CHAPTER 1

Marine bioacoustics and computation bioacoustics at the University of Pavia (Italy)

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1. Introduction

1.1 Presentation of the team

The Interdisciplinary Centre for Bioacoustics and Environmental Research was created in 1989 as a follow-up of the Bioacoustics Laboratory set in 1983 by Gianni Pavan at the Institute of Entomology of the University of Pavia. The research was initially devoted to the development of computer programs and devices to convert analog recordings into the digital domain to be entirely processed and visualized by computer. In those years this approach was pioneristic and produced the first computer system available in Italy to analyze and visualize bird songs digitally, initially by black and white spectrograms and then in colour, with the amplitude coded as different graded colours. These were the first steps of a new research branch named "computational bioacoustics". The new instruments were applied to diverse zoological groups: birds, frogs, insects, and then in 1989 the first analyses of underwater recordings of fishes (Torricelli *et al.*, 1990) and marine mammals made with stationary hydrophones.
In following years, the great interest in marine mammals and the concerns for their conservation drove new research interests and instrumentation development.

CIBRA began to organize visual and acoustic marine surveys in 1991. In years 1991 to 1993 surveys were conducted in cooperation with the Tethys Research Institute to investigate cetacean sounds and behavior in

Italian Seas by using a towed array of hydrophones built in the lab and connected to a portable computer equipped with a DSP board for sound acquisition and real-time spectrographic display (Borsani *et al.*, 1992; Pavan, 1992, 1994).

In following years the CIBRA team, initially composed by G.Pavan and J.F.Borsani, was joined by M.Manghi, M.Priano and C.Fossati. With the new team, research cruises with motorsailing boats were organized in Italian seas to study marine mammals and to develop techniques and protocols to identify, localize and track them.

In 1993 a new array was built by ALENIA ELSAG Sistemi Navali on specifications given by CIBRA. In years 1994 to 1997 cruises were organized entirely by CIBRA with renewed equipment (Pavan & Borsani, 1997). Given the limited storage provided by hard disks, in those years the recording of the sounds received by the hydrophones was made on DAT (Digital Audio Tape) recorders, with bandwidth limited to about 22 kHz (48 kHz sampling rate). Operators used to listen the received sounds with headphones; however we began to experiment real-time spectrographic analysis with sampling rates up to 100 kHz that turned out to be a fundamental tool to provide immediate visual feedback about signals, e.g. echolocation clicks, with frequencies largely exceeding the human hearing range (Pavan *et al.*, 2001). In those years our research evidenced the potential use of bioacoustics to study marine mammal populations and to perform environmental research by applying an interdisciplinary approach (Pavan *et al.*, 1996a, 1996b; Pavan *et al.*, 1997; Priano *et al.*, 1997).

To develop and discuss these ideas an international workshop was organized in 1994 at the School of Ethology hosted by the Ettore Majorana Center in Erice, Sicily (Fine *et al.*, 1997).

Despite the limitations given by the technologies available, relevant results were obtained, among them the description of the sperm whales' coda typical of the Mediterranean Sea (Pavan *et al.*, 2000), the real-time estimation of the size of sperm whales based on cepstrum analysis (Pavan *et al.*, 1997, 1999; Fossati *et al.*, 2003), and the dual-use of military equipment, e.g. sonobuoys, to detect marine mammals (Fossati *et al.*, 2003).

In 1995 we began to cooperate with the Italian Navy to study marine mammals and the possible impact of naval sonars (Pavan *et al.*, 1997).

The importance of this topic led to the participation of CIBRA to the NURC (NATO Underwater Research Center) panel to investigate on the mass strandings of beaked whales occurred in Greece in 1996 (Frantzis, 1998; Abraham *et al.*, 1998) and subsequently to the development of the SOLMAR (Sound and Living Marine Resources) project that turned into the MMRMP (Marine Mammals Risk Mitigation Program) in latest years. In this context CIBRA participated to the development of the NATO Policy (Ryan, 2009).

In the period 1999 – 2012 the main projects were related to the NURC activities and the participation to the SIRENA research cruises (http://solmar.nurc.nato.int/) and to other research on marine mammals' strandings (Podestà *et al.*, 2006). Within the MMRMP program the Office of Naval Research (US) provided funding for our project "Bioacoustic characterization of the Mediterranean Sea" (1999-2004).

Latest developments of the CIBRA activities were also concerned with the conservation of marine mammals and for this purpose CIBRA cooperates with ACCOBAMS and ASCOBANS to the definition and the implementation of guidelines to reduce the impact of anthropogenic noise in the marine environment (Pavan, 2007a, 2007b); in this context, on behalf of the Italian Ministry of the Environment, CIBRA created and actually maintains the online database of the National Stranding Network in cooperation with the Natural History Museum of Milan (http://mammiferimarini.unipv.it). CIBRA also cooperated (via associated company Right Waves) with Columbia University (NY, USA) to implement PAM Passive Acoustic Monitoring as requested by National Marine Fishery Service (USA) on Lamont-Doherty Earth Observatory seismic vessels (2004-2010). This experience gave CIBRA operators direct knowledge on many critical aspects of seismic surveys usually related with Oil and Gas exploration, a very sensitive branch of marine mammals' protection aspects.

1.2 Context of our research

The concern that man-made acoustic signals can affect marine mammals has increased over the past ten years, mainly within the context of low and mid-frequency active sonars and seismic surveys. Whether it is in support of acoustic risk mitigation measures or in the larger context of environmental monitoring, recent years have seen an increasing use of passive acoustics at sea.

Passive acoustics is a powerful tool to be used for (a) expanding knowledge about marine mammals' distribution, (b) monitoring underwater noise, (d) monitoring critical habitats, (e) evaluating the effects of sound exposure on animals' behaviour, (f) implementing mitigation policies, (g) planning and enforcing conservation policies.

To improve research capabilities and to support the Acoustic Risk Mitigation Policies being developed by many national and international civil and military organizations, we designed, built and extensively tested a complete set of equipment to provide an affordable and flexible tool for wide band acoustic detection and monitoring. The equipment provides detection, processing, storage and plotting capabilities to be used for both wide area surveys and local monitoring needs. The system, described in following chapters, includes towed arrays of hydrophones, signal acquisition hardware and software packages for real-time data analysis.

