# AOB - Acoustic Oceanographic Buoy: concept and feasibility

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*Abstract*— The AOB - Acoustic Oceanographic Buoy is the single node of a network of "smart" buoys for acoustic surveillance, Rapid Environmental Assessment (REA) and underwater communications. The AOB is a lightweight surface buoy with a vertical array of acoustic receivers and temperature sensors to be air dropped or hand deployed from a small boat. The received data is geotime and GPS precisely marked, locally stored and processed by on board dedicated DSP hardware. AOBs can exchange data over a local area network that includes submerged, sea surface (like for instance other AOBs) and air or land located nodes, allowing for the integration of all users in a seamless network. Specific software allows AOB usage in complex tasks such as passive or multistatic acoustic surveillance, acoustic observations for REA oceanographic forecast and model calibration, bottom and water column acoustic inversion, underwater communications and cooperating target tracking. The AOB was successfully deployed in several consecutive days during two Maritime REA sea trials in 2003 (Mediterranean), in 2004 (Atlantic) and for an high-frequency underwater communications experiment during MakaiEX, 2005 (Hawai). Data collected at sea shows that the AOB is a versatile, robust and easy to use tool for a variety of broadband underwater acoustic applications.

*Index Terms*— rapid environmental assessment, ocean tomography, acoustic sensing systems

## I. INTRODUCTION

Rapid Environmental Assessment (REA) is generally seen as an ensemble of techniques aiming at giving a broad coherent picture of the environmental situation of a given area at a given moment in time. In principle these techniques use as much data as possible and tipically include archival or ocean direct observations of temperature, currents, surface waves and bathymetry as well as meteorological information drawn from local stations or satellites (air temperature, winds, althymetry, sea surface temperature, etc). In many contexts REA also embraces the purpose of generating environmental forecasts at 24, 48 or more hours from the actual time. Often, in order to produce an REA nowcast in a given area requires sampling and generic observations in a much broader adjacent ocean volume. Typical cases are those that include a coast line beach front, the adjacent continental platform and the connected deep water ocean for a total surface that may vary from $10 \times 10$ km upto $50 \times 50$ km. If underwater operations are planned or suspected to take place in the target area, the REA environmental picture may be fed to appropriate acoustic numeric models for producing acoustic target detection predictions at present and future time. Of course the difficulty arises from the fact that these operations must be performed without having direct man/ship access to the area of interest and in a rapid survey fashion, i.e., tipically with only a few hours of remote observations. In general, REA encompasses a broad range of data gathering and data fusion techniques. The former include standard sampling aparatus such as air dropped XBT's, XCTD's, oceanographic samplers, satellite data, unmanned vehicles and archival data.

The main question here is whether it makes sense to collect also actual acoustic data and, in case, to what extent does the acoustic data improves the REA environmental picture estimate ? There has been a strong effort in this direction made by several works as for example the Haro strait experiment [1], [2], and data assimilation efforts [3], [4]. These studies tend to demonstrate that acoustic observations do improve the REA picture since they provide a mean observation in between transmitter and receiver with a high time resolution. Although research is still going on on a number of these topics, Acoustic REA (AREA) appears to be a promising concept.

