*Science-Technology Synergy for Research in the Marine Environment: Challenges for the XXI Century*
*L. Beranzoli and P. Favali and G. Smriglio, editors.*

# Geophysical Ocean Bottom Observatories or Temporary Portable Networks?

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Most of the scientific issues are multiscale for spatial scales as well as for temporal scales. There is a general consensus that it is necessary to install geophysical stations in oceans which are presently instrumental deserts. In this paper, we review the general constraints of a network of ocean bottom stations which should enable us to address these scientific issues by covering the different spatial scales from global down to local scale. The recent progresses made by Japanese, French, German, Italian and U.S. groups show that the technical challenge of installing long-term or 'even better' permanent geophysical ocean bottom observatories (coined GOBOs) is not out of reach. Different technological developments are presently explored and prefigure what will be the future geophysical ocean bottom stations and networks. They are integrating the concept of multiparameter station, which is demonstrated to have a great scientific interest. The installation of different kinds of sensors at the same place in a seismic station allows us to enhance the signal-to-noise ratio and opens wide the possibility of new discoveries. The finding of the excitation of normal modes in the absence of large earthquakes is emblematic in that respect. Such a multiparameter oceanic observatory includes at least broad band seismometers, microbarometers or pressure gauges, microthermometers, and possibly other sensors (e.g. electromagnetic sensors, strain meters, GPS). The design of the complete chain of acquisition, from the sensor to the distribution of data, will imply integration of all the technical progresses made in micromechanics, electronics, computer science, space science, and telecommunication systems.

There is also a real need for developing seismological and more generally geophysical arrays enabling us to address scientific issues at regional and local scales, particularly for understanding active processes in seismic and volcanic areas. The networks at all scales must be coordinated in order to constitute a hierarchical or multiscale network, which will be the basic tool for addressing scientific issues in geosciences. However, the strategy for developing reference GOBOs and temporary stations is not necessarily the same. The technological developments are largely dependent on the period of operation of the station: a long-term geophysical observatory is much more difficult to install and maintain than a time-limited station, due to the problems of power and data transmission. For example, the solution for ensuring the long-term operation is the installation of cables. The cables can be either laid down on the seafloor between the station and the sea-shore or installed vertically, in connection with a surface buoy, in order to ensure the link between sea floor and sea surface, where data can be teletransmitted and power can be provided by solar panels (diesel-powered or windmills).

Such a "heavy" observatory necessitates the use of a manned submersible, ROV or AUV. On the other hand, the installation of typically one hundred temporary "light" stations must be performed by usual oceanographic vessels using simple dropping procedures. The design of both kinds of stations will be detailed. Whereas GOBO should follow the multiparameter concept, a temporary station must be, for practical reasons, dedicated to a single parameter measurement. All the efforts necessary to achieve and maintain such a multiscale, multiparameter network represent a formidable technological challenge for the next decade.

## 1. INTRODUCTION

The last twenty years have seen the explosion of a new kind of seismology, broad band seismology. The Federation of Digital Seismographic Networks (FDSN) played a key role in promoting this new seismology and in coordinating the projects of several countries in broad band seismology, by proposing different standards for the sensors, a data distribution format and by avoiding the duplication of national efforts [1]. The same philosophy is followed by the geomagnetism community, which has launched the InterMagnet program. However, in spite of these international efforts, the global coverage of the Earth by digital seismic stations of global networks such as GEOSCOPE, IRIS/GSN and GEOFON, and regional networks (e.g. MedNet, CSN, CNSN, POSEIDON) is still very uneven. Most of the stations are located on continents and primarily in the Northern Hemisphere. Therefore, a large part of the oceanic areas (2/3 of the surface of the Earth) is devoid of seismic and geophysical instrumentation. At the same time, the broad band revolution also concerned the local networks and portable instrument arrays (e.g. PASSCAL in U.S.A., SKIPPY in Australia, GEOFON in Germany, RLBM in France). Such portable networks make it possible to investigate geodynamic processes at regional scales (around 100 km) such as continental roots, tectonic processes, deep origin of plumes.

The lateral resolution of tomographic models and detailed studies of active processes (e.g. earthquakes, volcanic activity of plumes and ridges, landslides), is primarily limited by the poor coverage of the oceanic areas by stations. The investigation of such processes is equivalent to looking at an object from only one side or to be blind in one eye. Consequently, a recommendation of recent prospective workshops (see for example the proceedings of the recent ION/ODP workshop [2]) was to promote the installation of long-term oceanic seismographic stations or even better, geophysical stations and observatories.

However, this is a very difficult task, due, firstly to the environmental hostile conditions prevailing at the bottom of the ocean, and secondly to the difficulty to correctly install stations on the sea floor, to maintain stable long-term observations, to retrieve data in real time, and to supply power for a long period of time. Due to the high cost of such observatories, the geosciences community has realized that these observatories have to be multidisciplinary.

These multiparameter geophysical ocean bottom observatories (hereafter referred as GOBO) are interesting not only from a financial point of view but also from a scientific point of view. Beauduin et al. [3] and Roult and Crawford [4] demonstrated that the co-location of broad band seismometers and microbarometers makes it possible to improve the signal-to-noise ratio for land stations. But the concept of multiparameter station is valid for land station as well as for ocean bottom observatories. The international organization, International Ocean Network (ION), was launched in 1993 in order to coordinate the international efforts in the design, site location and installation of ocean bottom observatories [5]. The same effort must be done for portable ocean bottom stations.

In this paper, we review different recent developments which are ongoing regarding instrumentation (sensors, pilot experiments on the sea floor), multiparameter stations, and data teletransmission. The relationship between technological developments and the duration of operation (short-term experiments, semi-permanent and permanent stations) will be discussed. We highlight the French contribution to this international efforts.

## 2. TOWARDS AN INTERNATIONAL OCEAN NETWORK

A uniform coverage of the Earth with geophysical observatories at different scales is particularly important from a scientific point of view for understanding the Earth dynamics. Different spatial scales can be considered: global scale (characteristic spacing of stations around 2,000 km), regional scale (typical dimensions: 1,000 km, spacing of the order of 100 km), local scale (dimensions smaller than 100 km). For the global scale, most emerged lands are now covered by broad band stations (Fig. 1). The site locations are coordinated through the FDSN [1]. Its initial goal was to obtain the best uniform coverage of the Earth as possible with a station spacing of around 2000 km, which corresponds to a number of stations around 100. This goal is largely overpassed and more than 200 stations are now part of the Federation network. This network includes all stations of global networks (GEOSCOPE, Geofon, IRIS/GSN), and selected stations of regional networks such as Chinese Seismograph Network (CSN), Canadian National Seismograph Network (CNSN), Mediterranean Network (MedNet, Italy), POSEIDON (Japan), Australian National Seismograph Network (ANSN). Though most of continents and emerged lands are adequately covered, the station coverage is still very uneven and dramatically unbalanced towards continents, particularly in the northern hemisphere. The same problem exists for geomagnetic stations. A large part of oceanic areas, particularly in the southern hemisphere, is devoid of instruments. From the scientific point of view, that means a strong aliasing of tomographic models and the impossibility to correctly investigate active processes occurring in these areas.

