Acoustic Tomography Ocean Monitoring System (ATOMS)

Contract number: PDCTM/P/MAR/15296/1999

24-month Progress Report

Coordinating Institution: CINTAL - Centro de Investigação Tecnológica do Algarve

Partners: Instituto Hidrográfico
CIMA - Universidade do Algarve
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Part A - Coordination Report

1 Progress

During the project second year of activity of the project "ATOMS - Acoustic Tomography Monitoring System", here below designated as ATOMS, a number of important tasks have been terminated while others have significantly advanced. The assembling and the at sea testing of the autonomous radio buoy data acquisition system (RDAS) has been successfuly completed. The simulation study of the small and large scale tomography system has also advanced significantely and nearly final results have been achieved in both cases. The only setback during this project second year was the main project sea trial for acoustic and oceanographic data acquisition that did not took place during the summer of 2002, as scheduled in the initial project proposal technical annex. This was mainly due to the unavailability of the research vessel NRP D. Carlos I, absolutely required to operate the vertical line array and deploy the sound source during a 2 week cruise at 50 to 100 miles off the coast.

Making reference to the Technical Annex of the proposal, most of the effort during this project second year was devoted to terminate tasks 1 and 2. In particular subtasks A1.2, A1.3 and A1.4 have been terminated, thus terminating main task 1. Most of the results obtained under these tasks were based on the INTIFANTE'2000 data set. Tasks A2.2 and A2.3 respectively dealing with the RDAS and sound source systems were also completed. The RDAS was completed during the summer 2002 and tested at sea during an engineering test sea trial from 23 - 25 September 2002 off the port of Lisboa, using the auxiliary ship NRP Auriga as a collaboration between partners EST, CINTAL and IH. The sound source was effectively delivered to Cintal during October 2002 by Eramer. The testing of the sound source system at sea is forseen during next spring. During this second year Eng. Ângelo Carmo from EST has left the project at the completion of the RDAS system and Dr. Vanessa Corré has also left CINTAL due to the shortage of funds and delay on the sea trial.

2 Terminated tasks

Task 1: Methods and algorithms

Sub-task A1.2: Development of scale-independent tomography inversion methods.
Responsible: CINTAL
Duration: 1 - 18 months

This sub-task has started during October 2001 after the overall oceanographic characterization of the ocean basin was terminated. This task was performed under the responsability of Dr. Orlando Rodríguez and took place in the last 8 months, being the object of one internal report and possibly of one conference publication. There might be some refinements of the work, specially regarding the range-dependent part, but for the purpose of the project this sub-task is considered as terminated.

Sub-task A1.3: Tomographyc inversion of filament features.
Responsible: CINTAL
Duration: 6 - 18 months

This task was poursued during the second year of the project and was terminated during July 2002 with the departure of Dr. Vanessa Corré. It resulted in one internal report and one international journal paper, already accepted for publication. Work was also performed on the existing data set from INTIFANTE'2000 by Eng. Cristiano Soares resulting in two conference papers (one invited) and one journal paper submitted to JASA. Eng. Cristiano Soares closely followed the work performed by Dra. Corré and is now able to implement and use the previously developed methods in the analysis of the real data during and after the sea trial of 2003. This sub-task is now terminated.

Sub-task A1.4: Analysis of SST satellite data.
Responsible: CIMA
Duration: 1 - 24 months

During the second 12-month period the following work was achieved: first, a comprehensive database was built (details may be found on the scientific part B); second, the analysis of the compiled database was performed and is provided interesting and revealing results about the circulation and general settings of the Cape São Vicente region. Some of the results are already published as conference and Symposium papers and a manuscript is accepted for publication at a refereed international journal (see dissemination list). This sub-task is considered terminated.

Task 2: Acoustic system assembling

Sub-task A2.2: Adaptation of the existing ULVA system.
Responsible: EST
Duration: 1-18 months

System testing and integration was performed before the summer 2002 in agreement with the schedule. Mechanical and electrical integration was a main concern during that period but was succefully achieved both in the lab electrical testing and at sea during the September engineering test thus, terminating this task.