The results obtained in many years of visual and acoustic surveys, together with the information collected by the Italian Stranding Network, are now being used for databases on the Mediterranean marine mammals in support of the European Defence Agency project "Protection of Marine Mammals" (EDA – POMM), in cooperation with the IT Navy, and of the implementation of the EU's Marine Strategy Framework Directive (2008/56/EC) in cooperation with ISPRA, an agency of the Italian Ministry of the Environment.

To support international cooperation, CIBRA organized several meetings, namely, the international workshop "Underwater Bioacoustics: Behavioural, Environmental & Evolutionary Perspectives" (Ettore Majorana Centre, Erice, Sicily, 4-9/11/1994), three IBAC (International Bio Acoustic Council) conferences (XV IBAC, Pavia, 24-26/10/1996; XXI IBAC, Cogne, 3-6/09/2001; XVIII IBAC, Pavia, 15-18/09/2007), the international workshops "4th Detection Classification and Localization of Marine Mammals" with the "1st Density Estimation of Marine Mammals" (Pavia, 10-13/09/2009), and it is now organizing the international workshop "Cetacean echolocation and outer space neutrinos: ethology and physics for an interdisciplinary approach to underwater bioacoustics and astrophysical particles detection" (Ettore Majorana Foundation and Centre for Scientific Culture, Erice, Sicily, 17-21/10/2013).

CIBRA is also committed to education and holds the course on "bioacoustics" for the degree in Nature Sciences.

1.3 Contents of this chapter

Most of our research was dedicated to the study of marine mammals' acoustic behavior, the monitoring and conservation of the marine environment, and the implementation of Acoustic Risk Mitigation Policies. The CIBRA approach was widely interdisciplinary, often driven by the need of developing new instruments to solve biological and technical problems, to support other research groups, and also to bring together experts in different disciplines to solve complex problems. Here we present the equipment and techniques we designed for marine bioacoustic research and the main application areas, ship based surveys and fixed platform monitoring.

2 Methods and Materials

2.1 Towed arrays

Besides new self-made instruments were under development, in 2003 CIBRA main acoustic equipment was the wideband dipole array built by ALENIA Sistemi Navali in 1993 connected to a completely renewed digital signal processing workstation developed in our lab for wideband signal acquisition, storage and real-time processing and display (Pavan *et al.*, 1997). During the period 1999-2007 we tested several sensors, cabling, connectors, array materials (hoses, spacers, stress members, filling, ballast) and architectures to setup a flexible system to be used on different platforms (Pavan *et al.*, 2001, 2004; Priano *et al.*, 2003) and contexts, including dolphinariums and fixed seafloor platforms (Riccobene *et al.* 2004, 2009). In 2007 we provided (via an associated Company) a towed array to Columbia University, NY, to be used for Passive Acoustic Monitoring (PAM) services on a seismic vessel owned by US Govern and operated by Lamont-Doherty Earth Observatory. In the period 2007 – 2010 CIBRA team gained wide experience in operating arrays and digital signal processing for PAM during seismic surveys with Columbia University – Lamont-Doherty Earth Observatory (Holst *et al.*, in press; Holst & Beland, 2010).

In the same period we built new towed arrays to meet the requirements of the research focused on the detection and tracking of beaked whales, with the double purpose of mapping their distribution and supporting the WHOI team in attaching DTAGs and performing BRS experiments in NURC SIRENA cruises. New sensors and preamplifiers were provided by COLMAR, a company based in La Spezia (Italy), on CIBRA specifications to reach proper bandwidth and SNR.

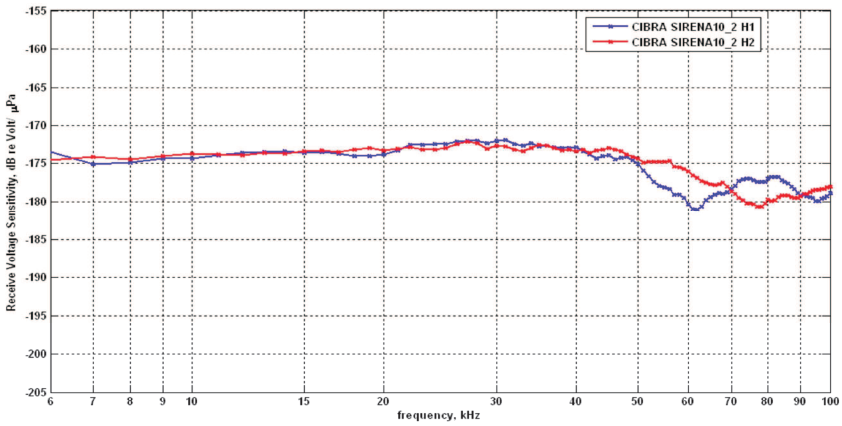

Figure 1: Frequency response and sensitivity of the array used in SIRENA 10 (Calibration was performed at NURC).

In early 2012 CIBRA was asked to provide acoustic support to a BRS study in the Ligurian Sea organized by St. Andrews University (UK) and Woods Hole Oceanographic Institution (USA) with ONR funding. CIBRA task was to detect, track and focal follow deep diving Cuvier's beaked whales to support tagging operations and provide real time feedback of animals' response to playback. New wideband, low noise sensors (designed in co-operation with COLMAR) were used with a new mounting architecture to increase operating depth and reduce self noise. Two arrays were prepared and towed in parallel, to guarantee tracking of diving animals without the R/L ambiguity that is typical of single towed arrays. A simple but effective structure was prepared and installed on deck (R/V was a 16mt long motorsailer, Aleph) to laterally separate the towing points and allow the two arrays configuration.

2.2 PAM Workstation

The CIBRA PAM Workstation provides multichannel wideband data acquisition and storage with real-time spectrographic display, continuous and on-event acoustic recording, data logging and navigation display, operator based acoustic classification and data distribution for real-time GIS plotting. Based on the previous experience with Unix and MS-DOS machines (Pavan, weblink; Pavan, 1992, 1994), the new workstation and its software were designed in 1997 (Pavan *et al.*, 2001; Priano *et al.*, 2003; Pavan *et al.*, 2009) to get benefits from the Microsoft Windows environment and then they were regularly improved to benefit of the new hardware capabilities available.