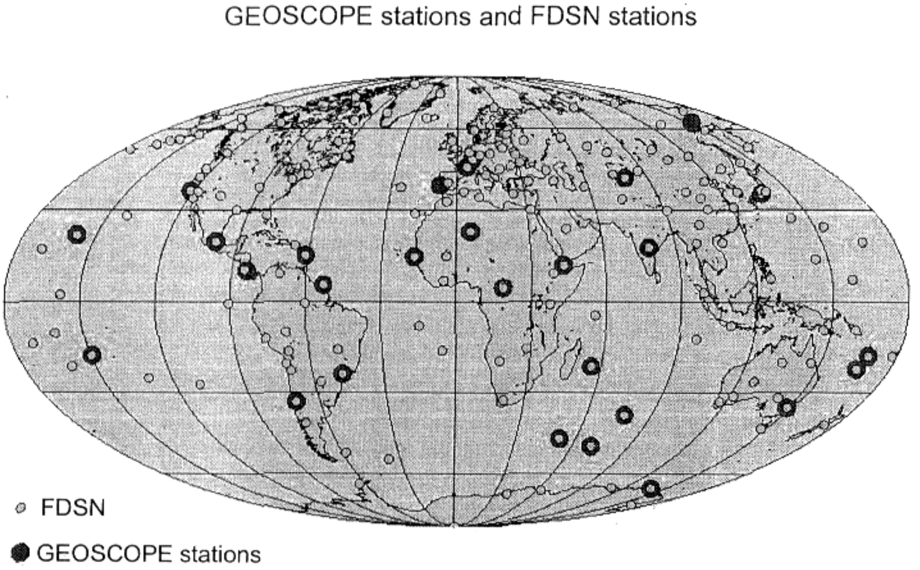


Figure 1. Broad band digital stations.

With the present station coverage, the lateral resolution of global tomographic models is limited to about 1000 km. For source studies, the azimuthal coverage of seismic sources is also very uneven.

The different scientific issues regarding global studies and active processes were extensively discussed in the ION/ODP workshop [2] held in Marseilles in January 1995. Even though all islands are instrumented, there will be large parts of oceans unsampled particularly in the Pacific Ocean and in the Indian Ocean.

### 2.1. Pilot experiments on the ocean floor

The installation of a network of GOBOs represents a "formidable" technological challenge and several pilot experiments have been carried out in order to unravel different technical issues. Several groups in Japan, France and U.S.A. have performed preliminary experiments focussed towards the goal of installing permanent seismic stations. In March 1991, a downhole set of broad band seismometers CMG3 was successfully placed in the ODP hole 843B in Japan sea but not recovered [6]; teleseismic events were recorded and broad band seismic noise spectra (0.03 s – 200 s) were obtained [7].

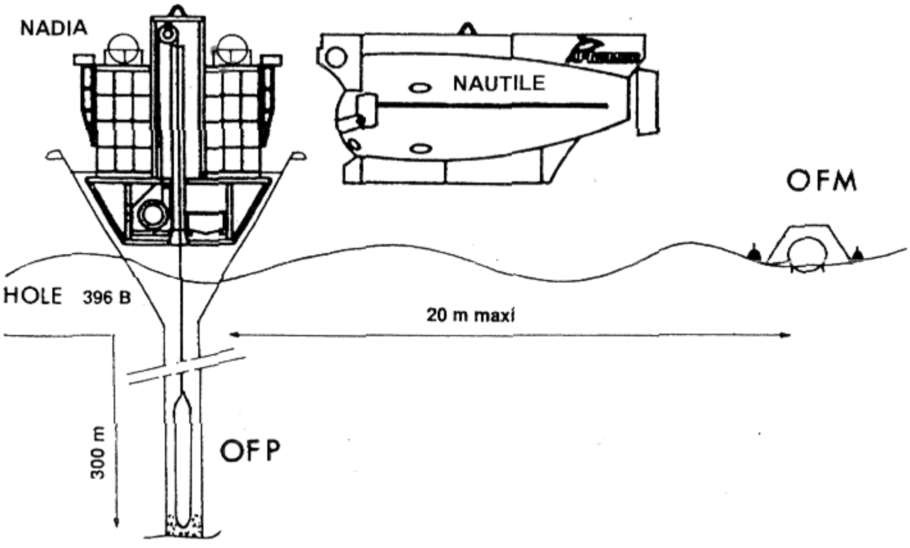


Figure 2. Sketch of the OFM/SISMOBS experiment [8].

### 2.1.1. SISMOBS/OFM

In May 1992, the French pilot experiment OFM/SISMOBS was successfully conducted and two sets of CMG3 broad band seismometers were installed, operated for more than one week and recovered [8].

The experiment (Fig. 2) took place in the North-Atlantic Ocean at 23°N and 43.3°W at the location of the DSDP hole 396B. A first set of CMG3 seismometers (called OFM) was installed on the sea floor at 20 m from the hole and was semi-buried within the sediments. It was possible to install a second set of CMG3 seismometers (named, OFP) into the hole down to –296 m below ocean bottom level. After the installation of both sets of seismometers, seismic signals were recorded continuously during 8 days for OFM and 5 days for OFP at a sampling rate of 5 samples per second. The different instrumentation tools were designed by a team of the Technical Division of INSU, now integrated into IPG-Saint-Maur. The experiment made necessary the simultaneous use of the oceanographic vessel NADIR, of the submersible NAUTILE, and the re-entry logging system NADIA. All the logistical support was provided by IFREMER. From a technological point of view, this experiment was a complete success.

The most important scientific results are the following [9]: the seismic noise is smaller in the period range 4~30 s for both OFM (sea floor seismometers) and OFP (downhole seismometers) than in a typical broad band continental station such as SSB (France, GEOSCOPE). But, more important, the noise is smaller than the noise at SSB up to 600 s for

OFM. This low level of seismic noise implies that the detection threshold of earthquakes is very low and it has been possible to correctly record teleseismic earthquakes of magnitude as small as 5.2 at an epicentral distance of 105° (Fig. 3).

Another important qualitative result is that the noise level tends to decrease as time goes on for both OFM and OFP [10]. It is observed that the amplitude of noise is systematically and rapidly decreasing for OFP at long periods ($T$ >50 s). For OFM, there is some tendency of noise decreasing with time but its variations are more erratic and can correspond to the normal variations of noise in a seismic station. The noise level decrease for OFP can be approximated by an exponential, but the asymptotic level corresponding to $t \to \infty$ is still larger for OFP than for OFM. However, the duration of the operation for OFP (5 days) is too short to have an accurate estimate of the exponential decay. That means that the equilibrium stage was not yet attained by the end of the experiment. Therefore, the key issue of whether it is important to install seismometers down boreholes or on the sea floor was still unresolved. This experiment demonstrated that a broad band seismometer carefully installed on the sea floor and semi-buried can present an excellent signal/noise ratio and provide useful seismic data.

