# THE GOATS JOINT RESEARCH PROJECT: UNDERWATER VEHICLE NETWORKS FOR ACOUSTIC AND OCEANOGRAPHIC MEASUREMENTS IN THE LITTORAL OCEAN

EDOARDO BOVIO
Acoustics Department
SACLANT Undersea Research Centre
Viale San Bartolomeo 400
19138 La Spezia
Italy


HENRIK SCHMIDT
Department of Ocean Engineering
Massachusett Institute of Technology
Cambridge
MA 02139
USA

**Abstract**

*Recent progress in underwater robotics and acoustic communication has led to the development of a new paradigm in ocean science and technology, the Autonomous Ocean Sampling Network (AOSN). AOSN consists of a network of fixed moorings and/or autonomous underwater vehicles (AUV) tied together by state-of-the-art acoustic communication technology. The Generic Oceanographic Array Technology Systems (GOATS) Joint Research Project (1998 - 2001) developed AOSN technology specifically directed toward Rapid Environmental Assessment (REA) and Mine Counter Measures (MCM) in coastal environments.*

*The research project combined theory and modelling of the 3-D environmental acoustics with experiments involving a prototype underwater vehicle network managed remotely by a surface platform, including moored sources and arrays, AUVs equipped with a variety of acoustic and environmental sensors, and reliable navigation and communication systems. To explore the utility of environmental forecasts of the coastal ocean for AUV mission planning, the information derived from the network sensors was assimilated with nested ocean modelling, consistently coupling basin scale oceanography with small scale ocean processes.*

*The paper summarizes the work performed and refers to the scientific publications derived from the GOATS JRP.*

## 1. Introduction

Recent progress in underwater robotics and acoustic communication has led to the development of a new paradigm in ocean science and technology, the Autonomous Ocean Sampling Network (AOSN) [1] [2] [3]. AOSN consists of a network of fixed moorings and/or autonomous underwater vehicles (AUV) linked by state-of-the-art acoustic communication technology.

In 1998 MIT and SACLANTCEN initiated a four years Joint Research Project (JRP), designated GOATS (Generic Oceanographic Array Technology Systems), for the development of environmentally adaptive AOSN technology applicable to Mine Counter

Measures (MCM) in coastal environments. The work combined theory and modelling of the 3-D environmental acoustics with three experiments (1998, 1999, 2000) involving AOSN and sensor technology.

The objective of the 98 sea trial was to use acoustic arrays deployed on the sea floor or mounted on an AUV to characterize the spatial and temporal characteristics of the 3-D scattering from seabed targets and the associated reverberation, including the effects of multipaths. This effort was aimed at establishing the environmental acoustics foundation for future sonar concepts exploring 3-D acoustic signatures for combined detection and classification of proud and buried targets in very shallow water. The work was done in cooperation with SACLANTCEN projects 031-6 (Remote large area search in coastal waters), 031-1 (Detection of buried mines) and 031-2 (Temporal classification of mines).

The GOATS'98 experiment provided a unique data set of three dimensional scattering and reverberation in shallow water, which has been essential for model validation and identification of features of the 3D acoustic field. In addition, the experiment showed that small and inexpensive AUVs such as the MIT *Odyssey* can be reliably deployed, operated and recovered in shallow water from a surface vessel. It was also demonstrated that AUVs are an excellent acoustic platform for new sonar concepts for littoral MCM [4] [5] [6].

Following the success of the GOATS 98 experiment, SACLANTCEN organized a workshop in January 99 [7] to extend the scope of the Joint Research Project to Rapid Environmental Assessment (REA) applications and to plan the sea trials. The goal was to exploit the adaptive sampling capabilities of the AOSN concept: the network can be designed to react to sensor responses. Thus, for example, REA surveys are optimized by adaptively concentrating the measurements in regions where rapid environmental changes are detected, and AUVs carrying MCM sonar can be programmed to change their survey patterns to optimize the classification of detected targets. By implementing the REA sensors directly into the MCM sonar platforms, or in the same network, the development of new environmentally adaptive sonar concepts becomes a realistic possibility.