The acquisition/processing/display system is based on a distributed architecture whose core is a powerful desktop PC with multiple sound acquisition devices and two displays. A lighter version can run on standard laptops. Processes can be concentrated on one PC or distributed on additional networked PCs to provide data backup, additional acoustic and navigation processing and display, including GIS plotting.
SeaPro is the core software developed at CIBRA. The latest version provides up to 8 channels sound acquisition, recording and display up to 192 and 384 kHz sampling rate to wav files, real-time frequency shifting and a directional display. A 2 channel version named SeaWave, is available as freeware. A special version, SeaDAQ, connected with National Instruments acquisition devices, allows up to 800 kHz sampling on one channel (Pavan *et al.*, 2001).
If GPS data is available (on a serial line or on a network connection) any data or file is time and geo-referenced.
SeaPro produces acoustic files in standard uncompressed .wav format, with 1, 2, 4 or 8 channels. Name of files can include several information as date, time, GPS coordinates, source, etc. to allow easy search in huge file catalogues. Seapro records continuously and file splitting, with no sample loss, can be adjusted as required, e.g. aligned at the beginning of each hour.
The direction display mode, named Red/Blue, provides intuitive cues of the sound-source relative position; this type of display can work on a single dipole array or on two dipole arrays towed in parallel.
Multiple instances of the software can be run on the same machine to monitor multiple acquisition boards or to provide multiple views of the same signals (a multiclient sound acquisition device is required for this task). To monitor the lower end of the spectrum, e.g. to display fin whale calls, the system can be set to zoom into low frequencies (0-250 Hz).

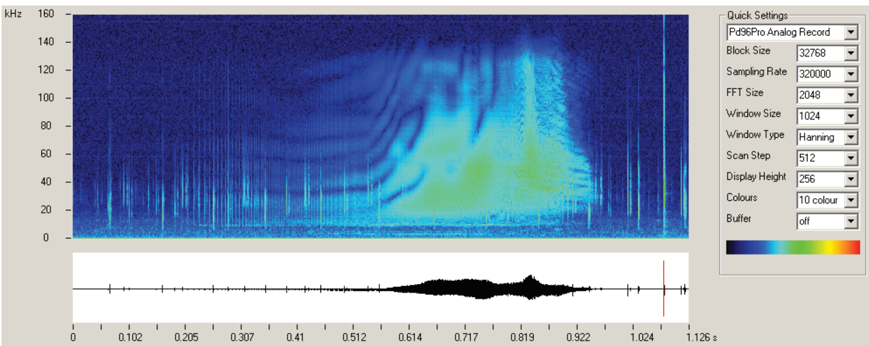

Figure 2: Sample spectrogram with 140 kHz bandwidth of a striped dolphin’s echolocation run (SIRENA 02).

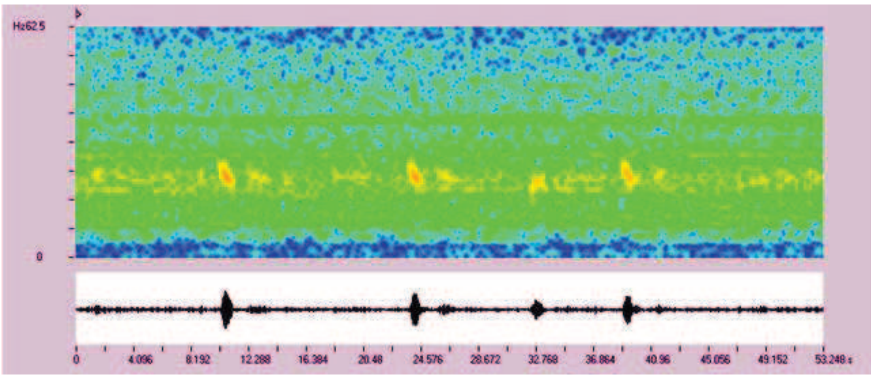

Figure 3: Sample spectrogram of fin whale sounds recorded by a sonobuoy in SIRENA 99.

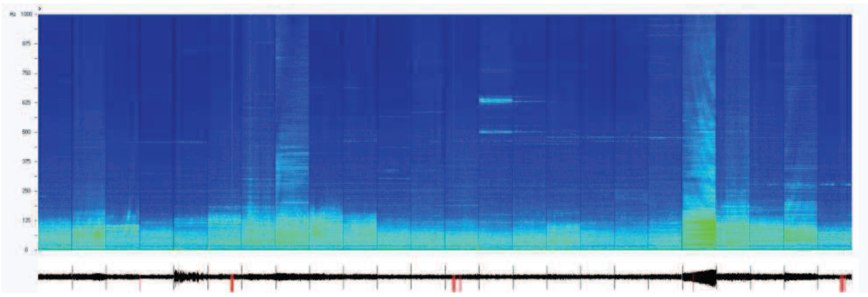

Figure 4: Sample spectrogram of the changes in the level and structure of background noise recorded by the low frequency hydrophone of SN1 in 24 hours. Each section shows 10 minutes taken every hour.

Other programs have been developed to support marine survey operations and specific applications such as mapping acoustic contacts on a GIS in real-time.

2.3 Software

WaveRecorder is a multichannel recording software that allows either continuous or scheduled recording. A special version named **SeaRecorder** has been developed for the NEMO/ONDE project (Riccobene *et al.*, 2009; see chapter 4.3.4) to maintain the synchronization of two stereo digital acquisition board receiving digital audio data from two stereo AD boards installed on the ONDE acquisition module.

NMEAManager receives NMEA navigation data from a GPS or from the ship's network and distributes by UDP $GPRMC strings to other applications running on the CIBRA cluster (SeaPro, AcousticLogger, OziExlorer, ArcView). In case the $GPRMC string is not available, it builds one using other NMEA sentences.

AcousticLogger assists operators in the classification and logging of acoustic detections. Trained operators listen to received sounds, when these are audible or frequency shifted, and observe the real-time spectrographic display produced by SeaPro to log acoustic detections and to classify them according to predefined categories.

Actual version allows to input quantity and quality of detected signals in 1 minute time slots, and, if required, when an event occurs. Data entered are immediately plotted on the navigation map and distributed as needed (visual team, bridge, active source operators, etc).

The software includes a panel to log array deployement/recovery, sonobuoy deployement, monitoring start/stop and other relevant events or user annotations. Each event generates a string message saved locally and broadcast by UDP.

OziNMEA feeds OziExplorer, a powerful shareware navigation software (http://www.oziexplorer.com), with NMEA strings distributed by NMEAManager. The program allows placing waypoints and detection bearings on the OziExplorer display.