In order to develop the AREA concept there are a number of issues that must be addressed. These can be divided under the following three topics: 1) harware issues as for example the requirement for an easy to deploy and easy to operate system for collecting acoustic data in a typical REA area, 2) acoustic data processing techniques to seamlesslly interact with the hardware and extract the relevant information online and 3) the amalgamation of the acoustically extracted information with the other generic REA data processing results in order to produce an acoustic compliant REA coherent picture. This paper concentrates in the first two issues. The material is organized as follows: section II gives an overview of the acoustic REA concept, features and requirements; section III explains in most detail how the AOB fullfils the AREA requirements and its main harware and software characteristics; section IV presents the results obtained with the AOB during the various experiments from 2003 through 2005; finally section V draws the conclusions and gives future perspectives for the AOB system in the AREA context.
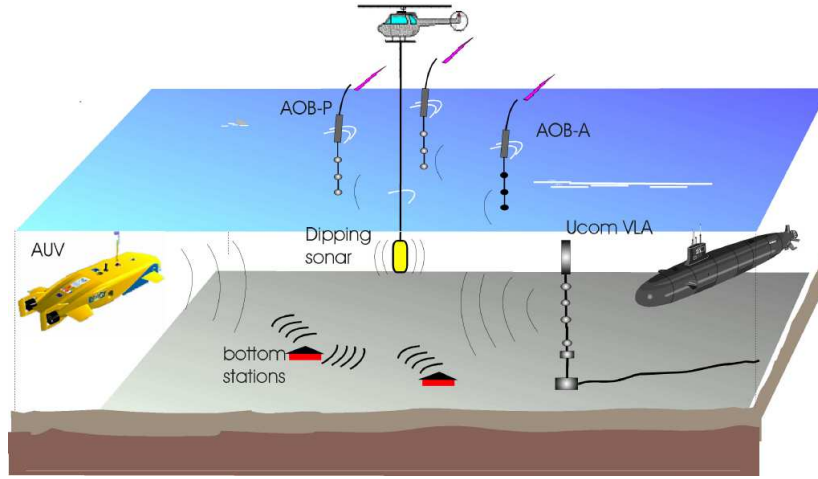
Fig. 1. *the Acoustic Oceanographic Buoy Joint Research Project (AOB-JRP) system concept.*

## II. THE AREA DATA COLLECTION SYSTEM

### A. The hardware

Throughout the world there exists considerable experience on developing operational acoustic systems for conventional active sonar, towed acoustic arrays and air dropped sonobuoys. There are is also a number of systems being developed for environmental surveillance for both short range (shallow water) and long range (ocean scale) tomography (or thermometry). Most of these systems are research directed aparatus, bulky and difficult to operate for their deployment requirements (ship cranes, low sea state, mooring limitations, etc). In one word, these systems are not suited for operational use. There are two ends on an acoustic system: the transmitting end and the receiving end. As one can imagine these two work in tandem and the simplification on one end may require an increase of complexity on the other end and/or a decrease of performance of the whole system, so there is a tradeoff. As an example, the limiting situation where an acoustic AREA system operates on listening mode only imposes severe constraints both on the hardware of the receiver side (longer arrays, broader frequency range) and a need to accept some loss of performance. Another issue to take into account is the operating frequency, since traditional tomography oceanic-type systems operate at low frequencies, say, well below 1 kHz. This implies bulky and expensive sound projectors and large aperture receiving arrays. An increase of operating frequency is rather interesting for decreasing the size (and cost) of the systems both at the transmitt and at the receive ends. However, this may have implications in the processing, with an increased sensitivity to both sensor positioning and to medium inhomegenities.

A third issue, always on the hardware topic, is the overall size and ease of operation from on board military vessels and/or aircrafts. The only real operational concept for acoustic standalone systems is that of sonobuoys, which became a standard and thus, should be adopted in terms of size, handiness and autonomy, as a target for AREA. Since existing standard sonobouys do not incorporate AREA, there is a requirement for developing a new sonobuoy hardware product specific for AREA.

### B. The data processing

A non exhaustive list of difficulties found on the data processing for AREA is as follows:

i) reduced number of sensors and/or reduced array aperture;
ii) an increasing frequency of operation with the related increasing sensitivity;
iii) a reduced bandwidth or a fluctuating signal (shipping or ambient noise) in passive mode;
iv) online processing requirements;
v) reduced or incomplete environmental information for baseline model setup;
vi) reduced spatial coverage and/or moving sources/receivers.

Among these, some tradeoff is also required as well as the development of new techniques or extending the existing ones to the AREA context.

### III. THE AOB - ACOUSTIC REA SYSTEM DESCRIPTION

As explained in the previous section, and to respond to the needs of AREA, it requires more than a simple change of the existing methods or data collection techniques, a whole philosophy and a complete system design from the hardware to the end user is required. Although the complete system details will not be presented here (see [5]), a overall glance through the system characteristics and design is given. The Acoustic Oceanographic Buoy original concept was laid down in the initial Joint Research Project (JRP) proposal maid by the consortium to NURC in 2003[1]. At that moment there was

little idea of subsequent developments introduced in the initial concept turning it into a whole sea-going REA capable system as depicted in figure 1.