Shortly after the workshop, the Office of Naval Research proposed to add an oceanographic component to the GOATS 2000 experiment in support of the Multi-Scale Environmental Assessment Network Studies (MEANS) [8] [9]. The final objective was to test the effectiveness of nested models for the real time forecast of the physical parameters (current speed and direction, wave height) that influence AUV operations in the littoral environment.

In addition, it was also decided to assess the performance of non traditional AUV navigation algorithms based on *a priori* knowledge of the bottom topography. This required a thorough survey [10] of Procchio bay, Island of Elba, the site of the GOATS 2000 experiment. Traditional instruments (side scan sonar, sub bottom profiler, multibeam echo sounder, underwater video camera, expandable penetrometer) were deployed from *Manning* and sea floor samples collected. The data were included in the SACLANTCEN geographical data base and provided a rich data set that characterizes the bathymery and the composition of the sea floor of the area and forms the ground truth reference for comparison with data collected subsequently by AUVs.

The interest of the international community has grown significantly since the initial days of the JRP, and several organizations asked to join the GOATS 2000 programme. MIT provided two *Odyssey* class AUVs, Florida Atlantic University (FAU) participated with their *Ocean Explorer* (OEX) vehicle, and the robotic department of the University of Montpellier (LIRMM) deployed its *Taipan* AUV for oceanographic measurements. WHOI delivered the acoustic modems to control the MIT vehicles. The Heriot Watt University contributed the SeeTrack software for the analysis of the video data collected by the OEX. FFI and NRLSC collected data to validate their bathymetric navigation algorithms. Finally a team of modellers

from the universities of Harvard, Colorado and SACLANTCEN developed and ran the oceanographic models to predict in real time the local conditions in Procchio Bay during the sea trial.

The GOATS 2000 experiment was conducted in September-October 2000: the REA component was in support of SACLANTCEN projects 01-B (Rapid environmental assessment of operational acoustic parameters) and 03-D (Environmental impact on MCM sonar design and performance), the MCM component was in support of project 03-G (Advanced mine hunting sonar for AUVs). MEANS was performed in cooperation with project 01-A (Rapid assessment of operational ocean parameters). An initial report was provided by the wash up meeting held at SACLANTCEN in January 2001 [11].

The scope of this paper is to describe the components of the GOATS AOSN, summarize the objectives and achievements of the experiments conducted in 1998, 1999 and 2000, referring to the scientific publications derived from the GOATS Joint Research Project.


## 2. Components of the GOATS AOSN

The GOATS prototype observational network is based on the *Odyssey* class vehicles developed by MIT, the *Ocean Explorer* developed by Florida Atlantic University, the *Taipan* AUV developed by LIRMM, the SEPTR profilers, Tower and Rail facility developed by SACLANTCEN. The vehicles and instruments were deployed from R/V *Alliance* and Workboat *Manning*.

The *Odyssey* II class autonomous underwater vehicles were chosen as the mobile sensor platform for the GOATS JRP because of their flexible architecture and proven performance. A substantial fraction of the vehicle is dedicated to wet volume, which allows support of a wide range of payload systems including CTD, ADCP/DVL, ADV, side-scan sonar, USBL tracking, OBS and video. The core vehicle has a depth rating of 6,000 m, weighs 120 kg, and measures 2.2 m in length and 0.6 m in diameter. It cruises at approximately 1.5 m/s with endurance of 3-12 hours, depending on the battery installed and the load. Included in the core vehicle are the guidance and navigation sensors necessary to support autonomous control: attitude and heading, pressure, altimeter, and LBL acoustic navigation. *Odyssey* is controlled using a behaviour-based layered architecture that allows complicated adaptive missions such as bottom following surveys, or tracking isothermal contours, while maintaining overriding safety procedures such as keeping a minimum distance from shore or avoiding obstacles. Various configurations of the *Odyssey* were used during the GOATS experiments [4] [12].