3 Applications

Equipment and software developed at CIBRA were mostly used for research cruises to study marine mammals, to map their presence and distribution, to implement mitigation policies in seismic surveys and SONAR tests, and to support other types of research such as tagging of sperm and beaked whales.

Following chapters summarize the main projects of the latest 10 years, mainly in the context of the NURC MMRMP and of the NEMO/ONDE project managed by INGV (National Institute of Geophysics and Volcanology) and INFN (National Institute of Nuclear Physics).

Research cruises with oceanographic ships and other projects allowed to collect a huge quantity of wideband recordings that are archived in the Marine Mammals Sound Library at CIBRA (Priano *et al.*, 1997). The Library holds more than 15TB of recordings made in a wide range of different environmental conditions and with different detection equipment, including stationary hydrophones, towed arrays of hydrophones, and sonobuoys; it offers the opportunity to test detection and analysis algorithms on recordings with a wide range of quality levels, signal to noise ratios, and overlapping biological and anthropogenic sounds.

3.1 Visual and acoustic surveys to study marine mammals acoustics

The cruises made in years 1991 to 1997 were fundamental for the development of the tools but also for learning how to manage surveys, behavioural studies, and also to understand the importance of using acoustic detection to reveal the presence of animals below the sea surface.

In 1999 we began to cooperate with Saclantcent, a NATO research center based in La Spezia (Italy), subsequently called NURC, initially for the program SOLMAR (Sound Oceanography and Living Marine Resources) and lately for the program MMRMP (Marine Mammal Risk Mitigation Project) aimed at developing methods and protocols to reduce the impact of high power sonars on marine life.

In following years we participated to several research cruises organized by NURC, formerly Saclancent. In those cruises, namely SIRENA 99, 00, 01, 02, and 03 we used our towed arrays and the PAM workstation to record underwater sounds for many different purposes (mapping distribution, studying behavior, tracking diving animals, mitigation). The availability of an excellent, stable, quiet and comfortable research vessel, the NRV Alliance, allowed performing wide area surveys with 24h/day acoustic monitoring and recording with trained operators shifting every 2-4 hours. This allowed producing maps of the acoustic contacts and related emitting species. The analysis of the data showed a clear dial cycle in the quantity of echolocation sounds from dolphins, with peaks in dark hours related with the nocturnal vertical movements of plankton and fish schools (Manghi *et al.*, 2003) along with new sound categories, e.g. the “nacchere” or “castanets”, emitted by striped dolphins foraging at night (Fossati, 2010). In these cruises were also made ultra wide band recordings of echolocating striped dolphins with sampling rates of 320, 400 and 800 kHz.

Research cruises, organized or co-organized by NURC (SIRENA 99-00-01-02-03-04-08-10-11; ZIFIO 05, CEDAR 05, MED09) allowed to improve the equipment and develop new instruments and protocols to conduct efficient visual and acoustic surveys. Information on these cruises is available on http://solmar.nurc.nato.int/

3.2 Detection and tracking of beaked whales

Beaked whales are a sensitive species due to the adverse response they have to active SONAR Navy exercises. Being deep divers and spending little time at surface (Barlow & Gisiner, 2006), acoustic investigation rapidly became essential in their study and protection.

The ability to detect the cetacean presence and map their distribution is a key point of mitigation strategies, either for the correct planning of naval operations or for the in-situ mitigation of risks. First complete description of their sounds comes from WHOI's DTAGs (Johnson *et al.*, 2003, 2004; Zimmer *et al.*, 2005).

In late September 2005, CIBRA participated to a NURC research campaign (Zifio 05) in the Ligurian Sea to study Cuvier's beaked whales, characterize their habitat, and attempt to remotely record their acoustic signals by using sub-surface hydrophones. Many research vessels (NURC, IT Navy, Private Institutes) took part to the operation, and several different acoustic tools and techniques used.

The CIBRA team worked onboard the Krill, a 12m catamaran, with its PAM equipment, based on a wideband towed array connected to a low-noise front-end to allow digital recording with nearly 90 kHz bandwidth (192 kHz sampling rate). CIBRA team recorded beaked whales' sounds and, for the first time, demonstrated the feasibility of acoustic detection of these animals with relatively simple and low cost equipment (Pavan *et al.*, 2006, 2009).

In summer 2008 we were asked to participate to Sirena 08, a NURC combined visual and acoustic transect survey designed to determine the presence and distribution of marine mammals in the Alboran Sea and to support subsequent tagging operations on Cuvier's beaked whales (*Ziphius cavirostris*) and long-finned pilot whales (*Globicephala melas*).

The transect survey was planned to cover the investigation area four times in 18 days to guarantee a homogenous coverage of the area. Passive acoustic equipment was used 24h/day. In 18 days of transect survey 3333 kilometers were covered at an average speed of 4.8 knots. 390 hours of acoustic monitoring were performed. Due to unfavorable weather conditions, visual survey was limited to 13 days and 504 kilometers on effort. Beaked whales were detected acoustically for 350 minutes, grouped in 59 clusters of contacts. Visual observations occurred 16 times (10 Cuvier's beaked whale, *Ziphius cavirostris* and 6 undetermined beaked whales).

The work done in SIRENA 08 definitively demonstrated that the acoustic detection of deep diving beaked whales is possible with arrays towed at a shallow depth (Pavan *et al*., 2010; Azzellino *et al*., 2011).

Results in both real-time and post-processing classification indicate the feasibility of reliable recognition of Cuvier's beaked whales' acoustic signatures, at least when not overlapped and masked by other odontocete sounds. In particular, the presence of delayed surface reflections of the echolocation clicks resulted to be an important classification cue indicating that the received sound originated from a toothed whale foraging at depth. This contextual information can easily be visualized by high resolution spectrograms and by time-delay estimation techniques, e.g. by accumulating detection time differences in time varying histograms (Zimmer *et al.*, 2008).

Based on the results of SIRENA 08, we have been invited to the research cruise MED 09, organized by NURC in co-operation with WHOI, for a visual and acoustic survey in a wide area of the western Mediterranean Sea to identify areas suitable for tagging beaked whales. For the first time CIBRA attempted a new approach intended to provide real time acoustic focal follow of deep diving beaked whales. Two dipole arrays were towed in parallel at same distance from the stern and laterally separated by a known distance. Signals were acquired and displayed on screen with the CIBRA workstation and a new display mode implemented in SeaPro. Thanks to the RB SeaPro display, operators could determine target bearing, plot them on the GIS, steer the main vessel and direct the tagging boat to the next surfacing area.

