Acoustic Tomography Ocean Monitoring System (ATOMS)

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

36-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 third year of activity of the project “ATOMS - Acoustic Tomography Monitoring System”, here below designated as ATOMS, there was no significant outcomes. This was due to a second postponement of the ATOMS sea trial from 2003 to the summer 2004, which left an empty period of time in the project schedule. The project partners are pursuing their research activity with background tasks while awaiting for the sea trial. The technical report of the autonomous radio buoy data acquisition system (RDAS) has been successfuly completed. The study of the small scale tomography system was completed and published on a peer-reviewed journal. Another simulation study was achieved and is the object of an internal CINTAL report.

Expecting the oceanographic cruise for the summer 2003, a proposal of sampling strategy and an interim cruise plan was produced. The preparation of equipment prior to the oceanographic cruise and the repair of the faulty pieces was done. Due to the delay in the realization of the ATOMS sea trial, a numerical modelling study was initiated to compensate the lack of ”in situ” information to characterize the filament structures along the SW Iberian Peninsula. The chosen modeling system was the Regional Oceanographic Modeling System (ROMS), developed by the Rutgers University, USA. This work is a co-operation with IPIMAR-Lisbon.

The task accomplished during this third year as related with the exploitation and analysis of the database compiled during the previous two project years. Some of the results are already published as conference, Symposia and international journals (see dissemination list below). The main results were: i) comparisons between remotely-sensed and anemometer-based winds along the SW Iberian Peninsula. ii) understanding of the wind-driven ocean circulation along the SW Iberian Peninsula. iii) notion of sharp current reversal along the southern Iberian Peninsula.

Thanks to an additional collaboration with the Saclant Undersea Research Centre the sound source and the ULVA/RDAS system developed under ATOMS is scheduled to be tested during the MREA’04 sea trial in March/April 2004, off the coast of Portugal.

2 Tasks under completion

Task 3: Sea trial

Sub-task A3.2: Full scale sea trial

Responsible: IH
Duration: month 12 - 18

This task was postponed to year 4 (July 2004).

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 2004 to be ready for the sea trial in July 2004, 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 delayed 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).

3 Conclusion

Apart from the sea trial the project third 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 2004, even if, according to IH, NRP D. Carlos I is scheduled to be available early 2004. The postone of the sea trial, has justified for the request of a total project extension of one full year, until October 2004. This delay will leaves very short time between the sea trial and the end of the project, which is obviously too short for data analysis and validation. During this project second year 18 scientific documents have been produced, among which 4 journal papers published and 2 submitted, 10 international conference presentations with proceedings and 2 other documents (internal reports and manuals).

Part B - Scientific Report

1 Introduction

There is evidence today that underwater acoustics is an incontestable tool for ocean exploration. In particular, when remote sensing of the oceanic water mass, and not only the sea surface, is desired, Ocean Acoustic Tomography (OAT) is the tool of choice. The term "classic OAT" is generaly adopted to designate the original Munk's proposal and related work [1, 2], which for most of it, deals with deep water long range estimates using travel time tomography. The introduction of matched-field ideas into tomography, leading to what is nowadays called Matched-Field Tomography (MFT) [3], was a significant step forward to the widespread of oceanic tomographic methods to other scenarios such as shallow water areas [4, 5, 6, 7, 8, 9], internal waves and tides estimation [8, 10] and range-dependent tomography [4, 11]. This last topic has received particular attention in ATOMS since the problem at hand, namely determining the upwelling filament onset and offset, define a strongly range-dependent acoustic propagation channel. One of the most stringent tasks in producing range-dependent tomographic estimates is the choice of the parameterization of the medium of propagation, that is a compromise between a high flexibility, to accurately represent the phenomena, and a low number of parameters being manageable in the inversion process. Such a parameterization was proposed in [11] and was showed to allow a high flexibility in modelling the California Coastal System upwelling. An alternative parameterization is now proposed in [12] and is discussed in greater detail in section 2.

Another important question to be taken into account in MFT is the choice of the objective function to be optimised. The crucial question here is to define the best representation in the optimization space that allows the most sensitive estimation of the parameter set. This is a particularly hard problem in presence of noise and model mismatch. In practice model mismatch can not be analitically handled while the presence of noise in the data is normally introduced by considering a deterministic observation corrupted by additive noise and defining a minimal statistic for the parameter vector. Such derivation is further complicated when the data available mixes different data types, such as the data observed in the spatial domain and in the frequency domain. An interesting derivation of such an objective function that allows a simple optimization procedure is proposed in [13] and is also summarized in section 3.

The environmental conditions related to the formations of the upwelling filament off Cape Sõ Vicente is an addressed issue under ATOMS project. Remotely-sensed QuikSCAT near-surface scatterometer winds in the vicinity of the Iberian Peninsula were compared to four anemometer sites (three land-based, and one in open ocean). The correlation and error statistics between each anemometer site and the surrounding SeaWinds data were analyzed. It was concluded that the QuikSCAT winds are adequate for oceanographic studies off the south-western Iberian Peninsula, at least west of 7.0 W. The relationships between the sea surface wind and the SST spatial patterns along the SW Iberian Peninsula have been empirically explored by canonical correlation analysis (CCA). Two modes reveal coherent SST and wind patterns along SW Iberia, the first one associated with coastal upwelling along the West coast and sporadic on the South, and the second one representing the upwelling-downwelling pattern along the southern Portuguese coast.