The OEX [13] is a modular vehicle, featuring a PC-104 Pentium executing the supervisory control structure, interfaced to a distributed communication and control network based on the open LONTalk network protocol, a modular power system and a modular payload capability. The modular design results in a field reconfigurable vehicle, well suited to experimental work. The vehicle consists of an aft propulsion/control/navigation section, a payload section and a forward nose cone. Located in the aft section are the propulsion engine, the control surface motors, the navigation sensors, the control computer, the RF and acoustic communication systems, and the battery packs. The navigation relies on a standard suite of sensors (tri-axial flux gate compass, precision rate gyros and accelerometers, Doppler Velocity Logger) that provide both relative and geodetic positional information. The modular design facilitates the inclusion of a variety of geodetic navigational instruments including a DGPS, long baseline (LBL), and ultra-short base line (USBL) acoustic tracking systems. The payload section contains the mission sensors and is attached to the aft portion by a bayonet mechanism that allows for quick payload changes. Elements in the payload are simply additional nodes on the LONTalk network and are integrated with the tail section with a

power conductor and a control line. The nose section contains a video camera, a flashing strobe, the emergency drop weight and the vehicle recovery line device. The depth rating of the vehicle is 300 m and its endurance with standard batteries is 50 km at 3 kn. During operations OEX can be tracked acoustically *via* USBL and communicate *via* the acoustic modem.

The *Taipan* is a small, low cost AUV developed by LIRMM [14], 1.8 m long, 15 cm diameter, weighing about 30 kg. The hull is watertight and trimmed a few hundred grammes positive. The aluminium interface between the nose and the main carbon fibre body holds the bow diving plane (actuated by a servomotor), the pressure sensor, the UHF and GPS antennas, the penetrator for CTD sensor cable, and the underwater connector used to connect the onboard electronics with the outside. *Taipan's* sensor suite comprises an electronic compass module including a three-axis magnetometer and a two-axis inclinometer provides roll, pitch, and yaw measurements. The position of the vehicle at the surface can be determined by GPS. The cruise speed is about 1.8 m/s (3.5 knots).

A **S**hallow-water **E**nvironmental **P**rofiler in **T**rawl-safe, **R**eal-time configuration (SEPTR) [15] was developed at SACLANTCEN in support of oceanographic modelling and rapid environment assessment programmes. SEPTR is intended for extended duration deployment in areas where water column instruments are at risk from fishing trawling, but with real-time data return and control *via* cellular or satellite communication. It consists of a trawl-safe bottom platform, which houses an Acoustic Doppler Current Profiler (ADCP), wave/tide gauge, ambient noise sensor array, and water column profiler buoy. The profiler buoy and associated winch are designed for autonomous vertical profiling of CTD and optical properties of the water column in depths down to 100m. The profiler buoy includes DGPS navigation and two-way communication while on the surface. It also includes acceleration and magnetic field sensors surface wave buoy measurements.

To allow broad band, low frequency (2-15 kHz) target and seabed insonification at a wide range of incident angles, covering the sub- and super-critical regimes, the TOPAS parametric transmitter was mounted on a telescopic tower on a 24 m linear rail deployed on the bottom [16]. The tower position was precisely controlled using an electric motor, operated remotely from a shore laboratory. The TOPAS transmitter was mounted in a pan-and-tilt assembly with a motion reference unit (MRU) so that arbitrary transmission directions could be precisely controlled. During GOATS'98, the scattering of TOPAS signals from targets and sea bed was detected by several arrays: a 16 hydrophone array mounted vertically on the tower, a 128 hydrophone horizontal array deployed at 5 m depth in various configurations relative to the target field, an array of hydrophones buried in the sediment near the targets, and an 8 element array mounted on the nose of the *Odyssey*. During GOATS 2000 only the AUV array was used.


