11 GEOSTAR-class observatories 1995–2012: A technical overview

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11.1 Introduction

From the scientific point of view, the deepwater environment represents the ultimate frontier for Earth observation and understanding fundamental processes (solid earth studies, as well as oceanographic, climatic and environmental investigations) (Kopf et al., 2012). Development and operation of seafloor observatories, defined as "unmanned stations, capable of operating for long-term at seafloor, supporting the continuous and stable operation of a number of instrumented packages related to various disciplines" (a more detailed but conceptually similar definition is proposed by NRC (NRC, 2000)), are now recognized as the essential approach to achieve full-time presence at deep seafloor and overcome the main limitations of the traditional ship-based approach, intrinsically episodic and inadequate to provide data at the temporal and spatial scales required (Favali and Beranzoli, 2006; Favali et al., 2010; Lampitt et al., 2010).

The distinction of in-situ investigations from other kinds of research (like ship cruises) is more evident in deep-sea science because "to be in-situ" raises significant technological challenges (Gasparoni et al., 1998; Ollier et al., 2002). The ocean bottom is remote, hostile, corrosive to delicate instruments and highly variable in temperature and pressure. Although some aspects are similar to space exploration (hostile environment, remoteness, etc.), others are rather different: energy from the sun is not available and efficient commu-

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nication links are not possible, making long-term operation in deep water very challenging as planetary activities. The first problem to be solved to establish a deep-sea observation capability is in fact to gain “the possibility to be there” in exactly the right place and for the required period of time (Beranzoli et al., 2002b; Favali et al., 2004).

Technology, and technology innovation in particular, plays a fundamental role in the development of advanced solutions capable of answering the challenging requirements of seafloor observatory science, introducing new capabilities or allowing old functions to be performed with greater efficiency (Ruhl et al., 2011, Aguzzi et al., 2012). Transfer of experiences from the oil&gas industry applications offers a unique opportunity of cross-fertilization, bridging the gap between the practice of offshore technology and the possibility of developing engineered solutions for scientific investigation (Favali and Beranzoli, 2006).

This contribution intends to provide a chronological and logical history of the GEOSTAR-class seafloor observatories (Favali and Beranzoli, 2009b), mainly focusing on the technological aspects.

11.2 The origins: ABEL and DESIBEL

Recognizing these needs and technological challenges, since 1989 the European Union (EU) has promoted a specific action within the R&D Framework Program, namely the Marine Science and Technology Programme (MAST), where important studies and projects were developed with EU support. In addition, dedicated international workshops and conferences were organized, contributing to the establishment of a European network among the different parties involved (academic and scientific institutions, industries, etc.) (Beranzoli et al., 2000b).

Within the initiatives promoted by the EU, two project studies in particular, carried out in the framework of the EU MAST-2 Programme, may be considered the origin of GEOSTAR concept: ABEL and DESIBEL.

The former project was a feasibility and financial study aimed at identifying the scientific requirements, possible technological solutions and opportunities for the development of an Abyssal BEnthic Laboratory (ABEL) (Berta et al., 1995). The basic requirements of the corresponding study can be summarized as follows: to ensure the possibility of carrying out in-situ scientific, multidisciplinary, autonomous seafloor observations and experiments, at water depths up to 6000m.

Awarded to Tecnomare, and carried out between 1992 and 1993, the study proved the feasibility of the concept of a benthic laboratory, capable of operating both in autonomous and controlled mode for periods of several months up to one year. The proposed configuration was a network of cooperating stations, capable of being reconfigured according to specific mission requirements.

The system, shown in Figure 11.1, includes a main station (main Benthic Investigation Laboratory) devoted to the execution of the most complex tasks, with a number of secondary fixed stations (Satellite Stations) acting as nodes of the measuring network and a mobile vehicle (Mobile Station) that extend capabilities of the fixed stations enabling

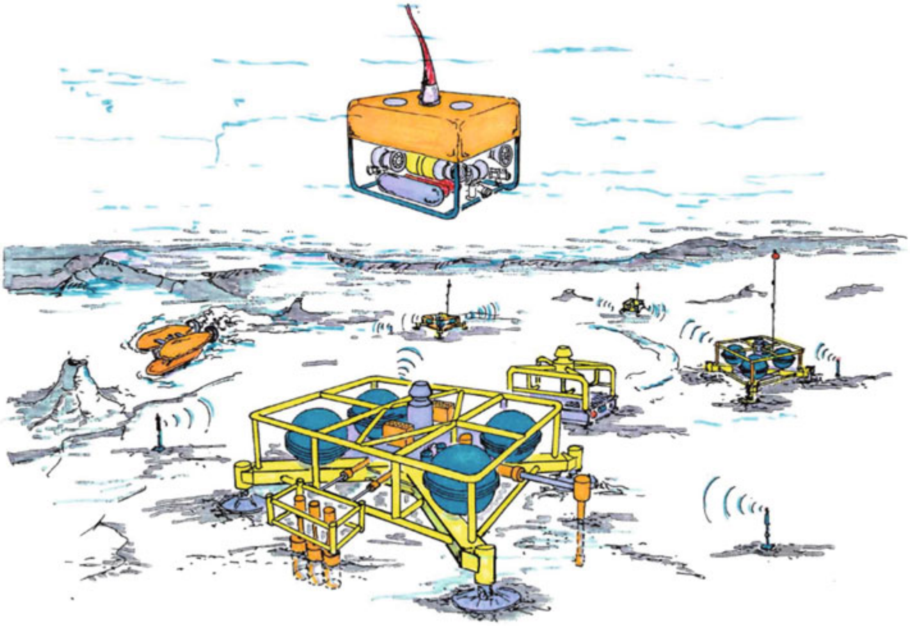

Figure 11.1 Tecnomare concept of Abyssal Benthic Laboratory (1993).

possibility of surveys in the investigation area and even interaction with the fixed stations. ABEL architecture also includes a dedicated module to deploy and recover the stations, as well as a shore station.

The ABEL concept represents the equivalent at deep seabed of an onshore multidisciplinary meteorological or geophysical laboratory. Significant analogies may be identified also with respect to past and ongoing studies of planetary stations.

The approach used to overcome limitations of systems presently in operation and to address technological development was based on three key elements:

- extension of the operating capabilities of the instrumented bottom stations, to ensure adequate support to the multiplicity of the scientific packages foreseen
- surface-assisted deployment and recovery, for accurate and controlled execution of the marine operations
- maximum interaction with the scientific or technical user during all phases of the mission, to allow remote control and effective operability of the stations.

All the above proposed technical solutions were translated into practice with the development of GEOSTAR.

The second study (DESIBEL) was aimed at investigating methods for deployment and intervention on future benthic stations (Rigaud et al., 1998). Within this latter study four concepts were investigated, namely:

- an active docking system with a mobile hook (LOMOS)
- an active docking system with a special ROV (REMORA)
- a light scientific ROV (ROV 6000)
- a free swimming vehicle (FREE MODULE).

For each concept, engineering studies were conducted as well as cross comparisons, mainly based on simulations of a variety of operational conditions. In particular, LOMOS turned out to be the most suitable solution where heavy payloads needed to be managed, such as the advanced benthic stations previously identified in ABEL study.

In parallel, several international conferences and workshops reconfirmed the need to "join forces" to achieve – even with different scientific objectives – the realization of multidisciplinary sea-bottom observatories and to extend at a global scale the existing land-based networks of permanent observatories of Earth processes (Frugoni et al., 2006). It was argued that such an approach would allow a significant overall cost reduction and contribute greatly to the development a new generation of "carriers" of scientific packages that are indeed required to advance the present understanding of a great variety of Earth processes.

11.3 GEOSTAR

In order to further proceed with the development process started with the ABEL feasibility study, seven scientific and technological European organizations[4] joined their efforts in the GEOSTAR (GEophysical and Oceanographic STation for Abyssal Research) project (Beranzoli et al., 1998; 2002a; Jourdain, 1999), aimed at the development of the prototype of an innovative deep sea observatory capable of carrying out long-term geophysical, geochemical and oceanographic observations at abyssal depths (4000m) (Berta et al., 1995; Gasparoni et al., 2002).

The concept proposed (and implemented in a two-phase project) is shown in Figure 11.2.

The observatory is characterized by original and innovative technological solutions such as:

- the open frame in light, non-magnetic alloy
- active devices for the deployment of specific packages (like the seismometer and the magnetometers)
- a dedicated data acquisition and mission management system, based on custom-built low power hardware

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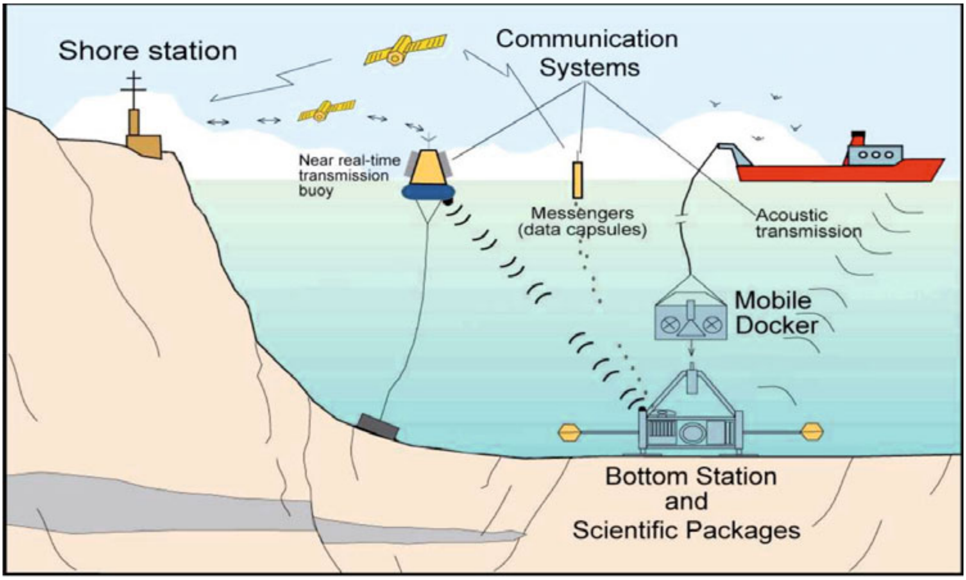


Figure 11.2 GEOSTAR concept (as proposed to the EU MAST III programme, 1995).

- autonomous mission capabilities, including power management and self-diagnostics
- possibility of being reconfigured according to different mission requirements and sites
- a dedicated deployment and recovery vehicle (Mobile Docker or MODUS), derived from LOMOS concept
- multiple possibility of interfacing with external devices (communication systems, deployment system) for continuous control of system status both during the deployment phase and during the mission.

The frame configuration is one key aspect of GEOSTAR's success (Beranzoli et al., 1998). It is a stand-alone autonomous unit, based on a four-legged aluminum open frame supporting all the scientific packages and the mission payload (such as the vessels housing the data acquisition and control system, the battery pack, the communication systems, etc.). For quicker and more reliable deployment and recovery the frame is equipped with a docking cone (Figure 11.3) on which the mechanical connector that mates with the Mobile Docker is mounted (Gerber and Clause, 2001; Clauss and Hoog, 2002).

The single frame, "heavy in water" concept provides important advantages over concepts based on multiple sensor packages managed by ROVs and underwater junction boxes:

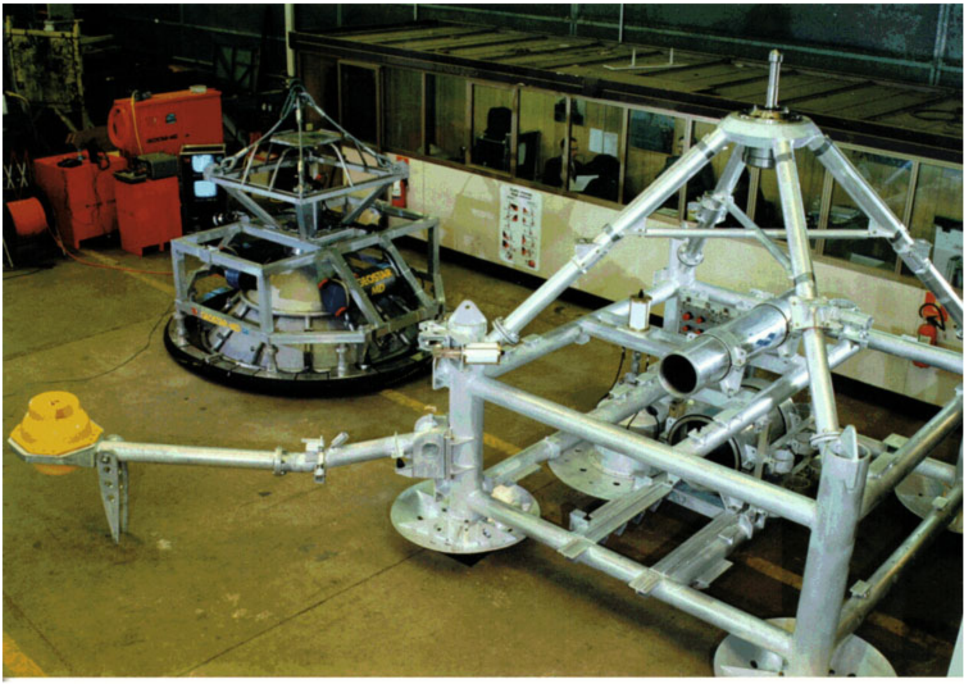


Figure 11.3 GEOSTAR Bottom Station frame (right) and mobile docker (left). Scientific payload not mounted. The magnetometer boom on the left of the Bottom Station is shown in the extended position; the seismometer module is partially visible at the left of the two pressure vessels.

- single operation required for deployment (and subsequent recovery)
- no volume reserved for buoyancy and recovery equipment
- increased reliability (no active device at seafloor)
- stable at seafloor
- insensitive to variations of payload
- the same vehicle (the Mobile Docker) can manage several Benthic Stations.

The open frame allows an easy and effective installation and access to the mission payload and gives a virtually unlimited possibility of reconfiguration/extension according to new or different requirements (Gasparoni et al., 1998). This characteristic was verified during the operational life of GEOSTAR (refer to Table 11.1, summarizing GEOSTAR payload configuration in the six missions carried out so far) (Beranzoli et al., 2000a, b; 2003).

The relative availability of volume and resources (electrical power, interfaces, acquisition and processing power) stimulated scientists to not limit their attention to commercial off-the-shelf sensors only, but also to conceive special, innovative instrumented packages specifically for GEOSTAR (Beranzoli et al., 2002a). Technology development work was

Parameter	Mission 1		Mission 2		Missions 3 and 4		Missions 5 and 6	
	Sensor	**Sampling rate**	**Sensor**	**Sampling rate**	**Sensor**	**Sampling rate**	**Sensor**	**Sampling rate**
Broad-band seismometer	Guralp CMG-1T	20 samples/s	Guralp CMG-1T	100 samples/s	PMD/Eentec EP-300-DT	100 samples/s	Guralp CMG-40	100 samples/s
Accelerometer							Guralp CMG-5T	100 samples/s
Scalar magnetometer	GEM Systems GSM-19L	1 sample/ min	GEM Systems GSM-19L	1 sample/ min	GEM Systems GSM-19L	1 sample/ min		
Vectorial magnetometer	INGV prototype	1 sample/ 10 s	INGV / Tecnomare prototype	1 sample/ 10 s	INGV / Tecnomare prototype	1 sample/ 10 s		
Gravity meter			CNR-IFSI prototype	1 sample/s	CNR-IFSI prototype	1 sample/s	CNR-IFSI prototype	1 sample/s
Hydrophone					OAS E-2PD	100 samples/s	OAS E-2PD	100 samples/s
Pressure							Paroscientific 8CB4000-I	1 sample/ 15 s (MISSION) 1 sample/5 s (EVENT)
ADCP	RDI Workhorse 300 kHz	1 profile/h	RDI Workhorse 300 kHz	1 profile/h	RDI Workhorse 300 kHz	1 profile/h	RDI Workhorse 300 kHz	1 profile/h

Parameter	Mission 1		Mission 2		Missions 3 and 4		Missions 5 and 6	
	Sensor	**Sampling rate**	**Sensor**	**Sampling rate**	**Sensor**	**Sampling rate**	**Sensor**	**Sampling rate**
CTD	Sea Bird SBE-16	1 sample/h	Sea Bird SBE-16	1 sample/h	Sea Bird SBE-16	1 sample/h	Sea Bird SBE-16 plus	1 sample/h
Turbidity	Chelsea Instruments Alphatracka II	1 sample/h	Chelsea Instruments Alphatracka II	1 sample/h	Chelsea Instruments Alphatracka II	1 sample/h	Wet Labs ECO-BBRTD	1 sample/h
pH / Eh	Wolfson Sensor Group prototype	(*)	Systea prototype (AMT sensors)	(**)	Tecnomare prototype (AMT sensors)	1 smp/6 h (calibration every day)		
Current meter			FSI 3D-ACM	2 samples/s	FSI 3D-ACM	2 samples/s	Nobska MAVS-3	5 samples/s
Automatic water sampler			McLane RAS-48-500	2 × 500 ml samples/ 10 days	McLane RAS-48-500	2 × 500 ml samples/ week		
Precision tilt meter	Applied Geomechanics 716	1 sample/h	Applied Geomechanics 716	1 sample/h	Applied Geomechanics 716	1 sample/h		
Compass			Falmouth Ostar	1 sample/h	Falmouth Ostar	1 sample/h	Falmouth Ostar	1 sample/h
Inertial Measurement Unit (Accelerometer + gyro)							Landmark LMRK10IMU-150-12-100	200 samples/s

* Automatic analyser also including H_2 and H_2S electrodes; developed but not installed for the mission

** Developed but not installed for the mission

Table 11.1 GEOSTAR payload and sampling rates.

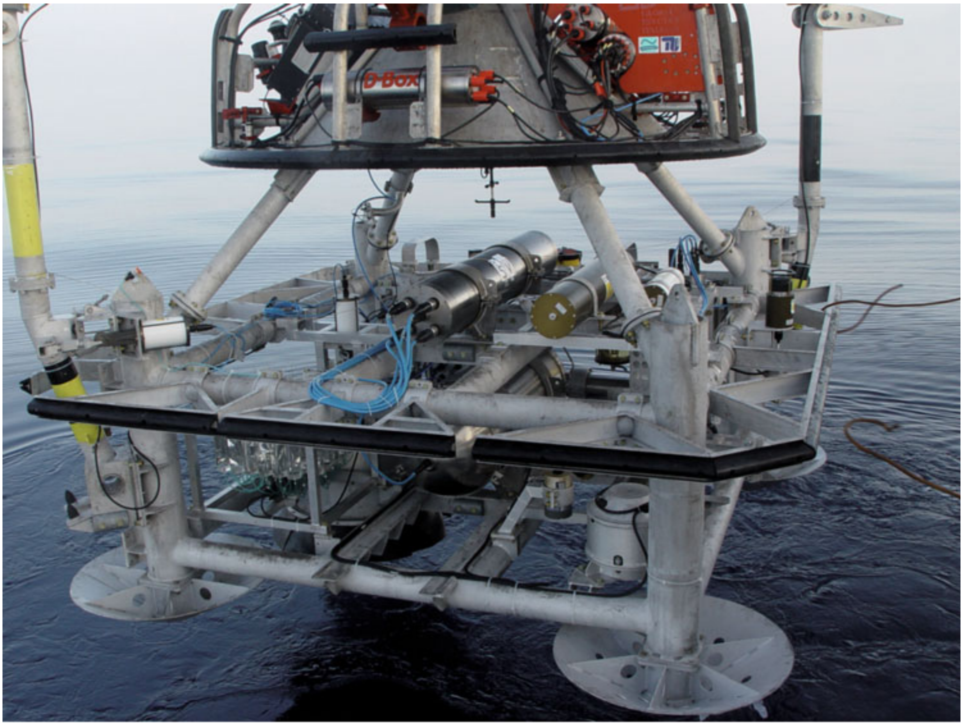


Figure 11.4 Typical GEOSTAR mission setup; note the payload arrangement on the open frame.

therefore not simply addressed to manage standard sensors, but also to develop customized underwater versions of sensors originally designed for different applications (this is the case with the vectorial magnetometer and gravity meter (Iafolla and Nozzoli, 2002)), to support the design of completely new packages (as with the automatic chemical analyzer) or simply to make available a platform where packages designed and developed by other institutions could be operated (Favali et al., 2002) (Figure 11.4, Figure 11.5 and Figure 11.6).

Particular attention was paid in the observatory design in order to take into account the specific requirements of the various scientific packages, in terms of mounting constraints and minimization of possible interferences. This applies in particular for the magnetometers and the seismometer, whose specific requirements do not allow a direct mounting on the Bottom Station frame, as the resulting measurements would be affected by noise and disturbances induced by the station itself and devices mounted on it. As regards the magnetometers, it had been decided to mount the glass spheres housing the sensors at the end of long booms (approx. 2.5m) hinged at two opposite corners of the Bottom Station frame. These booms are automatically extended when at the seabed, after a remote command by the surface operator; this ensures that the sensors are adequately located far from the Bottom Station structure that is the source of electronic noise.

Figure 11.5 Gravity meter (left) during customization work and laboratory tests; (right) Vectorial magnetometer integrated into a glass sphere.

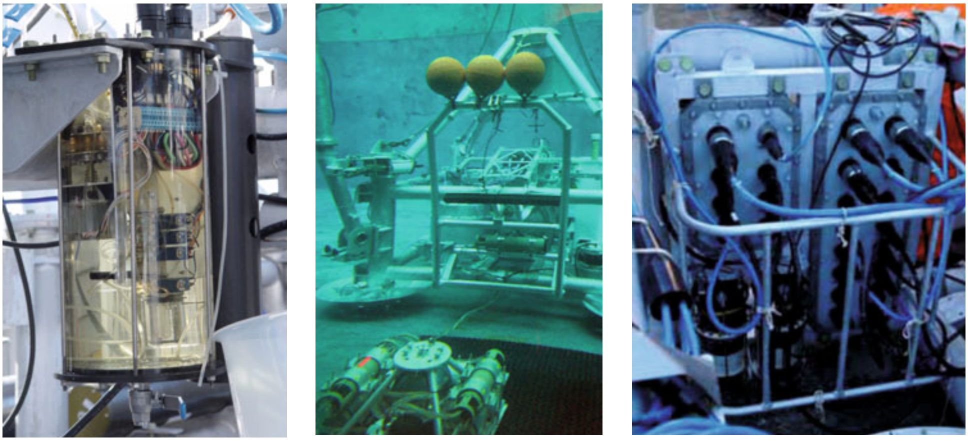


Figure 11.6 (Left) Prototype chemical analyzer engineered by Tecnomare. (Center) Experimental seismometer derived from a space prototype integrated to GEOSTAR frame during wet test in IFREMER basin. (Right) GEOSTAR junction box providing interfaces for payload.

Another active device has been conceived to manage the seismometer, in order to release it from the station and couple with the seafloor (Figure 11.7 and Figure 11.8). Again, this actuation is commanded by the surface operator. At recovery the instrument hangs below the station, suspended on a rope.

Both actuation systems have been designed and manufactured specifically from this application; basically they consist of modified Acoustic Releases directly interfaced to observatory electronics. Finally, all sensors whose measurements could be affected by an

Figure 11.7 Different arrangements for the seismometer. From left to right: Guralp seismometer first arrangement (GEOSTAR mission 1); same instrument with an upgraded arrangement (GEOSTAR mission 2 and SN1 first mission); arrangement for PMD seismometer (GEOSTAR missions 3 and 4, SN2 mission 1, SN4 mission 1); Guralp seismometer final arrangement in titanium sphere (SN1 missions 2 and 3).

Figure 11.8 Seismometer management systems (left) used in GEOSTAR, SN2, SN3 and SN4; (right) used in SN1.

excessive tilt of the Bottom Station once at seafloor are provided with suitable levelling systems: motorized and remote controlled for the seismometer, passive (gimbals) for the gravity meter and vectorial magnetometer.

The "heart" of GEOSTAR is the Data Acquisition and mission Control System (DACS), on which the most advanced functionalities depend. Long autonomy, high reliability, capability to manage a wide range of sensors and devices, capability to manage large quantities of data are the basic requirements that triggered the development of a dedicated hardware for:

- payload management and control
- mission management
- power management and control
- technical status parameters monitoring

This hardware has been designed to meet the requirements of complex and multidisciplinary instrumented systems operating at sea, taking into account the necessity to operate in critical conditions (reduced volume, limited quantity of energy, hostile environment) and according to standardization criteria constituting one of the peculiar characteristics of GEOSTAR-class observatories (Table 11.2).