The cruise was composed by two distinct phases: a survey to map the distribution of marine mammals, with a special focus on beaked whales, followed by a tagging phase to apply D-TAGs on beaked whales and test the ability of the PAM to track them during their dives.

The ability to track diving beaked whales is functional to make the tagging easier, by predicting the next surfacing time and location of diving whales, but also to track and monitor the acoustic behaviour of D-TAGged whales during Controlled Exposure Experiments (CEE) and Behavioural Response Studies (BRS).

The hardware set consists of 2 wideband, high sensitivity & low noise dipole towed arrays, to be deployed in parallel from the sides of the vessel. The sensors are placed at the vertices of a virtual square 8 m wide. Analog signals from the four hydrophones are filtered and digitized at 192 kHz sampling rate to be stored and displayed on the CIBRA workstation.

When beaked whale clicks are detected by the operator (either visually and/or acoustically via SeaPro frequency shifter), the RB (Red/Blue) display allows the operator to visually assess the position of the sound source (front/rear; left/right). The position can then be plotted on a geographical display along with vessel's position, thus making it possible to maneuver the vessel to stay in contact with the diving animals. During MED09 cruise the CIBRA PAM system was operational for 39 days. Cuvier's beaked whales were detected (single animals or groups) 45 times, with a contact duration ranging from 1 minute (in transit mode) to 56 min (in tracking / focal follows mode). Twenty acoustic focal follows were performed, with an average duration of 30 minutes each (range 18 –

56 min). For the first time it was possible to perform extended acoustic focal follows of diving Cuvier's beaked whales using passive acoustic detection systems (without the benefit of an undersea acoustic monitoring range, as had been used in previous similar studies in the Bahamas).

In 2010 and 2011 CIBRA participated to the SIRENA 10 and SIRENA 11 sea trials organized by NURC to perform marine mammal surveys in the Atlantic waters adjacent the Gibraltar Strait and in the Ligurian Sea. In these cruises the main goal was the acquisition of acoustic and oceanographic data to possibly correlate the presence of cetaceans with oceanographic features at different scale levels (Maugeri, 2012).

In 2012 CIBRA organized a research cruise within a project granted by ONR to WHOI and St. Andrews University. The goal of the cruise was find, track, tag and expose beaked whales (*Ziphius cavirostris*) to predefined sounds in order to record their behavior changes (BRS). The cruise was conducted in the Ligurian Sea waters, well known as a "hot spot" for this species. The platform was the Aleph, a schooner 16m long. CIBRA team designed, set up and managed the PAM system in order to detect and track the diving animals (assisting the visual team) and in order to certify any change in the acoustic behavior after the playback.

The main issue to face with was to transfer a tested setup of instruments from a large, dedicated and well equipped research vessel (NRV Alliance, see MED09) to a relatively small sailing boat (the schooner Aleph, http://www.ambientemare.org). The first problem was relative to the dimension of the boat and therefore his beam: the towing points of the arrays were too close each other to allow the right distance between the two arrays. This problem was solved through the design of an appropriate system of booms, easy to install and remove, safe and fast to control and, least but not last, cost effective. Another problem was relative to the power for the entire chain of instrument in term of supplied power and electric noise of the boat electrical apparatus. This problem was solved splitting the power supply and using autonomous batteries to feed the first part of the chain (up to the audio interfaces) and using an excellent, low noise inverter (connected to the boat electric system) to feed the laptops.

Even if there was no chance to perform a complete playback experiment, from the "acoustic point of view" the cruise was a real success: CIBRA team was able to transfer the instrumental set to a new platform facing new different challenges; and with this new setup the team was able to detect beaked whales and perform long acoustic tracks (up to about 20 hrs).

As well rendered in previous experiences, one of the key for the success of this kind of surveys is the personnel: a team composed by well trained and experienced operators is able to face expected and unexpected problems and to correctly interpret the data also considering the context and the local history of the observed phenomena, and identify good data for processing. Our approach, in fact, is based on a balance between operator and machine. The operator, thanks to her/his experience, can discriminate correct signals from false ones (still a hard task for automatic classification systems), and let the machine work just on meaningful data. This eliminates the false positives that, in critical situations like BRS or seismic surveys, can either stop the experiment pointlessly or fail to prevent a dangerous situation.

3.3 PAM for the protection of marine mammals in seismic surveys

Seismic surveys traditionally use underwater high power sound sources to investigate geological structures below the ocean bottom, mostly for oil exploration. Lots of seismic vessels continuously operate worldwide, locally generating a heavy acoustic pollution. In 2004 CIBRA was contracted by Lamont-Doherty Earth Observatory (Columbia Univ. NY, USA) to provide Passive Acoustic Monitoring services (Holst *et al.*, in press; Holst & Beland, 2010). This activity, besides it is now implemented on a number of vessels, presents a series of problems hard to solve that require highly skilled operators and well suited equipment.
The goal is to detect and possibly classify vocalizing animals, determine their position and distance. The information is then used according to the operating Marine Mammals Protection protocol (power – shut down of sound source, alert visual team etc.).
Difficulties inherent to this task are variable and related to each vessel. As a general overview, the first problem is the array design. These vessels operate worldwide, so the array should be able to pick signals from VLF baleen whales to VHF beaked whales. The vessels often tow lots of seismic equipment (airgun arrays, seismic arrays that can be kilometers long) and operate an extra “whale” array can be very problematic. The underwater environment is very noisy, with airguns’ blasts every few tens of seconds, flow noise, echosounders, sidescans etc. PAM array depth is also critical, first to avoid interaction with the seismic gear. PAM array has also to be towed close to the airgun, that is the center of the Safety Radius.
Software is also critical. The whole system has to be resistant to the electronic noise, generally very heavy onboard. Automatic detection software, even if largely used, are very hard to tune in such conditions and only an experienced acoustic operator is able to judge the real performance of the “wet side”. Results (acoustic contacts number)

published after seismic cruises (including the latter we participated) are generally way lower than what could be expected during a normal Marine Mammals dedicated cruise; this could be motivated by the avoidance the animals, by the not optimal detection capabilities onboard, or by a combination of both. This suggests that PAM on seismic vessels is generally still far from guarantee acceptable results. Misunderstandings or excessive confidence in hardware and software can lead to adverse results as marine mammal protection. The subject, according to our experience, should be re-negotiated with Oil companies and Protection Agencies on a base of a more strict control of field results.

