Robotic Ocean Vehicles for Marine Science Applications: the European ASIMOV Project*

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Abstract- **The key objective of the ASIMOV project is the development and integration of advanced technological systems to achieve coordinated operation of an Autonomous Surface Craft (ASC) and an Autonomous Underwater Vehicle (AUV) while ensuring a fast communication link between the two vehicles. The ASC / AUV ensemble is being used to study the extent of shallow water hydrothermalism and to determine the patterns of community diversity at vents in the D. João de Castro (DJC) bank in the Azores.**

I. PROJECT DESCRIPTION

This paper provides an overview of the ASIMOV project, a research and development effort initiated in January 1998 under the auspices of the Commission of the European Communities, through its MAST-III Programme. The ASIMOV project puts forward the key concept of coordinated operation of an Autonomous Surface Craft (ASC) and Autonomous Underwater Vehicle (AUV) for marine data acquisition and transmission. By properly maneuvering the ASC to always remain in the vicinity of a vertical line directed along the AUV, a fast communication link can be established to transmit navigational data and high level commands from the ASC to the AUV, as well as acoustic/vision data from the AUV to the ASC, and subsequently to an end-user located on board a support ship or on shore. Fast and reliable communications and precise navigation can thus be achieved by resorting to well proven technological systems. Figure 1 depicts the main systems required for combined vehicle navigation and control and for acoustic communications between the AUV and the ASC.

To give the work greater focus, the research and development efforts are aimed at performing realistic missions at sea, near the Azores islands, to determine the extent of shallow water hydrothermalism and the patterns of community diversity at the vents in the D. João de Castro bank; see Figures 2.a and 2.b. In the desired missions, the AUV is required to maneuver close to the seabed to detect the occurrence of bubble emissions from the vents and trigger the acquisition and transmission of time / position stamped acoustic and vision data to a support ship through the vertical acoustic channel, via the ASC.

Obstacle avoidance and bubble detection rely heavily on the development of a space-stabilized sonar head with vertical and horizontal transducer elements and the associated signal processing algorithms. Programming, executing, and modifying on-line mission plans for joint ASC/AUV operation were made possible through the development of dedicated systems for joint mission and vehicle control, as well as appropriate human-machine interfaces.

Special emphasis is being placed on demonstrating all the steps that are necessary to acquire, process, manage, and disseminate data on hydrothermal activity to a wide audience of scientists, over the Internet. The reader is referred to [1] for a description of the technological challenges posed in the course of the project and for complete details on system design, development and testing at sea.

II. KEY TECHNOLOGICAL DEVELOPMENTS

II.A Vehicle and Mission Control. Sonar Data Processing

Two robotic ocean vehicles are being used in the ASIMOV project (see Figures 3.a and 3.b): the DELFIM ASC and the INFANTE AUV, designed and built by the Institute for Systems and Robotics of the IST with the collaboration of the

* Work supported by the Mast Programme of the EU under contract no. MAS3-CT97-0092.