The architecture consists of different low power microprocessor units working in parallel (Figure 11.9). Number and type of units are selected case by case according to the complexity of the tasks and functionalities required by the experiments. Typical architecture of a GEOSTAR-class observatory includes:

- one Mission Control Unit, in charge of system configuration and supervision, interface with the communication systems, technical status monitoring
- a number of Payload Management Units, in charge of scientific packages data acquisition and control, data processing, data storage.

Weight (kN)	25.4 (in air), 14.2 (in water)
Dimensions (mm)	3500 × 3500 × 3300 (magnetometer booms retracted)
Design depth (m)	4000
Material	Aluminum 5083 (frame); titanium grade 5 (vessels); stainless steel (docking pin)
Data acquisition and mission control	4 boards (32 bit microcontroller MC68332)
Data storage	Hard disks, CompactFlash
Power supply	24 VDC, 3000 Ah Lithium-thionyl chloride
Power consumption (mA)	70 (idle mode), ~300 (mission mode)
Status parameters	Voltage, current, temperature, heading, tilt x/y, water intrusion, echo sounder

Table 11.2 GEOSTAR main characteristics (data refer to the last version).

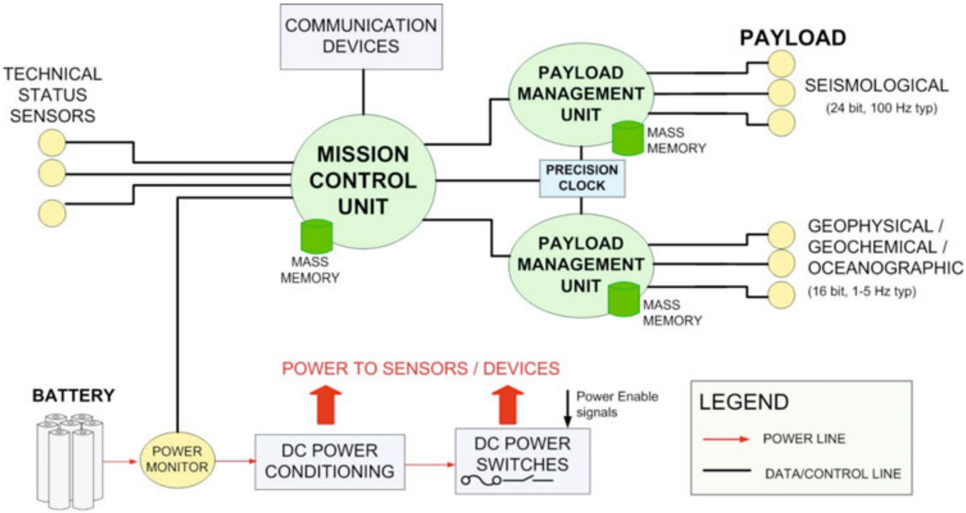


Figure 11.9 Reference architecture of a GEOSTAR-class observatory DACS.

The DACS is completed by auxiliary boards dedicated to power regulation, power switch (allowing switch on or off each instrumented package according to the preprogramed strategy or the occurrence of significant events like failures, energy loss, etc.), status monitoring (technical parameters like battery voltage, current, internal temperature).

A low power precision clock (rubidium) with long-term stability of 10-9 can be added to meet the requirements of seismological monitoring.

GEOSTAR deployment and recovery are ensured by a dedicated deep-sea vehicle (MODUS) – basically a special, simplified version of a Remotely Operated Vehicle – which is able to handle heavy payloads (up to 30 kN) with a weight of less than 10 kN (Figure 11.10). A comparison with the numbers of the few available deep-sea ROVs capable of operating at depths greater of 4000m (30–50 kN weight, 1–2 kN max payload), provides a clear idea of the efficiency and cost-effectiveness of the GEOSTAR concept. Unlike a standard ROV, MODUS has no free swimming capabilities and operates suspended from its electro-mechanical umbilical cable (25mm diameter, 1.8 kN/km weight in water) providing both power and fiber optic telemetry (Gerber et al., 2002). Electrical thrusters ensure mobility on the horizontal (x–y) plane, while the winch of the support vessel regulates its descent/ascent (z-axis). By means of visual (TV cameras) and instrumental (sonar) systems MODUS is capable of locating the predetermined installation area or find GEOSTAR for the subsequent recovery (Clauss et al., 2004) (Figure 11.11). An operation range of 5% of the water depth has been verified.

Figure 11.10 GEOSTAR–MODUS connection principle, based on docking pin (on GEOSTAR) and latching device (on MODUS).

MODUS guidance and control is ensured by a Surface Unit including monitors, PC with human-machine interface, joysticks for steering, and video recorders (Gerber and Claus, 2005)

Interaction with the user during the mission is one of the key functionalities for a seafloor observatory, enabling data transfer to the end users as well as full control of the mission.

Generally speaking, three basic configurations for a seafloor observatory can be identified, as regards the levels of interaction with the remote operator (and associated architecture of the communication infrastructure):

- autonomous operation; no connection apart from possibility of episodic access (e.g., from a ship of opportunity) where the observatory is provided with acoustic telemetry
- near-real-time connection (NRTCS); remote accessibility via underwater acoustic telemetry and a moored relay buoy connected to shore via radio or satellite, with limited capacity (in terms of quantity and bandwidth of transmission due to the acoustic telemetry)
- real-time connection to a shore station (via power and communication cable); enables "permanent" operation with full integration of the observatory in larger monitoring networks.

Levels of interaction are implemented according to the installation site location, available infrastructures and mission requirements. During the development of GEOSTAR-class observatories, all these configurations were implemented and operated in the field; in particular, GEOSTAR adopted the NRTCS scheme, with increasing levels of complexity and associated functionalities in the six missions carried out (see Table 11.3). SN2 operated in

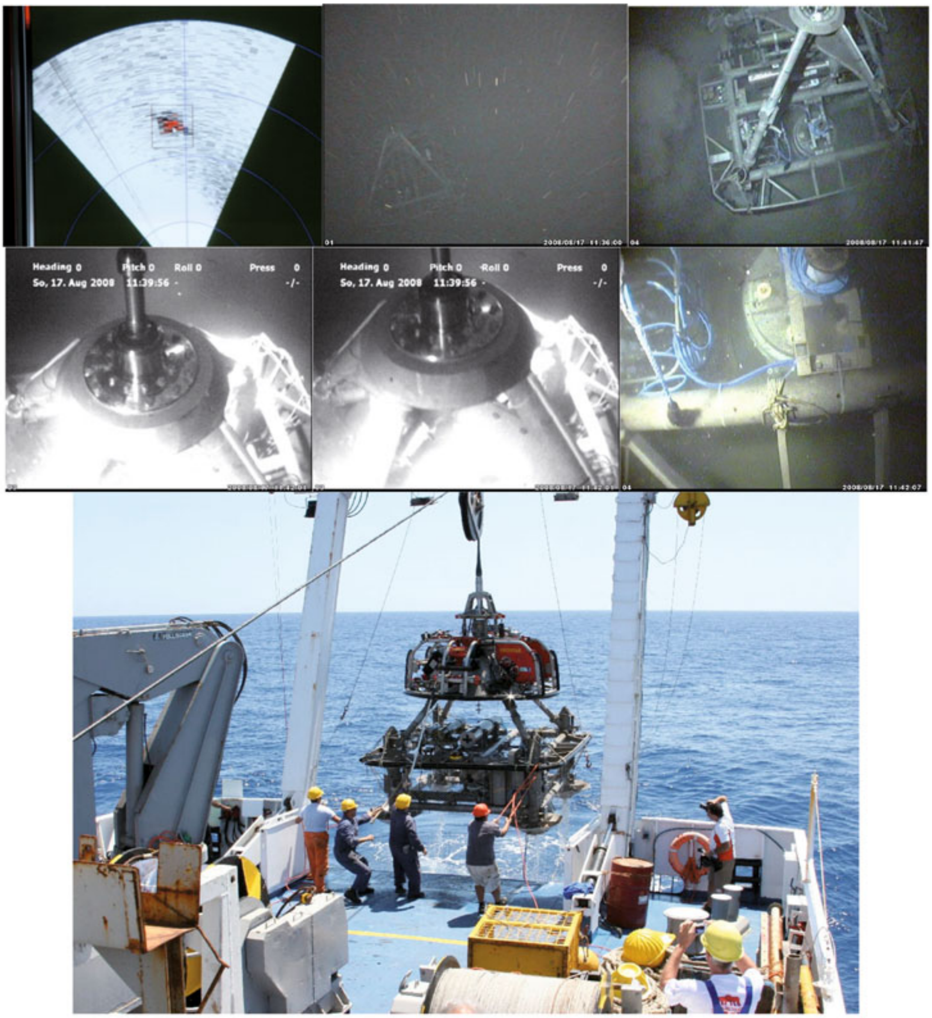


Figure 11.11 Typical recovery sequence of GEOSTAR (from top to bottom, left to right): observatory detected by the sonar, visual contact established, close approach, MODUS manually guided over the docking cone, MODUS lowered by the winch operator, docking complete, observatory onboard

autonomous mode, SN1 and GMM operated in autonomous mode but were also configured as a cabled observatory, SN3 and SN4 worked in near-real-time connection.

An essential component of the NRTCS architecture is a buoy moored in the immediate vicinity of the observatory and configured to operate as a communication relay between the observatory and the onshore remote operator (Marvaldi et al., 1998; Beranzoli et al., 2004). GEOSTAR buoy evolution is illustrated in Figure 11.12 and Table 11.4.

		Activated from surface	**Activated from seafloor**
Mission 1 (GEOSTAR 1) Adriatic Sea	Acoustic link • ship of opportunity	• Mission control commands • Summary data files upload	No functionality implemented
	Data capsules		ARGOS Messenger release (programmed or on event)
Mission 2 (GEOSTAR 2) Tyrrhenian Sea (offshore Ustica Island)	Acoustic link • shore station (via relay buoy) • ship of opportunity	• Mission control commands • Summary data files (mission, technical status) upload	No functionality implemented
	Data capsules		ARGOS Messenger release (programmed or on event)
Missions 3, 4 (ORION/ GEOSTAR 3) Tyrrhenian Sea (Marsili Seamount)	Acoustic link • shore station (via relay buoy) • ship of opportunity	• Mission control commands • Summary data files (mission, technical status) upload • Wave forms (seismic, hydrophone) upload	Automatic transmission • (at fixed intervals) summary data files (mission, technical status)
Mission 5 (NEAREST) Gulf of Cadiz (offshore Portugal)	Acoustic link • shore station (via relay buoy) • ship of opportunity	• Mission control commands • Summary data files (mission, technical status) upload • Event information (pressure, seismic) upload	Automatic transmission • (at fixed intervals) summary data files (mission, technical status) • (on event) event information (pressure, seismic)
Mission 6 (NEAREST) Gulf of Cadiz (offshore Portugal)	Acoustic link • shore station (via relay buoy) • ship of opportunity	same as Mission 5	Automatic transmission • (at fixed intervals) summary data files (mission, technical status) • event catalog (pressure, seismic) • (on event) event information (pressure, seismic)

Table 11.3 GEOSTAR-operator interaction levels.

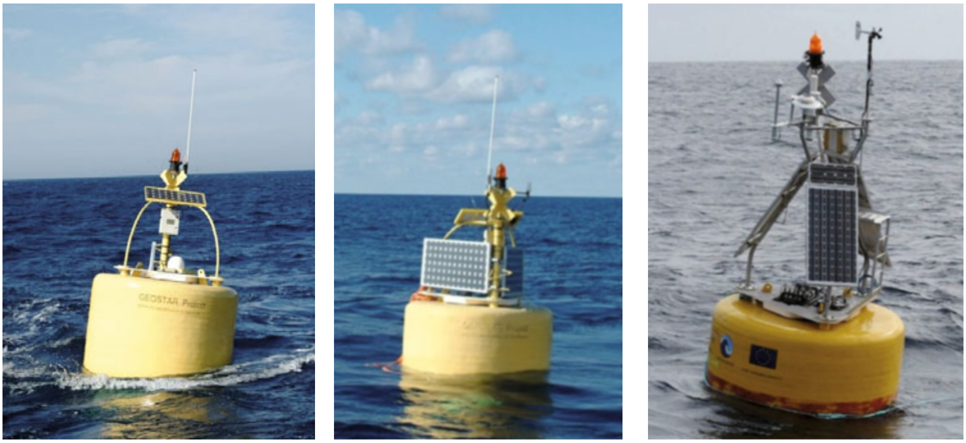


Figure 11.12 GEOSTAR buoy evolution: (left) mission 2; (center) missions 3 and 4; (right) missions 5 and 6.

Configuration	GEOSTAR 2 (mission 2)	ORION (missions 3,4)	NEAREST (missions 5,6)
Power	Primary lithium-thionyl chloride, 28 V 312 Ah	Lead-acid, 24 V 40 Ah recharged by 2×110 Wp photovoltaic panels	Lead-acid, 24 V 40 Ah recharged by 3×125 Wp photovoltaic panels
Communication (underwater segment)	12 kHz multimodulation acoustic modem	12 kHz multimodulation acoustic modem	12 kHz multimodulation acoustic modem
Communication (surface segment)	Inmarsat Mini-M VHF radio link	VHF radio link Iridium	Globalstar
Payload	Technical status parameters	Technical status parameters	Meteo station Barometric sensor Buoy attitude Technical status parameters

Table 11.4 GEOSTAR buoy main technical specifications.

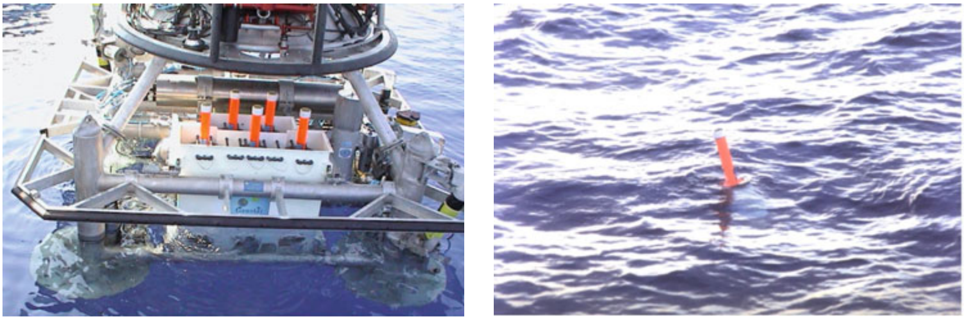


Figure 11.13 ARGOS Messengers (GEOSTAR mission 2 configuration) (left) during deployment; (right) released.

A second communication system was specifically developed for GEOSTAR, based on a set of releasable capsules called "Messengers", capable of transferring data by ARGOS satellite telemetry once arrived at the sea surface (Figure 11.13). Two types of Messengers were used:

- Expendable Messengers, released periodically (depending on the mission duration) or under particular conditions (i.e., in case of failure detection in the observatory); up to 32 Kbytes of data can be stored and then transferred through satellite telemetry
- Storage Messengers, released on external request (e.g., by operators on a ship), and storing up to 40 Mbyte of data.

11.3.1 GEOSTAR mission 1 (Adriatic Sea)

From the beginning, the GEOSTAR project was conceived as a two-step development process. The first phase (1995–1998) was carried out under the framework of EU Marine Science and Technology (MAST-3) program and was aimed at demonstrating the technology of the concept in shallow water and with a limited but essential set of functionalities implemented. The demonstration included a short mission (<1 month) in shallow water. The results of this represented a go/no-go point for the continuation of the project to the second phase, aimed at completing the technology development and carrying out the first deep-sea long-term mission with a complete payload and full capabilities implemented (Favali et al., 1998).

Due to the limited duration of the shallow water mission, the observatory was configured to operate in autonomous mode with the possibility of being interrogated from the ship of opportunity via vertical acoustic telemetry (12 kHz multimodulation acoustic modem ensuring up to 2400 bit/s). For the same reason, no dedicated surface logistics was developed (MODUS was managed through a rope and power/telemetry umbilical simply fastened to it); temporary pressure vessels for the DACS and battery pack were developed (in aluminum, 200m design depth); a smaller battery pack was used. The configuration included also three ARGOS Messengers (two expendable, one storage).

After an extensive phase of wet test in the IFREMER deep basin and TUB Berlin water circulation basin, GEOSTAR was deployed in August 1998 in the Adriatic Sea (offshore Ravenna) at the depth of 42m, and operated continuously for 450 hours. This mission had the goal of demonstrating all the capabilities of the system in real conditions. For the purpose of the technology demonstration, three main objectives were to be fulfilled:

- verify GEOSTAR capability to manage the scientific payload (and in particular the most demanding ones: seismometer and magnetometers)
- verify capability of the dedicated vehicle MODUS to manage GEOSTAR deployment and recovery procedures
- verify the possibility to interact with GEOSTAR during the mission, through the communication systems adopted.

Results obtained led to the conclusion that these objectives were fully achieved; all system capabilities and marine operations were successfully verified in real conditions, and important feedback obtained about the system enhancement in view of the second phase of the project (Gerber et al., 1999; Beranzoli et al., 2003).

The acoustic telemetry link ensured the ability to interact with the observatory during all phases of the mission (to check status of the system while at seabed, collect data, command Storage Messenger release, stop mission and lock seismometer masses), and at the same time represented an essential back-up of the cable link used during deployment. An Expendable Messenger was automatically released during the mission and its data successfully received via ARGOS.

Significant data regarding seismic events, magnetic field variations, water current and water characteristics of the area were collected and made available to scientists for proper analysis, demonstrating GEOSTAR's capability of operating as a multidisciplinary observatory.

Marine operations were carried out by the Italian R/V Urania (a medium-sized oceanographic ship, 1115 t gross tonnage, 61.3m overall length, 11.1m wide), that proved perfectly suitable to handle MODUS and the associated operational procedures (Figure 11.14).

11.3.2 GEOSTAR mission 2 (Southern Tyrrhenian Sea)

The goal of the second phase of the GEOSTAR project (EU GEOSTAR 2, 1999–2001) was to complete the technological development of the observatory and provide a full-scale demonstration of the concept during a long-term (6–12 months) scientific mission in a deep-sea site.

Work on the observatory was basically limited to an upgrade of its main subsystems in order to manage the extended payload and the new functionalities required. The temporary aluminum DACS and battery vessels used in mission 1 were replaced with new titanium vessels rated 6000m depth; the seismometer management system was also optimized; the number of ARGOS Messengers was extended to five (two Storage, three Expendable). The same approach was adopted for MODUS, whose hydrodynamic design was optimized and navigation payload increased (with the addition of sonar, colour camera and altimeter) (Gerber et al., 2002; Clauss et al., 2004).

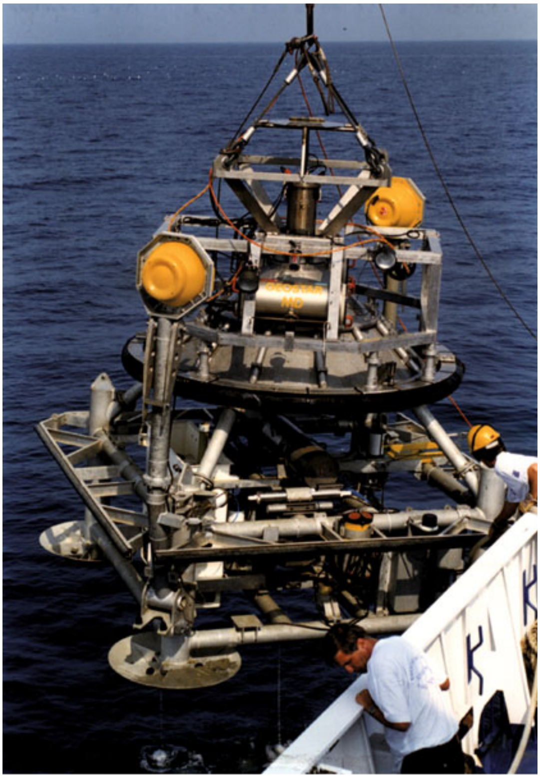


Figure 11.14 GEOSTAR recovery onboard R/V Urania at the end of the first mission (September 1998).

The two remaining subsystems necessary to complete the development of the GEOSTAR concept were the object of a dedicated work:

- the near-real-time communication system (Marvaldi et al., 2002), based on the development of a surface buoy (moored in the vicinity of the observatory deployment site) managing the operation of a satellite link (surface part) and an acoustic link (underwater part), and allowing a remote operator to interact with the observatory during the mission
- the observatory handling system, based on a dedicated electro-mechanical umbilical cable and winch, extending GEOSTAR's operativeness up to 4000m depth.

Mission 2 started in September 2000 and concluded in April 2001 with the system recovery. Deployment and recovery operations were managed by the same ship used for mission 1 (Figure 11.15).

The mission site selected was located in the abyssal plain of the Southern Tyrrhenian Sea, offshore Ustica Island, Italy. The site originally selected was about 3000m deep, but

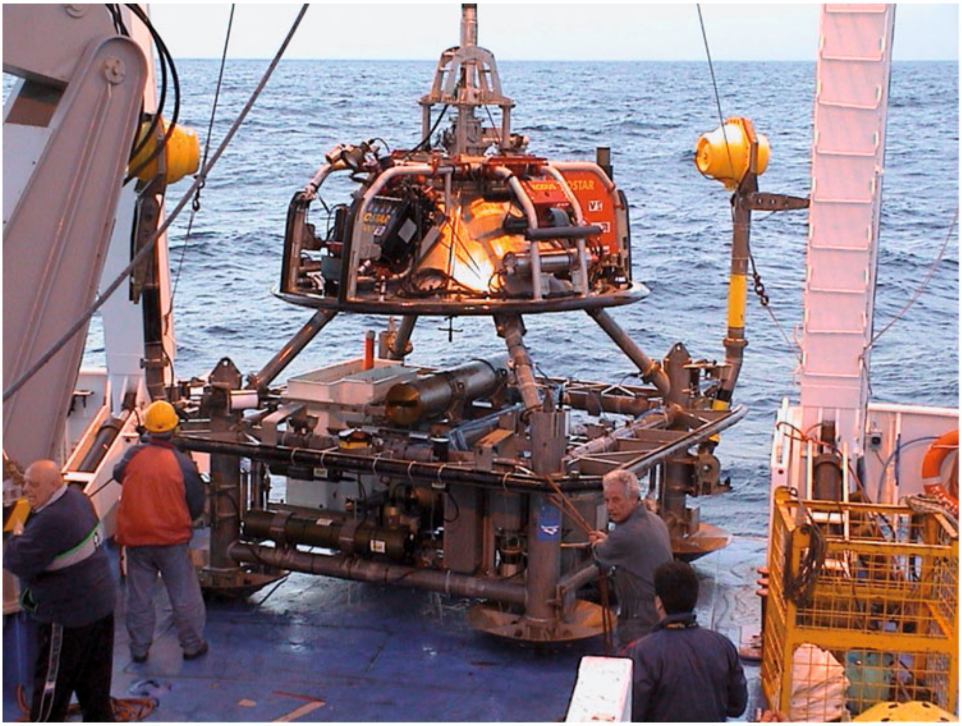


Figure 11.15 GEOSTAR recovered onboard R/V Urania at the end of mission 2 (March 2001).

due to technical problems with the umbilical termination during the preliminary test and two aborted tentative GEOSTAR's deployment, the water depth was reduced to approximately 2000m, while maintaining the full significance of the mission. After detailed investigation work by the manufacturer, the cause of the problem was identified in that, although formally rated at 4000m, the umbilical termination could not withstand pressures greater than 200 bar; the problem was then fixed and the handling system made available for subsequent applications (not limited to GEOSTAR-class observatories management and with a track record of 3700m depth reached).

The mission made it possible to demonstrate and confirm all system capabilities in deep-sea conditions.

Approximate 4150 hours of data (corresponding to 173 days of full operation) were collected with an acquisition efficiency of 99.6%.

During the mission a continuous set of geophysical, oceanographic and environmental parameters was acquired with a single reference time. Moreover, discrete water samples were collected for subsequent laboratory analysis. The complete dataset was downloaded from the observatory hard-disks just after the recovery; however, during the mission scientists and engineers could get real-time data access to the observatory from shore via the NRTCS (one interrogation per day) or via the periodic release of Messengers data capsules (one release per month). This allowed the execution of complete checks on the system functionality, as well as the start of the scientific data analysis while the mission was still ongoing. Quality of data collected was high, as demonstrated by the scientific literature so far produced (De Santis et al., 2006; Etiope et al., 2006; Iafolla et al., 2006).