Sub-task A2.3: Hardware and software implementation.
Responsible: EST
Duration: 1-18 months

This task was on time for the sea trial initally scheduled to take place in July 2002. Since the full scale sea trial was delayed, the at sea testing of the system was postponned to September, where the radio buoy was deployed and communication and acquisition were tested at various ranges and ship positions. The design and the implementation was proven feasible and successful (see cruise report in annex). Sub-task terminated.

3 Tasks under completion

Task 3: Sea trial

Sub-task A3.1: Engineering test
Responsible: IH
Duration: month 12

Due to the delay of the sea trial (from July 2002 to July 2003) a partial Eng. Test was performed during September 2002 to test the RDAS system developed under task 2 by EST.

Sub-task A3.2: Full scale sea trial
Responsible: IH
Duration: month 12 - 18

This task was postponed to year 3 (July 2003).

Task 4: Data analysis and validation

Sub-task A4.1: Application of optimized methods to acoustic data
Responsible: CINTAL
Duration: 12-36 months

This sub-task was delayed due to the postpone of the sea trial and is scheduled to start in the first quarter of 2003 to be ready for the sea trial in July 2003, in order to allow onboard data processing for online monitoring.

Sub-task A4.2: Analysis of acquired oceanographic data
Responsible: CIMA
Duration: 12-36 months

This sub-task has a delay due to the postponing of the full scale sea trial. However, most of the computational tools necessary to the analysis of in situ data that will be collected during the sea trial, have been developed in Fortran and MATLAB and tested for a number of situations. This will allow a straight access to preliminary results as soon as the sea trial takes place. A test of the mooring equipment has been accomplished in co-operation with the IH. Results of this test were included in a manuscript submitted for publication at a refereed international journal (see dissemination list).

4 Conclusion

Apart from the sea trial the project second year was completed with all tasks on schedule. Since filament structures are only expected to develop during the summer it is unfortunatelly necessary to postpone the full scale sea trial to July 2003. This delay will leave a very short time of about 2 months between the sea trial and the end of the project, which is obviously too short for data analysis and validation. It is therefore forseen to request a project extension of approximately 6 months for the completion of the project data analysis. Note that this extension is not due to delays on the development of the project itself but are solonely due to unreadyness of the research vessel NRP D. Carlos I, actually in dry dock for scientific equipment hull fixing. Its delivery is expected for the first quarter of 2003, thus on time for the sea trial in July 2003. During this project second year 14 scientific documents have been produced, among which 2 journal papers published and 3 submitted, 4 international conference presentations with proceedings (one of which invited) and 5 other documents (internal reports and manuals).

Part B - Scientific Report

1 Introduction

The strong dependence of sound velocity on ocean temperature allows, in principle, for producing temperature estimates from the measurement of sound velocity at various points in space. That is an inverse procedure known as Ocean Acoustic Tomography (OAT) [1],[2]. Initial methods were mostly dedicated to basin scale (100's of km) tomography and were later on ameliorated, by decreasing source-receiver geometry dependence [3], by extending existing methods to planetary scale monitoring [1], to sea-current estimation [2], to shallow water tomography [4],[5],[6],[7], [8],[9] and to internal waves and tides estimation [8],[10]. These classical methods for long range acoustic monitoring have been specifically applied at the scales of the portuguese EEZ for the purpose of this project (see section 2). OAT has several limitations that can be classified in two types: those related to the inverse procedure and requirements of a priori information and those geometrical that have functional implications. Inverse procedure limitations are mainly due to the fact that sound propagation in the ocean depends in many factors other than ocean temperature as for example pressure and salinity. If pressure is nearly linear with depth, salinity profiles show, in certain zones, quite strong variations both in depth and range. In shallow water tomography, other influent environmental parameters are for instance bottom characteristics such as bottom layering, compressional and shear speeds and attenuations, etc... Since sound propagation depends on some (or all) of these parameters, recovering ocean temperature requires the a priori knowledge (or estimation) of such parameters. The other type of OAT limitations are termed as geometrical and have functional implications since they deal with the need to precisely know the source(s)-receiver(s) relative position and source emitted signals at all times. These limitations have functional implications since they require the deployment of expensive complex systems for accurate estimation of source and receiver positions which strongly limitates OAT application.