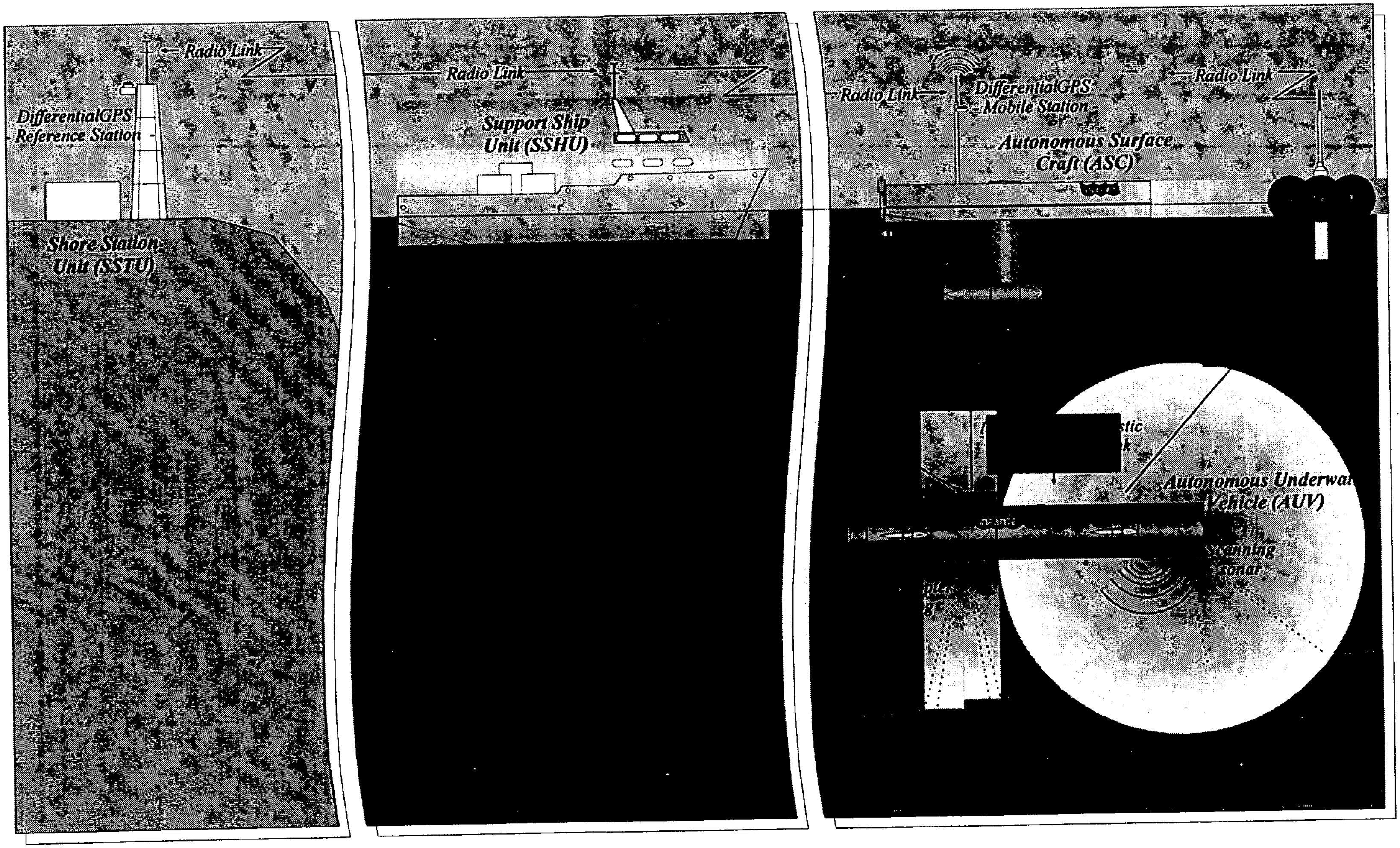


Figure 1. Coordinated Operation of the DELFIM ASC and the INFANTE AUV for scientific missions in the Azores.

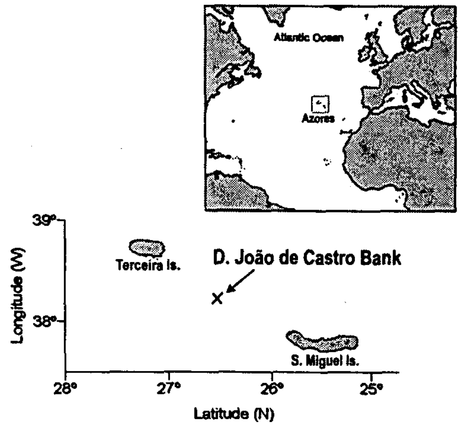


Figure 2.a The D. João de Castro bank

Portuguese companies RINAVE (Naval Engineering), Corinox (Mechanical Workshop), and Decatlo (Fiber Glass work). See [8] and [12] for complete details.

The DELFIM ASC was designed to perform automatic marine data acquisition and to serve as an acoustic relay between submerged craft and a support vessel. This enables the transmission of sonar and acoustic data via a specially developed acoustic communication channel that is optimized to transmit in the vertical. The DELFIM can also be used as a stand-alone unit, capable of maneuvering autonomously and performing precise path following (see [3]) while carrying out automatic marine and bathymetric data acquisition and transmission to an operating center installed on board a support vessel or on shore. This is in line with the current trend to develop systems to lower the costs and improve the efficiency of operation of oceanographic vessels at sea.