11.3.3 GEOSTAR missions 3 and 4 (Southern Tyrrhenian Sea)

The third and fourth GEOSTAR missions were carried out within the framework of ORION-GEOSTAR 3 EC project (2002–2005). The technical goal of ORION (Ocean Research by Integrated Observation Networks) was the development of a seafloor network for scientific research and early warning of major hazard events (e.g., earthquakes and volcanic eruptions) (Favali et al., 2006). The basic idea was therefore to extend the effective operational radius of the single observatory in order to better cover the area of interest, transferring at seafloor the standards and rules established for the traditional shore-based communication networks. For this purpose, ORION was conceived as a series of interconnected stations, hereafter referred as to “nodes”; each node being network-accessible from the others to exchange data and commands (Gerber and Clauss, 2005).

The network configuration implemented in the project (see Figure 11.16) is based on two satellite stations configured as hosts (i.e., nodes that do not forward messages to other networks) and a main station configured as a gateway (i.e., a node that forwards messages to other networks) (Beranzoli et al., 2004).

The main node (gateway) was an upgrade of GEOSTAR, while the two satellite nodes (named SN3 and SN4) were specifically developed, maintaining most of the peculiar characteristics of GEOSTAR, to ensure maximum standardization and interoperability. SN4 (originally foreseen in the ORION experiment) on request from the European Commission was developed in this project but used in the framework of a parallel project (ASSEM – Array of Sensors for long-term SEabed Monitoring of geo-hazards) for a long-term mission, to demonstrate compatibility and integrability of GEOSTAR technology in other European seafloor networks (Rolin et al., 2005).

Although the network developed in the project was limited to three nodes, its standard and modular architecture allow expansion and reconfiguration according to the specific requirements of future applications. The nodes communicate through horizontal acoustic telemetry, while existing shore networks (phone network, Internet, etc.) are interfaced with the ORION seafloor gateway through a near-real-time communication buoy, supporting the operation of a vertical acoustic telemetry (to communicate with the gateway) and a surface (satellite or radio) link.

New acoustic protocols were specifically developed according to ORION’s telemetry architecture. Moreover, GEOSTAR DACS was upgraded to manage the acoustic links together with the new payload and to implement new functionalities aimed at extending the level of interaction of the underwater network with the remote user, such as: automatically send periodical messages to shore (scientific and diagnostic data summaries, or autono-

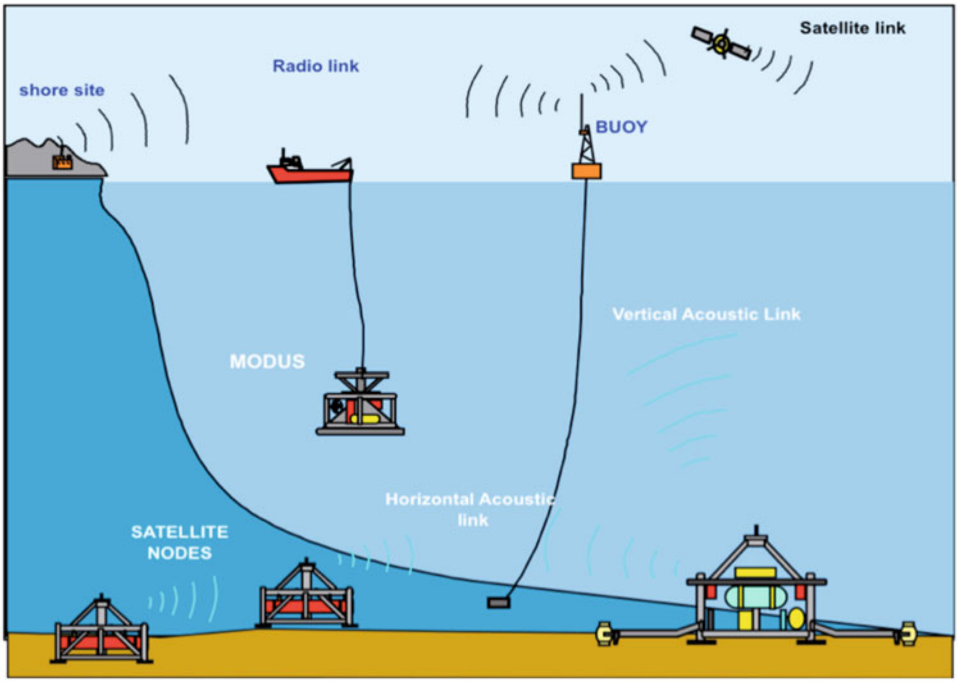


Figure 11.16 ORION concept (as proposed to EU Fifth Framework Programme, 2002).

mous alarm messages); manage messages from the satellite nodes; process hydrophone data to detect events; allow remote user to interrogate any node in the network; and send commands or request data.

Technological solutions developed in the project were demonstrated and validated in a pilot experiment dedicated to long-term continuous geophysical and oceanographic monitoring of Marsili seamount (Southern Tyrrhenian Sea), one of the largest underwater volcanoes in Europe.

GEOSTAR and SN3 were deployed from R/V Urania in December 2003 (Figure 11.17, Figure 11.18, Figure 11.19), at a depth of about 3350m.

The satellite node was placed at approximately 1300m from GEOSTAR.

From the start of mission 3, the system was affected by technical problems in the vertical acoustic telemetry that basically precluded any type of communication between the gateway and the surface buoy. For this reason, it was decided to continue the mission, leaving the observatories to operate in autonomous mode and anticipate recovery to fix the problems and proceed with a new deployment. Then GEOSTAR and SN3 were recovered in the period 23–30 April 2004, disembarked and stored in Catania INFN (Istituto Nazionale di Fisica Nucleare) workshop for the necessary technical interventions.

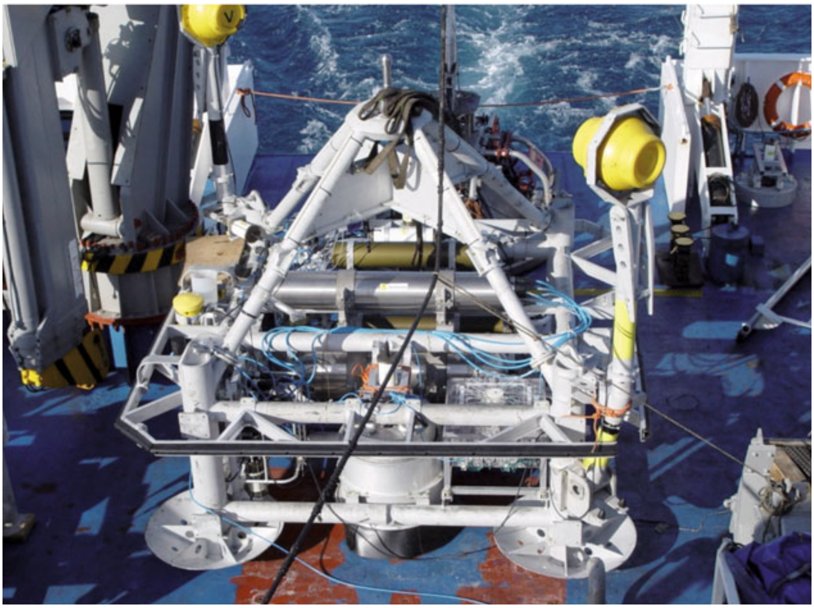


Figure 11.17 GEOSTAR onboard R/V Urania ready for deployment (mission 3, December 2003).

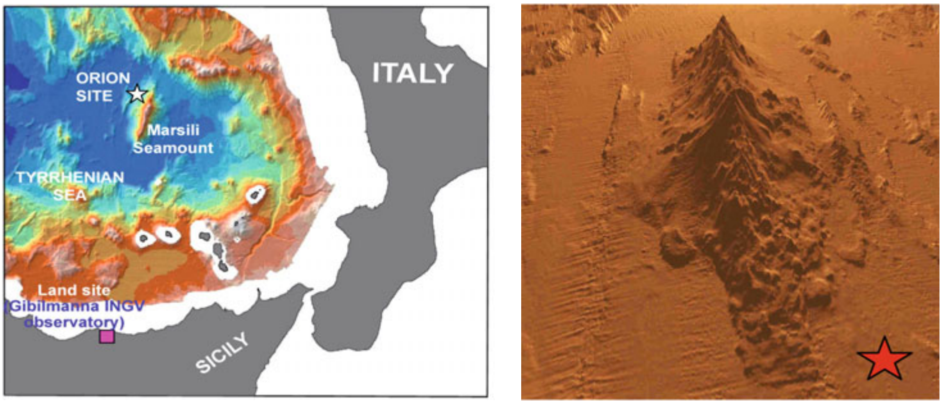


Figure 11.18 ORION mission site. (Left) geographic location of the site. (Right) 3D digital image of the Marsili Seamount seen from NW. Observatory network deployment site indicated by the star. Maps redrawn from Marani et al. (2004).

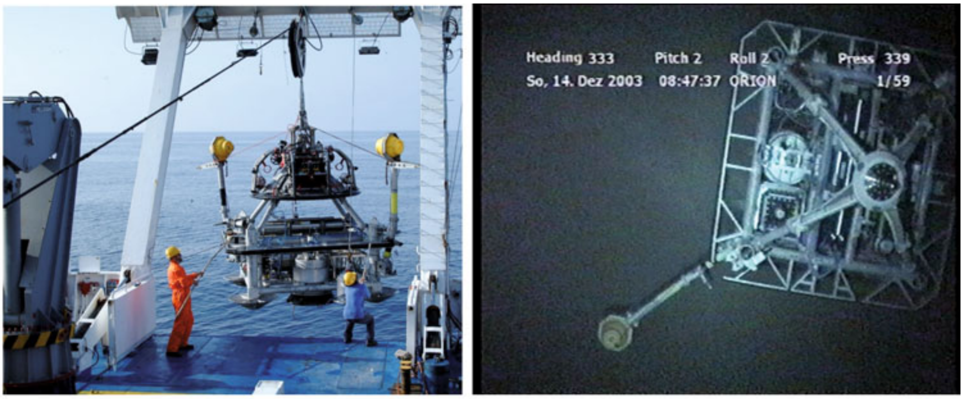


Figure 11.19 (Left) GEOSTAR deployed from R/V Urania, December 2003. (Right) GEOSTAR seen from MODUS immediately after completion of deployment phase and vehicle disconnection.

The observatories were redeployed in mid-June 2004, approximately in the same sites of the first mission, and the fourth mission started. The two observatories were left working until battery discharge and were finally recovered in April 2005.

This time, it was possible to demonstrate all the functionalities implemented: periodic messages from the observatories were received at the shore station and the remote operator was able to make direct interrogations. However, after two months of correct operation, the communication system evidenced new problems (to the buoy acoustic transducer and the radio link) and finally the buoy mooring line was broken.

In spite of the communication problems, GEOSTAR (and SN3) operated reliably throughout the mission duration, and analysis of data recovered indicated that both observatories were able to produce and transmit all the scheduled messages.

The two consecutive missions 3 and 4 demonstrated the validity of the ORION concept and provided many significant technical results. First of all, GEOSTAR operativity (observatory + intervention system + ship + procedures) was fully demonstrated at 3350m (the previous record was 1950m from the Ustica mission 2). With the same battery pack, GEOSTAR worked for 10,257 hours (corresponding to about 427 days of mission), reaching and significantly exceeding the original target of a 1-year operation.

Based also on the experience gained with the SN1 first mission (Monna et al., 2005), the original seismometer deployment procedure implemented in GEOSTAR-class observatories could now be considered well proven and qualified. During the mission period the seismometer recorded many (about 900) local, regional and teleseismic events. The high quality of seismic recordings confirmed the validity of the installation procedure (as developed and already tested in the GEOSTAR projects) and good ground coupling of the sensor.

The automatic chemical analyzer finally made its first mission, providing good quality data. The analyzer recorded more than 260 pH continuous data in parallel to the automatic water sampler that collected 38 samples for on-shore laboratory analyses on dissolved gas in water, cations and anions, minor and trace elements, radionuclides.

From the scientific point of view, for the first time, the Marsili volcano seamount was the object of a long-term monitoring activity. During the missions, an enormous quantity of data was acquired and made available for scientific evaluation (De Santis et al., 2007; Beranzoli et al., 2009). Data analysis evidenced significant geophysical and oceanographic time variations (Fuda et al., 2006). In particular, magnetic data allow the estimation of some conductivity structure at different depths under the Marsili volcano and gravimetric data show relevant signal patterns at low frequency (Vitale et al., 2009); seismic data show local activity with recurring events. Significant correlations between recorded time series could be related to the activity and structure of the volcano. GEOSTAR missions provided the starting point for a more ambitious activity to study the Marsili volcano, with objectives that overcome the pure scientific relevance of the phenomenon, and involve social and economic aspects such as natural hazard management (understand and monitor the risk of a possible eruption and associated risk of a catastrophic tsunami) and the renewable resource (the volcano as an offshore geothermal energy source).

Problems with the NRTCS buoy (mooring line rupture, unreliable operation of the vertical acoustic modem) were related to failures of commercial “off-the-shelf” products. Thus the validity of the concept was not affected and the problems occurred could be easily solved with a more careful specification and selection of the products.

11.3.4 GEOSTAR mission 5 (Gulf of Cadiz)

GEOSTAR missions 5 and 6 were carried out under the framework of the EU project NEAREST (Integrated observations from NEAR shore sourcES of Tsunamis: towards an early warning system), whose objectives included the development and test of an operational prototype of a near field tsunami warning system (Chierici et al., 2008). The prototype is designed to operate in tsunami generation areas for detection-warning purposes as well as for scientific measurements. The reference area of the project was the Gulf of Cadiz (offshore Portugal; Figure 11.20). The key elements of NEAREST concept are shown in Figure 11.21.

The tsunami detector is hosted inside the seafloor observatory, and includes a pressure sensor, a seismometer and two accelerometers. The tsunami detection procedure is based on a trigger on pressure and seismic events:

- seismometer: trigger on local strong earthquakes
- pressure: detection of sea level anomalies (tsunamis wave), triggering on processed sea level data compared to assigned threshold.

Pressure data are processed inside the observatory in real time and by means of an original tsunami detection algorithm conceived and implemented by INGV (Istituto Nazionale di Geofisica e Vulcanologia), IRA-INAF (Istituto Nazionale di AstroFisica–Istituto di RadioAstronomia) and CNR-ISMAR (Consiglio Nazionale delle Ricerche–IStituto di scienze MARine), and capable of detecting centimetric tsunami waves. The tsunami detector sends a near-real-time automatic alert message to surface when a seismic or a pressure signal exceeds a selectable threshold indicating a strong local earthquake or a tsunami wave event.

Figure 11.20 NEAREST installation site.

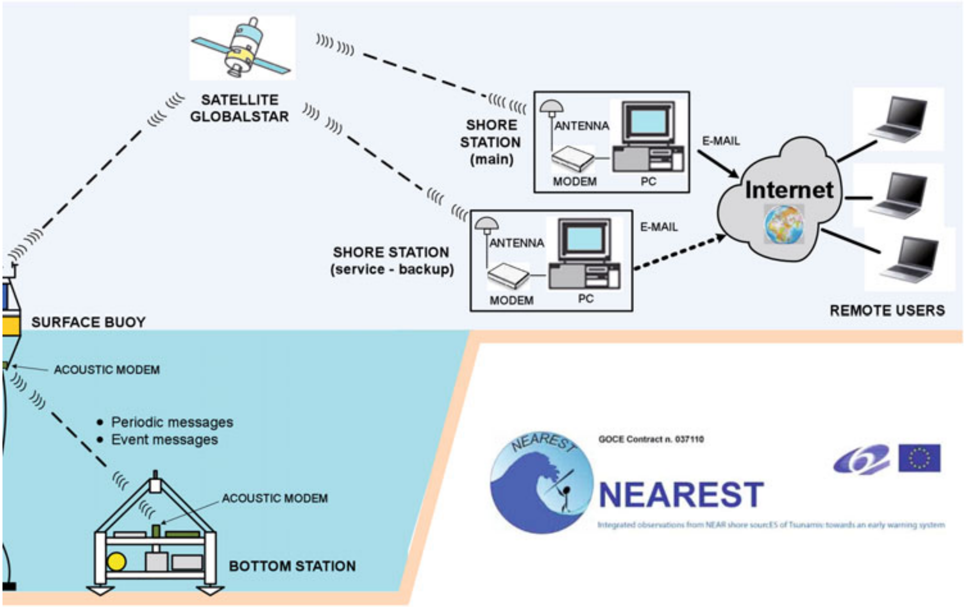
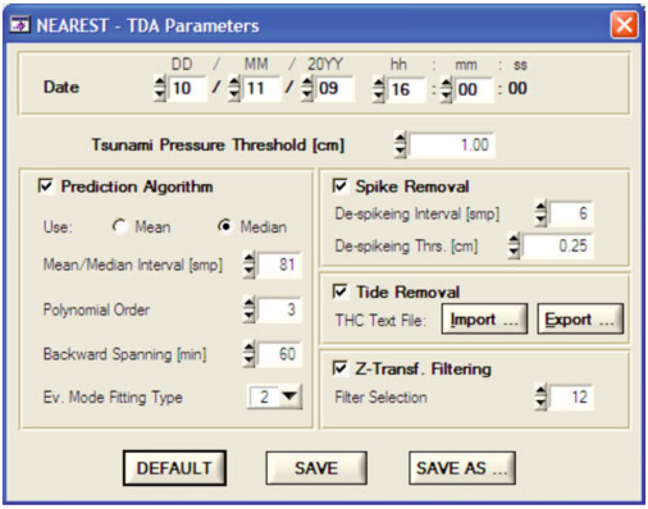


Figure 11.21 NEAREST concept.



NEAREST - TDA Parameters

Date DD / MM / 20YY hh : mm : ss

10 / 11 / 09 16 : 00 : 00

Tsunami Pressure Threshold [cm] 1.00

☑ Prediction Algorithm

Use: ○ Mean ● Median

Mean/Median Interval [smp] 81

Polynomial Order 3

Backward Spanning [min] 60

Ev. Mode Fitting Type 2

☑ Spike Removal

De-spikeing Interval [smp] 6

De-spikeing Thrs. [cm] 0.25

☑ Tide Removal

THC Text File:

☑ Z-Transf. Filtering

Filter Selection 12

Figure 11.22 Configuration of the tsunami detection algorithm.

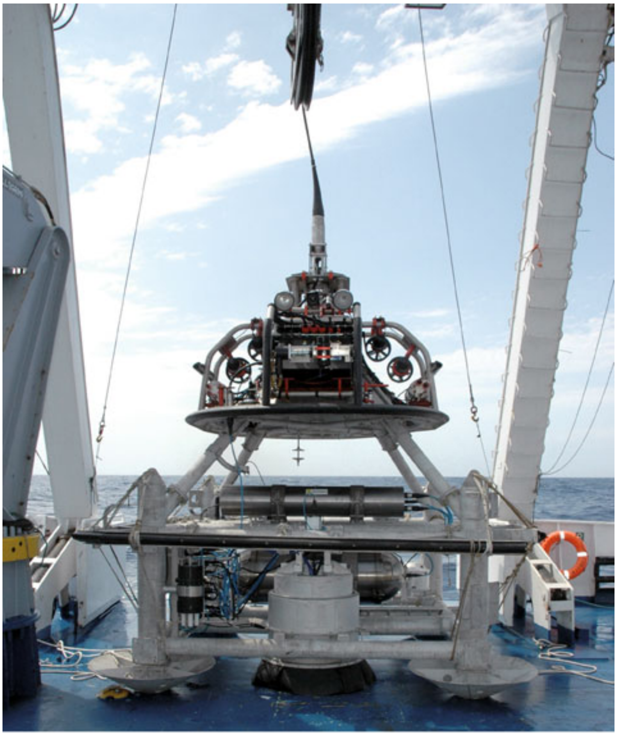


Figure 11.23 GEOSTAR ready for installation in Cadiz Gulf (mission 5, August 2007).

The algorithm is based on real time pressure data analysis, consisting of spikes and tide removing, low pass filtering and linear prediction: the output is then compared to a given pressure threshold allowing the detection of anomalous events (Chierici et al., 2008). Different configurations of the algorithm may be adopted, modifying a configuration file at mission start (Figure 11.22 shows the configuration panel of the tsunami detection algorithm). The algorithm can be reconfigured at any time, provided that the acoustic and satellite links are operational.

The Shore Station acts as a "Warning Center", in charge of collecting, integrating and evaluating data recorded at the sea bottom.

Thanks to its unique characteristics, GEOSTAR was selected to host the tsunami detector and be reconfigured and upgraded for the NEAREST experiment. Part of the payload used in previous missions (magnetometers and chemical analyzer) was removed, new instruments like a pressure sensor and Inertial Measurement Unit were integrated, old sensors (unavailable or not suited for the application) were replaced with new ones (seismometer and current meter) and the processing capability was improved with a new powerful CPU board dedicated to the real-time tsunami data processing.

In parallel, the buoy was configured according to project requirements, fixing the problems experienced in the previous mission: new mooring line, new low power electronics based on the standard GEOSTAR hardware, new instrumentation payload (meteorological station, GPS, satellite modem) and power supply (batteries and photovoltaic panels) (Figure 11.23).

GEOSTAR and the buoy were installed above an active, potentially tsunamigenic structure, the Marques de Pombal Structure at a depth of 3200m in August 2007. Mission 5 was therefore in operation.

During the experiment, all the sensors and software worked properly with the exception of a malfunctioning of the acoustic communication system located on the surface buoy that basically precluded any remote access to the observatory. Only direct interrogations from ship of opportunity, bypassing the buoy, were possible. In addition, the buoy suffered another failure to the mooring in November 2007; nevertheless, position data continuously transmitted by the ARGOS beacon allowed the prompt organization and execution of the recovery intervention.

The observatory was recovered in August 2008, one year after deployment (Figure 11.24). Subsequent analysis of scientific and technical data indicated a successful execution of all the mission tasks, including data acquisition and storage, automatic processing of pressure and seismometer data, automatic production and transmission of the data messages. However, due to the problems with the communication buoy the system was not fully able to demonstrate the feasibility of tsunamis warning detection and transmission.

11.3.5 GEOSTAR mission 6 (Gulf of Cadiz)

Following the results of mission 5, the decision was taken to organize an additional mission within the project and in synergy with the LIDO (Listening to the Deep-Ocean environment) Demonstration Mission funded by the EC project ESONET (European Seas Observatory NETwork) Network of Excellence, in order to get a complete demonstration of the communication chain between the seafloor abyssal station configured for the tsunami detection and the shore station.

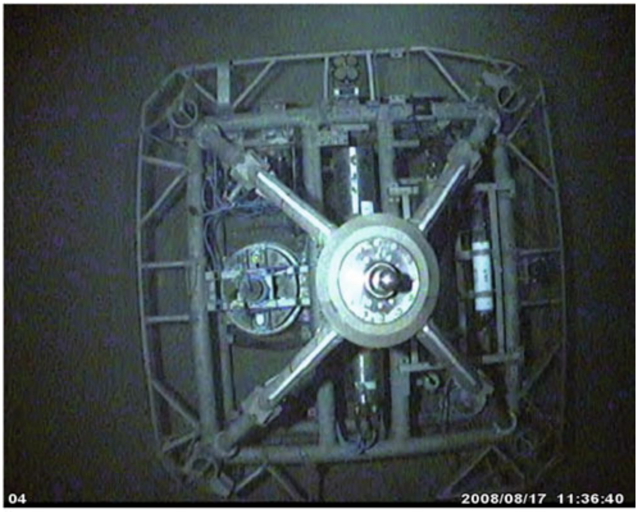


Figure 11.24 GEOSTAR seen by MODUS during the final approach before docking (August 2008).

