A New Multidisciplinary Marine Monitoring System for the Surveillance of Volcanic and Seismic Areas

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INTRODUCTION

Geohazards monitoring can benefit greatly from the integration of seafloor and land observations, because many of the most seismogenic zones and active volcanoes are situated in oceanic basins (NRC 2000). Similarly, many volcanic and seismic areas located in coastal zones extend their activities into nearby marine sectors. The known features of these marine activities are restricted to episodic events, and nothing much is known about the long-term processes. However, marine technology has advanced over the past two decades to the point where long-term and permanent observatories and networks are under development on the seafloor. This has allowed investigations of geophysical processes at both global and regional scales in the Pacific Ocean and the European margin, under different programs from the United States, Canada, Japan, and the European Community (see Delaney et al. 2000; Sturzmann et al. 2001; Shirasaki et al. 2003; and Romanowicz et al. 2006; for a review, see also Favali and Beranzoli 2006). Japan was the first country to work on the extension of its geophysical monitoring to the ocean floor (Kasahara et al. 2006), and now has eight cabled seafloor observatories operating to date within the framework of the ARENA (Advanced Real-time Earth Monitoring Network in the Area) project. At the present feasibility study stage, ARENA is designed to deploy a mesh-like network of underwater cables that connects both terrestrial and underwater observatories all around the Japanese archipelago (Massion et al. 2004).

In the Pacific Ocean, the NEPTUNE5 project was jointly undertaken by the United States and Canada in the late 1990s and is among the most representative examples of state-of-the-art marine technology (http://www.neptune.washington.edu). NEPTUNE is a major component of the Dynamics of Earth and Ocean Systems (DEOS) initiative (http://neptunepower.apl.washington.edu/np_home.html) and the Ocean Observatories Initiative/Ocean Research Interactive Observatory Networks (OOI/ORION) program (http://www.oceanleadership.org/ocean_observ), and it is aimed at establishing a lithospheric-scale, multidisciplinary observatory network over the Juan de Fuca plate. This network is based on high-speed, fiber-optic underwater cables for the power supply, the real-time data transmission, and the interactive control (Delaney et al. 2000). In 1997, the New Millennium Observatory (NeMO; http://www.pmel.noaa.gov/vents/nemo) was set up on the Axial Volcano seamount of the Juan de Fuca ridge (Wieland et al. 2000) as part of NEPTUNE, and in 2002–03 two NEPTUNE test beds were established, VENUS in Canada and the Monterey Accelerated Research System in the United States, known as MARS.

The European Commission (EC) has been promoting the development of multidisciplinary seafloor monitoring observation systems since the early 1990s through the funding of projects that have addressed the realization and operation of prototypes of observatories and networks (e.g., GEOSTAR,6 ASSEM,7 and NEAREST;8 for a review, see Favali, Beranzoli, D’Anna, Gasparoni, Marvaldi, et al. 2006). Relevant pilot experiments have been performed using these prototypes in the Mediterranean Sea and west Atlantic Ocean in the framework of these EC projects. This experience has led to the establishment of the submarine network SN-1, the first European cabled seafloor observatory, which is mainly devoted to real-time geohazard monitoring. SN-1 has been integrated into the Italian national seismic network and has been operating since early 2005, at 2,100 m water depth (w.d.) off-shore of the east coast of Sicily in southern Italy, which is one of the most seismically hazardous areas of the Mediterranean (Favali, Beranzoli, D’Anna, Gasparoni, and Gerber 2006). After more than 10 years of European collaborative projects and experiments on seafloor observatories, a special forum, the European Strategy Forum for Research Infrastructure (ESFRI), has been established by the EC. The ESFRI has identified a network of seafloor obser-

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6. GEOSTAR: Geophysical and Oceanographic STation for Abyssal Research.
7. ASSEM: Array of Sensors for SEabed Monitoring of geohazards.
8. NEAREST: Integrated observations from NEAR shore sourceES of Tsunamis.
vatories around Europe, from the Baltic Sea (northern Europe) to the east Atlantic Ocean and the Mediterranean and Black seas, as strategic for Earth and environmental sciences as well as for geohazard mitigation and sustainable development. Accordingly, in 2008, the European Multidisciplinary Seafloor Observatory—Preparatory Phase (EMSO-PP; http://www.emso-eu.org) project was started, with the objective of founding a European transnational institution charged with the realization of the observatory network (Favali and Beranzoli 2009).