In order to comply with the necessity for both simplicity and horizontal spatial coverage, the actual AOB system is formed by a series of reconfigurable nodes, where each node is either receiving only (AOB-P) or transmitt - receive (AOB-A), organized in a network randomly distributed over (or around) the area of interest. Each network node has its own processing capabilities and seamleassly integrate a air-wirless communication network for data and comand exchange between nodes and from nodes to a base station. In terms of size and autonomy each node is a sonobuoy-like system with, however, a modulable 16-acoustic and non-acoustic sensor vertical line array covering a wide frequency band up to 25 kHz. The data is pre-processed on each node with compact yet powerfull DSP hardware. Again for a matter of simplicity, nodes are free drifting and GPS localizable at all times. The GPS clock is used for data time stamping and synchronization.

The data processing can be separated into two different large sets of routines: those that are executed on each indvidual node and those that are run on the base station. The tasks run on each individual node include the processing of the non-acoustic data, namely the temperature information gathered along the water column sensors, the computing of the mean profiles, corrections made for sea surface motion and eventual array tilt by using the depth sensors information; another task accomplished on nearly real time on each node, is signal detection and time slicing which is a task highly dependent on the particular set of sequences being transmitted; Fourier transformation, frequency extraction and sample cross-covariance matrices estimations are also executed on board each node. Depending on the actual post-processing to be done on the base station the data reduction obtained from this pre-processing may reach a factor of 1:500. On the base station, supposed to be formed by a set of parallel computers, acoustic models are run for data focalization and inversion; the data is amalgamated from the various system nodes; next, data rendering and time-space interpolation is performed to obtain a big coherent picture from acoustic data only and then it is adapted to subsequent integration into REA data or oceanographic modelling for nowcast/forecast.

*A. The AOB2 node hardware*

The first version of the AOB - so called AOB1 - was a preliminary single node attempt using a large stainless steel container and a 4 hydrophone array without non-acoustic sensors (2003); this system was later updated to 8 hydrophones and 16 temperature sensors (2004). The data processing unit was a windows-based system with limited processing (no DSP) and poor remote connection capabilities. The AOB1 was used during the Maritime Rapid Environmental Assessment (MREA), NATO Undersea Res. Centre led sea trials in 2003 and 2004 (see [6], [7] respectively). Some results obtained during these sea trials will be shown below. The actual AOB node - herein referred to as AOB2 - is based on a sonobuoy-like alluminium container housing a very compact data processing unit based on the PC104+ architecture, including a



Fig. 2. *AOB2 being recovered aboard RV Kilo Moana, during the Makai Ex sea trial in September 2005, off Kauai I., Hawaii (USA).*

DSP unit and running Linux operating system for a greater flexibility and remote control. The AOB2 was first tested at sea during the Makai Experiment, off Kauai I. (Hawaii, USA) in September 2005. A picture of the AOB2 being deployed from R/V Kilo Moana, in September 2005 during Makai Ex, is shown in figure 2. Figure 3 shows a mechanical structure split view of the AOB2. Unlike its predecessor the AOB2 is split in two independent water tight containers, one for the electronics and the other for the battery. The two containers are rigidly attached to the same frame and interconnected via an external cable. The sensor array is mechanically attached to the battery container and electrically connected to the upper container. Both end cap connectors and cables running along the side of the AOB2 are protected by pyramidal shaped polyamid plates screwed along the frame. The 2m high mast screws on the buoys top cover via a water tight mechanical attach. Wireless and GPS cables are internal to the mast and have an appropriate passthrough on the AOB2s' top cover. The internal arragement of the electronics (shown in figure 4) uses a top cover suspended PC104+ stack with a number of COTS electronic boards and some specially designed boards such as the Signal Conditioning cards, systems ON/OFF controller, and signal - array cards power supplies. The AOB2 features a GPS card that provides positioning as well as time marking for data acquisition and time stamping. The wireless lan system provides online communications for real time positioning, AOB2 status and data monitoring/processing. In calm sea and using a directive antenna from a ship the wireless lan connection provided reliable communications up to 18 km. It is antecipated that this performance will be greatly reduced to only a few kms in agitated sea while it is believed that it
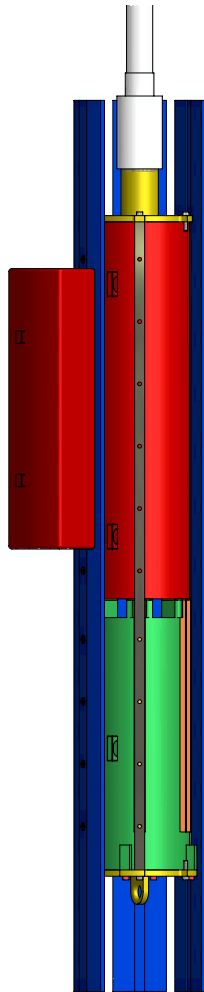
Fig. 3.   *AOB2 hardware: mechanical split drawing.*