The DELFIM is a small Catamaran 3.5 m long and 2.0 m wide, with a mass of 320 Kg. The propulsion system consists of two propellers driven by electrical motors. The vehicle is equipped with on-board resident systems for navigation, guidance and control, as well as for mission control. Navigation is done by integrating motion sensor data obtained from an attitude reference unit, a Doppler log, and a DGPS (Differential Global Positioning System) [11]. Transmissions between the vehicle, its support vessel, the fixed GPS station and the control center installed on-shore are achieved with a radio link with a range of 80 Km. The vehicle has a wing shaped, central structure that is lowered during operations at sea. At the bottom of this structure a hydrodynamically shaped body is installed that carries all acoustic transducers, including those used to communicate with underwater craft.

The INFANTE is an Autonomous Underwater Vehicle with a maximum operating depth of 500 meters. The vehicle is a major re-design of the MARIUS AUV, developed under the MAST-I and MAST-II Programmes of the EU in the scope of two projects coordinated by IST [10]. The INFANTE is equipped with advanced systems for navigation, guidance and control, as well as mission control. Navigation is done by integrating motion sensor data obtained from an attitude reference unit, a Doppler log, and a system for underwater positioning that relies on a set of four drifting buoys equipped with GPS receivers and hydrophones to capture the acoustic signals emitted by a pinger installed on the AUV (GIB system, developed jointly by ORCA Instrumentation and ACSA, France). Position updates from the GIB system are sent to the AUV via the acoustic downlink of Figure 1. Obstacle detection and avoidance, as well as terrain following, build on the acoustic sonar system designed by System Technologies and on sophisticated algorithms for sonar based maneuvering studied by ENSIETA [2]-[7].

Underlying the concerted operation of the two vehicles is a Mission Management Center (MMC), installed on-board a support ship (and possibly on shore at a future stage), that is vital for managing all the phases of coordinated vehicle operation. The MMC hosts the computers in charge of implementing a Mission Management System (MMS) that plays a key role during the Mission Preparation phase. During this phase, an operator without detailed knowledge of the technical aspects of robotic ocean vehicles can program a desired mission in a high level language and have it translated into a mission program that will be compiled, downloaded to, and run in real time on the computers installed on-board the ASC and the AUV. During Mission Execution, the MMS enables the operator to play a very active role in assessing the state of progress of the mission and modifying mission objectives, if required, based on mission-related and field data received from the AUV through the uplink communication channel. See [4] for a description of the system under development that builds on the CORAL software programming environment for Mission Control developed by IST [9].

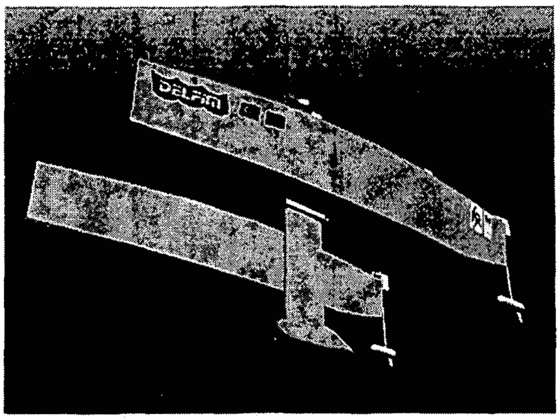


Figure 3.a The DELFIM ASC

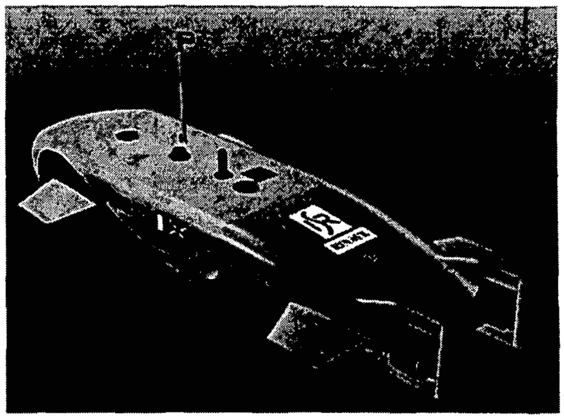


Figure 3.b The INFANTE AUV

Each vehicle hosts a kernel of a Joint ASC / AUV Mission Control System that is in charge of accepting the joint mission program provided by the Mission Management System, and scheduling and coordinating the concerted action of the two vehicles, while enabling on-line intervention from the end-user. Furthermore, each vehicle hosts a local Mission Control System that is responsible for guaranteeing the integrity of the vehicle, controlling its dynamic motion and the acquisition and transmission of scientific data, and interfacing with the respective Joint ASC / AUV Mission Control System kernel.