Recent catastrophes (e.g., the 2004 Sumatra earthquake and tsunami) have once again pushed scientific and technological research to develop new approaches to permanent installations on the seafloor, which also can be relied on for risk mitigation. In spite of this, in many of the most seismically hazardous and highly populated areas (e.g., off Chile, Mexico, and in Mediterranean countries such as Portugal, Italy, Greece, and Turkey), geohazard monitoring systems still remain exclusively land-based, with seafloor data generally acquired only on a temporary basis during episodic periods. The major causes that at present limit the extensive implementation of seafloor networks for geohazard monitoring relate to the need for the huge investment of funds, high management costs, and the technical and logistical difficulties involved in the deployment and maintenance of monitoring systems on the seafloor (Kasahara et al. 2006). For instance, the logistical elements—including ships, submersible vehicles, and specialized teams of operators—are too expensive for a single research institution, and assembling them thus demands cooperative efforts and cost sharing. In addition, some technical features, such as long-term power supplies and continuous transmission of high-sample-rate data, are critical features when using seafloor systems for geohazard monitoring. Indeed, in densely populated coastal regions, permanent seafloor monitoring networks can be effective for civil protection purposes only if they are equipped with real-time data transmission systems and are integrated into the land networks.

Acoustic underwater data transmission systems are considered suitable only for temporary monitoring experiments because of the high power supply needed for transmission and the limited baud rates (10^2 kbyte/s) in comparison to land networks (Favali and Beranzoli 2006). In contrast, although both electro-optical and coaxial underwater cables require expensive installation, they are at present the only facilities that can simultaneously guarantee a permanent power supply to seafloor modules, which extends their operative life indefinitely and provides continuous transmission of high-sample-rate data in real-time mode from the seafloor to the land.

In the case of shallow waters (100–200 m) and short distances (a few kilometers) from the coasts, a hybrid configuration for seafloor observatories can be adopted by merging transmission through underwater cables and conventional air-transmission systems (radio and satellite). In this configuration, the seafloor instruments and monitoring modules can be connected by means of a cable to a sea-surface buoy, which is in turn equipped with radio or satellite communication systems.

In the Campi Flegrei caldera (southern Italy), one of the most hazardous and populated volcanic areas in the world, the need for real-time monitoring for civil protection has led to national and regional cooperative projects for the development of a new marine system. This has been named CUMAS (Cabled Underwater Module for Acquisition of Seismological data), and it extends the land surveillance network toward the wide marine sector of the caldera (Figure 1). The Campi Flegrei
area is characterized by seismic and volcanic activity that also occurs in the submerged sectors, where only poor and episodic observations and measurements are available so far. Although based on commercial sensors, CUMAS relies on the original centralized management of a wide set of geophysical and oceanographic sensors, which operate with continuous data acquisition and real-time data transmission. All of the data acquired by the CUMAS sensors are managed by a unified system that allows their straightforward integration into the commonly operating geophysical monitoring networks. In addition, the communication system for the data transmission allows remote control of all of the devices installed, including modification of the acquisition parameters.

After installation and a test period, the CUMAS module is now operating as part of the surveillance network of the Campi Flegrei area and is providing continuous geophysical data to the monitoring center of the Neapolitan volcanic areas managed by the Istituto Nazionale di Geofisica e Vulcanologia (INGV), the Italian National Institute of Geophysics and Volcanology.

This report provides a description of the architecture, devices, and functions of CUMAS and presents the results of the first test period in terms of the quality of the data acquired and the reliability of the functions of CUMAS.