## 3. GOATS'98


The main objective of the GOATS 98 experiment was to study the 3D scattering of targets buried in the sea floor. Measurements were acquired by the shore laboratory independently or in coordination with the *Odyssey*. The AUV was operated from the *Alliance*, anchored approximately 600 m from the target area (Fig. 1). A typical mission took the AUV from the *Alliance* to the target area at a speed of 3 kn. In the target area, the AUV made several passes at less than 2 kn over the targets and received *via* the nose array the signals scattered by the sea floor and the targets insonified by the TOPAS. When the survey pattern was complete, the AUV returned to the *Alliance*. After surfacing approximately 100m from the *Alliance*, the AUV was towed back by the work-boat and hoisted onto the deck, where it was connected to the computer network to upload data from the navigation computer and the acoustic

acquisition system. The AUV navigation data were processed in order to verify the completion of the mission plan, and for parsing of the reduced navigation data with the acoustic data. Thirty-nine AUV missions were launched and completed, totalling 14 hours of submerged operations. The performance of the AUV was completely reliable, and no serious hardware problems were encountered. The control algorithms developed at MIT were capable of repeatedly performing the desired survey patterns in the target area with a navigation accuracy of a few metres using the LBL acoustic net deployed in the area. A detailed description of the sea trial is found in [4].
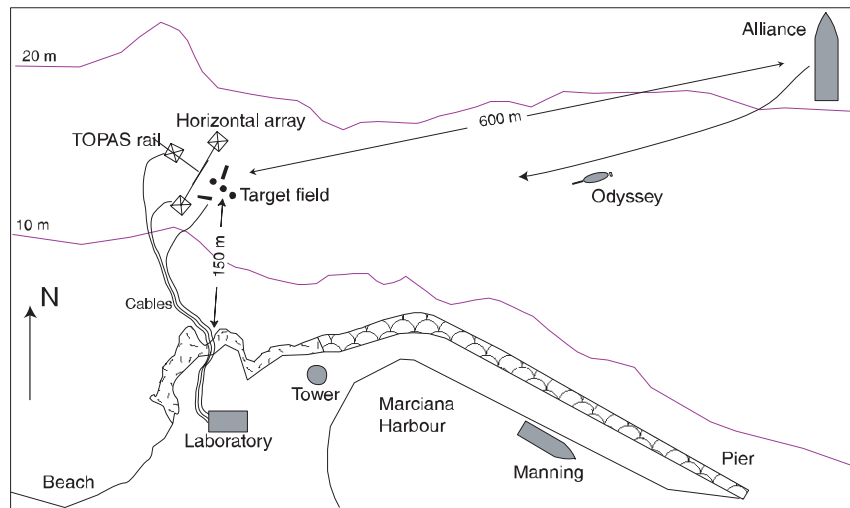


**Figure 1** *Schematic (not to scale) of GOATS'98 operational scenario at Marciana Marina, Island of Elba. Workboat Manning deployed the TOPAS sound source facility and the fixed arrays near the target area. A shore laboratory controlled the TOPAS sound source and recorded data from a 16-element vertical array, a 128-element horizontal line array, and a buried hydrophone array. Alliance anchored offshore was used as a platform for the AUV operation and data processing centre.*

The GOATS'98 experiment combined efforts of several groups at SACLANTCEN and MIT to provide a comprehensive dataset for addressing a wide range of fundamental scientific issues regarding bottom-interacting MCM acoustics. Spherical and cylindrical targets were deployed at different burial depths in a sandy seabed. The targets were insonified by a TOPAS parametric projector at both super- and sub-critical grazing angles, and the incident and scattered fields were recorded by receiver arrays, including a 16-element buried hydrophone array, a 16-element vertical line array next to the source, a 128-element horizontal line arrays suspended over the targets and an 8-element line array mounted in the nose of the MIT Odyssey IIb AUV.

Environmental data were acquired including coring for estimation of geoacoustic properties, stereo photography for roughness characterization, as well as a range of oceanographic measurements.

