Figure 5, black curves). This resemblance is also evident comparing the spectrograms computed over four days (Figures 6A and B). For both sensors, the spectrum maximum was located around 1 s and extended on the frequency band 0.6 s to 3 s, corresponding to the blue regions in Figures 6A and B, over the entire period analyzed. This suggests the same noise source for both signals. In addition, the day-night succession was clear in the spectrograms, with coincident minima in frequency and time revealing the influence of man-induced noise on both the acoustic and seismic noise. A feature of note is the maximum around the period of 10 s that lasted for the whole first day (Figure 6). Interestingly, the presence of this feature for the hydrophone is evidence that this sensor can efficiently record signals around this frequency, although it lies outside the nominal working frequency range provided by the supplier. Figure 6C shows the smoothed wind velocity signal obtained applying a four-hour mobile-window at the data recorded by the meteorological station on the CUMAS buoy over the same period on the spectrogram. The figure highlights a correlation between the wind velocity and the noise amplitude peaks of the seismometer and the hydrophone, at around 1 s. Moreover, during 21 May, when the highest wind velocities of the four-day period were recorded, a peak of noise at 10 s is present in the spectrograms. This apparent correlation between wind velocity and background seismic and acoustic noise was explored in detail over two restricted period ranges. The first range was selected around 1 s (corresponding to the blue regions of Figure 6) and extends from 0.7 s to 3.0 s. The second range extends from 0.03 s to 0.5 s, where there is no evidence of correlation. Figures 7A and B show the PSDs of the seismometer and the average noise of the hydrophone over the period ranges 0.03 s to 0.5 s and 0.7 s to 3.0 s respectively, over one week, including the four days of Figure 6, while Figure 7C shows the corresponding smoothed wind velocity signal. As a first significant result, this analysis indicates the identical behavior of the seismic and acoustic noise signals within both period ranges as further evidence of a common noise origin. In the range of 0.03 s to 0.5 s (Figure 7A), the day-night periodicity of the seismic and acoustic noise PSD that showed almost constant values from day to day is clearly evident, while no correlation appeared for the wind speed. With reference to the period range of 0.7 s to 3.0 s (Figure 7B), the seismic and acoustic noise had almost identical trends, witnessed by the overlapping PSD curves, with peaks in correspondence to those of the wind velocity. The amplitude of the seismic and acoustic noise peaks, however, do not correlate with the wind velocity maximum values, as evident especially on 25 May. The figure suggests that a modest peak wind is enough to create a high peak of seismic and acoustic noise in this frequency band; hence other factors not considered might contribute to the generation of noise. Some of these factors could be the wind direction or the saturation effect of noise at a fixed threshold wind speed; the latter has already been observed by other authors (Webb 1998).

Earthquake Recordings

As previously described, the seismic activity of the Campi Flegrei volcanic area is mainly present during the uplift phase of the bradyseism. Outside these periods of soil deformation...
no local earthquakes are detected, apart from some sporadic, very low magnitude seismic swarms near the Solfatara crater (see Figure 1).

Two seismic swarms occurred in January and May 2009, and the land seismic surveillance network detected a total of 208 microearthquakes, all of which had a magnitude lower than 1.0. Most of these low-energy events were recorded at the seismic station SFT only (see Figure 1), in the Solfatara crater, while 17 microearthquakes were recorded and located by a sufficient number of seismic stations. The hypocenter locations are on land, close to the Solfatara crater, down to 2 km in depth. During these two swarms, the CUMAS seismometer was unfortunately not operating. Consequently, only the data from the hydrophone can be analyzed.

Figure 8 (left panels) shows one of the located earthquakes ($M = 0.8$) as recorded by the CUMAS hydrophone of the CFSB station and by POZ, BAC, and NIS seismic stations of the surveillance network (see Figure 1). To reveal the signal-to-noise (S/N) ratio, Figure 8 (right panels) also shows the Fourier amplitude spectra for each station of both the earthquake signal (green) and a 10-s window noise (red). POZ station was 2.4 km from the hypocenter, while CFSB, BAC, and NIS were at a distance of 4.4 km, 4.6 km, and 5.7 km, respectively. The Fourier spectrum of the earthquake recording from the CFSB hydrophone was well above the noise signal spectrum for frequencies greater than 2 Hz, unlike those from BAC and NIS, both located at a comparable distance from the earthquake, although similar to that of POZ. This demonstrated that the
Figure 7. Amplitudes of the background noise recorded by the hydrophone and by the seismometer of the CFSB station versus time. A, B) Data filtered in the frequency bands of 0.03–0.05 s and 0.7–3.0 s, respectively. Black line: hydrophone data. Red, blue, and green lines: horizontal and vertical components of the seismometer, respectively. C) The smoothed wind speed signal obtained by data recorded by the sea-surface meteorological station of the CUMAS system.