**OVERALL DESCRIPTION OF CUMAS**

CUMAS is a marine module that was conceived for a multidisciplinary approach to long-term investigations. The system includes a seafloor station that hosts geophysical and oceanographic sensors that are connected by cable to a surface buoy that is equipped with a power supply, meteorological sensors, a GPS antenna, and a communication system that ensure the continuous transfer of the seafloor data to the INGV monitoring center (Figure 2).

The marine module sensors are designed to monitor a set of signals related to volcanic activity: the local seismicity and seafloor ground uplift and subsidence that is related to the bradyseismic phenomenon. In particular, the seafloor ground uplift and subsidence is monitored by a seafloor water-pressure sensor. Additional signals are recorded to characterize the marine environment from a single-point, three-component, water-current meter and water-temperature sensor. The overall system architecture is illustrated in Figure 3 and described in more detail in the following sections.

**The Seafloor Module**

The seafloor module has a frame of steel that is 1 m high and a square base of 1 m² that hosts the sensors. The acquisition systems and electronic devices are contained in a cylindrical vessel (Figure 4). The total weight, including the equipment, is about 430 kg in air.

The following sensors have been installed in the module:

- a three-component, broadband seismometer (0.033–40 s; Guralp CMG-40T OBS) that is housed in a 16-cm-diameter glass sphere with an auto-leveling platform;
- a low-frequency hydrophone (0.001–65 kHz; Sensor Technology model SQ03);
- a single-point, three-component, acoustic current meter (3D-ACM Falmouth);
- a differential pressure gauge (Series 8000 Paroscientific).

Further sensors for status and control are also hosted in the seafloor module: tilt and heading sensors, for measurement of the module attitude; and status sensors, for the monitoring of the acquisition systems (e.g., vessel internal temperature, power consumption, water intrusion).

The acquisition of the four data streams of the seismometer and the hydrophone is performed by a Quanterra Q330 digitizer, at a sampling rate of 100 sps and with a data backup hard disk of 20 Gbytes, using a F14 Baler unit. The data acqui-
Figure 3. General architecture of CUMAS: (A) surface buoy elements; (B) seafloor module systems. The surface and seafloor systems are connected through an electromechanical cable for seafloor module power supply and data transfer.
Aquisition system for the physical-oceanographic digital sensors and the status analog sensors is hosted in the cylindrical vessel. This acquisition system is an embedded computer (MOXA UC-7408 with Linux OS, http://www.moxa.com/Product/UC-7408.htm), which is equipped with a storage memory of 4 Gbytes for data backup.

Both these acquisition systems are linked via ethernet cable to a router connected to the electromechanical cable, for real-time data transmission to a WiFi apparatus hosted on the surface buoy. The electromechanical cable has a diameter of 23 mm and a length of 140 m. It is dedicated to carrying all of the signals (ethernet 10/100 Mbps, four differential pairs of RS-485 ports for the GPS) and for the power distribution (48 V DC).

As the distance between the GPS antenna on the surface buoy and the Q330 acquisition system on the seafloor exceeds the maximum distance allowed for GPS signal transmission, two electronic boards were developed to overcome this limitation (Guardato and Iannaccone 2008).

The Surface Buoy

The surface buoy is a semi-rigid structure with a metal pole 20 m in height that is anchored by an anti-torsion steel cable to a ballast of 17 tons (Figure 2). The buoy is equipped with ten rechargeable batteries that are connected to 16 solar panels (120 W each) and to a 400-W wind generator. A meteorological station provides local measurements (e.g., barometric pressure, wind velocity and direction, rainfall, temperature), to allow the eventual correlation of the air and seafloor data.

Additional equipment includes buoy status sensors (heading and tilt), an embedded computer of the same type as used for the seafloor module, and a DC/DC power converter (12 V to 48 V). A wireless WLAN bridge (Cisco Aironet 1300 series) equipped with an omnidirectional antenna performs the data transmission to the monitoring center. This communication system is based on a TCP/IP protocol that also allows the remote control of all the CUMAS devices. Table 1 provides a complete list of all of the sensors installed in the seafloor module and the surface buoy.