The comprehensive acoustic and environmental datasets acquired during the GOATS'98 experiment have proven to be extraordinarily rich and unique in terms of completeness of the supporting environmental measurements, and several scientific publications have been produced, with several more in preparation.

The first papers resulting from the experiment and the JRP described a new fundamental understanding of the physics underlying seabed penetration at sub-critical angles [17] [18], including a convincing demonstration of the dispersive nature of sandy sediment, and its

significance to bottom penetration. These two papers, by Maguer *et al.* are considered seminal by the ocean acoustics community and extensively cited.

Several papers deal with the processing of the bistatic synthetic aperture data acquired by the AUV, demonstrating the concept of bistatic SAS autofocusing and imaging [19] [20] [21]. The GOATS'98 dataset is unique in terms of full bandwidth SAS data.

The comprehensiveness of the receiver array configurations has lead to new understanding of the fundamental physics of interaction of sound with buried targets, above and below the critical angle for the seabed [22] [23]. The analysis is continuing.

The JRP has lead to several new developments in regard to modelling of acoustic interaction with the seabed. Specifically a unique modelling capability has been developed, providing a consistent prediction of 3-D scattering from seabed roughness and volume inhomogeneities, validated by the GOATS datasets [22] [23] [24] [25] [26] [27].

## 4. GOATS'99

The aim of this experiment in October 1999 was to provide preliminary environmental information on the area designated for the GOATS 2000 experiment. As accurate geo referencing is the pre-requisite for effective multi-sensor sea floor classification, a more specific technological goal was to test joint side scan sonar/multibeam survey methodologies and improve the SACLANTCEN geo-referencing standards. The *Edgetech* DF1000 SSS and the *Simrad* EM 3000 Multibeam were the main systems used. Procchio Bay was surveyed with the low frequency SSS and the inner Biodola and Viticcio bays were also surveyed at high frequency, with track spacing optimized for side scan sonar and multibeam ranges. Navigation was based on the Kinematic DGPS system and the cable layback of the Side Scan Sonar fish was measured to evaluate the sonar position relative to the ship. The cruise provided a data set including digital terrain model of the area, tiled sonar images, supervised bottom segmentation, measurement of bottom properties and video. All data have been incorporated in the SACLANTCEN networked GIS data base available on the Internet to selected users [28]. Figure 2 shows the bathymetry of Procchio Bay obtained by the NRL Stennis Space Center from the raw EM3000 multibeam data.
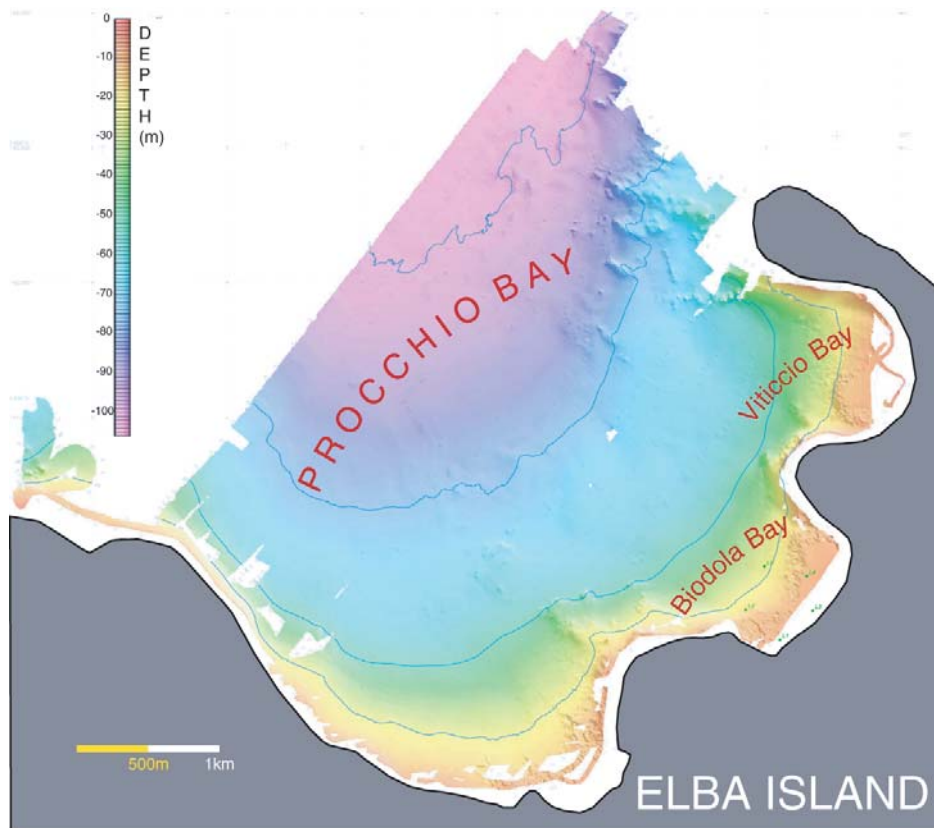
**Figure 2** *Bathymetry of Procchio Bay*