Fig. 4.   *AOB2 hardware electronics diagram.*

will increase if the base station is airborne. The core of the AOB2 is a Transmeta based CPU board having a low power consumption and without fan requirements. Data acquisition is achieved thanks to a dedicated board attached to the Texas DSP that is, itself, connected to the CPU. A portable hard disk at the bottom of the stack allows for several days of continuous data recording. There are a few interesting features of the AOB2 that should be pointed out. One is the automatic ON/OFF switch, that is triggered by a salt water sensor and avoids the system being bumped around during deployment or recovery with the electronics in working conditions (specially the hard disk). Another is an external Tbase2 and power supply connector that allows fast recover of the data and battery charging while the AOB2 is on the deck and without opening the containers. In other words the system is "serviced" right on the deck, just by opening a cap and connecting a cable. A last, but not least, interesting feature is the possibility of controlling the AOB2 from a handheld device like a PDA. During last sea trial Makai Ex, the AOB2 status and position monitoring was made possible at all moments from a PDA carried around in
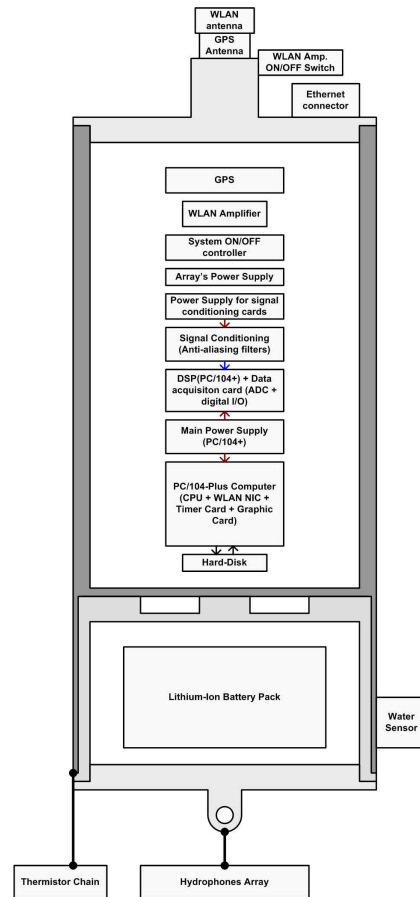
the ship, provided that there was a clear antenna connection or the AOB2 was close by the ship.

The AOB2 sensor array used during the Makai Ex'2005 was a 80 m long cable with 8 evenly spaced hydrophones and a 4m-spaced-16-sensor RBR-thermistor chain. Both the acoustic and non-acoustic sensors were housed in a air faired plastic wire protection together with a strength member rope. Wave decoupling was tentatively assured by a set of bungees inserted on the top of the array and straightness maintained thanks to a dead weight on the bottom. As this paper is being written, a new array system for the AOB2 is being developed, that comprises 16 hydrophones and temperature sensors, over a 64 m long array. Unlike in the old system, this new array uses a rather diferent concept where the data is transmitted digitally from each hydrophone to the surface bouy. So, in this system, each analog hydrophone/preamplifier set is replaced by a all digital electronic pack performing sensing, pre-amplification, 24-bit analogue-digital conversion, buffering and transmission throught a lowcost ethernet bus line.