Figure 8. Records of $M = 0.8$ Campi Flegrei earthquake: on 2009/05/23 at 19:30:16:00 UTC, depth = 2 km. Left panels: Unfiltered traces recorded by the hydrophone of the CFSB station and by the POZ, BAC, and NIS stations of the seismic surveillance network (as indicated; see also Figure 1). D = hypocentral distance. Inset: Blow-up of a 1.5-s time window centered on the $P$-wave arrival highlights the clear $P$ onset with the hydrophone record. Right panels: Corresponding Fourier spectra computed using: green curve: 10 s of noise preceding the $P$-wave arrivals; and red curve: 10 s of signal that included the $P$-wave arrival.
CFSB hydrophone was only slightly influenced by the noise sources that affected the land stations.

Further considerations of the seismic and acoustic noise can be seen in the analysis of regional event recordings. The CFSB three-component seismometer and hydrophone recordings of an earthquake that occurred in southern Greece (27 May 2008; \( m_b = 4.6 \); distance from CFSB station, about 930 km) are shown in Figure 9. For the hydrophone recording, the earthquake waveform was very clear, especially for the first \( P \)-wave arrival, which showed an S/N ratio greater than 5.0 (Figure 9A). Conversely, the waveform of the same earthquake on the recordings of the seismometer was completely masked by the seismic noise. The difference in the S/N ratio between the two sensors was even clearer in the frequency domain. Figures 9B and C show a comparison of the amplitude Fourier spectra of the noise preceding the \( P \)-wave arrival and the earthquake signal including the \( P \)-wave arrival for the hydrophone and for the vertical component seismometer, respectively. The seismometer \( P \)-wave spectrum was almost totally masked out by noise; the \( P \)-wave signal slightly exceeds the noise level only in the 3–10 Hz frequency band.

Conversely, for the hydrophone, in the same frequency band, the amplitude of the earthquake recording was evidently higher than the noise, with a S/N ratio >10.

To improve the S/N ratio, a high-pass filter with a corner frequency of 3 Hz was applied to the hydrophone and seismometer signals. The filtered signals are shown in Figure 9D. The filter significantly improved the S/N ratio of the seismometer, which finally showed the earthquake waveform enriched with \( S \)-wave arrivals. The S/N ratio of the hydrophone was instead only slightly increased by the filtering. We can then conclude that the hydrophone benefited by the filtering effects of the sea water on shear waves, thus producing less complex waveform recordings than the seismometer.

In addition, we were not surprised by the noisy signal of the seismometer, as this can also be ascribed to the non-optimal coupling of the sensor and the seafloor. A definite improvement in the coupling can be obtained by adopting a similar installation as for the GEOSTAR type of seafloor observatory (Beranzoli et al. 1998; Monna et al. 2005), where there was complete decoupling of the seismometer from the observatory frame. Alternatively, improvements in signal-to-noise ratio can be obtained installing the seismometers in boreholes (Suyehiro et al. 1995; Beauduin and Montagner 1996) or burying the sensors at shallow depths in the sediments of seafloor (Duennebier et al. 1991; Yamamoto and Torii 1986). The main problem with these kinds of solution is that they greatly affect the cost of installation. All these solutions were not implemented in this first experiment with CUMAS, as they were considered secondary with respect to the main goal of demonstrating the feasibility of real-time data transmission and of the use of this SBPR station for bradyseism detection.
PRACTICAL ASPECTS OF CUMAS INSTALLATION: LESSONS LEARNED

Field work in geophysical data acquisition implies well-known practical problems that can be related to the installation of the monitoring apparatus. However, in the case of seafloor data acquisition, further and diverse technical and practical issues have to be faced in addition to those associated with land work. This is mainly due to the fact that it is impossible for operator to physically access the installation site, and to the harshness of the marine environment. These problems were the subject of a session of the 2009 annual meeting of the Seismological Society of America, as many in the scientific community are still unfamiliar with them. With the aim of sharing the experience gained with the CUMAS experiment, we describe here some practical aspects that had to be handled, as well as the main shortcomings of some approaches that were tried.

The first important practical problem cropped up during the experiment design phase. The GPS antenna on the surface buoy and the Q330 acquisition system on the CFSB seafloor module had to be linked by a 140-m-long electromechanical cable. That length exceeded the maximum distance between these two devices allowed by the Ethernet standard on a Cat5 cable. Hence two electronic boards were developed and installed on the buoy and in the seafloor module, allowing the transmission of the GPS signal over an RS-485 serial cable, which can be kilometers long if needed (Guardato and Iannaccone 2008).

During the deployment operations, the same cable was also used to connect a laptop computer to CUMAS, to control the status of all of the equipment. However, a different laptop model was used for this task than the one used for the final checks on land. This apparently innocent change of terminal resulted in a fault in the communication with the marine module that was incorrectly attributed to hardware problems on CUMAS; this thus produced a months-long delay in the installation operations. Afterward, a thorough investigation and more tests revealed that the fault was due to the different sensitivities of the Ethernet cards of the two laptops, which prevented the detection of the Ethernet signal during the deployment phase due to the attenuation caused by the cable length. This problem can be easily solved by interposing an Ethernet switch between CUMAS and the portable computer to restore the voltage levels.