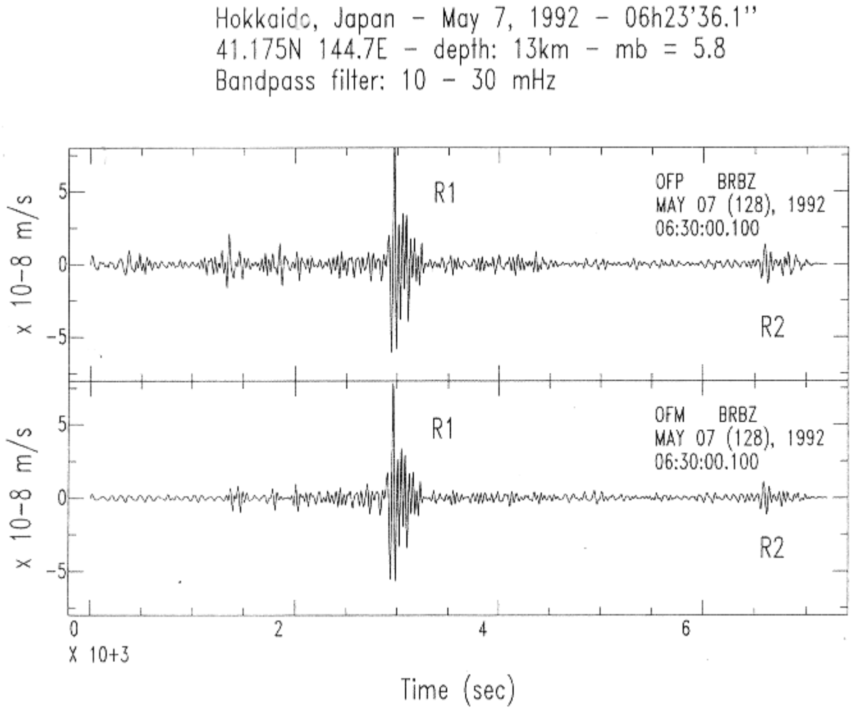


Figure 3. An example of earthquake recorded on both OFM and OFP vertical component.

### 2.1.2. MOISE: Monterey Bay Ocean bottom International Seismic Experiment

Following the international workshop of ION in Marseilles [2], a cooperative multiparameter project between IPG (Paris), UBO (Brest), MBARI (Monterey, California) and UC Berkeley was launched in order to test the feasibility of installing, operating and recovering different geophysical sensors (primarily broad band seismometers and electromagnetometers) on the sea floor during three months in order to investigate the covariations of the different signals recorded by these sensors. This experiment named MOISE was conducted from June to September 1997 off the California coast in the Monterey Bay on seafloor sediments at a depth of 1015 m. The different geophysical instruments were deployed by using the remotely operating vehicle (ROV) Ventana of Monterey Bay Aquarium Research Institute (MBARI). The experiment (Fig. 4) is described in [11]. Preliminary results are presented in [12] demonstrating the strong correlation between seismic noise and deep water currents. A systematic study of the seismic noise level variations is presented in [13].

It is shown that the seismic noise level was stable throughout the experiment. It is comparable to terrestrial station noise below 15 s, and displays strong diurnal variations at long periods. These diurnal variations can be removed from the vertical component by subtracting the effect of the horizontal components, decreasing the vertical noise by up to 40 db. Coherence between long period seismic, electromagnetic and environmental data was investigated. The coherence between the different signals is maximum near 12 hours, a consequence of tidal effects. The coherence between the vertical seismic signal pressure and current velocity is high throughout the experiment. There is no significant high coherence with the vertical magnetic field.

### 2.1.3. O.S.N1: February-June 1998

Plans in U.S. called for a three-phase approach [14]. In phase 1 (completed), pilot experiments are proposed to address the fundamental problems of sensor coupling in holes, noise, devising solutions for power, data retrieval and reliability on the multiple year time scale. In phase 2 (under progress), a small number of prototype observatories will be installed, immediately contributing data to the seismological community. In phase 3, the complete network Ocean Seismic Network (OSN) of 20~25 stations will be installed and will complement the IRIS/GSN.

An important experiment was carried out at the OSN-1 drill site (ODP hole 843B) 225 km south-west of Oahu, Hawaii, in water 4407 m deep. The noise level in the Pacific Ocean is known to be larger than in the Atlantic Ocean ([15] for a review). A complete description of this experiment can be found in Stephens et al. [16]. Three broad band seismic systems were tested: a seismometer (Guralp CMG-3T) resting on the seafloor, a seismometer (CMG-3T) buried within 1 m of the seaflor and a seismometer (Teledyne KS5400) clamped at 248 m beneath the seafloor in the hard rock basement. The instruments were deployed in early February and recovered in early June 1998. The results of the experiment confirm the previous results of the Japanese and French SISMOBS/OFM experiment. In the microseism and short-period band, the borehole sensor had the quietest ambient noise levels, particularly

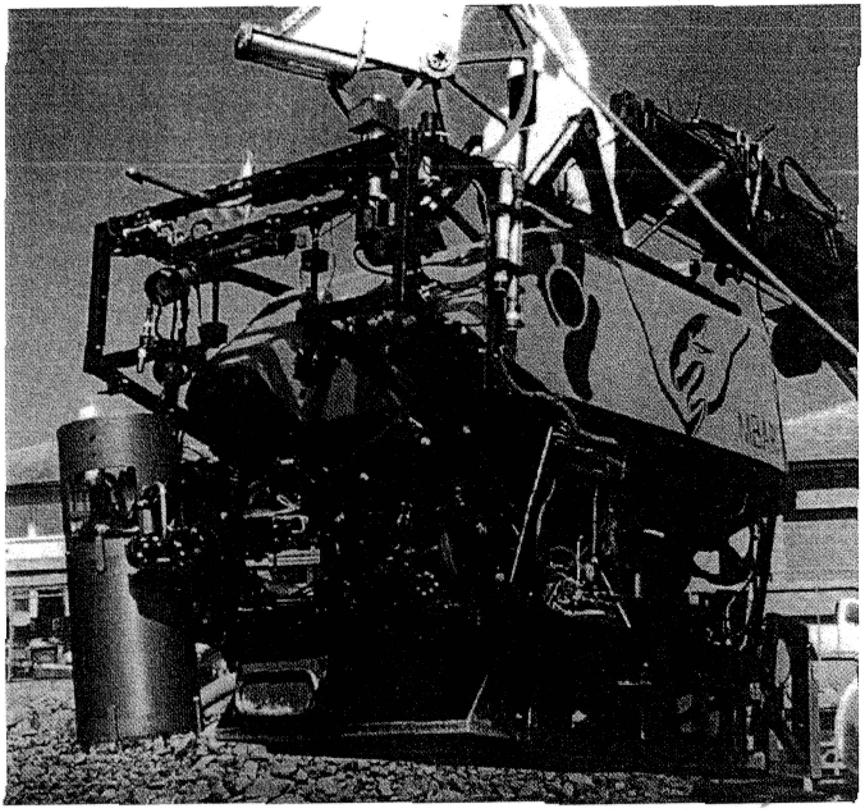


Figure 4. Monterey Bay Ocean bottom International Seismic Experiment. The ROV Ventana of MBARI is holding the seismic broad band package [11].

on the horizontal components. But at periods longer than 10 s (noise notch and infragravity wave band following the classification of Webb [15]), the buried sensor was as quiet or quieter than the borehole sensor. The good news again was that broad band seafloor seismic installations can yield quality data comparable to land stations, not only in the Atlantic Ocean but in the Pacific Ocean as well. The debate regarding borehole versus buried sensors is now closed. The borehole system can be used for permanent observatory sites provided that the sensor be cemented in place, which should reduce the noise level above 10 s.