The battery pack is formed by a series of Li-ion pre-packed cells delivering a staggering 48 Ah under 14.8 volts, allowing the AOB2 to strieve for more than 12 hours of continuous data acquisition. Thanks to the system ON/OFF programming and wakeup-on-lan capabilities it is possible to

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perform pre-programed acquisition with very little or no power consumption in the intervals when the system is shut off. In that case the AOB2s' autonomy is extended accordingly.
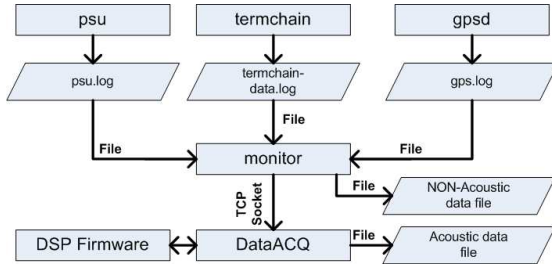
### B. The AOB2 node software



Fig. 5. *AOB2 internal software diagram.*

An important attribute to which the AOB2 howes many of its capabilities is the software that oversees and controls its behaviour. The system software control architecture is shown in the diagram of figure 5. Only Linux Open Source ressources were used for the operating system, that was stripped down to its minimal services including ftp, ssh, networking and development. The GPS module retrieves the required information from the NMEA string and makes it available on a TCP socket for other applications. The PSU module records voltage, current consumption and temperature information from the power supply unit for remote status control purposes, in particular to control the battery charge and internal container temperature. The TERMCHAIN module records the termistor chain data from the serial port and saves it in a suitable format for analysis. The DataACQ performs the acoustic data acquisition and storage; a number of operations are executed in the same loop, including data retrieval from the DSP, interaction with the DSP firmware, GPS time reading and marking of data files. Finally the MONITOR file is controlling the whole process and save status data, including non-acoustic and environmental data for posterior data playback.

### IV. AT SEA TESTING RESULTS

This section is not intended for a detailed reporting of scientific results obtained during at sea testing but simply to give an overview of the overall performance of the AOB1/AOB2 node prototype on a standalone configuration, and maybe give a glimpse of what the performance of the whole AOB network system would be.

### A. AOB1 testing during the MREA'2003 and 2004

As explained above, the AOB node prototype AOB1 was first tested at sea during the MREA sea trial in June 2003 in the area north of Elba I. (Italy) and then in April 2004 off the west coast of Portugal. Detailed data reports of these sea trials can be respectively found in [6] and [7]. Other results were presented in [8] and [9]. The source ship course and the 5-hour AOB1 drift over the bathymetry map of the area covered in the MREA'03 are shown in figure 6. Temperature estimation
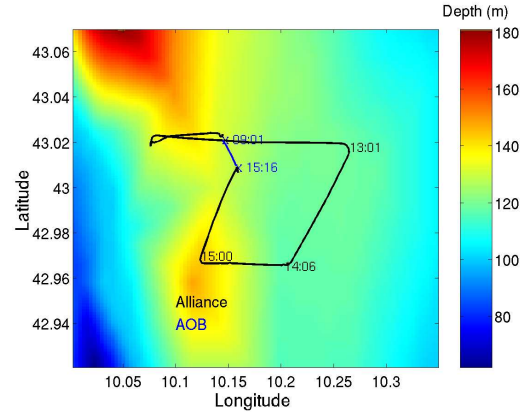


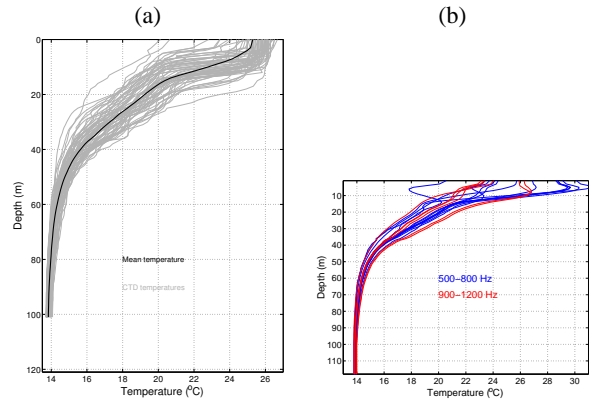Fig. 6. *MREA'03: GPS estimated AOB1 drift and NRV Alliance track during day June 21.*