## 5. GOATS 2000

The GOATS 2000 experiment had four broad objectives [29]: REA, MCM, MEANS oceanographic modelling and data acquisition to test navigation algorithms developed by FFI [30] and by NRLSC [31] using *a priori* knowledge of the bathymetry. The final goal of this effort is to concurrently build a map of an unknown area with the vehicle and use the map to navigate the vehicle [30] [32].

### *5.1 Rapid Environmental Assessment (REA)*

The experiment demonstrated the capabilities of AUVs as REA platforms for MCM in shallow and very shallow water. The *Ocean Explorer* equipped with a colour video camera and the Edgetech dual frequency DF-1000 side-scan sonar and the *Taipan* equipped with the Applied Microsystem CTD were launched from R/V *Alliance*, to transect the bays to the east side of Procchio to acquire side-scan sonar and to measure water mass properties such as current, salinity, density and temperature, for use by the nested oceanographic models studied by MEANS (Fig 3). The side scan sonar data were used to generate geo-referenced acoustic images for comparison with ground truth data collected in the same area during previous experiments [33]. The environmental information measured by the AUVs was fused in the SACLANTCEN GIS database [28] [34] [35]. The tiled side scan sonar images were processed with unsupervised segmentation algorithms [33] [36] that demonstrated the capability to distinguish in a quantitative way between different types of sea beds. The video

images collected by the OEX were organized in a geographical database using the SeeTrack software [37].
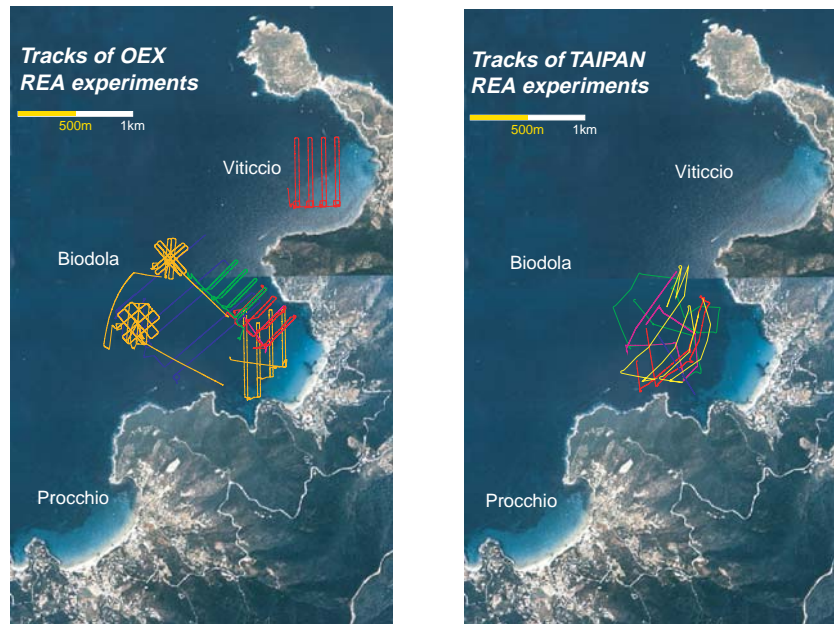