The conceptual system to be used under ATOMS employs acoustic transmissions through the filament structure between a ship suspended sound source and at least one remotely operated vertical array (see section 6). Such a system will have a continously changing geometry thus introducing potential mismatch in the OAT inversion process if not known or accounted for. Part of the effort during this year was spent on developing inversion procedures that are insensitive to geometrical mismatch by including geometrical parameters, such as source position (range and depth) and receiving array depth and tilt into the search space. This effort is briefly described below in section 3 under the title of *Blind Ocean Acoustic Tomography*.

Finally, another factor to be taken into account when applying OAT, is that the final result is an integral temperature profile over range, thus offering no resolution along the range separating source and receiver. In practice that is a consequence of the temperature stratification assumption often made. That is a severe drawback for the ATOMS purpose, *i.e.*, "to detect and invert a filament structure along range and depth and its evolution over time". The results obtained on realistically simulated data show that a uprising cold water filament can be detected in a consistent manner and at low SNR (see section 4).

2 Scale-independent OAT

Classical long range basin scale tomography should be, in principle, directly applicable to long term monitoring of the portuguese EEZ. Simulation based studies performed under the present project have shown, however, that accurate range-dependent propagation induced acoustic signals extremely dificult to invert for the mean relative temperature profile. Reliable inversions were only possible when bottom and surface interactions were neglected thus making the propagation range-independent. The study concluded that further investigation is needed to include bathymetry dependence into the inverse problem (see internal report 24, in attachment).

3 Blind Ocean Acoustic Tomography (BOAT)

Blind Ocean Acoustic Tomography (BOAT) is an ocean remote exploration concept similar to acoustic tomography, where both the emitted signal waveform and the source position are unknown. BOAT consists of a minimal environmental model of the area, a broadband matched-field processor and a genetic algorithm search procedure. In many instances, BOAT is similar to acoustic focalization [11], where only the site bathymetry is assumed to be known. This method was developed and presented in various papers (see, for example, documents 13 and 14 in annex) together with results obtained on the data set acquired during the INTIFANTE'00 sea trial, where an acoustic source was towed along both range independent and range dependent paths, with source-receiver ranges varying from 500 m up to 5.5 km and water depths varying from 70 to 120 m. The results obtained on several hours of data, show that source range and depth can be used as focalizing parameters, together with the Bartlett power to indicate model fitness. Using this three parameters it becomes clear when the environment is "in focus" and when it is "out of focus" leading to realiable estimates of the geometric and environmental parameters under estimation. One possible applications of BOAT is shown in document 14 in annex, where ship radiated noise is used for tomographic inversion. Whether that same approach can be used for detecting cold water filaments is discussed with realistic simulations in the next section and remains to be proved with real data to be acquired during the next year sea trial.

4 Tracking a cold water filament with acoustics

A new method of matched-field based inversion for estimating the range and time variability of ocean properties was developed. This method uses acoustic data from a single array-source pair. Since estimating range-dependent properties with such a simple configuration is a problem which solution may not be unique, the primary objective is to obtain the variability trend rather than very accurate estimates of the properties. Detection and global tracking of ocean fronts or eddies are possible applications of the inversion method. The inversion method is applied to a synthetic data set obtained during the simulated development of an upwelling filament. The objective consists in estimating the sound-speed profile of the filament, its position and width, and the variations of these properties with time. The performance of the method is first tested in the ideal case where no noise nor model mismatch is present. Results show the feasibility of tracking the upwelling and obtaining good accuracy for the parameter estimates within a reasonnable computational time. The presence of noise in the data or model mismatch degrades the accuracy of the parameter estimates. However the global rise of cold water can still be detected and localized under realistic conditions. Although the filament properties as well as the source and array positions have noticeable effects on the inversion results, no clear evidence of a parameter hierarchy was found. Detailed results can be found in a SiPLAB internal report and an accepted paper to the journal Acta Acustica (see documents 15 and 16 in annex).