## 2.2. Reference Geophysical Ocean Bottom Observatories on Global scale

The same three-phase scheme is also followed by other members of the ION community and the phase which requires installing a small number of prototype observatories is ongoing.

These sites were detailed in the ION proposal [5]. In May 1998, a hole was drilled in the middle of the Indian Ocean on the Ninetyeast Ridge. The installation should have been carried out in the framework of a French-Japanese cooperative project, but both partners are still waiting for funding from their respective agencies.

In November 1998, U.S. groups installed a junction box on the cable linking the Hawaiian archipelago and California coast about half-way, including broad band seismometers [17]. An unfortunate failure delayed the operation of this first ocean bottom observatory named H2O. It was repaired during Fall 1999 and instruments are providing seismic data to the IRIS DMC in Seattle. H2O is a good example on how to re-use retired telecommunication cables.

The main advantage of cable is that it enables us to provide power to the instruments and to transmit the data. Unfortunately, most of the ION selected sites are located far away from available cables, particularly in the Southern hemisphere. And the installation of several thousand kilometers long cables should be far too expensive to constitute an alternative to completely autonomous GOBOs.

In June 1999, during ODP Leg 186, two sites off the northeast coast of Japan were successfully drilled, in order to monitor seismic and aseismic crustal deformation associated with the subduction of the Pacific plate beneath Japan. Borehole strainmeters, tiltmeters and broad band seismometers (Guralp CMG-1) were installed at the bottom of the drilled sites. At least one set of instruments turns out to be operating correctly (Suyehiro, personal communication).

## 3. SHORT TERM STATIONS, REGIONAL AND LOCAL SCALE ARRAYS

Long-term GOBO will enable us to investigate global scale geodynamics and will serve as reference stations. However, in order to study active processes, the global ION network must be complemented by regional and local scale networks. Permanent regional networks are devoted to the study of structure for spatial wavelengths from the tens of kilometers to a maximum of 1000 km, and to the localization and study of regional earthquakes. The scales between 100 km and 1000 km in most of the oceanic areas is naturally out of reach so far. As for local networks (scale between a few kilometers and hundreds of kilometers), the number of permanent networks is very limited. They are located either where active processes occur (seismic or volcanic areas) or in quiet areas for nuclear test monitoring.

There is a real need as well, for high resolution experiments (scale smaller than 1 km or 100 m) which should be able to map interesting three-dimensional geological objects (e.g. faults systems, magma chambers). So far, regional and local networks cannot provide a uniform sampling of intermediate spatial wavelengths (between 10 km and 1000 km) and mini-scales (smaller than 1 km) for the large variety of geological environments. Only a limited number of tectonically active areas are covered and our knowledge in active processes occurring on plate tectonics boundaries below oceans (ridges, passive or active margins), or in the middle of plates (intraplate volcanism, plumes) is still very limited. The short wavelength structure, below the crust, in the deep mantle, in the D"-layer and in the core is very poorly known. The present coverage of stations does not enable us to address these issues with the available networks. The development of broad band portable networks such as SKIPPY in Australia [18] or PASSCAL in U.S.A. among many other initiatives in different European and Asian countries, has demonstrated that hot scientific issues on continents can be addressed by short-term (usually less than one year long) experiments. The new american initiative, U.S.-ARRAY, consists in developing a network of 1000 broad band (BB) instruments and recording systems.

However, such a portable broad band network is still missing in oceans. During the MELT experiment [19], it was possible to record long-period surface waves and body waves by using short-period instruments with broadened bandwidth, but the quality of data was rather poor due to the inappropriate sensors. However, this pilot experiment demonstrated the interest of such data for understanding the behaviour of ridges and dynamic processes.

### *3.1. GEODIS: Geophysical Diving Saucer*

In order to be efficient and achievable, a portable broad band (BB) seismic network must be easy to install and to recover, must have a low power consumption and must be reliable. If we imagine a network of at least 100 instruments, the main limitation of such a network will be its financial cost and the associated expenses in terms of sea campaigns and maintainance. Different institutions around the world are working on the design of such a network. We will detail the project named GEOphysical DIving Saucer (GEODIS) of the IPG of Paris which is developing such an instrument fulfilling these requirements.

On a small platform of small diameter (0.93 m), different boxes including three component broad band seismometers, power, recording system and eventually environmental sensors (e.g. pressure, temperature, currentmeter) are interconnected (Fig. 5). The height is 43 cm and the architecture is designed in order to look like a saucer to minimize the influence of bottom currents. The weight of inside water will be 140 kg (216 kg in air) and the round flat frame at its base enables a good coupling with the sea floor. The power will be provided by lithium batteries and should be smaller than 1 watt, in order to ensure a functioning for at least one year.

All components of GEODIS are designed to minimize their power consumption. The masterpiece of the instrument is the seismic sensor which is derived from the spatial technology (see next section). Such an instrument can be connected to other platforms through a cable. A first experiment will take place in autumn 2000 off Ustica Island in the Thyrrhenian sea (Gasparoni et al., this volume). GEODIS will be connected to the GEOSTAR platform [20]. This experiment is supposed to test the feasibility of the concept of GEODIS and to make a quantitative comparison as for the seismic noise with the CMG-3T seismic sensor installed on the GEOSTAR platform by the ING team. Two different ways can be used for installing GEODIS. It can be installed either as an autonomous station thrown off board or by using an installer.

In the first case, it is necessary to add a weight which will act as a ballast, connected at the bottom of GEODIS with an acoustic release. To get a positive weight balance, 6–8 benthos spheres can be assembled as a toroid. The spheres can be used to store enough Li batteries to operate for at least one year. A solid state mass memory similar to the ones designed for a small station on planet Mars (8 Gbytes) can be used inside the cylinder. In the second case, an "universal" installer must be designed. It is connected either to a classical cable or to a mixed cable with optical fiber and copper wire. The extremity of the cable is connected to the installer which includes standard submarine lights and video camera in order to select convenient site for installation and to recover GEODIS by the end of the experiment. A simple device enabling the communication between the installer and the station will be implemented, to check from the vessel, the quality of the installation and the good health of GEODIS. The same device can be used during the recovery for correctly stopping all cycles and to lock the different moving pieces of the seismometer.

The choice between these two options is only dictated by the cost. The second option is more expensive but should ensure a high reliability for the installation. The installer can be even improved by adding a digger to bury or semi-bury the sphere of the seismometer.