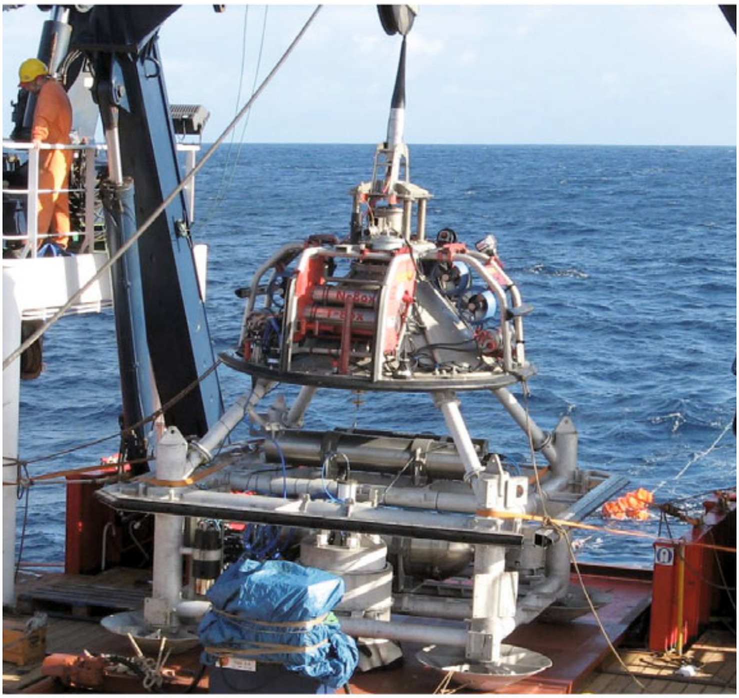
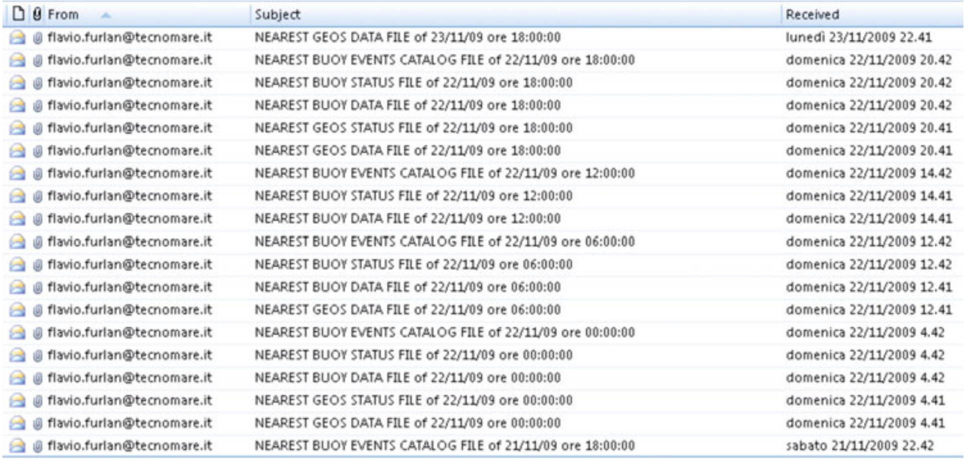


Figure 11.25 GEOSTAR before installation in Cadiz Gulf (mission 6, November 2009).



From	Subject	Received
flavio.furlan@tecnomare.it	NEAREST GEOS DATA FILE of 23/11/09 ore 18:00:00	lunedì 23/11/2009 22.41
flavio.furlan@tecnomare.it	NEAREST BUOY EVENTS CATALOG FILE of 22/11/09 ore 18:00:00	domenica 22/11/2009 20.42
flavio.furlan@tecnomare.it	NEAREST BUOY STATUS FILE of 22/11/09 ore 18:00:00	domenica 22/11/2009 20.42
flavio.furlan@tecnomare.it	NEAREST BUOY DATA FILE of 22/11/09 ore 18:00:00	domenica 22/11/2009 20.42
flavio.furlan@tecnomare.it	NEAREST GEOS STATUS FILE of 22/11/09 ore 18:00:00	domenica 22/11/2009 20.41
flavio.furlan@tecnomare.it	NEAREST GEOS DATA FILE of 22/11/09 ore 18:00:00	domenica 22/11/2009 20.41
flavio.furlan@tecnomare.it	NEAREST BUOY EVENTS CATALOG FILE of 22/11/09 ore 12:00:00	domenica 22/11/2009 14.42
flavio.furlan@tecnomare.it	NEAREST BUOY STATUS FILE of 22/11/09 ore 12:00:00	domenica 22/11/2009 14.41
flavio.furlan@tecnomare.it	NEAREST BUOY DATA FILE of 22/11/09 ore 12:00:00	domenica 22/11/2009 14.41
flavio.furlan@tecnomare.it	NEAREST BUOY EVENTS CATALOG FILE of 22/11/09 ore 06:00:00	domenica 22/11/2009 12.42
flavio.furlan@tecnomare.it	NEAREST BUOY STATUS FILE of 22/11/09 ore 06:00:00	domenica 22/11/2009 12.42
flavio.furlan@tecnomare.it	NEAREST BUOY DATA FILE of 22/11/09 ore 06:00:00	domenica 22/11/2009 12.41
flavio.furlan@tecnomare.it	NEAREST GEOS DATA FILE of 22/11/09 ore 06:00:00	domenica 22/11/2009 12.41
flavio.furlan@tecnomare.it	NEAREST BUOY EVENTS CATALOG FILE of 22/11/09 ore 00:00:00	domenica 22/11/2009 4.42
flavio.furlan@tecnomare.it	NEAREST BUOY STATUS FILE of 22/11/09 ore 00:00:00	domenica 22/11/2009 4.42
flavio.furlan@tecnomare.it	NEAREST BUOY DATA FILE of 22/11/09 ore 00:00:00	domenica 22/11/2009 4.42
flavio.furlan@tecnomare.it	NEAREST GEOS STATUS FILE of 22/11/09 ore 00:00:00	domenica 22/11/2009 4.41
flavio.furlan@tecnomare.it	NEAREST GEOS DATA FILE of 22/11/09 ore 00:00:00	domenica 22/11/2009 4.41
flavio.furlan@tecnomare.it	NEAREST BUOY EVENTS CATALOG FILE of 21/11/09 ore 18:00:00	sabato 21/11/2009 22.42

Figure 11.26 Automatic messages received from GEOSTAR and buoy during mission 6.

To fix the previously-occurring problems, a new model of acoustic modem was adopted and the buoy mooring line completely redesigned. Minor upgrades were finally implemented to GEOSTAR and the buoy (Figure 11.25).

The payload was the same as previous missions, with the addition of a stand-alone hydrophone, powered by a dedicated battery pack.

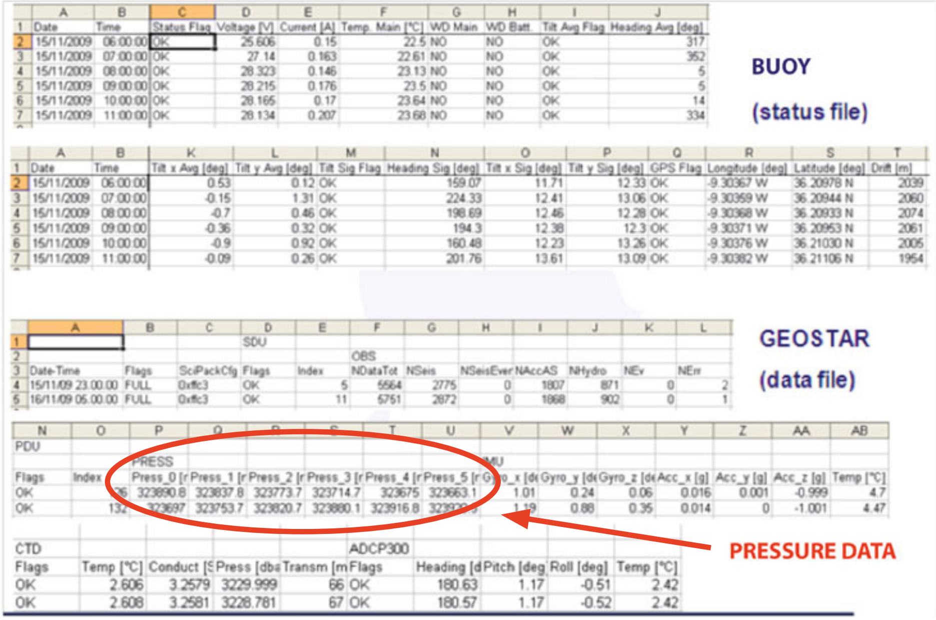
The new deployment cruise took place with the R/V Sarmiento de Gamboa in November 2009.

This time, the GEOSTAR-buoy-shore station communication link worked properly, demonstrating the validity of the concept. Messages automatically produced by GEOSTAR and the buoy were correctly received at the Shore Station and dispatched to the end users, according to the scheme already shown in Figure 11.21; Figure 11.26, Figure 11.27 and Figure 11.28 provide examples of the email delivered with the messages attached, the converted data (binary to spreadsheet) and a typical communication log respectively.

Operation of the communication link was, however, interrupted at the end of December 2009, due to occurrence of severe damages to the buoy instrumentation (probably caused by extreme weather conditions or ship collision). The GEOSTAR mission continued until July 2010 (when the mission was automatically stopped and the observatory put in IDLE mode to preserve the necessary energy to keep the rubidium clock working until recovery).

GEOSTAR was finally recovered in June 2011. Again, download and subsequent analysis of data proved the correct operation of the observatory during the mission; all the scheduled tasks were executed and, in particular, pressure events were detected.

With the conclusion of mission 6, the first European tsunami warning system based on simultaneous acquisition and processing of seismic and pressure data has been qualified and is now available for possible operational application.



	A	B	C	D	E	F	G	H	I	J
1	Date	Time	Status Flag	Voltage [V]	Current [A]	Temp. Main [°C]	WD Main	WD Batt.	Tilt Avg Flag	Heading Avg [deg]
2	15/11/2009	06:00:00	OK	25.606	0.15	22.5	NO	NO	OK	317
3	15/11/2009	07:00:00	OK	27.14	0.163	22.61	NO	NO	OK	352
4	15/11/2009	08:00:00	OK	28.323	0.146	23.13	NO	NO	OK	5
5	15/11/2009	09:00:00	OK	28.215	0.176	23.5	NO	NO	OK	5
6	15/11/2009	10:00:00	OK	28.165	0.17	23.64	NO	NO	OK	14
7	15/11/2009	11:00:00	OK	28.134	0.207	23.68	NO	NO	OK	334

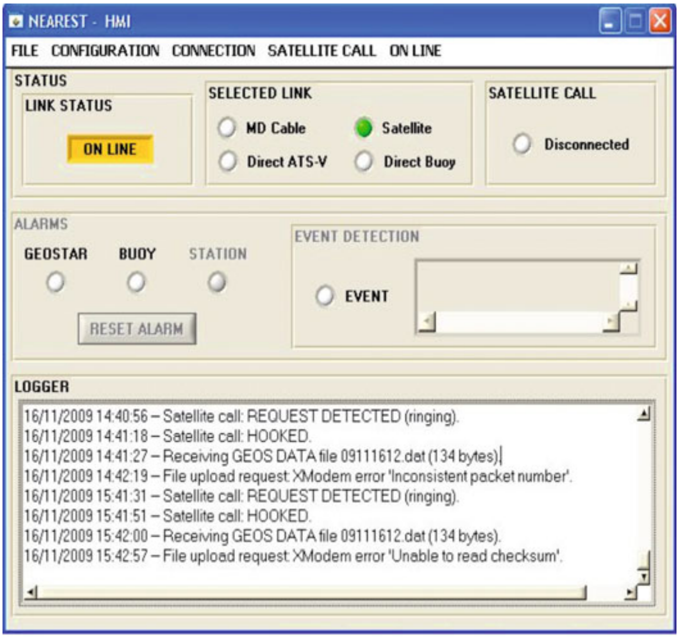
	A	B	K	L	M	N	O	P	Q	R	S	T
1	Date	Time	Tilt x Avg [deg]	Tilt y Avg [deg]	Tilt Sig Flag	Heading Sig [deg]	Tilt x Sig [deg]	Tilt y Sig [deg]	GPS Flag	Longitude [deg]	Latitude [deg]	Drift [m]
2	15/11/2009	06:00:00	0.53	0.12	OK	159.07	11.71	12.33	OK	-9.30367 W	36.20978 N	2039
3	15/11/2009	07:00:00	-0.15	1.31	OK	224.33	12.41	13.06	OK	-9.30359 W	36.20944 N	2060
4	15/11/2009	08:00:00	-0.7	0.46	OK	198.69	12.46	12.28	OK	-9.30368 W	36.20933 N	2074
5	15/11/2009	09:00:00	-0.36	0.32	OK	194.3	12.38	12.3	OK	-9.30371 W	36.20953 N	2061
6	15/11/2009	10:00:00	-0.9	0.92	OK	160.48	12.23	13.26	OK	-9.30376 W	36.21030 N	2005
7	15/11/2009	11:00:00	-0.09	0.26	OK	201.76	13.61	13.09	OK	-9.30382 W	36.21106 N	1954

	A	B	C	D	E	F	G	H	I	J	K	L
1				SDU								
2						OBS						
3	Date-Time	Flags	SciPackCfg	Flags	Index	NDataTot	NSeis	NSeisEver	NAccAS	NHydro	NEv	NErr
4	15/11/09 23.00.00	FULL	0xffc3	OK	5	5564	2775	0	1807	871	0	2
5	16/11/09 05.00.00	FULL	0xffc3	OK	11	5751	2872	0	1868	902	0	1

N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB
PDU														
		PRESS						IMU						
Flags	Index	Press_0 [r	Press_1 [r	Press_2 [r	Press_3 [r	Press_4 [r	Press_5 [r	Gyro_x [de	Gyro_y [de	Gyro_z [de	Acc_x [g]	Acc_y [g]	Acc_z [g]	Temp [°C]
OK	26	323890.8	323837.8	323773.7	323714.7	323675	323663.1	1.01	0.24	0.06	0.016	0.001	-0.999	4.7
OK	132	323697	323753.7	323820.7	323880.1	323916.8	[illegible]	1.19	0.88	0.35	0.014	0	-1.001	4.47

CTD					ADCP300				
Flags	Temp [°C]	Conduct [S	Press [dba	Transm [m	Flags	Heading [d	Pitch [deg	Roll [deg]	Temp [°C]
OK	2.606	3.2579	3229.999	66	OK	180.63	1.17	-0.51	2.42
OK	2.608	3.2581	3228.781	67	OK	180.57	1.17	-0.52	2.42

Figure 11.27 Examples of data messages of GEOSTAR and buoy during mission 6.



```
16/11/2009 14:40:56 – Satellite call: REQUEST DETECTED (ringing).
16/11/2009 14:41:18 – Satellite call: HOOKED.
16/11/2009 14:41:27 – Receiving GEOS DATA file 09111612.dat (134 bytes).
16/11/2009 14:42:19 – File upload request: XModem error 'Inconsistent packet number'.
16/11/2009 15:41:31 – Satellite call: REQUEST DETECTED (ringing).
16/11/2009 15:41:51 – Satellite call: HOOKED.
16/11/2009 15:42:00 – Receiving GEOS DATA file 09111612.dat (134 bytes).
16/11/2009 15:42:57 – File upload request: XModem error 'Unable to read checksum'.
```

Figure 11.28 Example of satellite calls log during mission 6.

11.4 SN1

Since the early phases of GEOSTAR development, it appeared evident that the concept offered significant opportunities of exploitation. This conviction was the origin to two parallel initiatives: (1) extending the onshore Italian seismic network to the offshore environment (leading to the development of SN1; (2) establishing the first application of a seafloor observatory in a polar environment (leading to the development of MABEL). The technical solution developed for both applications consisted of an optimized version of GEOSTAR, making the resulting observatory easier to handle but at the same time ensuring the highest level of standardization with GEOSTAR. Peculiar characteristics may be summarized as follows:

- smaller frame, fully compatible with Modus (Figure 11.29 allows comparison between GEOSTAR and SN1 dimensions)
- same deployment/recovery procedure and surface logistics (cable, winch)
- same seismometer installation device, positioned in the centre of the frame
- new battery pack, based on 12 V 480 Ah modules specially developed by SAFT and fitting into 200mm internal diameter vessels; this will become a standard for all GEOSTAR-class observatories
- same data acquisition and mission management electronics, reconfigured to fit into 150mm internal diameter vessels; this will become a standard for all GEOSTAR-class observatories.

Basically, the new architecture maintains the same functionalities of GEOSTAR, apart from the capability to host the Argos Messenger container and the extendable booms for the magnetometers.

Figure 11.29 Comparison between GEOSTAR (left) and SN1 (mission 1 center; mission 2 right).

In particular, SN1 maintains the open architecture, fully reconfigurable concept that is one of GEOSTAR's most peculiar characteristics; this made possible SN1 evolution from a battery-powered autonomous version mainly devoted to seismological monitoring, to a cabled version real-time connected to shore and supporting a fully multidisciplinary payload. Evolution of SN1 scientific payload is summarized in Table 11.5.

Sensor	**Mission 1**	**Mission 2**	**Mission 3**	**Sampling rate**
Triaxial broad-band seismometer	Guralp CMG-1T	Guralp CMG-1T	Guralp CMG-1T	100 Hz
CTD	Seabird SBE37-SM	Seabird SBE37-SM	Seabird SBE37-SM	1 sample/h
Gravity meter	IFSI prototype	IFSI prototype	IAPS prototype	1 Hz
Current meter	FSI 3D-ACM	FSI 3D-ACM	Nobska MAVS-3	2 Hz
Scalar magnetometer		Marine Magnetics Sentinel 3000	Marine Magnetics Sentinel 3000	1 sample/h
Vectorial magnetometer			INGV prototype (3-axes)	0.5 Hz
Low frequency hydrophone	OAS E-2PD	OAS E-2PD	OAS E-2PD	100 Hz
Low frequency hydrophone			SMID DT-405D(V)1	2 kHz
Inertial measurement unit			Landmark LMRK20-AHRS 150-02-100	200 Hz
Absolute pressure gauge			Paroscientific 8CB4000-I	4 to 60 samples/min
Differential pressure gauge			SCRIPP Institution of Oceanography, University of San Diego UCSD	100 Hz
ADCP			RDI, Workhorse Sentinel 600 kHz	1 profile/hour
Bioacoustics			4 hydrophones SMID TR-401(V)1	96 kHz
Compass			Falmouth Ostar Compass	1 Hz

Table 11.5 SN1 payload and sampling rates.

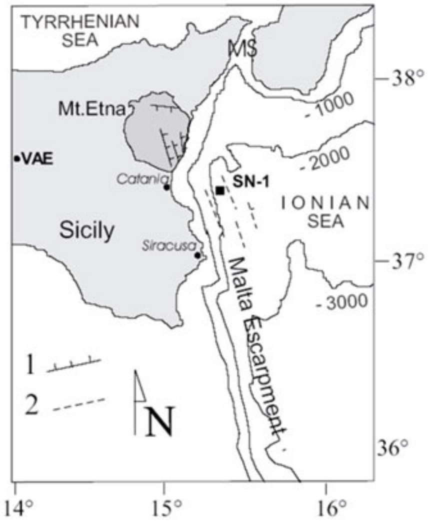


Figure 11.30 Tectonic sketch of Eastern Sicily (Ionian Sea) offshore area; SN1 installation site is indicated by the black square. MS=Messina Strait (redrawn from Monna et al., 2005).

11.4.1 SN1 mission 1 (Ionian Sea)

The SN1 project was developed in the Framework of the 2000–2003 Program of the Italian National Group for Defense against Earthquakes (GNDT) (Beranzoli and Favoli, 2005). The main objective of the project was to deploy a seafloor observatory in the Ionian Sea abyssal plain (Figure 11.30), a few tens of kilometers off the Eastern Sicily coasts and to integrate it into the existing onshore seismic network operated by INGV. The Ionian area facing Eastern Sicily is recognized as the site of important seismogenic underwater structures, the most important of which is the Ibleo-Maltese structure that is considered responsible for the most disastrous earthquakes of the area: Catania (1693, max. MCS intensity XI) and Messina (1908, max. MCS intensity XI).

In operation from October 2002 to May 2003, SN1 successfully completed the first mission at 2105m (about 25km east from Catania).

For this mission SN1 was configured to operate in autonomous mode (i.e., with internal data recording and battery power). The observatory was also provided with a vertical acoustic modem that allowed periodic interrogations from a ship of opportunity during the mission (Figure 11.31).

Deployment operations were carried out by the crane barge Mazzarò (Figure 11.32), demonstrating feasibility of GEOSTAR-class observatory management by a ship of opportunity. During the mission, high-quality seismic, gravimetric and environmental data were collected, confirming the correct operation of the observatory data acquisition and mission management system (Monna et al., 2005; Sgroi et al., 2007).

Figure 11.31 SN1 loading before the 2002 deployment.

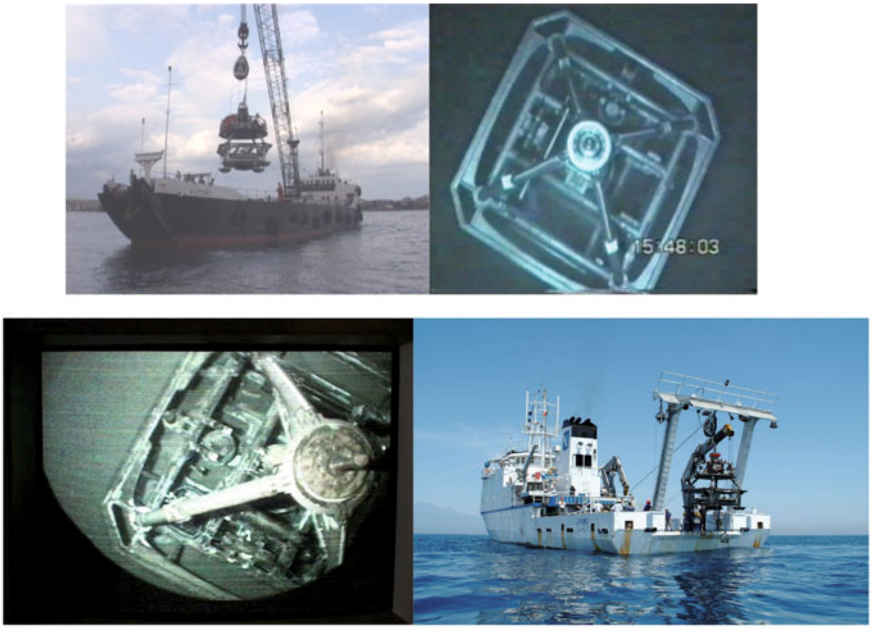


Figure 11.32 Selection of images of SN1 deployment (above) and recovery (below).

11.4.2 SN1 mission 2 (Ionian Sea)

Following the success of the first mission, it was decided to upgrade SN1 to become a cabled observatory, in view of a new deployment and connection to the 25km electro-optical cable installed in the same site by INFN (the Italian National Institute for Nuclear Physics). The main purpose of this was to support a scientific pilot experiment of natural neutrino detection in deep sea (NEutrino Mediterranean Observatory, NEMO Project) (Favali et al., 2006b, 2011).

The main peculiarity of the cable design is that 20km off-shore it is spliced into two separate tails, each about 5km long. Each tail is terminated into a frame equipped with two ROV-mate connectors (Ocean Design, 8 way hybrid); thus, two powerful independent infrastructures are available for the connection of seafloor experiments. Thanks to an agreement between INGV and INFN, the Northern Branch was reserved to SN1, while the Southern Branch is dedicated to support the NEMO pilot experiment detectors.

At the shore end, the cable is terminated in the INFN-LNS (Laboratori Nazionali del Sud) laboratory located in the Catania harbor.

The overall system configuration is shown in Figure 11.33.

The observatory upgrade was carried out in 2003–2004. The technical approach followed for this work was to add the new functionalities while maintaining the old ones; this resulted in a hybrid configuration, allowing SN1 to be powered from shore and communicating in real-time with the Shore Station located in the LNS-INFN laboratory inside

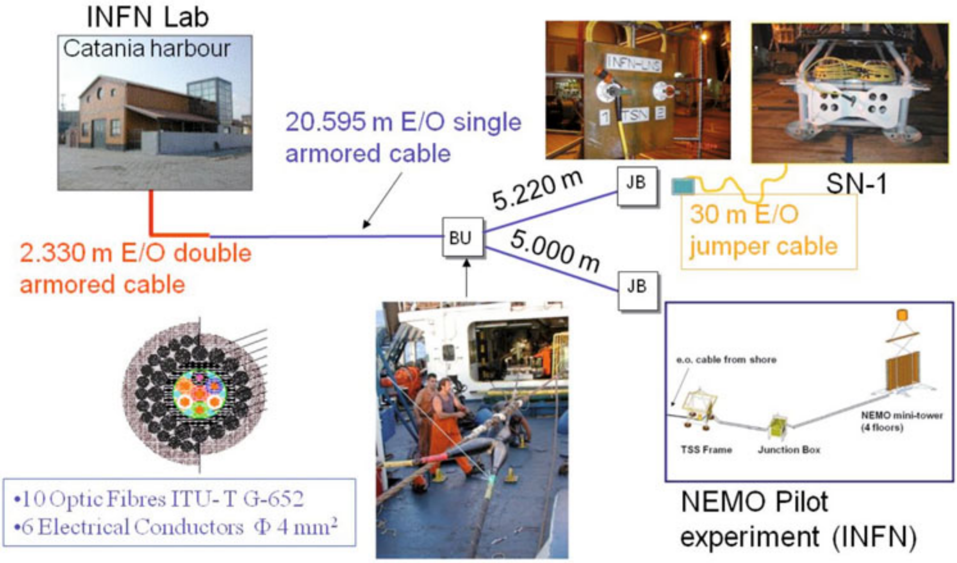


Figure 11.33 SN1 configuration for mission 2 (BU=branching unit, JB=junction box).