Recently documented poleward warm inshore counter-currents interact with the cold filament off Cape São Vicente. The processes driving its development were analyzed with the aid of wind data from QuickSCAT and land-based coastal stations, SST data from AVHRR radiometers, sea-level data from Topex/Poseidon and ERS-2 altimeters, and direct current measurements from moored ADCP's. The particular orientation of the SW Portuguese coast allows the development of differential patterns at the western and at the southern coasts. The relationship between the wind curl, the SST signal and the Sea Level Anomaly differences between the two coasts was established. The curl of the wind stress is postulated as a key element for understanding the surface circulation in the region.

The final scope of estimating oceanographic features from indirect acoustic measurements is to be able to incorporate that information into actual directly measured oceanographic data. The objective is to complement *in situ* measurements with acoustic remote data, to obtain a full picture of the oceanic volume mass. There are a number of techniques, known as data assimilation, that aim at coherent integration of data of different nature and from a variety of sources, to describe the same phenomena. Such an effort is underway in a study carried out at CINTAL's SiPLAB laboratory that could be applied to the upwelling filament observations under ATOMS [14]. Acoustic and direct oceanographic observations are being associated with temporal and spatial correlation lengths and their respective estimates through time and space interpolated within a state space representation model and optimal Kalman predictors. These techniques draw their roots from the work of Elisseff [15] and Lermusieux [16].

2 Range-dependent acoustic tomography

Acoustic tomography in range-dependent waveguides using a source-array pair represents an inverse problem with potentially many solutions. One of the aspects contributing to a successful inversion is the ability to correctely model the environmental variation through range: the suited model is the one that provides the best fit with the data and has the minimum number of coefficients. Obviously these are two contradictory requirements that call for a case dependent compromise. The present problem is to model an upwelling filament which is a localized uprise of cold water, introducing a high degree of range dependence. In this study a parameterization scheme with a reduced number of parameters is proposed in order to represent the spatial evolution of the filament using an asymmetric Gaussian function parameterized by two variances, an amplitude coefficient and a mean value. Using a real data example of the filament of the California Current System (CSS), this modeling scheme was tested on semi-synthetic data [12]. The results indicate that such an approach can be considered for an efficient modeling of a complex oceanographic feature.

3 The inchoerent cross-frequency processor

Matched-field based methods always involve the comparison of a physical model output and the actual data. The method of comparison and the nature of the data varies according to the problem at hand, but the result becomes always largely conditioned by the accurateness of the physical model and the amount of data available. The usage of broadband methods has become a widely used approach to increase the amount of data and to stabilize the estimation process. Due to the difficulties to accurately predict the phase of the acoustic field the problem whether the information should be coherently or incoherently combined across frequency has been an open debate in the last years. The work performed on this subject by Soares *et. all.* [13], provides a data consistent model for the observed signal, formed by a deterministic channel structure multiplied by a perturbation random factor plus noise. The cross-frequency channel structure and the correlation of the perturbation random factor are shown to be the main causes of processor performance degradation. Different Bartlett processors, such as the incoherent processor [17], the coherent normalized processor [18] and the matched-phase processor [19], are analysed and compared in light of the optimum processor performance. Finnaly a cross-frequency incoherent processor is proposed that is analytically shown to have the same performance as the matched-phase processor with however an extremely low computation complexity.

4 Characterization of the environmental background structure

4.1 Comparisons between remotely-sensed and anemometer-based winds along the SW Iberian Peninsula.

SeaWinds on QuikSCAT near-surface scatterometer winds in the vicinity of the Iberian Peninsula are compared to four anemometer sites (three land-based, and one in open ocean). In order to ameliorate differences in spatial and temporal resolution of the scatterometer and anemometers, different time and spatial averaging methods were analyzed. Using time-filtered anemometer winds and spatially-averaged, daily-composite SeaWinds data, the correlation and error statistics between each anemometer site and the surrounding SeaWinds data were analyzed. It was noted that the sites with the highest vector correlation and smallest mean bias were the sites on the Western side of the Iberian peninsula. It was also noted certain systematic directional biases in the data, probably due to orography around the land-based sites, and diurnal wind variations such as sea breeze. In the end it was concluded that the QuikSCAT winds are adequate for oceanographic studies off the south-western Iberian Peninsula, at least west of 7.0 W.