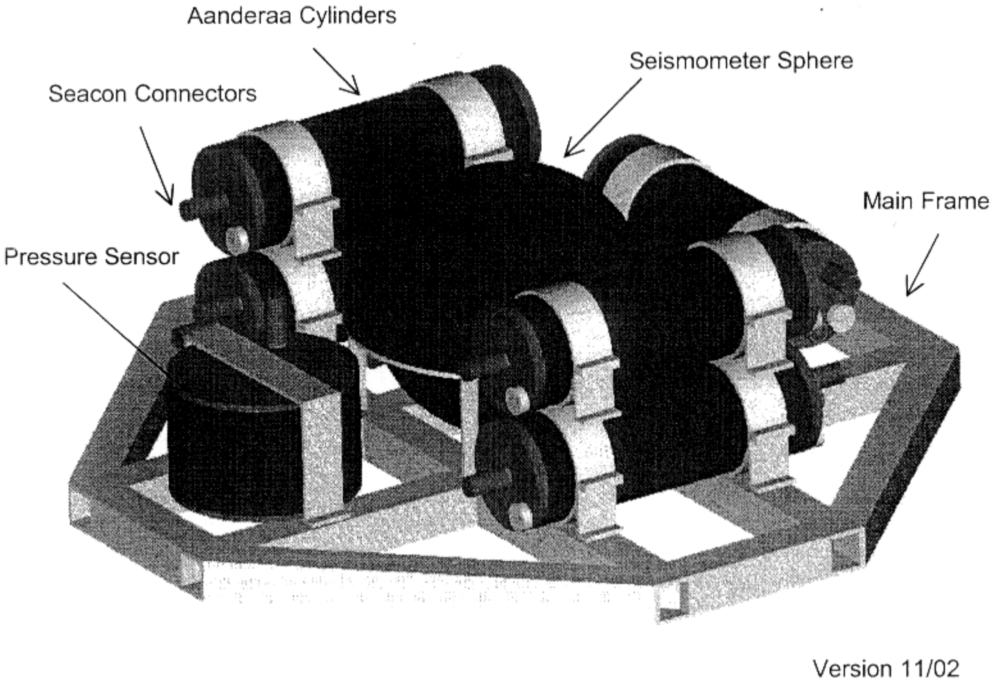


Figure 5. GEODIS: GEOphysical DIving Saucer designed by the Technical Team of OFM.

### 3.2. The sensor

The present technology does not make it possible the use a very broad band seismometer for automatic or robotics installation, required for the deployment of seismometers in hostile environments, such as ocean bottom, boreholes and comparable hot environments, cold locations such as Antarctica or on the surface of the other telluric planets of the solar system. Less sensitive seismometers, like the STS2 or CMG3 are then used, even if the noise is comparable or even less than levels recorded in the seismic vault. An improvement of the global network VBB instruments, for both the sensitivity, the miniaturisation and the automatic installation capability is then highly desirable. This improvement will be reached by the development of a new VBB 3-axis instrument in France, derived from the prototype presently designed for future planetary missions.

This type of seismometer is the second generation of a space-qualified seismometer after the OPTIMISM seismometer, which was onboard the two Small Surface Station of the Russian mission MARS96, launched in November 1996 but which unfortunately failed and was swallowed up by the South Pacific Ocean. Both sensors were designed to survive to high g load (up to 350 gram during 10 ms, where gram is the amplitude of the gravity field). The seismometer which will equip GEODIS is the terrestrial simplified version of the SEIS-NL seismometer developed to monitor the Martian seismic activity within the framework of the NETLANDER mission [21] planned for 2005. It is under development through a CNES R&T Program and its terrestrial version could be developed by the SODERN company in cooperation with IPG in Paris (Fig. 6).

The external part of the package is efficiently thermally insulated. Optional equipment, composed of a thermal/ current shield and an inclinometer will be available to reduce installation cost.

Cost issues will, however, forbid the use of such ultra-sensitive sensors for very dense portable networks. Moreover, and even if field tests have proved the possibility of reaching very low noise levels for surface installations [23], the micro-seismic noise of the seismometers deployed on the surface installation or in small holes is generally one order of magnitude greater and allows, without strong loss, the use of more noisy but much cheaper, miniaturised seismometers.

Such instruments will probably allow the development of seismic stations based either on a "bury and forget" philosophy or a "drop and forget" philosophy. The "bury and forget" philosophy may be used after a major earthquake in order to rapidly deploy thousands of sensors on a regional scale and for an operation time of a few weeks. The "drop and forget" strategy makes it possible to deploy seismic stations from the sea surface, by mini-penetrators, developed by Gekó-Prakla company for their internal use, able to penetrate the ground for a better seismic coupling.

### 3.3. Scientific targets: plumes, seismogenic zones

The scientific targets of such broad band ocean bottom portable arrays are numerous. Most of the active processes in the Earth take place below oceans or at the boundary between oceans and continents. The manifestations of these active processes can induce catastrophic events,

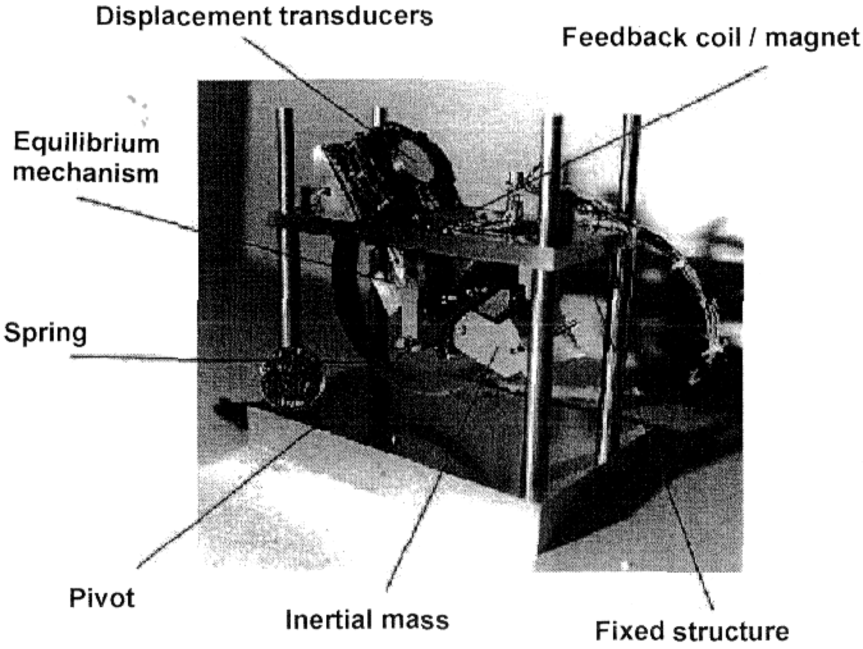


Figure 6. Very-broad band (UBB) seismometer, designed for future Martian missions [24].

in terms of strong earthquakes or volcanic eruptions. Generally, they are related to large scale material flow in the mantle, such as either upwellings, downwellings or even differential flows on both sides of a transform fault (North Anatolian fault, San Andreas fault, for example). In subduction zones, the installation of seismic stations on the oceanic side might enable us to understand the interaction of the subducting plate with the overlying plate, the role of fluids, and the processes involved in the digestion of sediments and oceanic crust. The most advanced projects are those of the Japanese, where a few ocean bottom stations connected to the seashore by cables, are already operating. Such a project exists as well in France where it is devoted to the investigation of the structure of the Antilles Arc, in order to understand the relationship between the seismogenic zone and the volcanic belt. The recent earthquake in Turkey (Aug. 18, 1999) draws attention on the part of North Anatolian fault located below the Marmara Sea, just to the south of Istanbul, where the next damaging seismic event might occur in the next 20 years [25].