3.4 Passive Acoustic Monitoring with deep seafloor hydrophone installations

INFN and INGV develop and run deep sea infrastructures and instruments for a wide range of scientific purposes including marine biology and, with CIBRA coordination, marine bioacoustics.
Our research began in 2004 with the NEMO-OnDE platform (Riccobene *et al.*, 2009) deployed at 2000m depth 25 km off the port of Catania (Sicily) and connected to the INFN-LNS (Italian National Institute of Nuclear Physics - Laboratori Nazionali del Sud) laboratory of Catania by fiber optic cables. The deep sea and shore infrastructures are capable to manage high data rates coming from networked sensors on the seafloor. Wideband acoustic data have been collected during 2 years of operations (2005-2006); CIBRA developed the acquisition software and coordinated the analysis of bioacoustics signals that revealed an unexpected presence of sperm whales with interesting seasonal variations (Pavan *et al.*, 2007; Pavan *et al.*, in press). These results were largely reported by international newspapers and journals (Nosengo, 2009). This pilot project led to the construction and installation in 2012 of the new SN1-OnDE observatory, funded under the LIDO Demonstration Mission of ESONeT (FP6) in collaboration between INFN, INGV (Italian National Institute of Geophysics and Volcanology) and other national and international institutions. SN1-OnDE is a multidisciplinary seafloor observatory designed to perform seismic monitoring and oceanographic studies (SN1), and wideband acoustic measures (OnDE). The SN1-OnDE observatory is a cabled node to the EMSO ESFRI insfrastructure (Favali *et al.*, in press) now operational offshore Catania. Another deep sea acoustic observatory has been recently deployed at 3000 m depth offshore Capo Passero (Sicily). The acoustic data management of both observatories is carried out within the Submarine Multidisciplinary Observatory (SMO) program, a FIRB project granted by the Italian

Ministry of the University and Research, hosted by INFN-LNS (http://web.infn.it/smo). CIBRA is partner of the project for the bioacoustics studies and G. Pavan is Associate Researcher at INFN-LNS.

This new station is able to provide wide band acquisition for sperm whales and other odontocetes as well as low frequencies fin whales' calls. Our objective is to describe the habitat use, study the sperm whales' seasonal movements, and, with the presence of a low frequency dedicated sensor, to map the presence of fin whales and measure the low frequency background noise. By using AIS data it will be possible to link measured noise levels to the ship traffic in the area and possibly identify the most noisy ships.

Other than the technical difficulties inherent to the installation and maintenance of the deep station and related infrastructures (not within CIBRA tasks), the analysis of big recording datasets is very time consuming. Automatic detection programs have been tested and proficiently used to extract sperm whales' clicks, but manual analysis is still required to get accurate reliable results. As this is time consuming and requires expert operators, new software are under development/test to make easier the processing of huge datasets.

This kind of fixed, long term platforms can fill the gaps linked to traditional surface surveys, usually concentrated during the good season and anyway rarely covering long time windows. Mapping seasonal use or concentration of animals may suggest migration patterns or particular use of the area (feeding, breeding…) and therefore support effective protection actions.

In this context we cooperate with the research team headed by H. Glotin at "LSIS - DYNI" (Laboratoire des Sciences de l'Information et des Systèmes - DYNamique de l'Information), University of Toulon Sud-Var, France, that specilizes in the development of algorithms to track the movement of diving sperm whales and to assess their size by estimating the delays among the pulses that constitute their echolocation clicks.

4. Conclusion

In the ten years described in this report there was an increase of concern about the impact of human activities on the marine environment and on marine mammals in particular. In response to this concern many efforts have been conducted to improve technologies for monitoring marine mammals population and passive acoustic methods proven to be an efficient tool for detecting the presence of animals and for describing their behavior. The technological transfer from military technologies to scientific research and the development of new technologies for the exploration of the sea allowed a diffusion of acoustic investigation techniques and an expansion of research in remote areas. Most recent developments tend to implement automatic methods for the identification/classification of received signals that are functional to the huge increase of data acquired by multiple, wideband sensor systems and by remote platforms, either stationary or moving.

We believe that our contributes to these developments are significant and our experience in multiple fields traced a route for other research groups. We are proud of having contributed to the early development of computational bioacoustics and, in latest years, to the development of a complete set of equipment to make marine bioacoustics research affordable. Twenty years of experience also demonstrated the efficacy of a multidisciplinary approach that connects many scientific branches to improve our understanding of the marine environment in support of its conservation.

5. Future work

To support further developments and an expansion of acoustic monitoring techniques it is required to greatly improve our ability to process huge amounts of data coming from multiple sensors along with the ability to integrate information from multidisciplinary sensors.

In the near future it is envisaged the replacement of traditional ship based surveys, expensive and limited in time and space, with fleets of autonomous vehicles able to move on the surface or below the surface to collect acoustic and oceanographic data. Another envisaged development is about deep multidisciplinary sensing platforms connected to the shore by fiber optic cable to monitor in real-time coastal and deep environments.

However, it is also required the improvement of the quality of the acquired data with the ability to perform spatial filtering to separate acoustic components generated by different sources. Traditional techniques, e.g. beamforming, require complex and expensive equipment, normally not affordable by small research teams. Smart sensors able to separate acoustic sources and transmit only relevant signals will increase the quality and usability of the data, with a reduction in data transmission and data storage needs. To achieve these goals it is also required to develop smart processing algorithms able to recognize/classify signals and describe acoustic scenes with minimal human supervision. This achievement will allow to reduce the time required to analyze data and also to exploit the full potential of autonomous vehicles in exploring

remote areas with near real-time transmission of summary data.
Another required development concerns the distribution of the data through high speed networks to support easy access to remote sensors, data sharing and collaborative analysis among research teams. However, the scientific collection of acoustic data, with the known limitations, is a unique opportunity to get information about remote or unexplored areas.