DATA MANAGEMENT SYSTEM

The goal of the CUMAS data management system is to integrate all the heterogeneous data streams (scientific and status) into a single data storage and handling system, and, furthermore, to integrate them into the monitoring center data management system of INGV. This handling system was developed using Earthworm (Johnson et al. 1995), since this software is used by the monitoring center for the management of the data coming from the seismic stations of the Campi Flegrei network; it is also widely used in seismology.

For data storage on disk, the standard Earthworm module (WaveServerV) was replaced with separate Winston software (http://www.avo.alaska.edu/Software/winston/W_Manual_TOC.html). This software package overcomes some of the limitations of the Earthworm module, such as the maximum size of data.
records on disk. It also offers additional features, such as compressed data retrieval and data display facilities.

The general layout of the data management system is illustrated in Figure 5, and it is implemented on a dedicated server that was installed at the monitoring center. Its main blocks are:

- the server, running the Linux Operating System (Debian distribution, version 4.0);
- an Earthworm installation (version 7.1), with modules for data acquisition and real-time data processing;
- a Winston installation (version 1.1), which imports the sensor data from Earthworm and stores them on disk (this program also implements the Winston Wave Server, replacing the standard Earthworm Wave Server module, which provides the recorded data to client applications);
- a MySQL installation, which is required by Winston to store the data; and
- a Web-based user interface to the data, which is implemented through CGI scripts under the Apache Web Server (this can display each channel over a time interval selected by the user as a virtual “helicorder” and allows the recorded data to be downloaded as files in SAC format).

### Data Acquisition and Processing

Some data streams produced by CUMAS can be straightforwardly imported into Earthworm through a standard real-time module. This is the case for the seismometer and the hydrophone streams, which are provided by the Quanterra Q330 digitizer. However, most of the data streams, such as those from the status sensors, current meter, and pressure sensors, cannot be directly integrated into Earthworm and instead require preliminary processing. Indeed, these data streams, which are low rated (1–10 Hz), are stored on the two embedded computers and archived in their mass storage as files in a custom format. Therefore, a series of steps are performed hourly:

- Each embedded computer collects its files, compresses them, and sends them to the monitoring center server via the SCP protocol.
- At the monitoring center server, the compressed data are stored in the original format for backup purposes and removed from the limited CUMAS storage.
- The data are then processed and parsed. Each channel is singled out and checked for integrity and data gaps. This processing is based on a program in the Python language. For each channel, the program converts the data samples from the original format into 4-byte integers, and then breaks down the stream into smaller packets that are compatible with the maximum packet size that Earthworm can handle. The resulting samples are converted into TraceBuf2 binary packets, which is the generic format for data recorded by a sensor in Earthworm. The TraceBuf2 packets are written as files onto disk in the final format required to be injected into the Earthworm ring buffer. This step is carried out by the standard file2ew module, which checks every few seconds for new files and reads them into memory in the ring buffer.

There are a few caveats, however. Since new data is received hourly, one-hour’s worth of data (or more, if there is a backlog) must not be inserted into Earthworm all at once, so as not to overload the available resources. In particular, there are several parameters to take into account, such as the maximum TraceBuf2 packet size, the size of the ring buffer, the rate