Fig. 7. *Temperature profiles during MREA'03: CTD measured (a) and inverted from acoustic data (b) of day June 21.*

was performed from the acoustic data by focalizing a number of environmental bottom and water column parameters (see details of the data inversion in [8]). Only 4 hydrophones were available for inversion and two frequency bands were used. Measured temperature profiles in the area are shown in figure 7(a) and inversion results in (b). It can be easily remarked that coherent results were obtained mostly for the upper frequency band which is believed to be due to the low number of hydrophones available and their location in the water column combined with the strong downward refracting gradient. Note that these results were obtained on board ship during the experiment, and actually available a few hours after the acoustic data was collected.

One of the MREA'2004 runs is shown in figure 8 where the area bathymetry is seen as pretty much constant, so a range independent model was used. As an example of another usage of the AOB system is source localization. Results are shown in figure 9. These results were obtained after focalization of the environment using tight bounds on the source location and then opened up for a wide range/depth search. This result is not perfect but one should take into account that only 3 hydrophones were used for this inversion and that false results
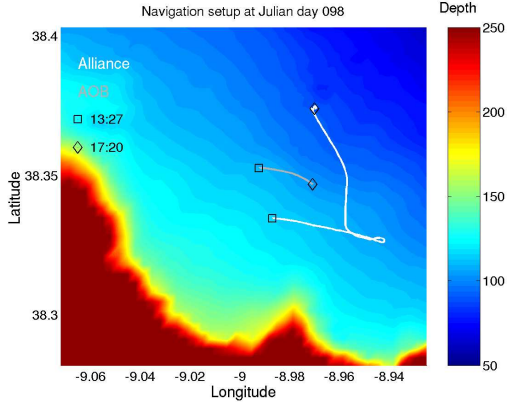
Fig. 8. *MREA'04: GPS estimated AOB1 drift and NRV Alliance track during April 8, 2004.*

can be easily rulled out by the one-to-one correlation of the unlikely wrong depth variations and the range estimates. Most of the obtained location misses are believed to be due to environmental water column/bottom mismatch. This result was obtained with a coherent broadband version of the subspace-based algorithm MUSIC adapted to matched-field processing.
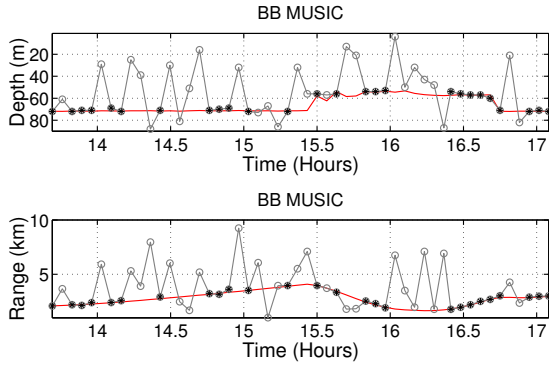


Fig. 9. *MREA'04 April 8, 2004: depth estimation (top) and range estimation (bottom) using the broadband MUSIC algorithm both for environmental and source localization.*

An attempt of AOB data assimilation for spatial temperature distribution over a wide shallow water area using realistic data was made in [10] where it is shown that amalgamation of point direct observations (CTDs) and acoustic inversions along several crossing propagation paths can significantly contribute to resolve a simulated complex eddy across the area.

### B. High frequency acoustics during Makai'Ex 2005

The Makai'Ex 2005 took place off the west coast of Kauai I. (Hawai,USA) and its primary objective was to study high frequency acoustic signal propagation in shallow water. Despite an initial plan for two AOB2 deployments, the AOB2 was actually deployed 6 times, mostly on consecutive days and one day it was deployed twice. The AOB2 and ship's

course during one of the deployments as appeared on the base station monitor is shown in figure 10. An example of
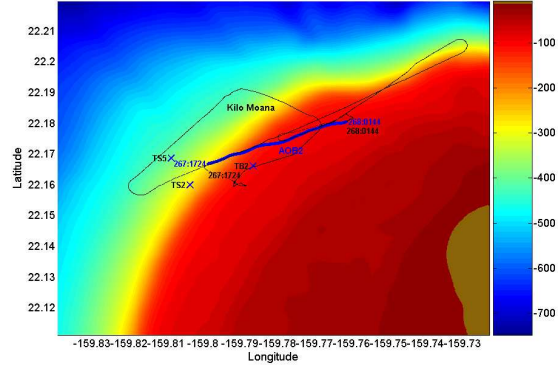