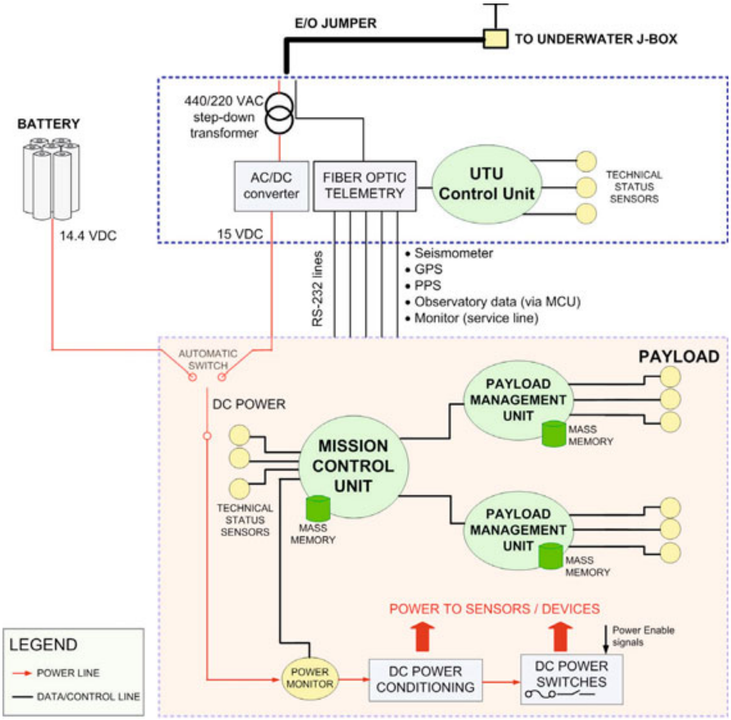


Figure 11.34 SN1 DACS architecture (mission 2).

Catania harbor, but at the same time having the possibility to be operated in autonomous mode (Favali et al., 2006).

SN1 architecture for the second mission is shown in Figure 11.34. The standard battery pack, connected to a switch that automatically determines the highest voltage source, ensures a temporary back-up in case of loss of power from shore. Note also the addition of a new unit (UTU) to the DACS architecture, managing external power and fiber-optic (FO) telemetry. New functions were implemented in the existing hardware and software; in particular, a third operational mode (REAL-TIME mode) was created in addition to the standard ones (MISSION mode and IDLE mode) always implemented in any GEOSTAR-class observatory. Basically, when in REAL-TIME mode, the payload data lines were directly switched to the FO telemetry, bypassing the internal storage. The SN1 Shore Station was then integrated to INGV land-based networks.

In January 2005, the observatory was deployed at the same site as the previous mission and connected to the submarine cable. Marine operations were carried out by the C/V Pertinacia and the observatory connection to the junction box was performed by a work class ROV equipped with manipulator (Figure 11.35).

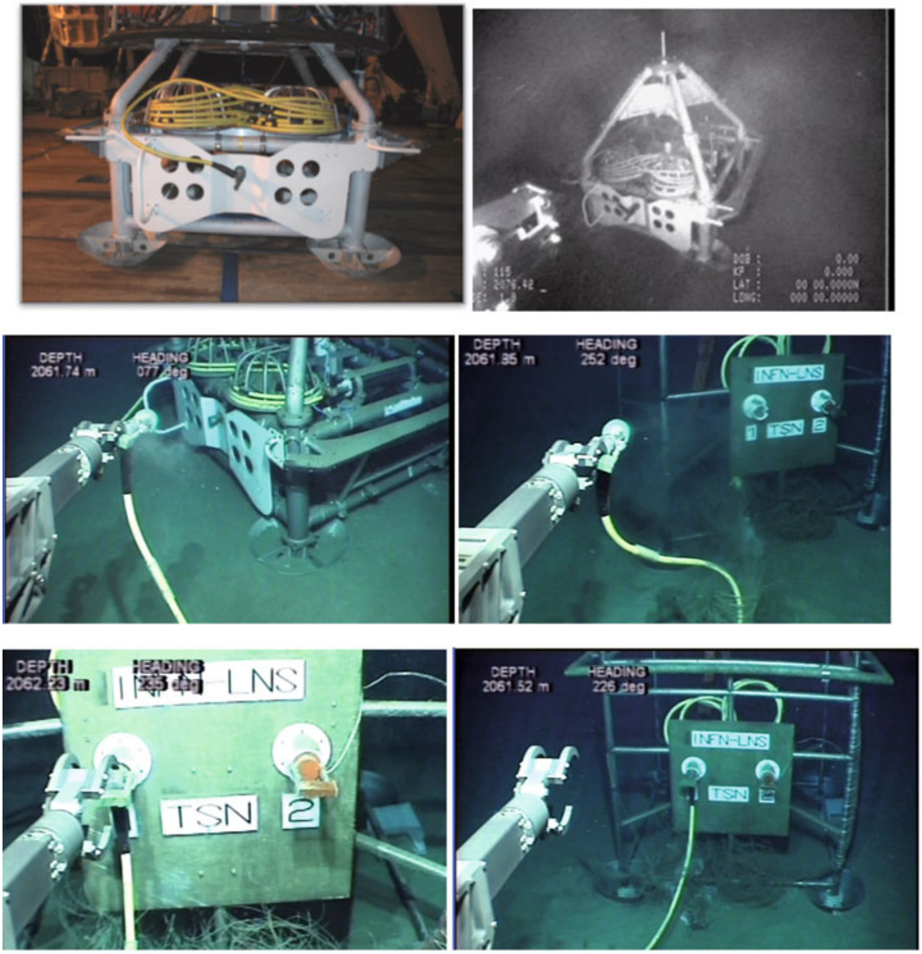


Figure 11.35 SN1 connection to the underwater junction box (SN1 mission 2, January 2005).

SN1 operated satisfactorily until recovery, which occurred in May 2008. Most of the time, it operated connected in real-time to shore, apart from a few periods of stand-by caused by damage to the umbilical cable in the shore vicinity. Integration of SN1 data with the Italian Seismic Network was also successfully verified.

At recovery the observatory was found in good condition, confirming the suitability of the concept to constitute the basis of permanent monitoring networks. With this mission, SN1 became the first real-time seafloor observatory in Europe and one of the few in the world. It was also the first seafloor observatory operative in one of the “key-sites” planned in the EC project ESONET.

11.4.3 SN1 mission 3 (Ionian Sea)

Thanks to the success of previous missions, a unique infrastructure was developed (observatory, cable, junction box, shore station) and the SN1 site had been selected as one of the nodes of the forthcoming European large-scale research infrastructure EMSO (European Multidisciplinary Seafloor and water column Observatory) (Favali and Beranzoli, 2009a), the network of seafloor and water column observatories recommended by ESFRI (European Strategy Forum on Research Infrastructures) addressing the long-term monitoring of environmental processes related to ecosystems, climate change and geo-hazards (Favali et al., 2011). To meet the challenging requirements of this initiative, SN1 was significantly upgraded (support obtained under the framework of EC project ESONET NoE) as briefly described below. With a marine operation similar to that carried out in 2005, in June 2012 SN1 was deployed again, connected to the submarine cable and finally, after successful completion of technical tests, commissioned for action. Since then SN1 has been providing real-time data to the Catania Shore Station and INGV seismological seismic network. SN1 is part of the first operative node in real-time of EMSO (NEMO-SN1, Western Ionian Sea; Favali et al., 2012).

The most significant technical aspects of the new observatory configuration (shown in Figure 11.36) are:

- significant extension of mission payload
- evolution from the previous hybrid configuration to a fully-cabled configuration
- new shore station architecture and functionalities.

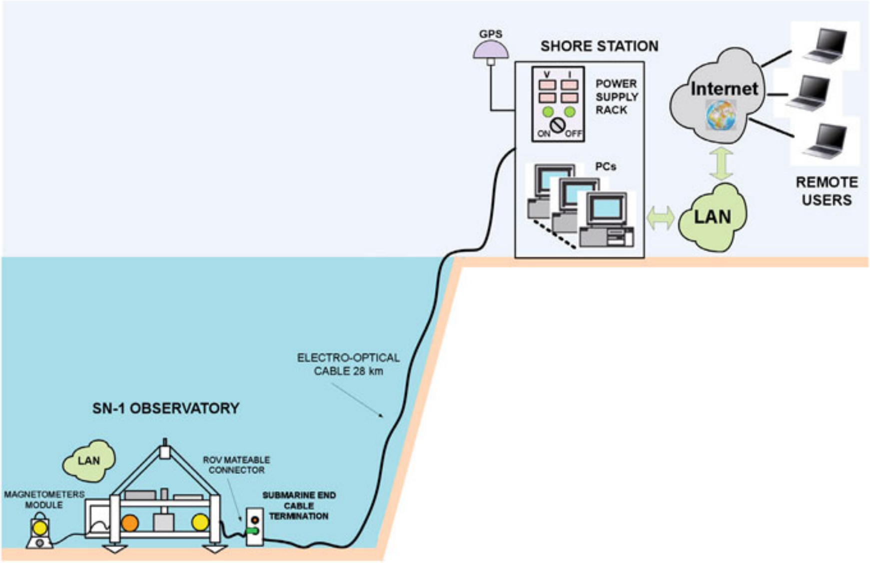


Figure 11.36 SN1 concept (mission 3 ongoing).

As regards the payload, SN1 is now capable of supporting a complete set of sensors for seismological, geomagnetic, gravimetric, accelerometric, oceanographic, hydro-acoustic and bio-acoustic measurements, most of which were not present in the previous configuration (Favali et al., 2012). One of the most significant features is the installation of acoustic sensors used for the passive acoustic detection of cetaceans to localize and fully track them. Monitoring marine mammals can help researchers to better understand their population trends in relation to climate changes and human impact. Thanks to their broad bandwidth, the hydrophones can detect a large variety of marine mammals. The system is also equipped with a tsunami detector (working on the same principle as the prototype developed and operated in GEOSTAR missions 5 and 6 and based on the simultaneous measurement of the seismic and bottom pressure signals and a new high performance tsunami detection algorithm) (Chierici et al., 2012).

The new configuration maintains the mechanical frame, the deployment and recovery procedure, the seismometer installation procedure and the interface with the electro-optical cable. Apart from the new internal arrangement (for the additional payload and devices), the most significant improvement is the adoption of a separate module for magnetometers designed to be handled by the ROV in charge of the observatory connection to the junction box.

Transition to a fully cabled architecture meant the complete redesign of the data acquisition and mission control system. A new DACS architecture was defined and implemented, removing all the Payload Management Units, the internal mass memories, batteries, acoustic telemetry and relevant interfaces.

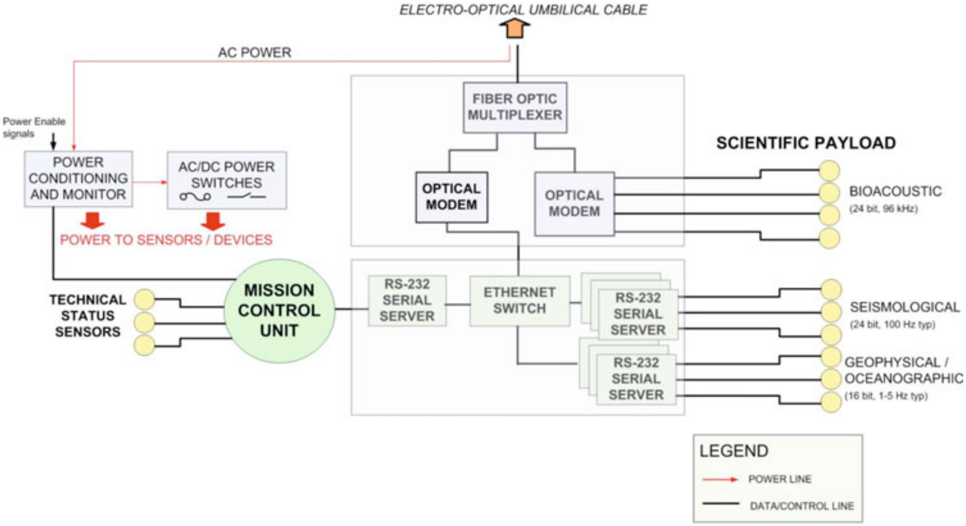


Figure 11.37 SN1 DACS architecture (mission 3 ongoing).

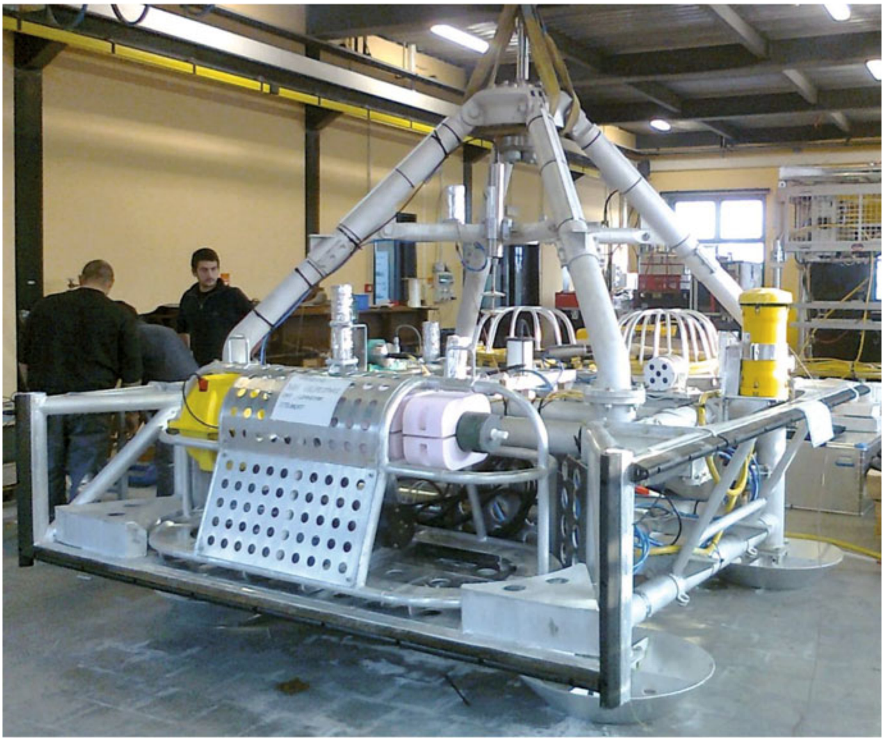


Figure 11.38 SN1 during final integration and dry test (2011).

The new control and telemetry system includes a TCP/IP-based network consisting of two local area networks, one onshore linking data acquisition and control computers and one offshore connecting the sensors. The communication system is designed to make it easy for observatory users to access the instruments and acquire the data onshore. Serial servers (i.e., Ethernet to RS-232 converters) allow transparent communications between topside and subsea instruments.

Figure 11.37 provides details about the new electrical architecture of the observatory.

A peculiarity of the communication system is the use of two redundant optical fibers to improve system redundancy and reliability. Furthermore, the system employs four separated CWDM (Coarse Wavelength Division Multiplexing) frequencies: two for acoustic data downlink, one uplink shore to sea for observatory control and one downlink for geophysical data.

The new SN1 Shore Station is installed, like the old one, in INFN-LNS (Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Sud) workshop at Catania harbour. It hosts the land termination of the cable, the onshore data acquisition system, the power supply for underwater instrumentation and the GPS antenna for time synchronization. A radio link up to 92 Mbps to LNS-INFN is available for data connectivity. From there, a high-speed

Ethernet link (1 Gbps) to the Internet is used for data access by scientific users and the general public. The Shore Station is capable of sustaining the intense data rate received from deep sea (about 50 Mbps) and distributing it over the Internet. High-rate data from deep sea are acquired by dedicated PCs, named Data Servers (DS).

A Control PC is dedicated to mission configuration settings (diagnostic alarm threshold, enable/disable sensors, etc.), managing SN1 operative modes IDLE – MISSION and remote control access through a client application.

A dedicated machine is equipped with RS-232 expansion cards for acquisition and data storage of oceanographic and geophysical payload.

Data Servers for acoustic data (ADS) are equipped with professional audio cards capable of sustaining the underwater hydrophones data stream. A first analysis code is implemented for real-time data, recording, visualization and listening of acoustic data. This code also provides real-time statistical measurements of the acoustic background, such as sound pressure density spectrum, that can be used in off-line analysis to locate acquisition time with presence of biological sounds.

Networking connectivity to authorized remote users is made through VPN (virtual private network).

The power system is designed to deliver sufficient power to the observatory providing isolation and fault protection, tripping off the power supply in case of ground fault or overcurrent. It can deliver up to 1 kVA and an adjustable output voltage up to 500 VAC. The isolated power is delivered to the observatory via the 4mm^2 conductors inside the umbilical. Other features include: automatic and manual voltage ramp control (soft start), visualization and RS-232 transmission of power status parameters (insulation resistance, currents and voltages). All relevant equipment – observatory, PCs, communication systems, etc. – operates from a dedicated UPS (Uninterruptible Power Supply).

11.5 MABEL (SN2)

The goal of the MABEL (Multidisciplinary Antarctic BEnthic Laboratory) project was to develop and operate a multidisciplinary observatory for the continuous and long-term measurement of geophysical, oceanographic and chemical parameters in Antarctic sea waters (Calcara et al., 2001).

In the Polar regions, the peculiar advantages of the seafloor observatory approach are even more evident, considering the hostile environment and logistic difficulties as well as the perspective of studies in these areas. In particular, Antarctica is scientifically considered to be of strategic importance for the comprehension of many complex phenomena that are not only related to regional processes but, more importantly, to the condition, dynamics and sustainability of the whole planet.

From the technical point of view, the logistical issues forced the adoption of solutions ensuring minimization of costs; in particular, a new deployment procedure was defined that did not use the MODUS and associated equipment (electro-optical umbilical and dedicated winch).

Sensor	**Manufacturer and model**	**Sampling rate**
Seismometer	PMD/EENTEC EP300-DT	100 samples/s
CTD	SeaBird SBE 16 Seacat	1 sample/h
Transmissometer	Chelsea Instruments Alphatracka II	1 sample/h
Current meter	FSI 3D-ACM	2 samples/s
Chemical analyser (pH, Eh)	INGV/Tecnomare prototype (with AMT sensors)	1 sample/2 days
Automatic water sampler	McLane RAS 48-500	500ml sample/8 days

Table 11.6 MABEL (SN2) payload and sampling rates.

Weight (kN)	16.3 (in air), 9.5 (in water)
Dimensions (mm)	2900 (L) × 2900 (W) × 2900 (H)
Design depth (m)	4000
Data acquisition and mission control	2 boards (32 bit microcontroller MC68332)
Data storage	Ruggedized Hard Disk (120 GB), 2 × CompactFlash
Power supply	12 Vdc, 1920 Ah Lithium-thionyl chloride 24 Vdc, 890 Ah Lithium-thionyl chloride
Power consumption (mA)	<70 (idle mode), <180 (mission mode)
Status parameters	Voltage, current, temperature, heading, tilt x/y, water intrusion, echo sounder

Table 11.7 MABEL (SN2) main characteristics.

Most of the work was therefore focused on the adaptation of the GEOSTAR-class observatory concept to the challenging and peculiar logistics and environmental conditions. In this respect, the qualification tests represented a significant part of the activities carried out (Cenedese et al., 2004).

As regards the mechanical layout, MABEL shares with SN1 the same frame design. The most peculiar aspect characterizing MABEL's mechanical design is the modification of the upper cone, which makes possible the MABEL deployment using a simple rope and standard winch (Figure 11.39). Basically, the solution consisted in integrating a lifting point for a standard acoustic release into the cone, avoiding any interference to the subsequent recovery by MODUS; the problem was solved by designing a special ring, mounted inside the cone below the docking pin. The solution is fully reversible, i.e., the ring can be

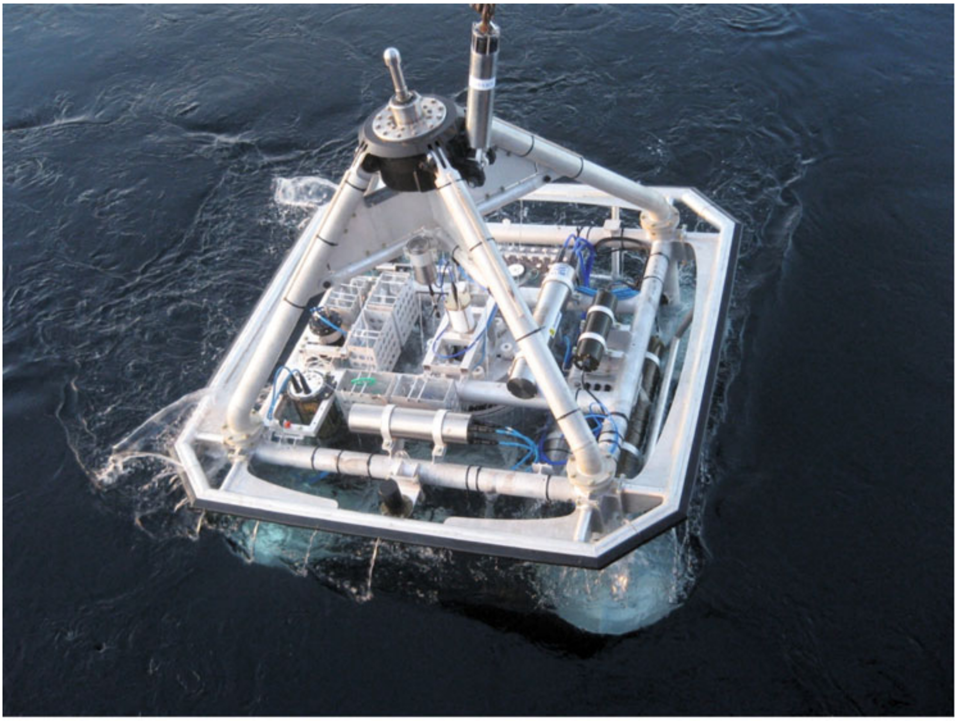


Figure 11.39 MABEL (SN2) deployment in the Weddell Sea, Antarctica (December 2005).

removed, allowing MABEL to return to the original configuration; at the same time other GEOSTAR-class observatories can be equipped with the same device.

The main drawback of this solution was the control of MABEL status sensors (echo sounder, etc.) on periodic acoustic interrogation during deployment.

As regards mission management, most of the efforts were dedicated to minimize power consumption and ensure operation in cold conditions. Further upgrades of the well-proven GEOSTAR hardware led to an average power consumption of less than 180 mA @ 12 VDC (Table 11.7).

To further increase mission autonomy, a second 24 VDC battery pack was developed, in addition to the standard 12 VDC, 1920 Ah pack. The additional 24 VDC, 890 Ah pack (developed by SAFT and featuring the same modular architecture and dimensions of the 12 VDC pack) was dedicated to the chemical analyzer and the precision clock.

Qualification of the MABEL system and procedures in polar environment was object of specific activities during the project. A first phase of tests was carried out in 2002 at HSVA Hamburg Large Ice Model Basin (ARCTECLAB) (Figure 11.40) with the financial support of the European Commission Human Potential and Mobility Program. Work included:

- deployment and recovery sequences in cold temperatures (water about 0°C, air −15°C)
- execution of simulated missions in cold water (including a 3-day mission at 5m depth on the bottom of the ice tank)
- acoustic communication tests in cold water
- chemical analyzer operation in cold temperatures.

Tests demonstrated the capability of the observatory to operate in Antarctic conditions.

MABEL DACS and seismometer were then subject to dedicated qualification tests in cold climatic chamber (Electrolux, Italy) down to −20°C, successfully.

In addition, the standard hard disks were replaced with rugged versions, with extended temperature range.