**Figure 3** *The Ocean Explorer, equipped with sidescan sonar and video camera, and the TAIPAN, equipped with a CTD sensor, performed several REA experiments in Biodola and Viticcio bays.*

### 5.2 Mine Counter Measures (MCM)

The rippled field and a field of proud and buried targets (Fig 4) at the main test site in Biodola Bay was insonified by the *TOPAS* parametric sound source mounted on the SACLANTCEN tower at a variety of incident and aspect angles. The acoustic MIT AUV sampled 3-D reverberation and target echoes using survey patterns similar to those used in GOATS'98, obtaining data for validation of numerical models of mono- and bi-static seabed reverberation [19] [23]. A second field of proud targets including exercise mines such as the *MP80, Manta* and *Rockan*, was imaged at different aspects by the *OEX* instrumented with the 390 kHz Edgetech side scan sonar. The experiment demonstrated the potential of high frequency side scan sonar at multiple aspects for classification of proud targets [38] [39].
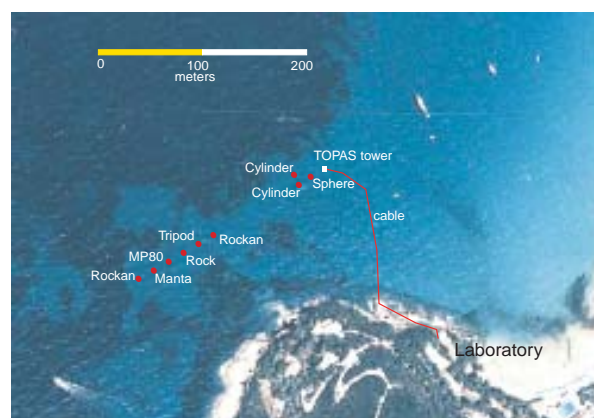


**Figure 4** *The location of the two mine fields used for the MCM experiment. The Odyssey AUV operated close to the TOPAS tower, the OEX surveyed the mine field on the left.*