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References

Abraham, D., Zimmer, W., and Pavan, G. (1998), "Passive processing and analysis of acoustic data", in D'Amico A. (Editor), summary Record, SACLANTCEN bioacoustic panel, La Spezia, Italy, 15-17 June 1998, SACLANTCEN SM-133, 2.38-2.48

Azzellino, A., Lanfredi, C., D'Amico, A., Pavan, G., Podestà, M., and Haun, J. (2011). Risk mapping for sensitive species to underwater anthropogenic sound emissions: model development and validation in two Mediterranean areas. Marine Pollution Bulletin 63: 56-70.

Barlow, J., and Gisiner, R. (2006). Mitigation, monitoring and assessing the effect of anthropogenic sound on beaked whales. J. Cetacean Res. Manage. 7(3), 239-249.

Borsani, J.F., Pavan, G., and Notarbartolo di Sciara, G. (1992). An acoustic study of sperm whales (*Physeter catodon*) and other cetaceans in the Southern Tyrrhenian sea and the Western Ionian sea. European Research on Cetaceans, Cambridge (UK), 6: 171-173.

Favali, P., *et al.* (2013)- NEMO-SN1 Abyssal Cabled Observatory in the Western Ionian Sea. IEEE Journal of Oceanic Engineering, 38(2): 358-374.

Fine, M., Lugli, M., Mainardi, D., Pavan, G., and Torricelli, P. (a cura di) (1997). "Underwater Bioacoustics: Behavioural, Environmental & Evolutionary Perspectives". Proceedings of the Workshop organized by the International School of Ethology (Centro Ettore Majorana, Erice, 4-9 Novembre 1994). Volume I. Mar. Fresh. Behav. Physiol., 29 (1-4): 1-276. Volume II. Mar. Fresh. Behav. Physiol., 30 (1).

Fossati, C. (2010). Analisi bioacustiche di vocalizzazioni di Stenella (*Stenella coeruleoalba*, Meyen, 1833) nel Mar Mediterraneo. Dottorato di Ricerca in Biologia del Comportamento. Ciclo XXIII. Univ. Parma.

Fossati, C., Manghi, M., Pavan, G., and Priano, M. (2003). Dual use technology on cetacean research in the Mediterranean Sea: wide area aerial surveys with audio recordings from air-launched sonobuoys. European Research on Cetaceans, 17: 435-437.

Fossati, C., Manghi, M., Pavan, G., and Priano, M. (2003). Stima acustica della crescita di un capodoglio (*Physeter macrocephalus* Linneaus, 1758) ricatturato in Mar Ligure. Atti Soc. it. Sci. nat. Museo civ. Stor. nat. Milano, 144 (I): 75-81.

Frantzis, A. (1998). Does acoustic testing strand whales?, Nature 392: 29.

Holst, M., and Beland, J. (2010). Marine mammal and sea turtle monitoring during Lamont-Doherty Earth Observatory's ETOMO marine seismic program in the Northeast Pacific Ocean, August–September 2009. LGL Rep. TA4597-3. Rep. from LGL Ltd. (King City, Ont.) for Lamont-Doherty Earth Observatory of Columbia Univ. (Palisades, NY), Nat. Mar. Fish. Serv. (Silver Spring, MD), and Dep. Fish. Oceans (Vancouver, BC). 80 p.

Holst, M., Smultea, M. A., MacLean, S., Sayegh, A.J., Fossati, C., Stoltz, S., Goldstein, H.H., Beland, J., and Yin, S. (in press). Visual-acoustic survey of cetaceans during an academic seismic study in the southeast Caribbean Sea, April-June 2004. Caribbean Journal of Science.

Johnson, M. P., and Tyack, P. L. (2003). A digital acoustic recording tag for measuring the response of wild marine mammals to sound. IEEE J. Ocean. Eng. 28, 3–12.

Johnson, M., Madsen, P. T., Zimmer, W. M. X., Aguilar de Soto, N., and Tyack, P. L. (2004). Beaked whales echolocate on prey. Proc. R. Soc. London, Ser. B 271, S383–S386.

Manghi, M., Fossati, C., Pavan, G., and Priano, M. (2003). Diel occurrence of characteristic acoustic emission in feeding striped dolphins (*Stenella coeruleoalba*). European Research on Cetaceans, 17: 65-67.

Maugeri, G. (2012). Visual and acoustic detection of Cuvier's beaked whale (*Ziphius cavirostris*) in the Ligurian Sea. Thesis for the Master

of Science in Marine Biodiversity and Conservation (EMBC), Ghent University (Belgium), Faculty of Sciences, Department of Biology.
Nosengo, N., (2009). The Neutrino and the whale. Nature, 462: 560-561.
Pavan, G. (1992). A portable DSP workstation for real-time analysis of cetacean sounds in the field. European Research on Cetaceans, Cambridge (UK), 6: 165-169.
Pavan, G. (1994). A digital signal processing workstation for bioacoustical research. Atti 6 Conv. Ital. Ornit., Torino, 1991: 227-234.
Pavan, G. (2007). Guidelines to address the issue of the impact of anthropogenic noise on marine mammals in the ACCOBAMS area. Report prepared for the 4th ACCOBAMS Scientific Committee. ACCOBAMS SC4 Doc 18.
Pavan, G., and Borsani, J.F. (1997). Bioacoustic research on cetaceans in the Mediterranean Sea. Mar. Fresh. Behav. Physiol., 30: 99-123.
Pavan, G., Borsani, J.F., Fossati, C., Manghi, M., and Priano, M. (1996). Acoustic research cruises in the Mediterranean - 1994. European Research on Cetaceans, 9: 85-88.
Pavan, G., Borsani, J.F., Manghi, M., and Priano, M. (1996). Interactive Digital Sound Library on cetaceans of the Mediterranean Sea. European Research on Cetaceans, 9: 81-84.
Pavan, G., Fossati, C., Manghi, M., and Priano M. (1999). Acoustic measure of body growth in a photo-identified sperm whale. European Research on Cetaceans, 12: 254-258.
Pavan, G., Fossati, C., Manghi, M., and Priano, M. (2004). Passive acoustics tools for the implementation of Acoustic Risk Mitigation Policies. In "Proceedings of the workshop on Active sonar and cetaceans", 17th ECS Conference, March 2003, P. G. H. Evans and L. A. Miller Eds., European Cetacean Society Newsletter no. 42 – special issue: 52-58.
Pavan, G., Fossati, C., Priano, M., and Manghi, M. (2009). Acoustic detection of Cuvier's beaked whales (*Ziphius cavirostris*). In: Dolman S., McLeod C. & Evans P.G.H. (Eds.), 2009. Proceedings of the Workshop " Beaked Whale Research". ECS Special Publication Series n. 51. 21st Annual meeting of the European Cetacean Society, San Sebastian, Spain, 26th April 2007. Pag. 31-35.
Pavan, G., Francia, C., Fossati, C., and Caltavuturo, G. (2010). Studio della distribuzione dello Zifio attraverso il rilevamento e riconoscimento dei segnali acustici emessi in immersione. Atti XLI Congresso SIBM. Biol. Mar. Mediterr. 17 (1): 408-409.
Pavan, G., La Manna, G., Zardin, F., Internullo, E., Kloeti, S., Cosentino, G., Speziale, F., Riccobene, G. and the NEMO Collaboration (2008).