Fig. 10. *Makai Ex 2005: GPS estimated AOB2 drift and R/V Kilo Moana track during Julian day 268.*

the time-frequency plot of the received signal sequence on an hydrophone located at 55m depth is shown in figure 11. It can easily be seen that a 3 kHz bandwidth modulated signal centered on 10 kHz is being received for the first 6.5 seconds or so. A second signal shows a sequence of 8 - 14 kHz linear frequency modulated (LFM) up sweeps[1] followed by a multitone signal in the same frequency band and finally an M-sequence. Just before the end there are a series of LFMs in the band 8.5 - 11.5 kHz. Note that the first and the second signals are being received from sound sources situated in two different locations since they clearly have different strengths. The record is extremely clear, there is a low frequency noise in the lower band and a 16 kHz cutoff frequency introduced by the AOB2 antialiasing filters. No tomographic inversion
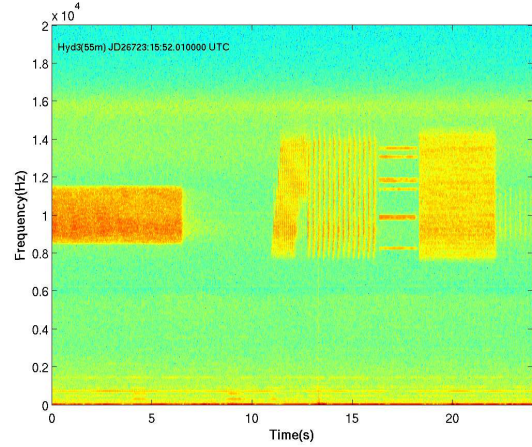


Fig. 11. *Makai Ex 2005: received signal on hydrophone3 at 55 m depth, during Julian day 267 at start time 23:15 UTC showing source 1 transmission ending and source 2 transmission starting.*

has been achieved so far in these signals since environmental

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[1]the first LFMs are distorded by the transmitting transducer.

effects are much more detailed and masked by such variability as that introduced by surface scattering and source/receiver motion even though the background signal propagation can be easily accounted for with current ray tracing acoustic models. Using a standard baseline environment the geometry shown in figure 12 can be easily accounted for to reproduce the channel 8 - 14 kHz response on an hydrophone located at 55 m depth as shown in figure 13, thus giving good perspectives for data inversion.
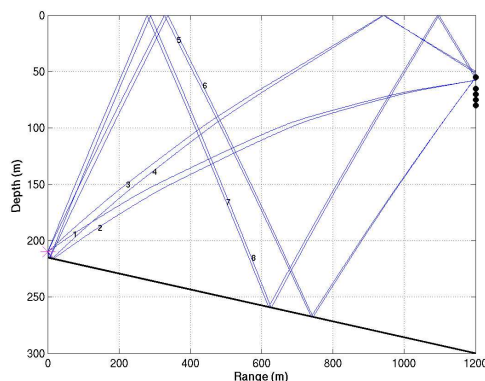


Fig. 12. *simulated ray trace diagram for the source 2 emitted signal as received on AOB2 hydrophone at 55m depth using Makai Ex 2005 geometry.*
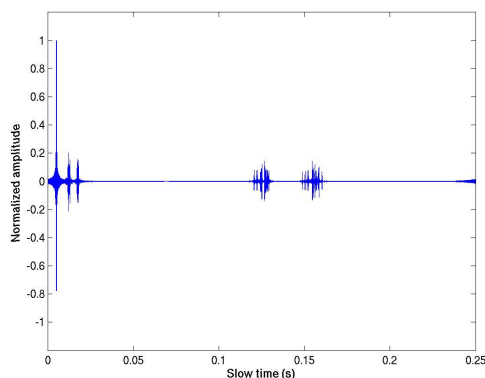