## 5.3 Multiscale Environmental Assessment Network Studies (MEANS)

A nested modelling and assimilation capability was provided by the Universities of Harvard and Colorado and SACLANTCEN [40] [41]. A local model at 20 km scale, covering the north shore of Elba and Procchio Bay was nested within a 200 km scale model covering the Ligurian sea. At the basin scale these models were nested within the NAVO Mediterranean sea model (Fig 5). Environmental data acquired by the SEPTR buoy and AUVs in Procchio Bay were assimilated into the local model providing a now-casting and forecasting capability for the experimental area. On the regional scale, the environmental sampling was performed by R/V *Alliance* at night and data were exchanged *via* Internet [42]. The basin-scale NAVO Mediterranean Sea model was constrained by satellite remote sensing data [43] including surface temperature and altimetry. An optimized AUV mission planning that takes in account the current conditions forecasted by the oceanographic models has been developed by [44].
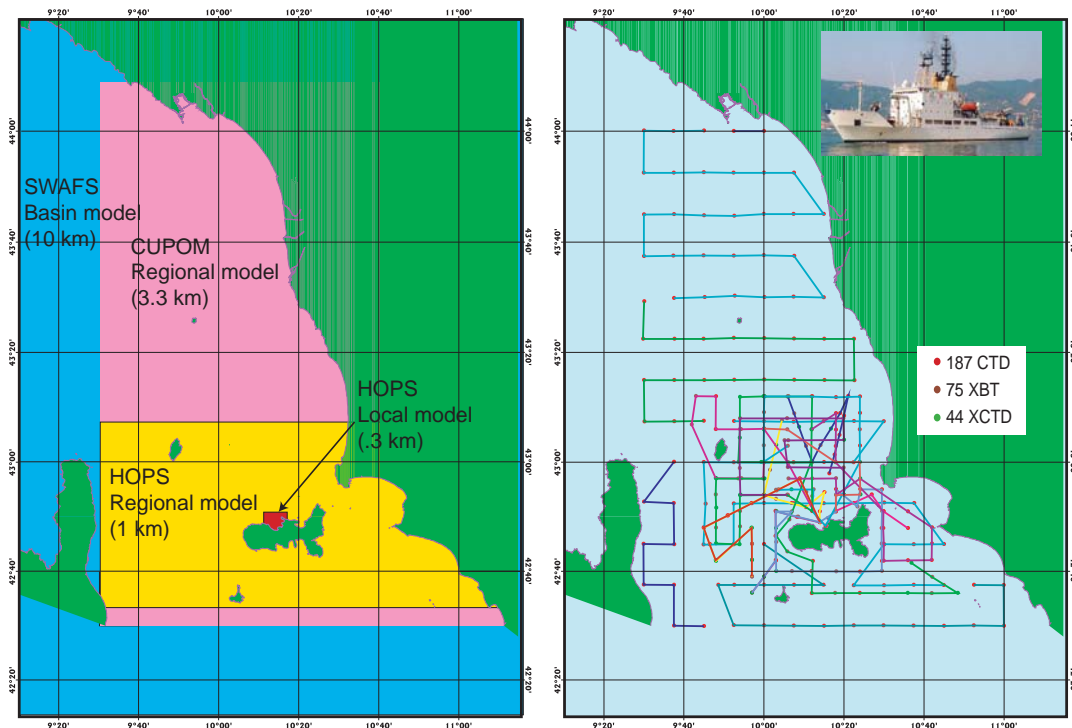


**Figure 5** *On the left are shown the predefined model domains for the MEANS experiment. On the right the location and type of oceanographic measurements performed by Alliance during GOATS*

## 6. Conclusions

The GOATS JRP was a demonstrable success in many different ways.

It was shown that SACLANTCEN is particularly suited to host complex multi-disciplinary and multi-national experiments: the engineering facilities, the availability of R/V *Alliance* and *Manning* and the wide scientific expertise at the Centre, allowed rapid integration of innovative ideas and technologies from different countries, to demonstrate the effectiveness of autonomous underwater vehicles as platforms for military and scientific applications. The scope of the work has been broad ranging from basic research such as the fundamental understanding of multistatic scattering from proud and buried targets, to prototype development such as the SeeTrack software.

The intermediate results and the video of the experiments have been shown in numerous NATO conferences and have contributed to raise the awareness of nations and military commands regarding the potential applications of the AOSN technology. The growing interest by the NATO community has stimulated numerous military and civilian visitors to witness the 2000 experiment from R/V *Alliance* and *Manning*.

The GOATS JRP also demonstrated the effectiveness of the Virtual Laboratory concept: scientists from many different nations and organizations worked for a period of four years exchanging ideas, acquiring and analyzing data and documenting their work, using mainly the Internet and the communication facilities available at the Centre and on R/V *Alliance*. During the 2000 trial, modellers located at SACLANTCEN, Harvard and Colorado Universities, interacted in real time with the scientific crew of R/V *Alliance*, to implement a truly adaptive oceanographic sampling experiment.

The three Elba experiments allowed the acquisition of a large (and probably unique) data set that will contribute significantly to progress in several fields: 3D modelling of target and bottom scattering, sound penetration in the sea floor, traditional and non-traditional AUV navigation, nesting of oceanographic models and their applicability to AUV mission planning, automatic bottom classification and automatic detection of proud objects. The variety and the quality of the work already performed in these areas, which will continue for some years, is documented in a large number of papers already published as shown in the bibliography of this article.

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