5 Characterization of cold filament structures

The first task accomplished during this second year was the building of a comprehensive database. That database consists on various data sets such as:

a) 8-year (June-1994-June-2002) compilation of weekly Sea Surface Temperature (SST) composites at 1x1 km2 pixels for the whole Madeira region (Canaries to Ireland);

b) all available data from the NASA SeaWinds scatterometer on board the QuikSCAT satellite at $0.25° \times 0.25°$ grid;

c) hourly wind data from 1998-2002 taken at Sines, Sagres and Faro;

d) monthly National Center for Environmental Prediction (NCEP) Sea Level Pressure (SLP) Reanalysis for the North Atlantic from 1948-Jul 2002 at $1° \times 1°$ grid;

e) monthly and weekly Sea Surface Temperature (SST) analyses at $1° \times 1°$ grid from i) Comprehensive Ocean Atmosphere Data Set (COADS) and ii) Optimally Interpolated SST of Reynolds and Smith (1994) (OI-SST) from 1980-2002;

f) monthly winds for the North Atlantic Ocean at $1° \times 1°$ (1960-1998) and $2° \times 2°$ (1995-2002) grid from i) COADS and ii) Australia surface wind from Integrated Global Ocean Services System (IGOSS) Products Bulletin;

g) hydrographic database with data from NODC, NOBC, SISMER, and other sources

Then, most of computational tools have been developed in FORTRAN and MATLAB. These have been tested for a number of situations. Analysis of cruise hydrographic and Acoustic Doppler Current Profiler (ADCP) data with these computational resources will permit the onboard fast-access to the preliminary results. Test of the mooring equipment has been accomplished. A test comprising the deployment of two buoy-mounted RDI 150 kHz ADCP plus release systems on the shelf area off Tavira and Vila Real de Santo António was performed in December 2001, in cooperation with the IH. The successful retrieval of the moored instruments permitted to get familiar with the pattern of currents along the shelf and its relation with the wind pattern.

Analysis of the compiled database has permitted to understand the complex circulation scheme in the southwestern Portuguese region. The North Atlantic Oscillation (NAO) essentially governs the forcing regime of large scale (Hurrell, 1995). The principal component of the leading EOF of seasonal (winter) SLP over the North Atlantic Sector (20-70N, 90W-40E) provides a robust index to measure its intensity. Positive NAO depicts the strengthening of the Azores High-Icelandic Low pressure dipole and implies activation of the frequency of northerlies (upwelling-favorable) wind along the western Iberian Peninsula. Contrary situation occurs for negative NAO index. Attempts to link the large scale forcing and mesoscale features in the study region have been attempted. It could be observed that the NAO index is positively related with a normalized estimation of filaments integrated per year from 1981-1990. However the acquisition of finer both time and space resolution data sets permitted to observe large spatio-temporal variability of the oceanographic climate. Analysis of the QuikSCAT winds show that over 50% of the overall variability may be explained by the leading EOF mode. This mode itself shows two preferential orientations, corresponding with SW and NE wind patterns over the SW Iberian Peninsula. Although on a rough scale these situations could be explained by seasonality along the study area, strong inter-seasonal variability modifies the initial conceptual model. Hence, the understanding of the smaller scale processes is being undertaken at this phase of the study. Subsequent forcing modes are put forward as modulators of the general pattern and therefore responsible for the generation of mesoscale features of relevance for the regional oceanography. This work is being published in 2 submitted journal papers and 1 conference presentation (documents 21, 22 and 23 in annex).