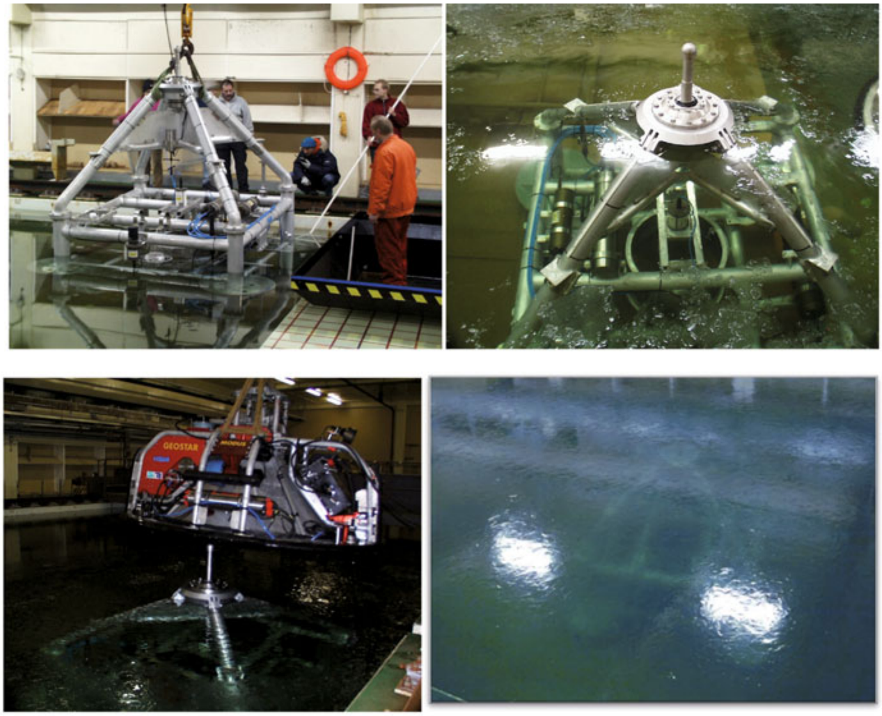


Figure 11.40 MABEL (SN2) qualification tests in HSVA Basin, Hamburg (2002).

11.5.1 MABEL (SN2) mission 1 (Weddell Sea, Antarctica)

MABEL deployment was scheduled during the 2005–2006 cruise of R/V Polarstern in the Weddell Sea (Antarctica). The selected site was located at a water depth of approximately 1874m, 60 miles offshore Neumayer German Station. Operations were carried out on 5 December 2005. A first tentative deployment was aborted at approximately 200m due to a water alarm inside DACS, halting the operation, and recovering MABEL on board. The DACS vessel was checked and a problem of condensed water discovered in proximity to the water detector. DACS was then closed again in a controlled environment (0°C and dry atmosphere). A few hours later, the deployment procedure was started again. During the first part of the descent, the observatory's functionalities were checked by periodic interrogations by acoustic telemetry; close to the seabed, reliability of transmission becomes too poor due to excessive noise from ship propellers.

Touchdown occurred ca. 3 hours from launch. The mission was started automatically on 6 December 2005, 16.00 UTC with the seismometer release.

On 1 January 2006, Polarstern returned to the deployment site, allowing successful execution of some interrogations with the acoustic modem. The observatory was correctly found in mission and all functionalities verified. Summary data records (containing average hourly technical and scientific data) relevant to four different mission days were also recovered.

After one year (Polarstern cruise 2006–2007) a first attempt to recover MABEL failed due to bad weather conditions and the inadequate positioning of the MODUS winch onboard Polarstern.

At that time, MABEL was interrogated via acoustics and found in idle mode, as expected; several summary messages (scientific and technical) were successfully recovered before leaving the observatory in place. Data collected made it possible to get a reliable and significant picture of the mission.

Another recovery cruise was organized two years later (Polarstern cruise 2008–2009); this time (16 December 2008) MABEL was successfully recovered (Figure 11.41, Figure 11.42) and all data made available to scientists for analysis (Gerber and Clauss, 2009).

For the first time ever, a deep sea multidisciplinary observatory was installed and successfully operated in the extreme conditions of polar waters. Polarstern proved to be perfectly suitable for MABEL management. Polar conditions proved to be critical for the operation of some commercial scientific sensors (namely, the automatic water sampler and the current meter); problems experienced may, however, be easily overcome with a more careful selection and qualification phase of the observatory payload.

11.6 SN3

With the successful results obtained from GEOSTAR mission 2, in mid 2001 the technological development of the observatory could be considered complete and ready for the execution of new scientific missions. From the technical point of view, a new challenge was identified: extend the observation capability of a seafloor observatory (basically limited to

Figure 11.41 (Left) MODUS during final approach to MABEL (SN2). (Right) MABEL successfully recovered.

Figure 11.42 MABEL (SN2) on board R/V Polarstern (December 2008).

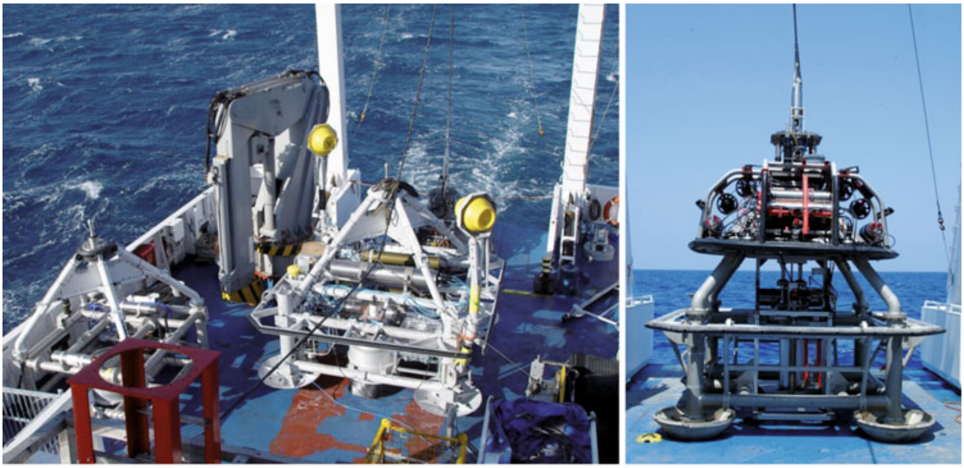


Figure 11.43 SN3. (Left) on board R/V Urania during the December 2003 deployment cruise (photo allows comparison with GEOSTAR). (Right) SN3 with ASTRA ready for deployment.

the deployment point), making possible monitoring over a whole area and at the same time maintaining a near-real-time access to the data.

To reach this goal, the concept of a "network of seafloor observatories" (derived from the ABEL study) was proposed, based on a main observatory operating as a gateway to the underwater network, and satellite observatories operating as nodes of the network, ensuring the coverage of the area of interest (Beranzoli et al., 2004).

The ORION-GEOSTAR 3 project (2002–2005) offered the opportunity of implementing and demonstrating this concept; in parallel to the GEOSTAR and buoy upgrades, two new observatories were developed (SN3 and SN4).

As regards the mechanical design, SN3 maintains the architecture and dimensions of SN1 and SN2. However, the frame was customized to host ASTRA (Automated Sensor Burial Tool for Set-Up of Subsea Seismic Networks), a special module developed within the project and aimed at carrying out a remotely controlled burial of a seismometer inside sediment, to improve the seismometer-seabed coupling. For this purpose, the frame design was modified including a removable section, allowing the observatory to be configured in two alternative ways (Figure 11.44):

a) mounting the standard seismometer assembly, adopted in all GEOSTAR-class observatories

b) mounting ASTRA.

Figure 11.44 Comparison between SN3 configurations; (left) with ASTRA; (right) with a standard seismometer.

In the "standard" configuration, SN3 was used for the two consecutive ORION missions, while in the second configuration SN3 was used for the execution of shallow water demonstration tests of ASTRA.

SN3 electronic (hardware/software) architecture derives directly from the standard GEOSTAR-Class observatory architecture shown in Figure 11.9. In this case, three CPU boards were adopted: the Mission Control Unit and two Payload Management Units (one dedicated to the seismometer, the other to the hydrophone).

Specific functionalities were implemented to make SN3 operate as a "satellite" of GEOSTAR from the network point of view.

First of all, capability to manage a horizontal acoustic communication link was implemented. This link allows SN3 to send its data to the Shore Station via GEOSTAR (which acts as a "gateway") and the relay buoy; the ORION system design also allows contact between SN3 and the surface (ship of opportunity or the Shore Station via GEOSTAR, buoy and radio relay link), to send commands or download data, thus using the acoustic network at its full potential.

The mission software was upgraded, so to the standard functionalities of all GEOSTAR-class observatories (related to data acquisition and storage, mission management, status monitoring) was added the following capabilities required by the project objectives:

- capability of automatic generation and transmission of periodic messages

- real-time processing of hydrophone data and automatic detection of events by means of a standard Short Term Averaging/Long Term Averaging (STA/LTA) triggering algorithm, implemented in the dedicated CPU unit managing the hydrophone
- implement a new mission data structure named Event Message produced in case of event detection
- possibility to download seismometer or hydrophone wave forms, corresponding to any period of the mission: this is particularly useful, e.g., in the case of occurrence of a seismic event.

The main characteristics of SN3 are shown in Table 11.8, and the payload and sampling rates in Table 11.9.

Weight (kN)	14 (in air), 8.5 (in water)
Dimensions (mm)	2900 × 2900 × 2900
Design depth (m)	4000
Data acquisition and mission control	3 CPU boards (32 bit microcontroller MC68332)
Data storage	Hard disks, CompactFlash
Power supply	12 VDC, 1920 Ah Lithium-thionyl chloride
Power consumption (mA)	120 (idle mode), ~350 (mission mode)
Status parameters	Voltage, current, temperature, heading, tilt x/y, water intrusion, echo sounder

Table 11.8 SN3 main characteristics.

Parameter	Missions 1 and 2	
	Sensor	Sampling rate
Broadband seismometer	PMD/EEntec EP300-DT	100 samples/s
hydrophone	OAS E2PD	100 samples/s

Table 11.9 SN3 payload and sampling rates.

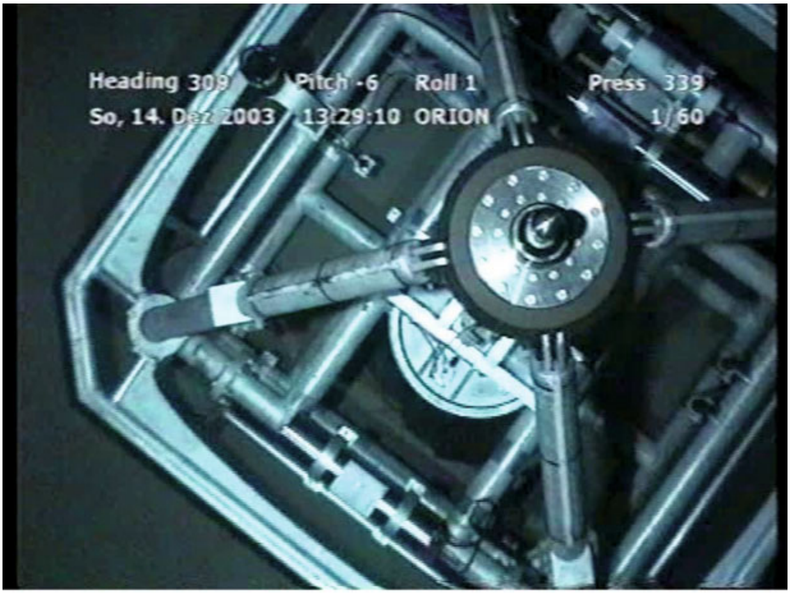


Figure 11.45 SN3 seen by MODUS immediately after deployment at seabed.

11.6.1 SN3 missions 1 and 2 (Southern Tyrrhenian Sea)

SN3 missions were carried out in parallel with GEOSTAR's third and fourth missions (Figure 11.45). For details on the installation site, see Section 11.3.3.

From the technical side, the two missions provided further confirmation of the maturity and soundness of the GEOSTAR-class observatory concept, in particular as regards distinctive aspects such as the effectiveness of the deployment and recovery procedures, the quality of the seismometer management procedure, the reliability of the data acquisition and mission management hardware and software.

In spite of technical problems with the vertical acoustic telemetry system that affected the entire first mission and part of the second, networking and near-real-time communication were demonstrated: SN3 was able to periodically (every 6 hours, i.e., 4 times a day) send summary technical messages and data messages to surface through the communication path. These are short packets, compatible with the low bandwidth of the acoustic link but at the same time sufficiently exhaustive about the health status of the observatory.

SN3 was also able to reply to the acoustic commands/queries issued from the Shore Station, that are relayed from the radio link, the buoy and GEOSTAR in turn; this operation is quite complex, requiring many hops and some time to complete.

Besides the technical results, SN3 gave its significant contribution to the scientific mission, providing a set of seismological data that complemented those collected by GEOSTAR in its parallel mission. However, efficiency of data collection was smaller, due to technical problems with the seismometer which caused a higher number of data packets to be lost by the acquisition system and a sudden failure of the sensor during the first mission.

11.7 SN4

SN4 was originally conceived to be the third node of the ORION experiment. In this scenario, SN4 would have operated as a satellite node of an underwater seismological network (including also GEOSTAR and SN3) and consequently it would have the same architecture and functionalities already described for SN3. Instead, the role and configuration of SN4 were changed at the specific request of the EU commission to integrate one of the ORION nodes into the shallow water experiment that the parallel EU project ASSEM was going to develop in the Corinth Gulf (Greece) (Rolin et al., 2005).

The new mission requirements imposed a significant revision of the observatory configuration; notably, a new mechanical architecture was studied to comply with the logistic constraints of the experiment, particularly as there was no possibility of using MODUS for the deployment and recovery of the observatory. The problem to solve was to develop a new version of a GEOSTAR-class observatory, maintaining most of its distinctive characteristics but at the same time making it manageable in a different way both from the logistic (installation, recovery) and logical (communication interface) point of view. Different concepts were studied, including pop-up configurations (basically an evolved OBS); the final choice was again to rely on the potentialities offered by the single frame, open architecture. SN4 was therefore designed as a "heavy" (although significantly lighter than the sister versions) observatory, deployable with a simple rope and acoustic release and with provision to host different recovery systems (adaptable according to the logistic facilities available; details will be given in the description of the missions) (Figure 11.46).

De facto, SN4 represents the smallest GEOSTAR-class observatory maintaining full compatibility with the original seismometer management system. Standardization also involves:

- data acquisition and control hardware, including the precision clock
- payload supported
- battery pack
- acoustic telemetry
- the basic mission management functions implemented, including
  - acquisition from all scientific packages and status sensor
  - preparation and continuous update of hourly data messages
  - management of bidirectional communications via hydro-acoustic telemetry link
  - actuation of commands received (e.g., data request, system reconfiguration, restart)
  - complete data back-up on internal memory.

The main technical features and scientific payload of SN4 are summarized in Table 11.10 and Table 11.11.

Weight (kN)	6.6 (in air), 1.5 (in water)
Dimensions (mm)	2000 × 2000 × 2000
Design depth (m)	600
Data acquisition and mission control	3 boards (32 bit microcontroller MC68332)
Data storage	Hard disk, CompactFlash
Power supply	12 VDC, 1920 Ah Lithium-thionyl chloride
Power consumption (mA)	120 (idle mode), ~450 (mission mode)
Status parameters	Voltage, current, temperature, heading, tilt x/y, water intrusion, echo sounder

Table 11.10 SN4 main characteristics (data referred to the last version).

Parameter	**Mission 1**		**Missions 2 and 3**	
	Sensor	**Sampling rate**	**Sensor**	**Sampling rate**
Broad-band seismometer	PMD/EEntec EP300-DT	100 samples/s	Guralp CMG-40T	100 samples/s
Hydrophone	OAS E2PD	100 samples/s	OAS E2PD	100 samples/s
CH_4	Capsum METS	1 sample/s	Franatech METS	1 sample/s
CH_4 with pump			Franatech METS + SeaBird SBE-5T	1 sample/s (pump ON for 5 min every 30 min)
CTD			SeaBird SBE-16plus	1 sample/10 min
Turbidity			WET LABS Echo-BBRTD	1 sample/10 min
Current meter			NOBSKA MAVS-3	5 sample/s
Dissolved oxygen			Aanderaa Optode 3830	1 sample/s

Table 11.11 SN4 payload and sampling rates.

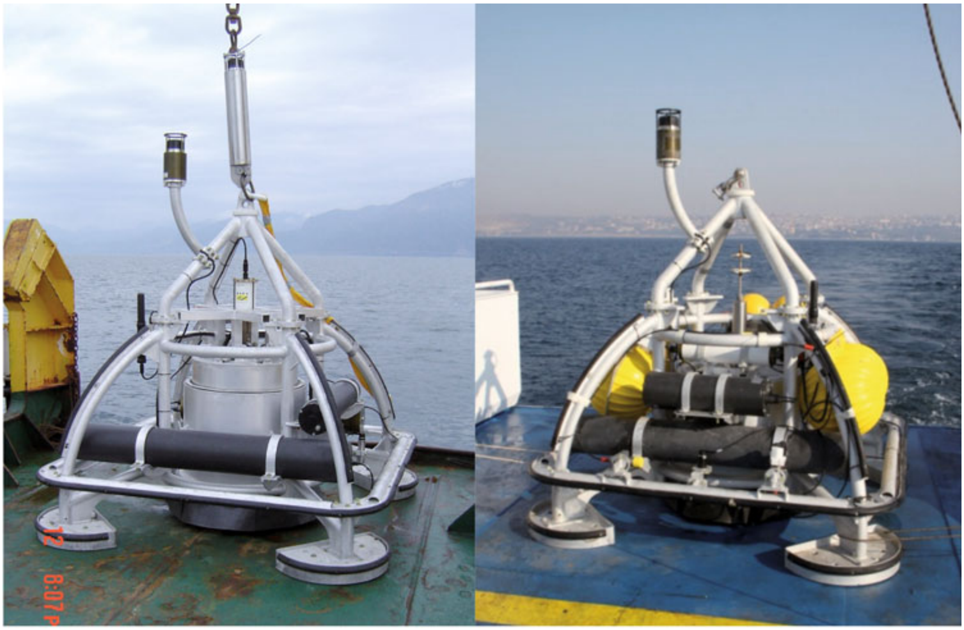


Figure 11.46 SN4: (left) 2004 configuration; (right) 2009 configuration.

11.7.1 SN4 mission 1 (Corinth Gulf)

Parallel to the ORION project that led to the development of SN3 and the Marsili pilot experiment, the EU project ASSEM was aimed at developing a seafloor network for the continuous monitoring of marine geo-hazards (Rolin et al., 2005). Two experiments were planned, the first in an area with a slope instability risk (offshore Norway), the second in an area characterized by an active fault (Corinth Gulf, Greece) representing the most active extensional basin in Europe, with high rates of margin uplift (several mm per year). The array of measurement nodes developed for the Corinth Gulf experiment included pore-pressure sensors, tilt meters and extensometers (Figure 11.47). Integrated to this network, SN4 provided continuous monitoring of seismic activity as well as methane release from the seafloor. For details about the scientific payload adopted, together with data acquisition rates, see Table 11.11.

Since SN4 is deployed jointly with other EC ASSEM nodes, it also carries a hydroacoustic modem capable of communicating towards a surface transducer (from a ship, or attached to a buoy). This acoustic link allows for a bidirectional communication to be established with a remote operator using a transducer from a ship: this was the case during deployment operation; SN4 could also communicate acoustically with a buoy placed near it at the sea surface. In fact, one of the main targets of the ASSEM project was to test and demonstrate the feasibility of a network of seabed nodes, communicating to the surface through acoustic modems, and delivering data summaries during their operation to a ded-

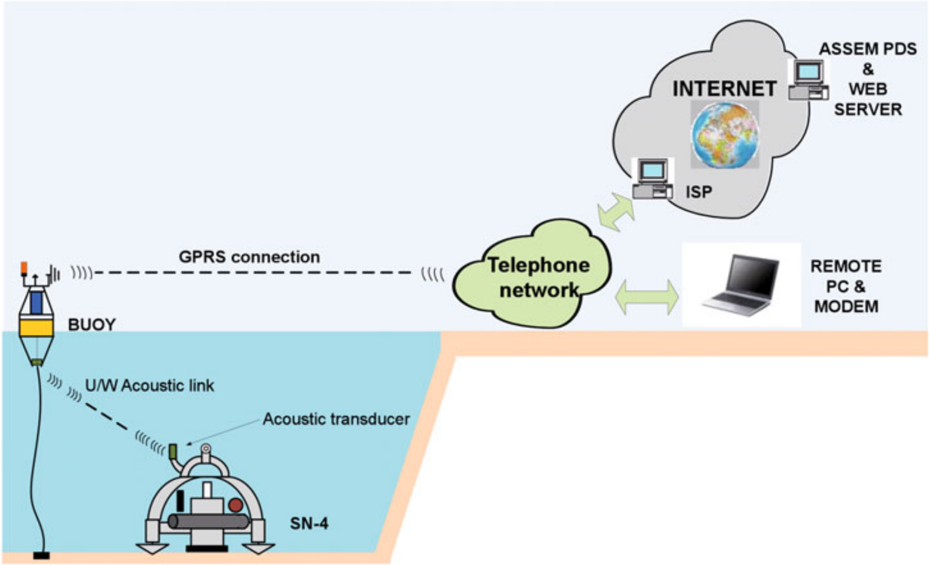


Figure 11.47 SN4 concept (mission 1).

icated "server" in order to publish relevant data on a dedicated website. This purpose was accomplished by using different communication media: in the case of SN4, the acoustic link reaches a surface buoy, whereas a GPRS modem instigates a phone call to an Internet Service Provider in order to transfer all the data collected by the buoy during time. Finally, summary data are collected on a Permanent Data Server so that they can be published on a dedicated website.

Moreover, SN4 could be reached with a PC connected to a phone line, and interrogated to check for system health and to retrieve relevant data, e.g., seismic waveforms.

For this mission, an assisted recovery was planned, based on an underwater intervention by an available ROV or manned submersible; for this purpose, SN4 was equipped with a sling terminating with a ring (both clearly visible in Figure 11.48). The recovery procedure consisted in engaging the ring with the manipulator and attaching it to a rope deployed from the same ship.

SN4 was installed on 20 April 2004 (379m depth) and recovered on 24 November 2004. The observatory operated uninterruptedly all of the time (approx 5230 hours), carrying out all the tasks programmed.

During the period, the relay buoy was operative (until approximately mid July 2004), the networking worked and the effectiveness of bidirectional link from SN4 to ASSEM PDS and to remote PC for data retrieval was proved.

On 28 April 2004 immediately after the occurrence of a significant earthquake in the area, the communication infrastructure allowed for the first time the retrieval of the seismic waveform from the Tecnomare laboratory (see Figure 11.49).

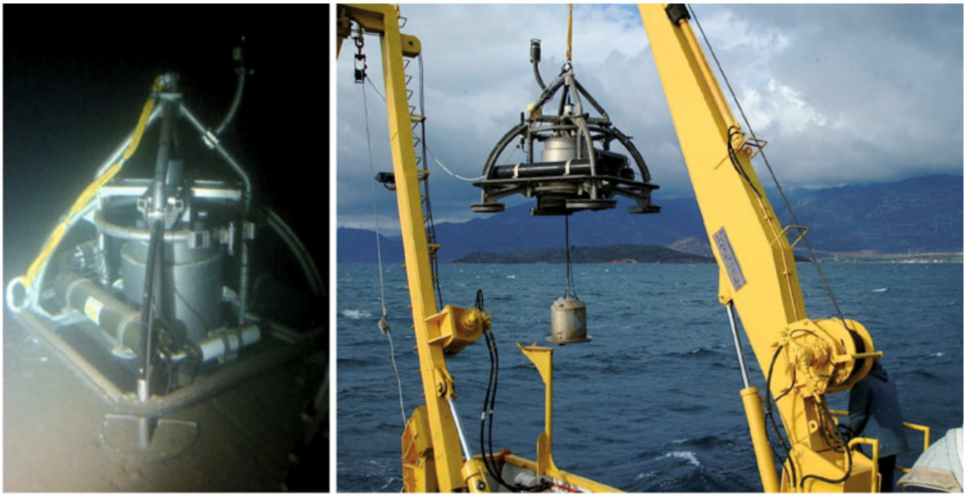
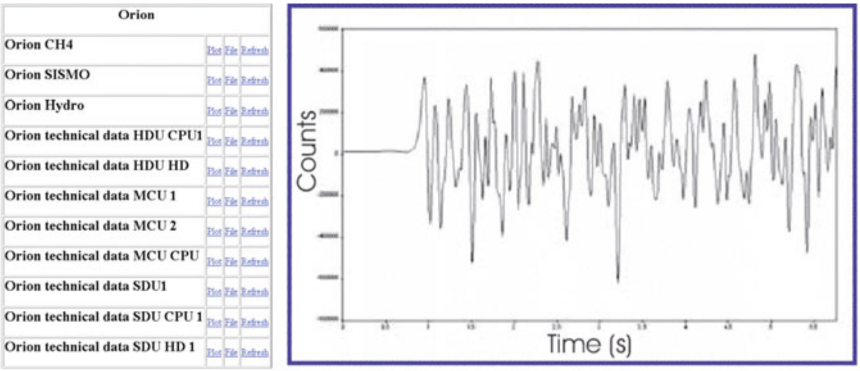


Figure 11.48 (Left) Underwater photograph of SN4 in Corinth Gulf taken from NCMR THETIS ROV. (Right) SN4 being recovered onboard R/V AEGEO (note the seismometer hanging below the frame).