As for the upwellings, their surface manifestations, mid-ocean ridges and plumes, are usually less dramatic, but their structure is not well understood. Plumes are probably the most mysterious geological objects. Their origin at depth (asthenosphere, transition zone between

400 and 1000 km, D-layer) is still debated. Their geodynamic role in the opening of ridges, in plate reorganization, and in biological crises is probably the most exciting scientific issue for the next decade. Several ongoing initiatives in Europe propose to address these issues. A project named MAGIA (Multiscale Approach of Geohazards Investigation in Azores) is going to be proposed to the European Community. The proposal, foreseing the coordination of CGUL (Lisbon, Portugal) and the involvement of French, German, Italian and Spanish groups, proposes a multiscale approach in order to find the origin at depth of the Azores plume, to understand its interaction with the mid-Atlantic ridge and the associated geohazards. Figure 7 presents the area of investigation where a regional broadband network on the seafloor and in islands will be complemented by dense, classical OBS deployments along lines. These two scales of study should enable us to relate the regional scale heterogeneities (larger than 50 km) to short scale heterogeneities (smaller than 50 km). At an even smaller scale, some seismic reflection experiments should shed some light on the crustal

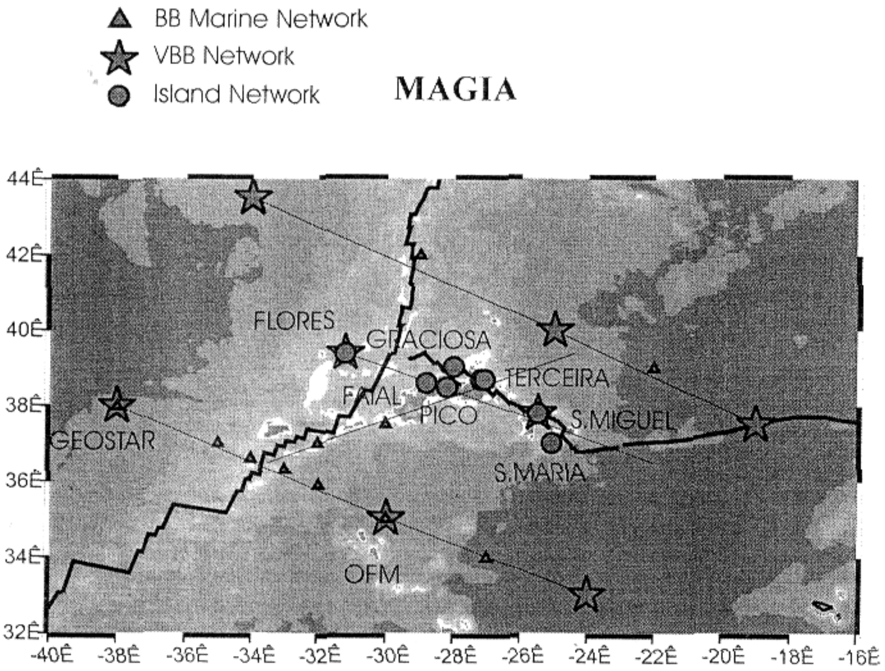


Figure 7. The MAGIA experiment (Multiscale Approach of Geohazards Investigation in Azores) is an European project involving CGUL (Lisbon, Portugal), and several institutions in France, Germany, Italy and Spain.

structure between Azores and the Mid-Atlantic Ridge. All these projects will be coordinated under a larger umbrella, the project Monitoring of the Mid-Atlantic Ridge (MOMAR).

Another ambitious program devoted only to the investigation of oceanic plume was launched in 2000, under the intiative of GEOMAR (Kiel, Germany), IPG (Paris, France) and the University of Cambridge (UK). In order to solve its scientific objectives, the Plume Oceanic Project plans to develop a network of 100 broad band ocean bottom stations. A first target might be the La Reunion Plume in the Indian Ocean.

## 4. DISCUSSION: LONG-TERM OBSERVATORIES VERSUS TEMPORARY STATIONS

The technological issues regarding long-term observatories or temporary stations are quite similar. However, the technological developments are largely dependent on the period of operation of the station: a long-term geophysical observatory is much more difficult to maintain than a temporary ocean bottom station, due to the problems of power supply, failures and data retrieval and transmission. The scientific purposes are different as well, though complementary. Long-term observatories can be used as reference stations and as nodes for short-term experiments with a dense coverage of stations. The best solution for ensuring the long-term operation is the installation of cables. The type of installation is dependent on the distance from the sea-shore. For a short distance from the coast (less than 200 km), the cables can be laid down on the seafloor between the station and the sea-shore. But, for large distance (more than 200 km), the solution consists in installing a moored buoy, connected through a vertical cable. The cable ensures the link between the surface buoy at the sea surface and the sea floor. The only way to operate on a continuous and long-term basis is an ocean floor observatory, to collect and teletransmit data in real-time. Power can be provided by solar panels, diesel generators or windmills.

### 4.1. General strategy

In spite of many advances performed by American, Japanese and French groups, many technical problems are still pending. Due to the high cost of GOBO, the ongoing plan consists of trying to associate different geophysical communities interested in long-term ocean bottom observations. Such a coherent strategy should enable scientists from different fields to develop a synergy by coordinating their efforts. A GOBO must be able to address several scientific issues at a global scale, fulfill different scientific constraints and will need several sensors, which must be independent in order to constitute a scientific module. The concept of modular observatory provides a large degree of freedom to the different scientific groups in the design of their specific sensor and should make the maintenance of the system easier. The notion of standardization is also intimately associated with the concept of independent modules. The different scientific modules have to be connected to a central module by standard connectors.

The central common module is the brain and the heart of the GOBO. The whole observatory is organized around it. It is composed of several units, having different functions and providing different facilities, power supply, data storage systems, sending commands to each dedicated module, communication with the outer world through a cable connected to a buoy on the surface and teletransmission to data centers. The cable between the ocean floor and the surface, makes it possible to provide data on a timely basis and eventually to send orders to the different modules from a vessel. From a technical point of view, the observatory shares common modules (power, dataloggers, recording systems, transmission of data), which should be very versatile and are almost independent of any kind of scientific needs. A first step should be achieved in GEOSTAR-2 project where messengers with Gbytes of data can be automatically released and recovered on a regular basis from bottom station up to the sea surface.