| Table 1: Scientific and Status Sensors for the Seafloor Module and the Surface Buoy |
|---|---|---|
| Sensor | Number of Channels | Sampling Rate (sp s) |
| **Sea Floor Module** | | |
| Scientific Sensors | | |
| Seismometer | 3 | 100 |
| Hydrophone | 1 | 100 |
| Current Meter | 3 | 2 |
| Water Temperature | 1 | 2 |
| Pressure sensor | 1 | 10 |
| Status Sensors | | |
| Heading and tilt (x, y components) | 3 | 1 |
| Power consumption | 2 | 1 |
| Vessel internal temperature and pressure | 2 | 1 |
| Water intrusion alarm | 1 | 1 |
| Voltage and current to the cable | 2 | 1 |
| **Buoy** | | |
| Scientific Sensors | | |
| Wind direction and speed | 2 | 1 |
| Air temperature | 1 | 1 |
| Air pressure | 1 | 1 |
| Rainfall | 1 | |
| Status Sensors | | |
| Heading and tilt (x, y components) of the buoy | 3 | 1 |
| GPS (Latitude, Longitude, satellite numbers) | 3 | 1 |
| Voltage and current to the sea floor module | 2 | 1 |
| Internal temperature and pressure inside box | 2 | 1 |
at which the packets can be processed by the various modules within Earthworm, and the maximum data rate that Winston can handle, which is in turn also limited by the data insertion rate in the MySQL database and the actual hard disk speed, as well as other factors.

To address these issues, all of the available raw data is converted into TraceBuf2 packets as fast as possible, placing the resulting files into a buffer. Then another process makes the files available for the file2ew module at a throttled rate. Other problems can arise in either Earthworm or Winston if the data received is not in chronological order, so the files are sent from CUMAS in the same order, and the packets are handed over to the file2ew module in strict chronological order.

Data Display

Once the data have passed through Earthworm, they can be displayed and downloaded through a specifically developed Web-based interface. This interface is implemented in the Apache Web Server through CGI scripts (mostly Linux shell scripts). For data display, a built-in commodity in the Winston Wave Server is used that produces a virtual “helicorder” of the data as an image sent to the browser, in response to HTTP requests. The helicorder parameters, such as the time window, vertical scale, and clipping limits, are provided through the URL. On top of this feature, a user-friendly interface has been built with a list of the available channels and descriptions and buttons, sliders, and widgets (e.g., a JavaScript calendar) to control the helicorder parameters (see Figure 6). This interface is useful for the day-to-day monitoring of CUMAS activity and status, as data gaps or anomalous responses can be promptly identified.

A richer data visualization and processing interface is also provided by Swarm (http://www.avo.alaska.edu/software/swarm). Through Swarm, it is possible to list the available data channels from the server, obtain a day’s-worth of data as helicorders, display the waveform data over a time period or in real time, and process the waveform through filters or by performing spectral analysis. Another advantage of Swarm is that it communicates directly with Winston and can thus exploit some additional features that the Winston Wave Server has over the traditional Earthworm Wave Server, such as compressed data exchange.

Data Download

To retrieve the actual data, a Web page is provided that lets the user select the time window and channels of interest and passes the request to our GetWave program. This program in turn interfaces with a standard Earthworm module (Waveman2Disk) that communicates with the Winston Wave Server to obtain a series of files in SAC or ASCII format. GetWave is also in charge of adding the available metadata to the file by filling in the SAC file header with the station and instrument details, as well as with the optional user-supplied earthquake details.

TEST DESCRIPTION AND RESULTS

In early May 2008, CUMAS was deployed in the Gulf of Pozzuoli in about 100 m w.d., and in the days that followed, the first data were acquired by the Earthworm system at the monitoring center. Some examples of the data acquired by CUMAS are presented in this section.
Seismic Data
Regional and teleseismic events and signals produced by underwater explosions caused by fisherman were recorded; however, no local earthquakes were detected. This is not unusual; indeed, in the Campi Flegrei volcanic area, seismic activity is present only during the uplift phase of bradyseism (De Natale et al. 2006). Figures 7 and 8 show examples of seismic recordings from CUMAS of a teleseismic event and of a signal produced by fish blasting, respectively. The teleseismic signals were bandpass-filtered between 2.5 s and 40 s. The traces show very clear first arrivals and surface waves that were well-recorded on both horizontal and vertical components of the seismometer (Figure 7).