Short term and long term bioacoustic monitoring of the marine environment. Results from NEMO ONDE Experiment and Way Ahead. In: Computational bioacoustics for assessing biodiversity. Proceedings of the International Expert meeting on IT-based detection of bioacoustical patterns. Frommolt K.H., Rolf Bardeli R., Clausen M. (Eds.) Published by Federal Agency for Nature Conservation, Bonn, Germany: 7-14.

Pavan, G., Manghi, M., and Fossati, C. (2001). Software and hardware sound analysis tools for field work. Proc. 2nd Symposium on Underwater Bio-sonar and Bioacoustic Systems. Proc. I.O.A., Vol. 23 (part 4): 175-183.

Pavan, G., Nascetti, D., Manghi, M., Priano, M., Fossati, C., Borsani, J.F. (1997). Bioacoustic research on Sperm Whales in cooperation with the Italian Navy. European Research on Cetaceans, 10: 82-86.

Pavan, G., Priano, M., Manghi, M., and Fossati, C. (1997). Software tools for real-time IPI measurements on sperm whale sounds. Proc. Underwater Bio-Sonar and Bioacoustics Symposium. Proc. I.O.A., 19 (part 9), Loughborough, UK: 157-164.

Pavan, G., Priano, M., Manghi, M., Fossati, C., and Bergamasco, C. (1997). Sperm whales (*Physeter macrocephalus* L.) off the north-west coast of Corsica, France, in summer 1996. Acoustic and surface behaviours. European Research on Cetaceans, 11: 218-221.

Pavan, G., Hayward, T., Borsani, J. F., Priano, M., Manghi, M., Fossati, C., and Gordon, J. (2000). Time Pattern of Sperm Whale Codas Recorded in the Mediterranean Sea 1985–1996. J. Acoust. Soc. Am, 107 (6): 3487-3495.

Pavan, G., Thomas, L., and Adam, O. (Editors) (2010). Proceedings of the 4th International Workshop on Detection, Classification and Localization of Marine Mammals Using Passive Acoustics and 1st International Workshop on Density Estimation of Marine Mammals Using Passive Acoustics. Applied Acoustics, Volume 71 (11): 991-1112.

Pavan, G., Zardin, F., Pirrotta, G., and Riccobene, G. (in press) A Long-Term Passive Acoustic Monitoring of Sperm Whales In the Ionian Sea. Aquatic Conservation Biology

Podestà, M., D'Amico, A., Pavan, G. Drougas, A., Komnenou, A. and Portunato, N. (2006). A Review of *Ziphius cavirostris* (G. Cuvier, 1823) Strandings in the Mediterranean Sea. J. Cetacean Res. Manage. 7(3): 251–261.

Priano, M., Pavan, G., Fossati, C., and Manghi, M. (2003). Sound Analysis Workstation for the implementation of Acoustic Risk Mitigation Policies. European Research on Cetaceans, 17: 74-76.

Priano, M., Pavan, G., Manghi, M., and Fossati, C. (1997). The Cetacean Sound Library of the Interdisciplinary Centre for Bioacoustics and Environmental Research of the University of Pavia. Proc. Underwater Bio-Sonar and Bioacoustics Symposium. Proc. I.O.A., 19 (part 9), Loughborough, UK: 245-249.

Riccobene, G., and NEMO team (2009). Long-term measurements of acoustic background noise in very deep sea. Nucl. Instr. and Meth. A. 604 (2009) S149-S157.

Riccobene, G., Cosentino, L., Musumeci, M., Pavan, G., and Speziale, F. (2004). Acoustic detection of UHE neutrinos: a station for measurement of the deep sea acoustic noise. Nuclear Instruments and Methods in Physics Research A 518 (2004): 220–222.

Ryan, K. (2009). NATO Undersea Research Centre marine mammal risk mitigation rules and procedures (SP-2009-002). NURC Report. La Spezia, Italy: NURC.

Torricelli, P., Lugli, M., and Pavan, G. (1990). Analysis of sounds produced by male *Padogobius martensi* (Pisces, Gobiidae) and factors affecting their structural properties. Bioacoustics, Inghilterra, 2 (4): 261-275.

Zimmer, W.M.X., and Pavan, G. (2008). Context driven detection/classification of Cuvier's beaked whale (*Ziphius cavirostris*). In: New Trends for Environmental Monitoring Using Passive Systems. IEEE Proc. ISBN 978-1-4244-2815-1. DOI 10.1109/PASSIVE.2008.4786992.

Zimmer, W.M.X., Harwood, J., Tyack, P.L., Johnson, M.P., and Madsen, P.T. (2008). Passive acoustic detection of deep-diving beaked whales. J. Acoust. Soc. Am. 124 (5): 2823-283.

Zimmer, W.M.X., Johnson, M. P., Madsen, P. T., and Tyack, P.L. (2005). Echolocation clicks of free-ranging Cuvier's beaked whales (*Ziphius cavirostris*). J. Acoust. Soc. Am. 117 (6), 3919-3927.

Web documents:

Pavan G., SeaPro - Sound Emission Analyzer Professional. http://www.unipv.it/cibra/seapro.html

Pavan G., The history of the CIBRA Digital Signal Processing Workstation. http://www.unipv.it/cibra/res_dspwstory_uk.html

Pavan G., Digital Signal Processing Workstation (version 1990-1994). http://www.unipv.it/cibra/res_dspw1994_uk.html

Pavan G., CIBRA Digital Signal Processing PAM Workstation. http://www.unipv.it/cibra/res_dspw2004_uk.html