During the days following the deployment of CUMAS, the seismic and pressure sensors operated correctly. The seismometer correctly recorded teleseisms, regional events, and explosions in the water. Then, from around the end of June 2008, the vertical component of the seismometer started to show attenuation that worsened with time, resulting in the complete loss of signals in January 2009. From January 2009 on, the horizontal components also stopped working. After the system was recovered in July 2009, it was found that some water had entered into the glass sphere housing of the seismic sensor, although the housing was sealed according to the procedure recommended by the manufacturer.

The pressure sensor showed a similar track record of working conditions: it correctly operated for about six months and then failed. After inspection, there was evidence of some water inside this sensor, too.

It is worth noting that the seismometer installation adopted in CUMAS is common in marine deployment, and even at much greater depths than CUMAS. The pressure gauge is also a commonly used marine sensor. Their early failures at shallow depths might indicate a lower reliability than advertised for these widely used sensors.

The digital tilt/heading sensors and state sensors proved very useful to achieve the correct orientation during the deployment phase of CUMAS. Software was developed to graphically render the orientation of the underwater module in a Web browser in real time during its deployment and to display some status variables and to control some outputs (Figure 10). CUMAS had a stable orientation on the seabed while recording: the analysis of the header and tilt data over the whole working period showed fluctuations below the sensors’ sensitivity. This was not surprising, since geotechnical surveys conducted before the installation revealed that the seabed chosen for this deployment is composed of very compact sediments.

Although the steel frame of CUMAS was protected by anti-fouling paint, the particular marine environment of the Gulf of Pozzuoli, with abundant flora and fauna and an average water temperature of 14°C at the CFSB site (about 100 m water depth) favored the growth of organisms on the sensor vessels, such as squid eggs, mussels, and a large variety of algae (Figure 2). This gradually reduced the functionality of some of the devices, suggesting the adoption of more effective protection for all of the module components in the future.

CONCLUSIONS AND SUGGESTIONS FOR FUTURE DEVELOPMENTS

The CUMAS deployment was the first step toward the extension of the Campi Flegrei monitoring system to the seafloor. Geophysical data were acquired for some months from the sea bottom using a broadband seismometer, a hydrophone, and an SBPR. Additional status and sea-surface data (e.g., meteorological data) were also acquired. Despite the failures that prevented the continuous acquisition of data throughout the working period, important and useful insights were indeed obtained for the forthcoming phases of design and development of a more permanent seafloor monitoring network in the Gulf of Pozzuoli.

We performed an initial assessment of the S/N ratio of the seismometer, hydrophone, and pressure sensor signals. The earthquake recordings and noise analysis of the hydrophone signal demonstrated that in this specific application to the Campi Flegrei volcanic area, the sensor presented some peculiar features. The hydrophone signal showed simpler waveform recordings than the seismometer due to the filtering effects of the seawater on shear waves. This is particularly useful when several seismic events occur over a short time period, as in the case of the seismic swarms that are typical of volcanic areas. In addition, the S/N ratio of the hydrophone signal was greater than that of the
The observed high noise level of the CFSB seismometer was probably due to the type of installation of the sensor on the CUMAS frame. As demonstrated by Monna et al. (2005), the decoupling of the sensor housing from the frame can significantly reduce the effects of frame vibration on the recorded seismic signals. The revision of the CUMAS frame and of the seismometer installation is already ongoing with regard to these modifications.

Finally, the use of the pressure sensor in the CUMAS experiment enabled a detection threshold to be assessed for the bradyseism phenomenon (1.4 cm). To try to lower this threshold, improvements in the pressure data analysis and further experiments covering other marine sectors of the caldera will be carried out. The expected achievements should in turn provide additional positive ideas about the design of the marine network. However, full characterization of the deformation process in the area will require observations of slow horizontal seabed movements. Thus, one of the main efforts in the preparatory steps leading to the network design lies in research activities focused on the technology for the detection of these slow movements and the adoption of appropriate data analysis.

Figure 10. Application developed for real-time retrieval of some hardware status parameters from the CUMAS underwater module, displayed on a Web page. In particular, the application was useful during the deployment phase. Left to right, from top to bottom: water intrusion alarm, position lights (controlled by the user), module tilt along two axes, module heading, voltages and electrical currents in the electronics boards, and internal pressure and temperature.

seismometer. This last characteristic is of paramount importance for a densely populated area like Pozzuoli, where the background seismic noise is strongly affected by human activities. Indeed, the cultural seismic noise was dominated by horizontally polarized shear waves and Love waves, which were not efficiently converted into compressional acoustic waves at the seabed-water interface. This implies that detection of an earthquake signal on the acoustic recordings is straightforward. In view of the design of the future seafloor network for the seismic surveillance of Campi Flegrei, this suggests that the monitoring infrastructure be based predominantly on an extensive installation of hydrophones. Moreover, in our case, this design choice provides the benefit of the simpler and cheaper installation of hydrophones, compared to sea-bottom seismic stations. While the use of hydrophones in this area is recommended to increase the capacity of P-wave detection and improve the location of earthquakes that occur in the marine sector, the broad-band seismometer remains the reference sensor for seismological studies. Indeed, as the availability of three components allows the reconstruction of the particle motion of the different wave trains over an extended frequency band, the seismometer is fundamental for the identification of tectonic and volcanic earthquakes in such a complex area.
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