Figure 8 shows the unfiltered signals produced by an underwater explosion and recorded by the seismometer and hydrophone of the CUMAS system. The first part of the signal is well-recorded by both instruments, while the second part of the signal, which is of low frequency, is particularly evident in the seismometer about 15 s after the first arrival. This phase is a path effect and is visible also on the seismograms of seismic stations located close to the coast; it has been interpreted as multiple reflections in the water layer.

Physical Oceanographic Data
Continuous recordings of seafloor water pressure, water temperature, and sea-bottom currents are plotted in Figure 9 for the period 16–19 June 2008. The pressure data clearly show tidal oscillations and a further periodic signal with period of about 20 min, which appear very clearly during the period from 17/06/2008 00:00 to 19/06/2008 00:00. The temperature trace shows weak variations of a few percent around the mean value of around 14.5 °C. At this depth, the temperature in the Gulf of Pozzuoli is almost constant (Stabile et al. 2007).

Meteorological Data Acquired by the Surface Buoy
Examples of the data acquired by the meteorological station are shown in Figure 10 for the rainfall and the mean air pressures, air temperatures, and wind velocities measured during the period of 12–30 May 2008. The temperature and wind measurements show temporal variations linked to the day/night changes, which are particularly evident for days with high pressure when the wind and temperature increase during the daylight hours and decrease in the course of the night. A period of high wind speed ( > 4 m/s, with a maximum of 12 m/s) occurred during the day between 19 and 22 May, 2008, which corresponded to the peak of minimum pressure and the main peaks of rainfall.
▲ Figure 7. CUMAS seismological recording (station code CFSB): (A) Teleseismic event (02/05/2008, 01:33:36.4 UTC, Aleutian Islands, Alaska; $M_w$ 6.6) with the vertical and horizontal components for the CFSB station; (B) detail of the first-wave arrival. The data were filtered using a bandpass filter with corner frequencies of 0.02 Hz and 0.4 Hz.

▲ Figure 8. Recordings of an underwater explosion set off by a fisherman that occurred on 7 May 2008 in Pozzuoli Bay and was recorded by CUMAS (station code CFSB) from the hydrophone (top) and by the three-component seismometer.
Figure 9. Data acquired by the CUMAS multisensor system during the period 16–19 June 2008. From top to bottom: pressure, water temperature, and sea-water bottom current, collected along the x, y, and z directions.

Figure 10. Meteorological data acquired by the instruments installed on the surface buoy system (from top to bottom): mean atmospheric pressure, rainfall, air temperature, and wind speed.
CONCLUSIONS AND PERSPECTIVES

A seafloor multisensor module with real-time data transmission, known as CUMAS, has been successfully deployed in the Gulf of Pozzuoli, in the Campi Flegrei caldera, which is one of the most hazardous volcanic areas in the World. CUMAS records seismological signals and provides measurements related to the water-current system. A test for the detection of sea level changes, potentially related to the seafloor uplift or subsidence, is ongoing with the use of the pressure gauge data.

A surface buoy is equipped with additional sensors for meteorological measurements and receives the continuous scientific and status data streams from the CUMAS station via cable. These data are then transmitted by a wireless system to the INGV monitoring center in Naples. CUMAS is fully integrated into the geophysical land-based monitoring system that is managed by INGV, and it is the first off-shore station of the local network. An Earthworm-based system provides user-friendly data visualization and retrieval, which was adopted to straightforwardly integrate all of the data acquired by CUMAS with the land data, which is managed by a similar system.

Following the results of a previous investigation performed using two ocean-bottom seismometers that were deployed in Pozzuoli Bay (Vassallo et al. 2008), CUMAS was deployed in a site that was selected to improve the performance of the present seismic network in terms of the detection threshold of the local seismicity and of hypocenter errors.

CUMAS will provide long-time-series data that will allow, for the first time, the study of the evolution of the volcanic activity and related phenomena in the marine sector of the Campi Flegrei caldera, which to date has only been investigated on the basis of land data. CUMAS is the first node of a marine network that is at present the subject of a feasibility study that will cover most of the submerged Campi Flegrei volcanic area and will be integrated into the local monitoring systems.

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