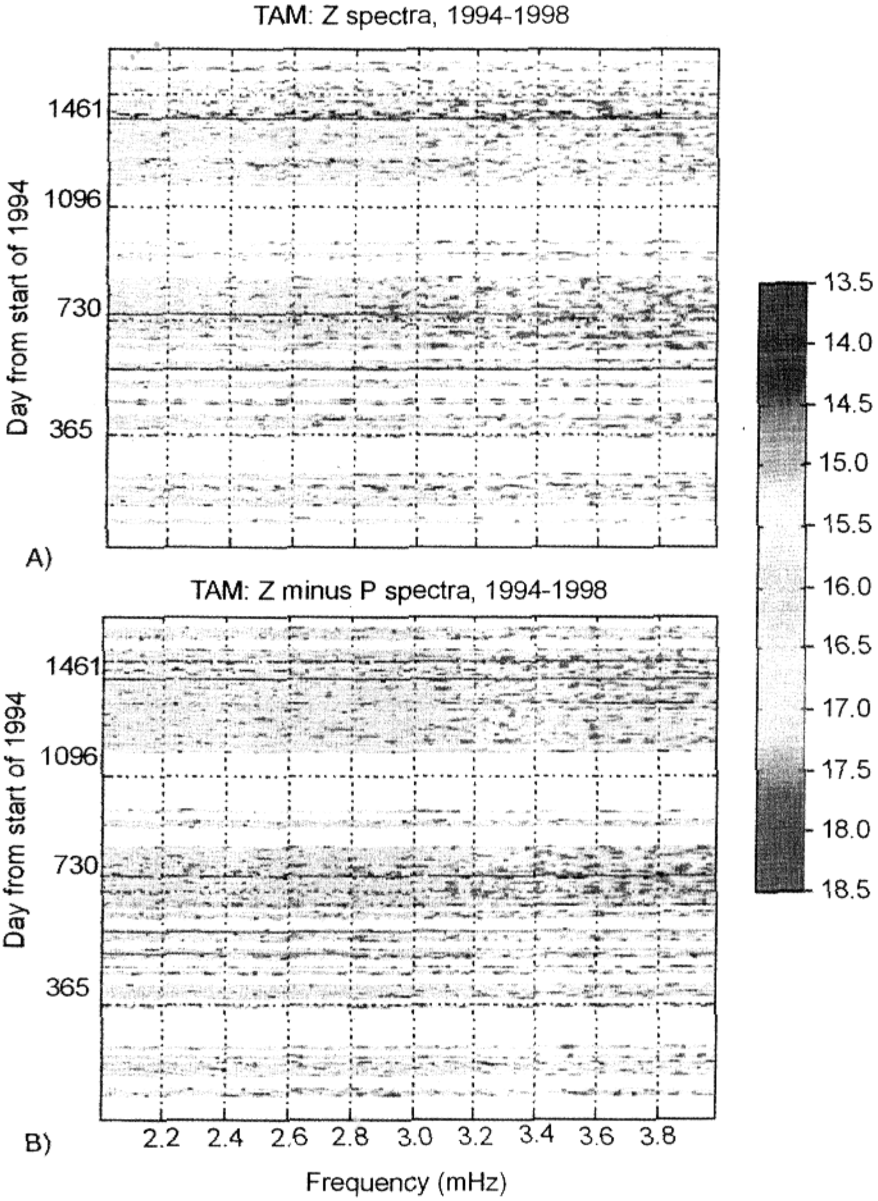
Therefore, the design of a GOBO must follow the basic philosophy presented previously of multidisciplinarity and modularity. We detail in the next section, what might be the scientific interest of multiparameter stations. Such a philosophy is not necessarily the best one for temporary deployments. The multiparameter concept tends to make the design of the station, its installation (use of manned submersible, ROV or AUV) and its recovery during sea campaigns more complex. Thus, it tends to multiply the causes of failures. In order to reduce the cost of a large number of non-permanent stations, we can accept a degree of reliability smaller than for permanent observatories. Therefore, it is likely that for portable ocean bottom arrays, each station must be dedicated to one sensor, seismic or electromagnetic.

However, the recording of environmental parameters such as pressure, temperature and currents are highly desirable.

### 4.2. Multiparameter stations

Since the beginning of the nineties, the concept of multiparameter stations is emerging. Firstly, it enables us to improve the signal-to-noise ratio of signal or equivalently to separate the signal due to seismic waves and the signal due to the fluids envelopes of the Earth (ocean and atmosphere). Secondly, the purpose is, in a sense, more empirical and regards the investigation of correlations between independent physical parameters relevant to a complex scientific problem (earthquake prediction and more generally active processes). For example, the multiparameter observations around Corinth Gulf show a nice correlation on land between seismic anisotropy and magnetic anisotropy [26]. Thirdly, it allows us purpose is to realize economies of scale by allowing sensors required by disciplines to use the same power source, recording and data transmission systems and to simplify operations and maintenance organization.

For the first kind of application, some progress has been made and some preliminary results were obtained in the GEOSCOPE station of SSB (Saint-Sauveur-en-Badole, France) and TAM (Tamanrasset, Algeria). Since 1989, microbarometers were installed in SSB, where two sets of STS1 seismometers [27] were present. The complete design of the experiment is presented in Beauduin et al. [3]. It is observed that microbarometric pressure is correlated with the horizontal acceleration component signals of seismic noise. The vertical component



TAM: Z spectra, 1994-1998

TAM: Z minus P spectra, 1994-1998

Figure 8. Excitation of normal modes in the absence of earthquakes. Top: before pressure correction. Bottom: after pressure correction [4].

of seismic noise is only correlated to pressure at long periods (larger than 500 s). After selecting a seismic signal without earthquakes, it is possible to calculate the transfer function between pressure and seismic noise (amplitude and phase). It is then possible to remove the effect of pressure from the seismic signal. Montagner et al. [28] present an example of such a calculation, where two earthquakes hidden in the noise are perfectly observed after correction. However, Beauduin et al. [3] show that the correlation between pressure and seismic signal is not systematic and is largely dependent upon the quality of the installation of sensors. This means that in a conventional land-based station, where there is easy access to the sensors, the simultaneous recording of pressure and seismic signal can only be an indicator of a problem in the installation.

The same kind of approach was followed by Roult and Crawford [4], who showed that it is possible to detect more clearly, free oscillations of the Earth in the absence of earthquakes by subtracting the effect of the atmospheric pressure (Fig. 8). Multicomponent seafloor instruments have also proven useful for improving the seismic signal and for determining crustal structure independent of seismic sources.

Crawford et al. [29] use autonomous seafloor packages containing a broad band seismometer and a differential pressure gauge to measure the seafloor deformation under pressure forcing by ocean waves (Fig. 9). They invert the deformation/pressure transfer function to determine crustal structure, and, in particular, to detect and quantify low shear velocity regions such as magma chambers and regions of high hydrothermal circulation.

The compliance signal is generally between 0.002 and 0.05 Hz, requiring instruments sensitive to lower frequencies than typical OBS seismometers and hydrophones.They use Lacoste-Romberg vertical gravimeters or Streckeisen STS-2 broad band seismometers as the acceleration sensor, and differential pressure gauges [30] to measure the pressure variations. These instruments have also been used to demonstrate that low-frequency seafloor seismic noise can be reduced by subtracting this "compliance" signal [31] and, in the case of a non-stable emplacement, a significant low frequency tilt noise signal can be removed from the vertical component by either precisely leveling the seismometer, or subtracting coherent horizontal noise from the vertical signal [29]. In the future, the compliance sensors will be constructed using broad band seismometers (either the STS-2 or a Guralp CMG-3) and a combined differential pressure gauge/hydrophone sampled at 50 Hz to create a truly broad band instrument sensitive to high frequency processes such as airgun shots and microearthquakes as well as low-frequency information such as seafloor compliance and teleseismic earthquake arrivals. These results demonstrate the utility of this simultaneous recording for stations installed in hostile environments (planet Mars, ocean bottom, drill holes) where it is almost impossible to check and modify the installation of seismometers on a regular basis.