4.2 Understanding of the wind-driven ocean circulation along the SW Iberian Peninsula.

The relationships between the sea surface wind and the SST spatial patterns along the SW Iberian Peninsula have been empirically explored by canonical correlation analysis (CCA). These comparisons have been done at two spatio-temporal scales. First, the large scale has been considered on the basis of monthly, one-degree spatial resolution OI.SST maps and COADS winds along the Eastern North Atlantic between 30 and 50°N from 1981-1997. Then, a finer scale CCA was done by analyzing weekly AVHRR SST images with $\approx$4 km spatial resolution and 0.25° QuikSCAT winds over SW Iberia from 1999-2002. For the large-scale CCA, modes #1 (explaining 26% of SST and 36% of wind variances, canonical correlation 0.49), #2 (55% of SST and 36% of wind var., cc=0.42), and #3 (39% of SST and 23% of wind var., cc=-0.37) show features relevant to upwelling in the SW Iberian region. These modes appear significantly correlated with both the NAO and the Quasi-Biennial Oscillation (QBO), as shown by cross-correlation with these indices and the spectral density estimates of the canonical time components.

The finer scale CCA revealed at least two coherent SST and wind patterns along SW Iberia. Canonical mode #1 (49% of SST and 51% of wind var., cc 0.49) showed wind vectors parallel to the west coast. Conspicuous wind curl is observed east of Cape St. Vincent. The corresponding SST pattern was associated with coastal upwelling, which was generalized along the West coast and sporadic on the South, although it intensified lee of the main capes. The wind pattern showed significant spectral peaks at the 3-month and 1-month bands. The associated SST pattern also showed the monthly peak, although most of the energy grouped in the 8-month band. Canonical mode #2 (52% of SST and 60% of wind var., cc=0.32) appeared orthogonal to the previous mode, as shown by the EOF decomposition of the single fields. The wind field basically represented upwelling-downwelling pattern along the southern Portuguese coast, which was accompanied by marked SST anomalies at the same region. Both the wind and SST modes showed the maximum energy towards time scales longer than 6 months, although a secondary peak at 25-28 days was also significant.

4.3 Notion of sharp current reversal along the southern Iberian Peninsula.

The occurrence of warm, poleward counter-currents during the upwelling season inshore the upwelling jet along SW Portugal has been recently documented with the aid of thermal satellite images. This flow is apparently strongly wind-dependent and has its source on the inner Gulf of Cádiz. It flows at mean velocities of ≈20 cm/s separating the coastal jet offshore. It frequently turns around the Cape St. Vincent where its associated volume transport increases northwards. At times, the warm counter-current appears very energetic and breaks trough the upwelling jet off Cape St. Vincent, hence isolating a pocket of upwelled water offshore. The processes driving the development of this coastal counter-current were analyzed with the aid of wind field data from spaceborne QuikScat and land-based coastal stations, SST field data from spaceborne AVHRR radiometers and sea-level data from spaceborne T/P and ERS-2 altimeters. It was showed that the particular orientation of the SW Portuguese coast allows the development of differential patterns at the western and at the southern coast. The relationship between the wind curl, the SST signal and the Sea Level Anomaly differences between the two coasts was observed. The strongest SLA differences between the west coast and the south coast coincided with the most energetic developments of the warm counter-current. These episodes where strongly related to the curl of the wind field over the shelf regions as computed from the QScat data.

Additionally, direct current measurements of this counter-current were presented. So far, the observation of this current was precluded after autumn because of the lack of SST contrast. Current profiles taken in November-December 2001 from two ADCP's moored at ≈30 m depth in the Gulf of Cádiz are presented. These data are complemented with tide gauge and bottom temperature observations at the mooring sites, plus wind data from coastal stations and a nearby ocean buoy. Over the 10 days of deployment time, the current pattern over the surface layer (above 15 m) appeared to be roughly eastward, showing strong links with the local wind field forcing. However, the instruments recorded strong current reversal at the bottom layer (below 15 m depth) half way through the recording period, where the sub-inertial flow drastically changed from ≈0.25 m/s westward to ≈0.17 cm/s eastward, parallel to the bathymetric contours. This current shift coincided with the fall of water column temperatures by more than 1.7°C in less than two days, as shown both by "in situ" measurements and satellite-inferred SST's. A linear model for the alongshore velocity including the alongshore pressure gradient, the bottom friction and the wind stress drag showed that predicted accelerations were positively and significantly correlated with the observed ones ($r=0.60$, $p<0.05$). However, the model overestimates the accelerations for both the poleward and the equatorward flow, and the considered terms alone do not explain the observed accelerations. Hence, other factors rather than the wind stress itself must be accounted to explain the alternating current pattern. As documented in recent studies in Southern California, the curl of the wind stress is postulated as a key element for understanding the surface circulation in the region.

5 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 and the unability to represent highly range-dependent features commonly present in the ocean. Both of these issues were investigated during ATOMS, demonstrating that it is indeed possible, at least with semi-synthetic data, to invert for the water column characteristics (mainly temperature profiles) without explicitely knowing relative source-receiver positions with great accuracy. To that end a few techniques were shown to be a significant step forward when attempting to optimaly combining the cross-frequency information received at a vertical array of sensors. Semi-synthetic data was also used to demonstrate, using two different techniques, that range-dependency along the source-receiver plane could be accounted for with suitable environmental modelling. It remains to be demonstrated that these two ideas can be applied together on actual experimental data. That step is left for next project year that, hopefully, will see the acomplishment of the sea trial at the Cape São Vicente site.

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A List of project publications

A.1 First year

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(attached to this report)