Central to the implementation of the above systems is the concept of viewing all the modules inside each one of the vehicles as nodes in a *local area network*. The corresponding distributed control architecture is supported on the industry standard real-time network CAN-bus and on Ethernet. Some of the nodes are devoted to relatively simple sensors and actuators, while others host powerful processors for more demanding computational tasks. The two vehicles, the support ship, and the store station are also viewed as local area network nodes in a *wide area network* that is supported on efficient air and underwater communications [1]. The development of the local and wide area networks, which is now completed, will afford engineers and scientists the means to interface their systems effortlessly and have easy access to vehicle / sensor data during operations at sea.

II.B Sonar System

The ASIMOV Sonar System (developed by System Technologies) has been designed to provide a variety of sonar services suitable for Autonomous vehicles. The Architecture of the Sonar system is based upon the use of single or multiple sonar heads that can be interfaced to the INFANTE AUV computer network. Access to any of the Sonar services is made by logging onto a Sonar Server. The server is responsible for managing and sharing sonar resources and ensuring that vehicle safety critical functions, such as Obstacle Detection, will always take priority over any other less critical function, such as gathering environmental data.

For the INFANTE AUV installation, several sonar functions may be required during a mission, for example: i) Midwater Obstacle Detection, ii) Terrain Obstacle Detection, iii) Obstacle Location, iv) Obstacle Tracking, v) Obstacle Feature Identification, vi) Point Echo Sounding, vii) Swathe Echo Sounding, viii) Sidescan Survey, ix) Sub-bottom surveys, and x) Detection of Anomalies in the Water column. This list is by no means exhaustive, but illustrates the requirement for a general purpose Sonar system design that can accommodate more that one mission function. The alternative would be to have a specialized sonar for each job. By considering the minimum amounts of data required for each function, it was decided that general-purpose sonar head's resources may be 'time shared' between more than one user. So long as the highest priority mission critical users get sufficient data at the right time, the sonar head can then be used during 'idle time' to perform lower priority activities.

A major requirement for the ASIMOV sonar was that the data should be as 'user friendly' as possible. In practice, this means that beam shapes are as accurate and as 'clean' as possible to reduce echo ambiguities. It was also considered that the sonar should be stabilized in attitude to improve data quality and usefulness to the end user.

The ASIMOV Sonar Head incorporates a stabilized transducer drive mechanism that allows the transducer to be trained over a 270 degree super-hemisphere. Figure 4 illustrates the Sonar Head mechanical arrangement. The drive mechanism has fast servoing capability to give good stabilization response and allow rapid changes of scan direction. The stabilization of the sonar requires that vehicle attitude information is made available to the sonar over its data link, or via an auxiliary communications port. The transducer has several elements that are capable of generating a variety of beams, over a range of frequencies and beam widths. The choice of which transducer element, and what data the sonar will gather at any particular time are all selectable by the users.

Figure 4. Sonar Head Schematic Design

Communications with the sonar head are conducted over a networked data link, which allows several sonar heads to be used simultaneously. This feature allows mission specific sonars to easily be integrated, and gives flexibility to an AUV supervisor to re-allocate sonar resources if redundant sensors are installed. The Sonar system has several 'potted' functions available to allow simple high level control, but is equally capable of being controlled directly by a user's own special software. The development of the ASIMOV sonar system has progressed to the point where a system has been in-water tested, and integration with higher level AUV supervisor functions is underway.

II.C Acoustic Communication System

One of the main purposes of the ASIMOV project is to demonstrate the potential applications of underwater autonomous vehicles (AUVs) in demanding scientific missions. Several factors that have so far hindered the widespread use of AUVs in practical applications can be traced back to the limited amount of data that can be exchanged in (almost) real-time between the vehicle and a mission control center using acoustic modems. Most notably, such lack of interactivity prevents end-users from assessing the unfolding of missions, and re-directing the vehicle when appropriate.