The next question is: what should be an ideal standard multiparameter station and can this concept be adapted to portable stations? A multiparameter station classically includes broad band seismometers, high frequency seismometers, microbarometer, microthermometer, electromagnetic sensors, GPS receiver. According to local requirements, it should be possible to add strainmeters, gravimeters, and any kind of environmental modules and geochemical sensors. Such a philosophy was followed in the design of the GEOSTAR platform [20],

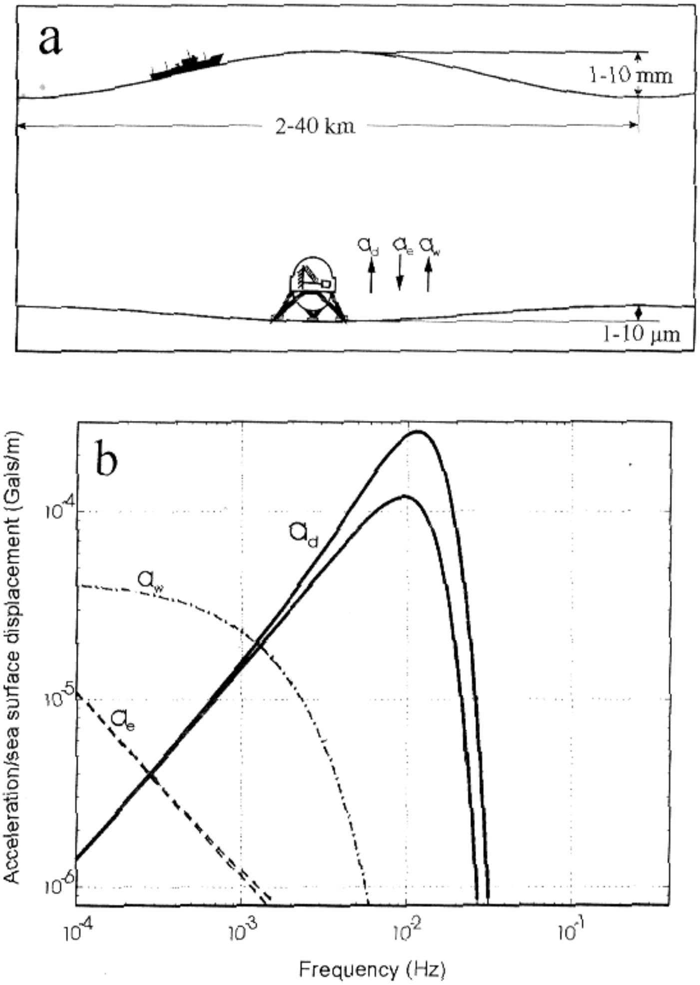


Figure 9. Compliance sensor: a) description of the experiment; b) transfer function between the acceleration and the sea surface displacement.

1998), but the limitations of such a station are its cost, its weight and its inherent complexity. It is likely that a reasonable approach might be to co-locate different dedicated stations, following the procedure used during the MOISE experiment [*11,13*].

### 4.3. Temporal scale

According to the previous discussion, the main difference between GOBOs and portable stations concerns the period of operation. An important application of long-term observatory results from the long-time series of signals. Observatories enable us to investigate the time- dependent earth processes. With the recent controversy of discovery of differential rotation of the Earth's inner core [33, 34], a time-dependent seismology is emerging. The compilation of past magnetic observations since the 18th century, has made it possible to investigate the secular variations of the magnetic field and to gain insight on the flow in the outer core at the core-mantle boundary.

Since most sensors are recording present physical fields (magnetic, seismic, gravity fields), they only provide information on the instantaneous Earth, by comparison to the geological time scale. If we want to study the time evolution of phenomena, the upper bound of the temporal scale is the human lifetime or in the best case, the history of mankind. Therefore, for time-scales larger than thousands of years, the paleosciences (e.g. paleomagnetism, geology, geochemistry) will still be necessary for providing invaluable information on the evolution of the Earth system. The future networks will only be able to save data on time-scales around a century. However, even at this time scale, there are very interesting geophysical phenomena, such as the earthquake or volcanic cycles. These examples demonstrate the necessity of installing a global network of ocean bottom observatories which will have to work on a long-term basis (several decades).

### 4.4. Multiscale approach

As advocated previously, scientific issues involve many spatial scales. The consequence of this statement is that it is necessary to investigate and relate these different scales and, therefore, to have geophysical networks at different scales. The basis of such a network based on the concept of hierarchical network or multiscale network was presented in Montagner et al. [28]. The goal of this network is to provide observations at all spatial scales, with a *uniform distribution* of sub-networks. It can be easily understood that such a perfect network leads to an exponential increase in the number of stations and is rather unrealistic. In order to solve this problem, the selection of nodes can be dictated by scientific needs and interests. The community investigating active processes, will propose to install local and mini-scale networks where active processes can provide the most valuable observations, i.e. in tectonic areas (along plate boundaries or for investigating intraplate volcanism or oceanic plumes).

As for the instruments in the stations, it is unlikely that there will be only one kind of sensors for the whole network. Since there is a direct relationship between wavelength $\lambda$ and frequency $f$, it is obvious that, as scale is decreasing, sensors must be sensitive to higher frequencies. However, due to technological progress, the number of instruments might be quite limited (two or three types of sensors). For example, in seismology, broad band seismometers can cover the frequency range 0.001~80 Hz and industrial short period seismometers can span higher frequencies. So far, there are networks at all scales, but the important point regards the coordination of the different networks, which have to share the same philosophy on the standardization of sensors, data format (such as SEED format) and data distribution. The complete coverage of the global scale is presently ongoing with the extension of the global network of the FDSN towards the ocean thanks to ION. This global network should enable us to investigate the structure of the whole Earth down to scales around 1000 km. The scales between 10 km up to 1000 km can be investigated by portable broad band seismic networks which are exist for emerged lands and under development for oceanic areas.

## 5. CONCLUSION

The networks which are presently under development, must be considered as the instrument of the whole geoscience community. The design of the future network will have to present an even distribution of stations at all scales and to make the whole dataset available on a timely basis. It includes not only the sensor but the complete chain, from the acquisition to data storage and distribution. This whole chain has to be designed in a coherent manner, in order to save time and money. If the geoscience community agrees on this concept of hierarchical (or equivalently multiscale) network, a global strategy must be defined, and the networks at all scales have to be coordinated. The part of the world where most of the scales are poorly investigated is the ocean. The priority in the next years might be to achieve the global scale coverage of the Earth and the development of portable ocean-bottom array with at least 100 stations. The efforts necessary to achieve such a multiscale network represent a formidable technological challenge for the next decade.

## ACKNOWLEDGMENTS

This work was partly supported by INSU-OFM (1999), Seismological Laboratory, URA/CNRS 7580, Institut de Physique du Globe, Paris.

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