Orion			
Orion CH4	Plot	File	Refresh
Orion SISMO	Plot	File	Refresh
Orion Hydro	Plot	File	Refresh
Orion technical data HDU CPU1	Plot	File	Refresh
Orion technical data HDU HD	Plot	File	Refresh
Orion technical data MCU 1	Plot	File	Refresh
Orion technical data MCU 2	Plot	File	Refresh
Orion technical data MCU CPU	Plot	File	Refresh
Orion technical data SDU1	Plot	File	Refresh
Orion technical data SDU CPU 1	Plot	File	Refresh
Orion technical data SDU HD 1	Plot	File	Refresh

Figure 11.49 (left) SN4 technical summary data page as seen from ASSEM PDS dedicated webpage; (right) acoustically retrieved waveform of 28 April 2004, Corinth Gulf earthquake (M4.6).

Reliable operation of SN4 was confirmed just before recovery, when the observatory was successfully interrogated from the ship and the transmission of autonomous messages at the programmed times verified.

Good quality seismic data (98.5%) and hydrophone data (100%) were recovered, allowing scientific analysis from INGV seismologists. Also, 100% of methane sensor measurements were correctly acquired, but with no practical value due to an almost instantaneous drift of the sensor leading to meaningless data. This experience, associated with the outcomes deriving from the parallel operation of GMM offshore Patras, evidenced a gap in the long-term reliability of the underwater methane sensor technology.

11.7.2 SN4 missions 2 and 3 (Marmara Sea)

In the framework of EU project ESONET NoE, SN4 was selected for the execution of a demonstration mission in Marmara Sea, recognized as a seismic gap that will be probably filled in during the next decades by a large (M ≥7) earthquake along the North Anatolian Fault (NAF) system (Gasperini et al., 2012b). In this scenario, long-term multidisciplinary observatories play an essential role for their unique capability to continuously monitor natural processes that are either very episodic, or statistically require long time series to be detected. Again, a GEOSTAR-class observatory was selected, being the only well-proven technology available in Europe fully meeting the requirements of the application.

Payload was significantly enhanced compared to the previous mission, aiming at better quantifying the temporal relations between fluid expulsion, fluid chemistry and seismic activity along the NAF (Gasperini et al., 2012a). In particular, a new broadband seismometer was selected and integrated with gas and oceanographic sensors allowing identifying local signals related to the fluid expulsion events and eventual local or distant earthquakes that may influence gas migration and seepage processes (Marinaro et al., 2008).

Two methane sensors working in parallel were adopted (following feedback from previous experiences and laboratory qualification and test phases), one directly exposed to the environment and the other connected to a small pump flushing fresh water in front of a sensor membrane, in order to eventually reduce biased signals induced by water turbulence effects. The sensor mounting arrangement is shown in Figure 11.50 (the two methane sensors are visible in the foreground, attached to the internal side of the bumper).

In this application, the hydro-acoustic telemetry link was used only to communicate with a ship of opportunity, to check for system status during descent towards the seabed and for periodical interrogation; hence, the networking functionalities developed for the ASSEM experiment were disabled.

While the deployment procedure remained unchanged (rope terminated with acoustic release), the recovery procedure was redesigned to allow SN4 recovery without any underwater intervention (either by diver or by ROV) and, consequently, reduce economic and logistic efforts. For this purpose, a recall buoy canister was integrated in the observatory, equipped with 400m of recovery rope. Accordingly, the total weight in water of the observatory was reduced to 0.15 kN (about 150kg) by installing four glass spheres on the frame and optimizing the mechanical design. In this way, it was possible to carry out all the marine operations by a light ship of opportunity (the 32m R/V Yunus, owned and operated by Istanbul University).

The site selected for the mission (approx 166m depth, coordinates 40.73 N, 29.40 E) is on the offshore extension of the active NAF, which has been the source of many destructive earthquakes and presents with continuous seismic activity and methane degassing. SN4 operated for one year, in two consecutive missions of about 6 months each.

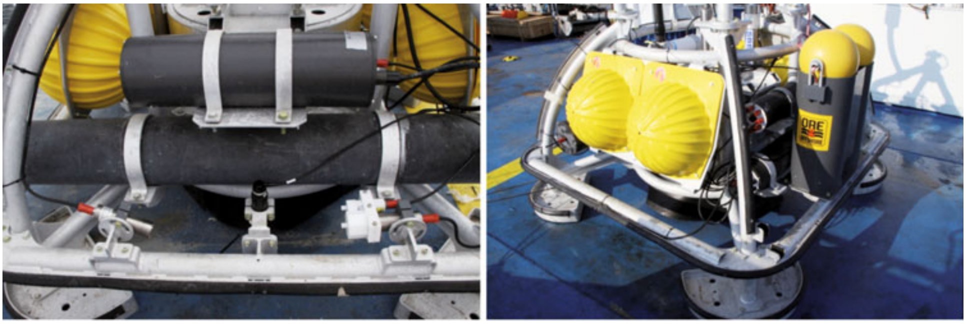


Figure 11.50 (Left) Methane sensors arrangement (the one fitted with a flow-through pump is visible on the right). (Right) Detail of the frame with two buoyancy spheres and recovery system based on a pop-up buoy and rope canister.

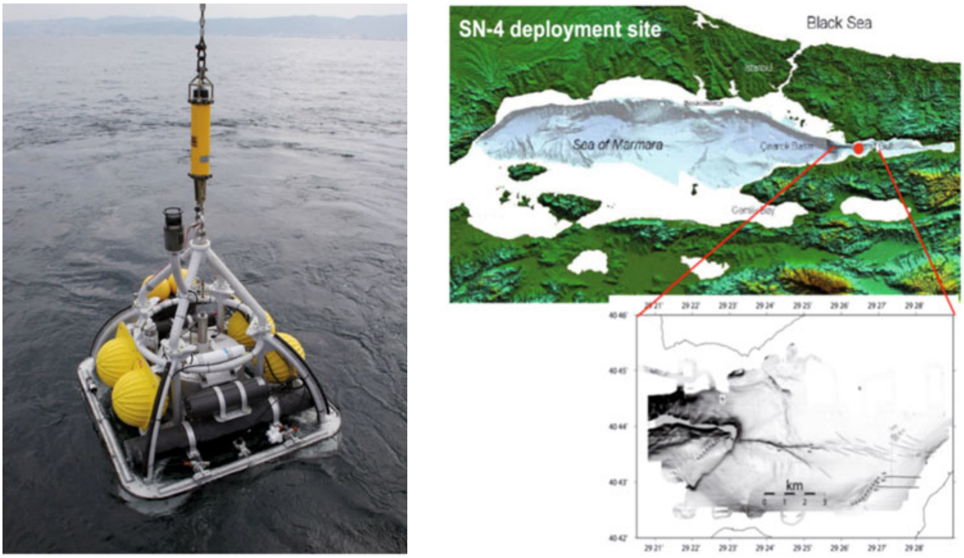


Figure 11.51 (Left) SN4 during deployment in Marmara Sea (2009). (Right) the mission site.

SN4 mission 2 was carried out between October 2009 and March 2010 (Figure 11.51). SN4 and its payload operated with complete reliability over the whole period, corresponding to 3863 hours (almost 161 days) acquisition time.

At the end of the mission, SN4 was recovered to download data and replace the battery pack and the methane sensors. Servicing of the observatory was carried out at ITU pier at Tuzla (Turkey).

Figure 11.52 (Left) SN4 during recovery from mission 2. (Right) R/V Yunus that managed SN4 deplyoment and recovery.

Then, SN4 was redeployed in the same site and mission 3 was carried out between March and September 2010. Unfortunately, during this period, the observatory was trawled by fishermen, capsized and moved from the deployment site. This fact affected the significance of data produced by some sensors (in particular the seismometer). Nevertheless, recovery operations, although more complex, were successful and the observatory suffered only minor damage (Figure 11.52).

SN4 missions 2 and 3 represent the longest monitoring of temperature + gas + seismicity at seabed, ever done (Marinaro et al., 2011). A significant number of CH_4 peaks were detected (with frequency about 1 peak every 2 days), showing significant correlations with other parameters (temperature, pressure, dissolved oxygen, turbidity) and patterns similar to those observed during past missions 1 and 2 of the GMM observatory (operating in a gas-bearing pockmark in the Patras Gulf, Greece; see next section). Broadband seismometers recorded low-frequency signals in correspondence with these events, possibly related to vibrations induced by gas seepage. This time, methane sensor technology proved to be mature for long-term applications in seafloor observatories.

Once again, synoptic observation from multidisciplinary sensors proved to be fundamental for a better comprehension of complex and poorly understood phenomena. Redundancy of critical sensors is also opportune especially in case of long-term, autonomous missions where the remote operator may have little (or no) control of the system status.

Summing up, SN4 proved to be a highly cost-effective and efficient observatory, operable with very limited and simple logistics and capable of providing high-quality scientific data; its robustness was also proved during the unexpected phases of the third mission.

For future applications, SN4 can be reconfigured to operate as a cabled observatory, ensuring permanent real-time monitoring of the Marmara Sea and thus the study of relationships between fluids and seismicity.

11.8 GMM

GMM (Gas Monitoring Module) is a light observatory specifically designed for long-term gas monitoring at the seafloor. Gas seeps, either offshore or onshore, reflect deep hydrocarbon generation processes and may provide useful information on the nature of the exploitable natural gas.

On the other hand, seeps may also represent hazards for humans and buildings, because of the explosive properties of methane; gas in marine sediments and onshore soil can, then, damage building and infrastructures by gas-pressure build-up or by degradation of geotechnical properties of ground foundations. Not least, seeps are a source of greenhouse gas for the atmosphere; offshore seeps may release large amounts of methane that can enter the atmosphere, especially if the depth of the seep is shallower than 200–300m (Etiope et al., 2005).

In the offshore environment, detection of gas seepage is much more complicated than onshore and, so far, it has been accomplished through techniques based on rough “sniffers” to detect hydrocarbon anomalies in near-bottom waters, or by direct, expensive and time-consuming sediment sampling and analysis.

The present approach to study the occurrence of methane in seawater was then based on the combination of the peculiar characteristics of GEOSTAR-class observatories (the single-frame architecture, the multiparametric approach, the custom-developed data acquisition and mission control hardware and software) with the use of a new generation of solid-state methane sensors available on the market.

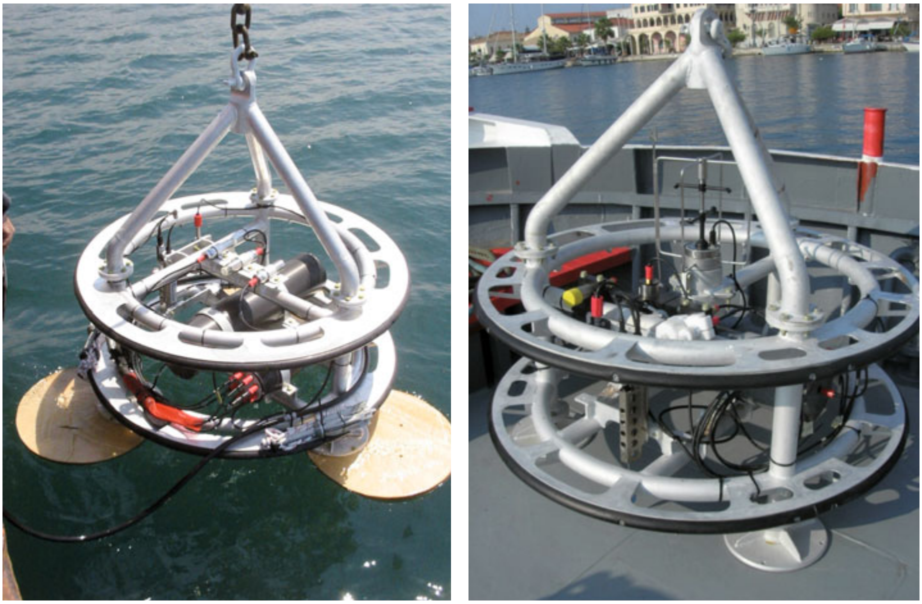


Figure 11.53 GMM: (left) 2004 configuration; (right) 2010 configuration.

The GMM frame is based on a light circular aluminum tripod. The feet are oversized to prevent settlement into the sediment. Each foot can hold a steel ballast to increase stability, if necessary. Design allows modification of frame height by the installation of flanged extension tubes bolted directly to the feet (Figure 11.53).

GMM electronics perform the following tasks: acquisition from all scientific packages and status sensors; preparation and continuous update of hourly data messages, transmitted on request; scientific payload management (switch on/off of individual sensors according to command from the remote operator); processing of methane data to detect occurrence of events (sudden variations of methane concentration); management of commands received (e.g., data request, system reconfiguration, restart); back-up of data in internal mass memory (Marinaro et al., 2004).

GMM main characteristics are summarized in Table 11.12.

GMM has been developed in the framework of the European Commission ASSEM project and since then has been used in the Patras Gulf (two consecutive missions, 2004–2005) and (after upgrade work for payload extension) in Katakolo harbor (2010–2011).

11.8.1 GMM missions 1 and 2 (Gulf of Patras)

The scientific goal of the first two GMM missions was the long-term monitoring of an active pockmark located in the Gulf of Patras (Corinth Shelf, Greece), 40m water depth and 1.5km distance to shore (Marinaro et al., 2006) (Figure 11.54).

GMM scientific payload and sampling rates for the Patras Gulf missions are summarized in Table 11.13. At that time, no experience of long-term operation of methane sensors was available anywhere in the world; this fact led to the decision to adopt three methane sensors mounted in series (“revolver” type configuration), including a master and two back-up sensors (normally powered off and activated in case of failure or bad functioning of the master). Alternatively, the observatory could be configured to operate a back-up (“auxiliary”) sensor in parallel to the master one, allowing for data comparison. The methane sensors mounting arrangement is clearly visible in Figure 11.58, with the three sensors

Weight (kN)	1.5 (in air); 0.7 (in water)
Dimensions (mm)	1500 (diameter) × 1550 (height)
Design depth (m)	1000
Data acquisition and mission control	1 board (32 bit microcontroller MC68332)
Mass memory	Compact Flash
Power supply	12 V, 960 Ah Lithium-thionyl chloride
Power consumption (mA)	80 (idle mode); ~150 (mission mode)
Status parameters	Voltage, current, temperature, pressure, acceleration, water intrusion

Table 11.12 GMM main characteristics.

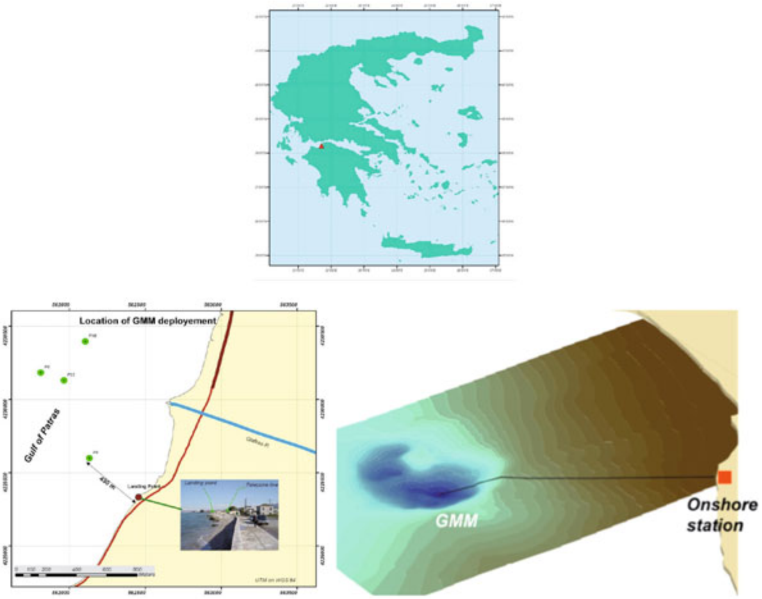


Figure 11.54 GMM installation site (missions 1 and 2).

Parameter	Missions 1 and 2		Mission 3	
	Sensor	**Sampling rate**	**Sensor**	**Sampling rate**
CH_4	3 × Capsum METS	1 sample/s	Franatech METS	1 sample/5s
CH_4 with pump			Franatech METS + SBE-5T	1 sample/5 s (pump ON for 5 min every 30 min)
H_2S	AMT GmbH electrode microsensor	1 Hz for 30s every 10 min	AMT GmbH electrode microsensor	1 sample/5s
CTD	SeaBird SBE-37-SI Microcat	1 sample/10 min	SeaBird SBE-37-SI Microcat	1 sample/min
Turbidity			WET LABS Echo-BBRTD	1 sample/5s
Current meter			FSI 3D-ACM	2 sample/s
Dissolved oxygen			Aanderaa Optode 3830	1 sample/min

Table 11.13 GMM payload and sampling rates.

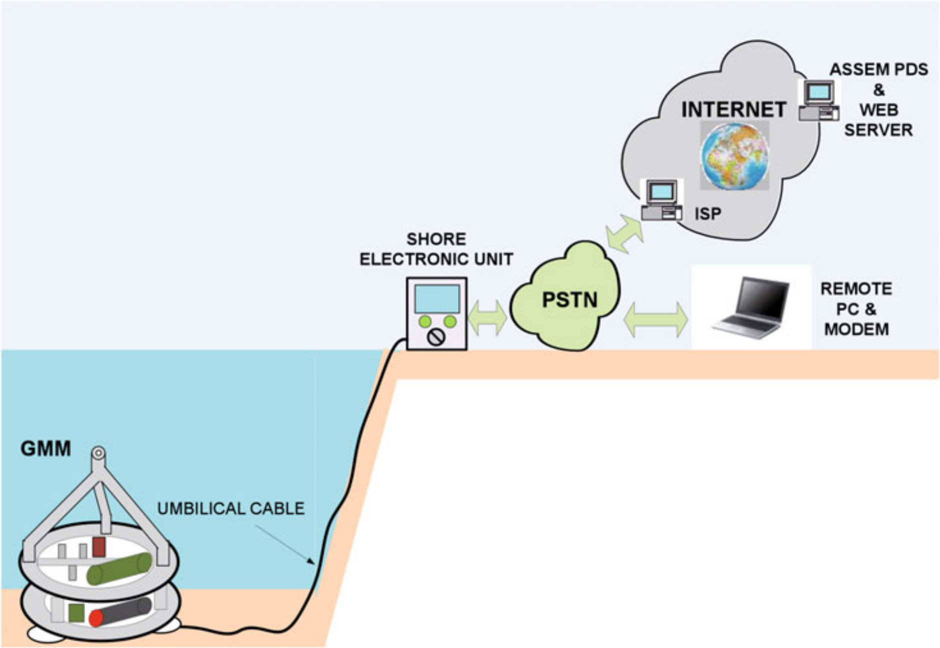


Figure 11.55 GMM cabled concept (missions 1 and 2).

placed horizontally on the top of the frame. Methane sensors were associated to an H2S sensor and a CTD (conductivity, temperature and depth).

Due to the favorable site characteristics, the observatory was simply lowered to the seafloor with a rope and positioned in the desired place by divers.

In addition to the scientific goal of the mission, the ASSEM project had the technical goal of demonstrating the feasibility of a network infrastructure connecting several seabed observatories (called “nodes”), sharing common communication protocols and interfaces and furthermore allowing for a centralized data collecting, publication and storing facility. A remote server PC of the ASSEM PDS (Permanent Data Server) located in the IPGP (Institut de Physique du Globe de Paris) was devoted to collecting and archiving datasets coming from offshore observatories via different communication paths somehow (acoustic modems, phone line, GSM, GPRS, ...) connected to the internet. Moreover, IPGP facilities were in charge of publishing datasets to a dedicated website. The solution developed for GMM connection to the ASSEM network differs from the one adopted for the rest of the observatories. Thanks to the proximity to shore, a cable connection was selected for GMM, while the other ASSEM nodes (deployed in deeper sites) were connected via underwater acoustic/surface GSM telemetry, managed by a moored relay buoy (Figure 11.54).

The underwater cable served to connect GMM to a Shore Unit equipped with a phone line modem providing a remote telemetry link to the Greek public telephone network. The configuration is shown in Figure 11.55.

Figure 11.56 (Left) GMM ready for deployment in Patras Gulf; (center) Shore Unit; (right) umbilical cable.

For safety reasons, GMM was not powered through the umbilical cable. Instead, it was provided with a 12 V, 960 Ah battery pack (half of the standard 1920 Ah battery pack developed for the other GEOSTAR-class observatories) ensuring six months of autonomous operation.

Periodically during the mission, GMM was able to initiate a telephone internet connection through a local Internet Service Provider (a dedicated account was created for this purpose): the GMM Shore Unit was equipped with a modem with embedded TCP/IP features, making easier the work of GMM microcontroller (who itself has not the processing power to properly handle TCP/IP stack complexities, while acquiring data at the same time).

This way, during the whole mission period GMM was able to send data packets to the remotely accessible ASSEM PDS on a daily basis. Datasets consisted of summary technical (status parameters) and scientific measures which got published on the project's dedicated web server.

Furthermore, having a dedicated phone line and number, the GMM seabed observatory could be easily contacted in real-time (e.g., for diagnostics, data download and mission/ sensors reconfiguration), just by "calling" it with another phone line modem connected to a remote PC.

This link allowed early detection of a failure relating to the methane sensors; this led to the decision to stop the mission and recover the observatory for the necessary servicing operations. GMM was therefore recovered at the end of September 2004 and redeployed one day later, after CH_4 and H_2S sensor replacement. In the second mission, GMM operated until mid-January 2005.

Summarizing, GMM worked throughout six months in the two consecutive missions (April–July 2004 and September 2004–January 2005). The combined monitoring period amounted to 201 days (4824 hours of data acquisition in total). The data acquisition and control system worked without failure throughout the monitoring period, allowing data transmission and control in near-real-time via cable and modem links. This represented

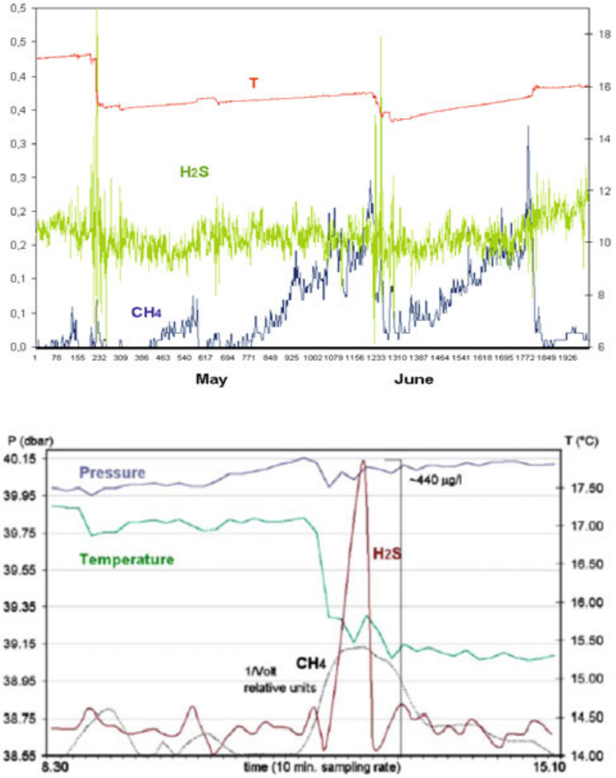


Figure 11.57 Examples of gas seepage events detected by GMM (Marinaro et al., 2006).

the first long-term monitoring ever done on gas leakage from pockmarks by means of CH_4+H_2S+T+P sensors. The results show frequent temperature T and pressure P drops associated with gas peaks; in particular, over 60 events occurred in 6.5 months, likely due to intermittent, pulsation-like seepage (Marinaro et al., 2006) (Figure 11.57). Decreases in temperature in the order of 0.1–1°C (up to 1.7°C) below an ambient T of ca. 17°C (annual average) were associated with short-lived pulses (10–60 min) of increased CH_4+H_2S concentrations. This seepage "pulsation" can either be an active process driven by pressure build-up in the pockmark sediments, or a passive fluid release due to hydrostatic pressure drops induced by bottom currents cascading into the pockmark depression. Redundancy and comparison of data from different sensors were fundamental to interpret subtle proxy signals of temperature and pressure which would not be understood using only one sensor.