6 Autonomous bouy data acquisition system

An important goal to be achieved under ATOMS was to enhance the facilities of an existing underwater acoustic acquisition system (ULVA). The ULVA system was used during the INTIMATE'00 sea trial, where some drawbacks were identified: a) data dropouts, b) noise and c) limited autonomy. In its original conception the ULVA system has no ability to store data locally (on the buoy): the data was sent on line to a remote peer (usually to onboard ship), where it was monitored and archived. This operation is supported by a radio link that achieves a relatively high throughput (about 2.4 Mbps) and is prone to malfunction due to weather conditions, interfering sources, etc. Obviously the ship's moneuvering is also limited, since she must stay in a close radius to the ULVA: in the INTIMATE'00 sea trial it was observed that for distances greater than 6km the radio link was inoperative. Last but not least, the radio emitter on the buoy has a high energy consumption in order to achieve such a data throughput which is also a main limiting factor for a battery operated system.

In the light of the ATOMS experiment the above enumerated constraints to ship movements and system autonomy were important, because the area of interest where is much larger than that covered by a ULVA radio linked ship. Also it is desirable to observe the phenomenon (cold water filaments) during a relatively long period (2 weeks), thus the autonomy limitations. To overcome these difficulties, in the scope of the ATOMS project a modification of the original ULVA system was proposed. This new system, named Remote Data Acquisition System (RDAS/ULVA), has the possibility for local data storage and can operate in a stand alone fashion. However online data quality control is still supported.

Those objectives were accomplished by introducing an embedded PC based system on the buoy: an "intelligent" system that allows industry standard storage facilities (hard disks), as well as large stand alone operation capabilities. The remote data quality control and acquisition system status monitoring is possible by a newly introduced wireless lan link. The use of "open technologies" for the hardware and the software was a priority request at system specifications, since this allows future systems improvements at relatively low cost and future transparent system integration in a network of instruments.

At this momente the RDAS/ULVA system setup is in a final stage. During September 2002 took place the ATOMS'02 engineering test where the system was successfully tested at sea (see document 17 and 18). An RDAS engineering manual is being prepared and is included in annex (document 19).

7 Conclusion

One of the main reasons that have retained OAT to be widespreadly used in ocean environmental monitoring is related to the difficulty of precisely controling both the emitting and receiving systems. One of the efforts made in this project was directed towards the developement of methods and systems for OAT, made as independent as possible from the emitting system.

On the methods side, it was shown that it is possible to obtain inverse OAT results without using any information about the emitting system, as for example, its location and/or emitted signal. It was even proved with real data that such methods were efficent using ship noise as sound source. It was also proved that it is, in principle, possible to detect a cold upwelling filament, in a range independent fashion from the observation of the acoustic data transmitted along a single propagation transect. On the system side, an advanced add on to existing vertical receiving array was tested at sea and proved successful to self-record the acoustic data and simultaneously provide signal monitoring at high data rates and at long distances (up to 18 km). To the authors knowledge, this system represents a world premiere for the purpose of OAT exploration.

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A List of project publications

A.1 First year

[**1.**] JESUS S. "Tomografia Passiva Costiera - Data Report, Phase 1", SiPLAB Report 01/01, March 2001.

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A.2 Second year

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[**16.**] Corré V. and Jesus S.M., "Tracking upwelling filaments using matched field inversion", accepted ACTA ACUSTICA, November 2002.

[**17.**] Campanha de Teste de Sistemas - ATOMS'02, CINTAL, 2002.

[**18.**] Relatório de Campanha de Teste - ATOMS'02, CINTAL, 2002.

[**19.**] RDAS manual

[**20.**] Soares C. and Jesus S., "Broadband Matched-Field Processing: coherent vs. incoherent approaches", submitted to Journal of Acoust. Soc. Am., August 2002.

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(attached to this report)