Although acoustic modems use sophisticated processing techniques to compensate for severe distortions that affect the transmitted waveforms as they propagate through dispersive underwater channels, fundamental limitations restrict the data rates that can be reliably achieved. Acoustic transmission takes place almost exclusively in the vertical in the framework of the ASIMOV project, thus providing a comparatively benign communication channel where high data rates are attainable. An Autonomous Surface Craft (ASC) moving in tandem with the AUV is the key technical component that enables vertical transmission without restricting the AUV's manoeuvrability. Besides relaying mission data to the base station through a high-speed radio link, the ASC also provides navigational data to the AUV.

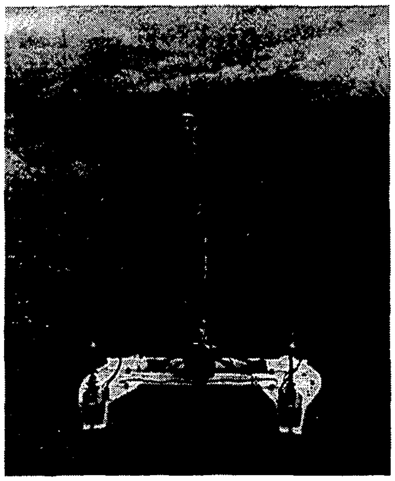
Reference [5] discusses the specifications and implementation of the INFANTE AUV/ DELFIM ASC acoustic links, and illustrates their performance under real conditions. The operating scenario contemplated in the project is a shallow water volcanic plateau near the Azores islands, where hydrothermal sources are to be automatically identified and studied. Preliminary surveys have revealed high ambient noise levels across all candidate modem operating frequencies.

Two acoustic data links are used between the AUV and ASC, as illustrated in Figure 1. A bi-directional low-speed link (up to 300 bps) using robust non-coherent modulation transmits critical data between the two vehicles. A high-speed (30000 bps) unidirectional link using M-PSK modulation is used mainly for transmission of compressed still images from the AUV to the ASC. Important design considerations involve the acoustic compatibility between the two systems, as it should be possible to transmit emergency commands to the AUV through the low-speed link even when the high-speed link is active in the reverse direction. This requirement significantly restricts the placement of transducers to avoid pre-amplifier cross-saturation while retaining a compact mechanical assembly. Transducer directivity also needs to be carefully considered, as there is a delicate balance between the accuracy of the positioning systems that ensure an adequate AUV/ASC configuration and the optimal directivity that minimizes intersymbol interference in the communication channel.

Apart from transducer customizations, the low-rate link is based on one of ORCA'S commercially available solutions. The high-rate link, however, was specifically designed for this project. The reader will find in [5] interesting discussions on the choice of a suitable DSP platform and on several topics related to packet formatting and synchronization, Doppler compensation, timing/carrier recovery and channel equalization. Given the high operating noise levels, special attention was given to signal-space coding strategies (Trellis-Coded Modulation) that provide some gain while retaining robust performance under carrier phase instabilities. See [1] for a description of the acoustic systems developed under the ASIMOV project and [5] for a presentation of experimental results obtained during the ASIMOV'99 Summer mission in the Azores.

III. TESTS AT SEA AND SCIENTIFIC RESULTS. FUTURE WORK

During the period from July 1998 to December 1999, several tests were carried out at sea to evaluate the performance of the systems developed. The reports [1] detail results of tests with the: i) Acoustic Communication System (in Brest and in the Azores), ii) Sonar System (in the United Kingdom and the Azores), iii) Sonar Data Processing System



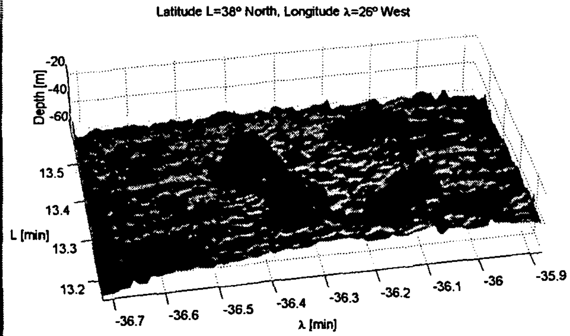


Figure 5.a The DELFIM ASC; Figure 5.b Bathymetric map of the DJC bank

(in Brest), and iv) Vehicle and Mission Control Systems (in the Azores and near Lisbon).