11.8.2 GMM mission 3 (Ionian Sea)

The "pioneering" experience of the Patras Gulf missions evidenced some critical aspects of the methane sensors (concerning in particular long-term stability, repeatability and cross-sensitivity), limiting their immediate transfer and operational use in long-term applications. Feedback from the mission allowed sensor manufacturers to upgrade the product. In addition, INGV and Tecnomare organized a dedicated qualification phase in laboratory, testing the two commercially-available underwater methane sensors (Franatech METS and Contros Hydro-C) in controlled conditions, in order to verify their reaction time and their response to temperature variations and water turbulence, either in the presence or in the absence of methane in solution. On the basis of the results obtained, adoption of a pump and a flow-though chamber, able to provide a constant water flow in contact with the sensitive membrane, was then recommended to avoid bio-fouling on the membrane (hence to increment long-term autonomy) and to reduce eventual signal variations induced by changes in water currents (Marinaro et al., 2011).

In the framework of EU HYPOX (in situ monitoring of oxygen depletion in hypoxic ecosystems of coastal and open seas, and land-locked water bodies) project, GMM was recently used in the Katakolo harbor (Ionian Sea, Greece). This area is heavily affected by intense gas seeps, posing a severe hazard for local tourist activities and at the same time providing a unique natural laboratory to study seepages and their impact in the oxygen budget in the seawater.

For this mission, GMM payload was extended (see Table 11.2) and the observatory configured to operate completely in autonomous mode (battery powered, internal data storage, no communication with external devices/users). Detection of gases (O_2, CH_4 and H_2S) is associated with physical-chemical factors, i.e., temperature, pressure and conductivity. Gas

Figure 11.58 Comparison between methane sensor arrangement in GMM. (Left) 2004 configuration (three sensors in series). (Right) 2010 configuration (two sensors, of which the one fitted with flow-through system is visible on the right).

Figure 11.59 (Left) GMM deployment in Katakolo harbor. (Right) GMM recovery after conclusion of mission 3.

detection is based on the use of oxygen, methane and hydrogen sulphide sensors commercially available. This time two methane sensors were adopted (see Figure 11.58), operating in parallel; one was fitted with pump and flow-through chamber, while the other was directly exposed to the environment, thus allowing performance comparison during time.

GMM was deployed on 22 September 2010 and recovered on 17 January 2011 (Figure 11.59).

The observatory successfully operated over the whole mission period (101 days), with 100% data acquisition efficiency. Preliminary analysis shows periods of O_2 decrease (hours) associated with enhanced CH_4 events. Short-term events of T and P drops are associated to CH_4 peaks (as observed in other seepage sites). Data from the two methane sensors show good correlation and absence of drift.

11.9 Conclusions

A fleet of seafloor observatories has been qualified during 18 missions at water depths of up to 3350m, duration up to 3.5 years and operation in autonomous, acoustic linked or cabled (real-time) configuration.

Basic data on these missions (sites, depths, duration and reference projects) are provided in Table 11.14. GEOSTAR and the five derived observatories are characterized by an innovative and alternative concept with respect to other ongoing applications, that proved to be technically sound, cost-effective and suitable to serve the challenging goals of seafloor observatory science.

Full operativeness was achieved (equipment, procedures, personnel, logistics) and high quality scientific data collected.

System	Mission	Site and depth	Period	Project
GEOSTAR	1	Adriatic Sea (42m)	August 1998, 450 h	GEOSTAR (1995–1998)
	2	Tyrrhenian Sea (1950m)	Sep 2000–Apr 2001	GEOSTAR 2 (1999–2001)
	3	Tyrrhenian Sea (3350m)	Dec 2003–Apr 2004	ORION-GEOSTAR 3 (2002–2005)
	4	Tyrrhenian Sea (3350m)	Jun 2004–Apr 2005	ORION-GEOSTAR 3 (2002–2005)
	5	Gulf of Cadiz (3200m)	Aug 2007–Aug 2008	NEAREST (2006–2010)
	6	Gulf of Cadiz (3200m)	Nov 2009–Jun 2011	NEAREST (2006–2010) ESONET (2007–2011) LIDO-DM
SN1	1	Ionian Sea (2105m)	Oct 2002–May 2003	GNDT (2000–2003)
	2	Ionian Sea (2105m)	Jan 2005–May 2008	NEMO
	3	Ionian Sea (2105m)	Jun 2012-on	EMSO (2008 on)
SN2	1	Weddell Sea (1874m)	Dec 2005–Dec 2008	PNRA–MABEL (2005–2009)
SN3	1	Tyrrhenian Sea (3350m)	Dec 2003–Apr 2004	ORION-GEOSTAR 3 (2002–2005)
	2	Tyrrhenian Sea (3350m)	Jun 2004–Apr 2005	ORION-GEOSTAR 3 (2002–2005)
SN4	1	Corinth Gulf (379m)	Apr 2004–Nov 2004	ASSEM (2002–2004)
	2	Marmara Sea (167m)	Oct 2009–Mar 2010	ESONET (2007–2011)
	3	Marmara Sea (167m)	Mar 2010–Sep 2010	ESONET (2007–2011)
GMM	1	Corinth Gulf (40m)	Apr 2004–Jul 2004	ASSEM (2002–2004)
	2	Corinth Gulf (40m)	Sep 2004–Jan 2005	ASSEM (2002–2004)
	3	Ionian Sea (<10m)	Sep 2010–Jan 2011	HYPOX (2009–2011)

Table 11.14 Mission data.

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References

Aguzzi J., Company J.B., Costa C., Matabos M., Azzurro E., Mànuel A., Menesatti P., Sardà F., Canals M., Delory E., et al. (2012) Challenges to the assessment of benthic populations and biodiversity as a result of rhythmic behaviour: Video solutions from cabled observatories., in: Gibson, R.N., R.J.A. Atkinson, J.D.M. Gordon, R.N. Hughes, D.J. Hughes, I.P. Smith (Eds), Oceanography and Marine Biology: An Annual Review 50, 235–286.

Berta M., Gasparoni F. and Capobianco M. (1995) Abyssal Benthic Laboratory (ABEL): A novel approach for long-term investigation at abyssal depths. J. Marine Systems 6, 211–225.

Beranzoli L., De Santis A., Etiope G., Favali P., Frugoni F., Smriglio G., Gasparoni F. and Marigo A. (1998) GEOSTAR: A Geophysical and Oceanographic Station for Abyssal Research. Phys. Earth Planet Int. 108(2), 175–183.

Beranzoli L., Braun T., Calcara M., De Santis A., Di Mauro D., Etiope G., Favali P., Frugoni F., Montuori C., Palangio P. (2000a) GEOSTAR, an observatory for deep-sea geophysical and oceanographic researches: Characteristics, first scientific mission and future activity. Mem. Soc. Geol. It. 55, 491–497.

Beranzoli L., Braun T., Calcara M., Calore D., Campaci R., Coudeville J.-M., De Santis A., Etiope G., Favali P., Frugoni F. et al. (2000b) European seafloor observatory offers new possibilities for deep-sea study. EOS, Trans. AGU, 81(5), 45–49.

Beranzoli L., Braun T., Calcara M., Calore D., Campaci R., Coudeville J.-M., De Santis A., Di Mauro D., Etiope G., Favali P., et al. (2002a) GEOSTAR: Geophysical and oceanographic station for abyssal research. Elsevier Oceanography Series 66, 307–315.

Beranzoli L., Favali P. and Smriglio G. (Eds) (2002b) *Science-Technology Synergy for Research in the Marine Environment: Challenges for the XXI Century*. Developments in Marine Technology, 12, Amsterdam: Elsevier.

Beranzoli L., Braun T., Calcara M., Casale P., De Santis A., D’Anna G., Di Mauro D., Etiope G., Favali P., Fuda J.L., et al. (2003) Mission results from the first GEOSTAR observatory (Adriatic Sea, 1998). Earth Planets Space 55, 361–373.

Beranzoli L., Calore D., Favali P., Marvaldi J. and Nicot M. (2004) *ORION-GEOSTAR-3: A Prototype of Seafloor Network of Observatories for Geophysical, Oceanographic and Environmental Monitoring*. ISOPE-Int. Soc. Offshore and Polar Engineers, Proc. 14th Int. Offshore and Polar Engineering Conf., Toulon, May 23–28.

Beranzoli L. and Favali P. (2005) SN1 – The first Italian seafloor observatory for seismic monitoring. In: M. Maugeri (Ed.), *Seismic Prevention of Damage: A Case Study in a Mediterranean City*. Advances in Earthquake Engineering 14, 367–376. Southampton (UK) and Boston (USA):

Beranzoli L., De Santis A., Calcara M., Ciafardini A., De Caro M., Favali P., Frugoni F., Iafolla V., Lo Bue N., Marinaro G., et al. (2009) Multiparametric seafloor exploration: The Marsili Basin and Volcanic Seamount case (Tyrrhenian Sea, Italy). Third IASME/WSEAS International Conference on Geology and Seismology (GES'09), WSEAS Press, 153–157.

Calcara M., Beranzoli L., Braun T., Calore D., De Santis A., Etiope G., Favali P., Frugoni F., Gasparoni F., Montuori C. and Smriglio G. (2001) MABEL: A multidisciplinary benthic laboratory for deep sea, long-term monitoring in the Antarctica. Terra Antarctica 8(2), 115–118.

Cenedese S., Calcara M., D'Anna G., Evers K.-U., Favali P. and Gasparoni F. (2004) MABEL – The first seafloor observatory for multidisciplinary long-term monitoring in Polar environment. ISOPE-Int. Soc. Offshore and Polar Engineers, Proc. 14th Int. Offshore and Polar Engineering Conf., Toulon, May 23–28.

Chierici F., Zitellini N., Favali P., Beranzoli L., Pignagnoli L., Embriaco D., Carrara G., Marinaro G., Lo Bue N., Monna S., et al. (2008) Tsunami warning prototype in the frame of the EC NEAREST project, Rendiconti online. Soc. Geol. It. 2, 1–3.

Chierici, F., P. Favali, L. Beranzoli, A. De Santis, D. Embriaco, G. Giovanetti, G. Marinaro, S. Monna, L. Pignagnoli, G. Riccobene et al. (2012) NEMO-SN1 (Western Ionian Sea, off Eastern Sicily): A cabled abyssal observatory with tsunami early warning capability. ISOPE-Int. Soc. Offshore and Polar Engineers, Proc. 22nd Int. Offshore and Polar Engineering Conf., Rhodes, July 17–22.

Clauss G. and Hoog S. (2002) Deep sea challenges of marine technology and oceanographic engineering. In: L.P. Beranzoli, P. Favali and G. Smriglio (Eds) *Science-technology Synergy for Research in Marine Environment: Challenges for the XXI Century*. Developments in Marine Technology 12. Amsterdam: Elsevier, pp. 133–142.

Clauss G., Hoog S., Stempinski F. and Gerber H.W. (2004) Advanced deepwater intervention with MODUS – Latest results from model tests and full scale operations. In Proceedings of 14th International Offshore and Polar Engineering Conference (ISOPE 2004) Vol II, Toulon (France), pp. 377–386.

De Santis A., Di Mauro D., Cafarella L., D'Anna R., Gaya-Piqué L.R., Palangio P., Romeo G. and Tozzi R. (2006) Deep seafloor magnetic observations under GEOSTAR project. Ann. Geophys. 49 (2/3), 681–694.

De Santis A., Di Mauro D., Cafarella L., Palangio P., Beranzoli L., Favali P. and Vitale S. (2007) Extending magnetic observations to seafloor: The case of GEOSTAR and ORION missions in the Adriatic and Tyrrhenian Seas. Publ. Inst. Geophys. Pol. Acad. Sc. C-99 (398), 114–123.

Etiope G., Marinaro G., Favali P., Furlan F., Cenedese S. and Gasparoni F. (2005) New technologies for methane leakage monitoring from seafloor – description and first operational results. Poster presented at the 7th Offshore Mediterranean Conference, Ravenna (Italy), 16–18 March, 2005.

Etiope G., Favali P., Fuda J.L., Italiano F., Launbenstein M., Millot C. and Plastino W. (2006) The Benthic Boundary Layer: Geochemical and oceanographic data from the GEOSTAR-2 observatory. Ann. Geophys. 49 (2/3), 705–714.

Favali P. and Beranzoli L. (2006) Seafloor observatory science: A review. Ann. Geophys. 49(2/3), 515–567.

Favali P. and Beranzoli L. (2009a) EMSO: European Multidisciplinary Seafloor Observatory, Nuclear Instruments and Methods. Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 602, 21–27, doi:10.1016/j.nima.2008.12.214.

Favali, P and Beranzoli L. (2009b) GEOSTAR technology. ESONEWS, The Newsletter of the European Seas Observatory Network 2(3), 1–8.

Favali P., Smriglio G., Beranzoli L., Braun T., Calcara M., Etiope G., Frugoni F., Millot C., Fuda J.-L., Marani M.P., et al. (1998) GEOSTAR – Scientific goals of the project and results of the first test phase. IEEE-OCEANS '98 Conference Proceedings, vol. 2, 1088–1090, doi: 10.1109/OCEANS.1998.724404.

Favali P., Smriglio G., Beranzoli L., Braun T., Calcara M., D'Anna G., De Santis A., Di Mauro D., Etiope G., Frugoni F., et al. (2002) Towards a permanent deep sea observatory: The GEOSTAR European experiment. In: L. Beranzoli, P. Favali and G. Smriglio (Eds) *Science-technology Synergy for Research in Marine Environment: Challenges for the XXI Century*. Development in Marine Technology 12, Amsterdam: Elsevier, pp. 111–120.

Favali P., Beranzoli L., Calcara M., D'Anna G., Etiope G., Frugoni F., Lo Bue N., Marinaro G., Monna S. and Montuori C., et al. (2004) Single-frame multiparameter platforms for seafloor geophysical and environmental observations: Projects and missions from GEOSTAR to ORION. OCEANS '04. MTTS/IEEE TECHNO-OCEAN '04, Vol. 4, 2000–2007, doi: 10.1109/OCEANS.2004.1406450.

Favali P., Beranzoli L., D'Anna G., Gasparoni F., Marvaldi J., Clauss G., Gerber H.W., Nicot M., Marani M.P., Gamberi F., Millot C. and Flueh E.R. (2006) A fleet of multiparameter observatories for geophysical and environmental monitoring at seafloor. Ann. Geophys. 49 (2/3), 659–680.

Favali P., Beranzoli L., D'Anna G., Gasparoni F. and Gerber H.W. (2006) NEMO-SN1: The 1st "real-time" seafloor observatory of ESONET. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 567(2), 462–467, doi:10.1016/j.nima.2006.05.255.

Favali P., Person R., Barnes C.R., Kaneda Y., Delaney J.R. and Hsu S.-K. (2010) Seafloor observatory science. In: J. Hall, D.E. Harrison and D. Stammer (Eds) Proceedings of the OceanObs'09: Sustained Ocean. Observations and Information for Society Conference 2, Venice, Italy, 21–25 September 2009, ESA Publication WPP-306 ISSN:1609-042X, doi: 10.5270/OceanObs09.cwp28.

Favali P., Beranzoli L., Italiano F., Migneco E., Musumeci M. and Papaleo R. (2011) NEMO-SN1 observatory developments in view of the European Research Infrastructures EMSO and KM3NET. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 626–627, S53–S56, doi:10.1016/j.nima.2010.04.139.

Favali P., Chierici F., Marinaro G., Giovanetti G., Azzarone A., Beranzoli L., De Santis A., Embriaco D., Monna S., Lo Bue N., et al. (2012) NEMO-SN1 abyssal cabled observatory in the Western Ionian Sea. IEEE J. Oceanic Engineering, doi: 10.1109/joe.2012.222.4536.

Frugoni F., Beranzoli L., Favali P. and Basili A. (Eds) (2006) Special issue dedicated to Giuseppe Smriglio. From land networks to seafloor observatories. Ann. Geophys. 49(2/3), 515–879.

Fuda J.L., Millot C., Hoog S. and Gerber H.W. (2006) Analysis of ADCP data above a bottom observatory. Ann. Geophys. 49(2/3), 715–728.

Gasparoni F., Calore D., Campaci R. and Marigo A. (1998) GEOSTAR – Development and test of an innovative benthic station for long term observations at abyssal depths. In: Proceedings of the IEEE Conference OCEANS '98 (on CD-ROM).

Gasparoni F., Calore D. and Campaci R. (2002) From ABEL to GEOSTAR: Development of the first European deep-sea scientific observatory. In: L. Beranzoli, P. Favali and G. Smriglio (Eds) *Science-technology Synergy for Research in Marine Environment: Challenges for the XXI Century*. Developments in Marine Technology 12. Amsterdam: Elsevier, pp. 143–159.

Gasperini L., Polonia A., Del Bianco F., Etiope G., Marinaro G., Favali P., Italiano F. and Çağatay M.N. (2012a) Gas seepage and seismogenic structures along the North-Anatolian Fault in the Eastern Marmara Sea. Geochem. Geophys. Geosyst. 13(10), Q10018, ISSN:1525-2027, doi:10.1029/2012GC004190.

Gasperini L., Polonia A., Del Bianco F., Favali P., Marinaro G. and Etiope G. (2012b) Cold seeps, active faults and the earthquake cycle along the North Anatolian Fault system in the Sea of Marmara (NE Turkey). Bollettino di Geofisica Teorica ed Applicata 53(4), 371–384, doi: 10.4330/bgta0082.

Gerber, H.W., G.Clauss, 2001. Development and operational optimization of MODUS - the GEOSTAR subsea docking station, Proceedings of OMAE 2001 Conference, Rio de Janeiro (Brazil), 3-8 June 2001.

Gerber H.W. and Clauss G. (2005) Space shuttle MODUS – Key system for the installation of networks of Benthic Stations. In: Proceedings of OMAE 2005 Conference, Haikidiki (Greece).

Gerber H.W and Clauss G. (2009) MABEL: Recovery operation of the first long-term heavy benthic laboratory in the deep sea of Antarctica. In: Proceedings of the 28th OMAE International Conference on Ocean, Offshore and Arctic Engineering, 31 May–5 June 2009, Honolulu (Hawaii, USA), paper 80251.

Gerber H.W., Favali P., Smriglio G., Gasparoni F., Marvaldi J. and Coudeville J.-M. (1999) GEOSTAR benthic observatory: Technological results. J. Acoust. Soc. Am. 105(2), 1169, doi: http://dx.doi.org/10.1121/1.425545.

Gerber H.W., Clauss G. and Hoog S. (2002) MODUS: Remotely operated carrier for abyssal research – Experiences in the Mediterranean Sea. In: Proceedings of ISOPE 2002 Conference, paper No.2002-JSP-320.

Iafolla V. and Nozzoli S. (2002) Gravimeter for deep sea measurements. In: L. Beranzoli, P. Favali and G. Smriglio (Eds) *Science-technology Synergy for Research in Marine Environment: Challenges for the XXI Century*. Developments in Marine Technology 12. Amsterdam: Elsevier, pp. 183–197.

Iafolla V., Nozzoli S., Fiorenza E. and Milyukov V. (2006) Deep-sea gravity measurements: GEOSTAR-2 mission results. Ann. Geophys. 49(2/3), 695–704.

Jourdain J.Y. (1999) First trial of GEOSTAR, the geophysical and oceanographic European station for abyssal research. In: G. Ollier (Ed.) EC Project Information Booklet EUR18885, p.31.

Kopf A., Camerlenghi A., Canals M., Ferdelman T., Mevel C., Pälike H., Roest W., Ask M., Barker-Jørgensen B., Boetius A., et al. (2012) *Deep Sea and Sub-Seafloor Frontier*. White Paper European Commission, pp. 58.

Lampitt R.S., Favali P., Barnes C.R., Church M.J., Cronin M.F., Hill K.L., Kaneda Y., Karl D.M., Knap A.H., McPhaden M.J., et al. (2010) In situ sustained Eulerian observatories. In: J. Hall, D.E. Harrison and D. Stammer (Eds) *Proceedings of the OceanObs'09: Sustained Ocean*. Observations and Information for Society Conference 2, Venice, Italy, 21–25 September 2009, ESA Publication WPP-306, doi:10.5270/OceanObs09.pp.27.

Marani M.P., Gamberi F. and Bonatti E. (Eds) (2004) *From Seafloor to Deep Mantle: Architecture of the Tyrrhenian Back-arc Basin*. Mem. Descr. C. Geol. d'It., LXIV.

Marinaro G., Etiope G., Gasparoni F., Calore D., Cenedese S., Furlan F., Masson M., Favali P. and. Blandin J. (2004) GMM-a gas monitoring module for long-term detection of methane leakage from the seafloor. In: G. Etiope and P. Favali (Eds) *GEM-Geologic Emissions of Methane from Lands and Seafloor: Mud Volcanoes and Observing Systems*. Environmental Geology 46/8, 1053–1058, doi:10.1007/s00254-004-1092-2.

Marinaro G., Etiope G., Lo Bue N., Favali P., Papatheodorou G., Christodoulou D., Furlan F., Gasparoni F., Ferentinos G., Masson M. and Rolin J.-F. (2006) Monitoring of a methane-seeping pockmark by cabled benthic observatory (Patras Gulf, Greece). Geo-Mar. Letters, doi: 10.1007/s00367-006-0040-4.

Marinaro G., Etiope G., Favali P., Beranzoli L., Gasperini L., Gasparoni F., Furlan F., Geli L., Henry P. and Çağatay M.N. (2008) SN4 seafloor observatory in Marmara Sea. Rendiconti on-line Soc. Geol. It. 2, 1–3.

Marinaro G., Etiope G., Gasparoni F., Furlan F., Bruni F. (2011) Gas seepage detection and monitoring at seafloor. Paper presented at the 10th Offshore Mediterranean Conference, Ravenna (Italy), 23–25 March 2011.

Marvaldi J., Blandin J., Podeur C., Coudeville J.M., Antoine J., Barbot D., Fellmann D. and Rhodes D. (1998) GEOSTAR – Development and test of a communication system for deep-sea benthic stations. In: *Proceedings of the IEEE Conference OCEANS '98* (on CD-ROM).

Marvaldi J., Aoustin Y., Ayela G., Barbot D., Blandin J., Coudeville J.-M., Fellmann D., Loaëc G., Podeur C. and Priou A. (2002) Design and realisation of communication systems for the GEOSTAR project. In: L. Beranzoli, P. Favali and G. Smriglio (Eds) *Science-technology Synergy for Research in Marine Environment: Challenges for the XXI Century*. Developments in Marine Technology 12. Amsterdam: Elsevier, pp. 161–181.

Monna S., Frugoni, F., Montuori, C., Beranzoli, L. and Favali, P. (2005) High quality seismological recordings from the SN1 deep seafloor observatory in the Mt. Etna region. Geophys. Res. Lett. 32, doi:10.1029/2004GL021975.

NRC (National Research Council) (2000) *Illuminating the Hidden Planet. The Future of Seafloor Observatory Science*. Washington D.C.: National Academy Press.

Ollier G., Favali P., Smriglio G. and Gasparoni F. (2002) Perspectives and challenges in marine research. In: L. Beranzoli, P. Favali and G. Smriglio (Eds). *Science-technology Synergy for Research in Marine Environment: Challenges for the XXI Century*. Developments in Marine Technology 12. Amsterdam: Elsevier, pp. 3–9.

Rigaud V., Semac D., Nokin M., DESIBEL Team, Tietze G., Amann H., Goetz V. and Pascoal A. (1998) New methods for deep-sea interventions on future benthic laboratories. DESIBEL project: Final results, comparison of concepts and at sea validation. In: *Proceedings of OCEANS '98*, IEEE Conference Nice (France) (on CD-ROM).

Rolin J.-F., Blandin J., Lykousis V., Strout J.M., Etiope G., Favali P., Briole P., Ballu V., Papatheodorou G., Ferentinos G., Cathy D. and Masson M. (2005) Common issues between cabled and non-cabled observatories in ASSEM project. OCEANS 2005 – Europe 2, 872–877, doi: 10.1109/OCEANSE.2005.1513171.

Ruhl H.A., André M., Beranzoli L., Çağatay M.N., Colaço A., Cannat M., Dañobeitia J.J., Favali P., Géli L. and M. Gillooly, et al. (2011) Societal need for improved understanding of climate change, anthropogenic impacts, and geo-hazard warning drive development of ocean observatories in European Seas. Progress in Oceanography 91, 1–33, doi:10.1016/j.pocean.2011.05.001.

Sgroi T., Beranzoli L., Di Grazia G., Ursino A. and Favali P. (2007) New observations of local seismicity by the SN1 seafloor observatory in the Ionian Sea, off-shore Eastern Sicily (Italy). Geophys. J. Int. 169, 490–501, doi:10.1111/j.1365-246X.2007.03348.x.

Vitale S., De Santis A., Di Mauro D., Cafarella L., Palangio P., Beranzoli L. and Favali P. (2009) GEOSTAR deep seafloor missions: Magnetic data analysis and 1D geoelectric structure underneath the Southern Tyrrhenian Sea. Ann. Geophys. 52(1), 57–63.