Fig. 13. *modelled impulse response in the 8 - 14 kHz band as predicted with a simple ray-trace model on a hydrophone located at 55m depth using Makai Ex 2005 geometry.*

## V. CONCLUSIONS

The assessment of environmental conditions of a coastal area, either for simple monitoring or for conducting military operations, has been a subject of considerable interest in the last years. The effort of the oceanographic community has been concentrated on perfectioning modelling and data assimilation tools for environmental conditions nowcast and forecast. Acoustic measurements are nowadays being used as complementary source of information for ameliorating environmental predictions, specially when aiming at acoustic predictions for

covert operations in hostile waters. Actual acoustic receiving systems for environmental information retrieving are generally built for research purposes and do not fulfill the requirements for operational use. The AOB system is a pre comercial full featured toll with both an air dropped sonobuoy like system to form a spatially distributed network of acoustic receivers and a software backend for data processing and real time result delivery. A single node system prototype has envolved in the last three years and is now being tested in a full featured multi node version for rapid online response. The emphasis is now on the software development for data inversion, integration and suitable display. AOB system capabilities are not limited to REA but can be extended to other activities such as 3D passive/active source localization, autonomous vehicle tracking and time reversal steering techniques for covert underwater communications.

## REFERENCES

[1] P. Elisseeff, H. Schmidt, M. Johnson, D. Herold, N.R. Chapman, and M.M. McDonald. Acoustic tomography of a coastal front in haro strait, british columbia. *J. Acoust. Soc. Am.*, 106((1)):169–184, July 1999.
[2] P. Elisseeff, A. Schmidt, and W. Xu. Ocean acoustic tomography as a data assimilation problem. *IEEE Journal of Oceanic Engineering*, 27(2):275–282, 2002.
[3] P.F.J. Lermusieux and C.S. Chiu. Four-dimensional data assimilation for coupled physical-acoustical fields. In Pace and Jensen, editors, *Impact of Littoral Environment Variability on Acoustic Predictions and Sonar Performance*, pages 417–424, Kluwer, September 2002.
[4] P.F.J. Lermusieux and C.S. Chiu. Transfer of uncertainties through physical-acousticalsonar end-to-end systems: A conceptual basis. In Pace and Jensen, editors, *Impact of Littoral Environment Variability on Acoustic Predictions and Sonar Performance*, pages 603–610, Kluwer, September 2002.
[5] A. Silva, F. Zabel, and C. Martins. Acoustic oceanographic buoy: a telemetry system that meets rapid environmental assessment requirements. *to appear Sea-Technology*, September 2006.
[6] S. Jesus, A. Silva, and C. Soares. Acoustic oceanographic buoy test during the mrea'03 sea trial. Internal Report Rep. 04/03, SiPLAB/CINTAL, Universidade do Algarve, Faro, Portugal, November 2003.
[7] S.M. Jesus, P. Felisberto, A.J. Silva, C. Soares, L. Farinha, and C. Martins. Acoustic maritime rapid environmental assessment during the mrea'04 sea trial. Internal Report Rep. 02/05, SiPLAB/CINTAL, Universidade do Algarve, Faro, Portugal, March 2005.
[8] C. Soares, S.M. Jesus, A. Silva, and E. Coelho. Acoustic oceanographic buoy testing during the maritime rapid environmental assessment 2003 sea trial. In *Proc. of European Conference on Underwater Acoustics*, pages 271–279, Delft, The Netherlands, July 2004.
[9] C. Soares and S.M. Jesus. Matched-field tomography using an acoustic oceanographic buoy. In S.M. Jesus and O.C. Rodríguez, editors, *Proc. of European Conference on Underwater Acoustics*, Carvoeiro, Portugal, June 2006.
[10] P. Felisberto and S.M. Jesus. An hybrid acoustic-oceanographic method for estimating the spatial distribution of sound. In S.M Jesus and O.C. Rodríguez, editors, *Proc. of European Conference on Underwater Acoustics*, Carvoeiro, Portugal, June 2006.