During the Summer of 1999, extensive tests were performed at Praia da Vitória Harbour (island of Terceira, Azores) and in D. João de Castro bank to test the navigation and control systems of the DELFIM ASC, as well as the communication and sonar systems in the actual, acoustically noisy environment of the bank. Furthermore, sidescan and sonar data were obtained and further processed by ENSIETA to locate vents and to obtain a digital terrain map of the area for future use. Figure 5.a shows the DELFIM ASC at the beginning of a mission in D. João de Castro bank, in the process of acquiring bathymetric data automatically. Figure 5.b is a bathymetric map of the area that shows the remains of an old volcano crater. See [1] for a report on the methodologies adopted by ENSIETA and the IST for map building based on a mechanically scanned pencil beam sonar and an echousounder, respectively. The bottom part of Figure 6 shows a sidescan image of the bank obtained by traversing the crater from West to East. Two separated parts of the old volcano rim and hydrothermal activity (showing up as faint plumes) are clearly visible.

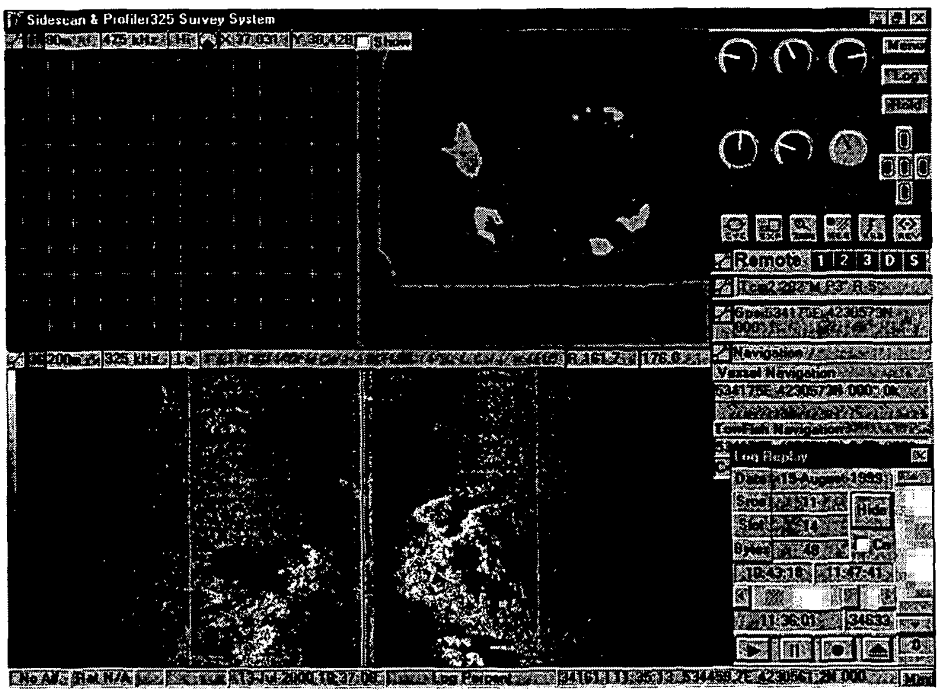


Figure 6. Sidescan Image of the D. João de Castro bank

During the missions in the Azores, the IMAR/DOP-UAzores provided extensive logistic support, including the Águas Vivas and Arquipélago vessels for vehicle and equipment transportation, and mission support. Scientists from the IMAR/DOP-UAzores and the University of Wales, Bangore performed scientific data collection with the objective of building the embryo of a habitat map of the D. João de Castro bank. One hundred eighteen species were documented at the bank. It was noticed that the species do not differ significantly from those in other shallow water offshore banks. However, species diversity seems to be lower close to venting sites, probably due to an increase in toxicity. With the objective of investigating differences in organism settling in venting and non-venting areas, several settlement traps were deployed at the end of the 1999 Summer mission. The traps will be recovered and examined in the Summer of 2000. Water samples were collected around the bank to detect methane plumes and other biochemical parameters. Their analysis seems to indicate the presence of venting activity at depths of 200 meters. Further work will aim at superimposing on a same map the bathymetry of the bank, together with scientific data related to the presence / intensity of venting, as well as other biological and geological data.

The project has reached the end of the first phase of basic system development and testing. The second phase will witness the complete integration of all systems developed by the different partners on the DELFIM ASC and the INFANTE AUV, and the execution of scientific missions in the Azores using the two vehicles working in cooperation.

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