SAMARUC a programmable system for passive acoustic monitoring of cetaceans

Ramón Miralles[1], Guillermo Lara[1], Alicia Carrión[1] and José Antonio Esteban[2]

[1] Instituto de Telecomunicaciones y Aplicaciones Multimedia,
Universitat Politècnica de València,
8G Building - access D - Camino de Vera s/n - 46022 Valencia (Spain)

[2] Parques Reunidos Valencia S. A. L'Oceanografic,
Ciudad de las Artes y las Ciencias, Valencia, Spain

Corresponding author: rmiralle@dcom.upv.es

Abstract

This paper reports the work carried out by iTEAM researchers in Passive Acoustic Monitoring (PAM) for underwater monitoring of cetaceans. It includes a description of novel signal processing algorithms for detection and classification of aquatic mammal species as well as a hardware system called SAMARUC specially designed in collaboration with marine biologists.

Keywords: Signal processing, Passive Acoustic Monitoring, Marine Bioacoustics Signal Processing, Signal Detection and Classification.

1. Introduction

Underwater passive acoustic monitoring (PAM) is a non-intrusive technique that can be used successfully to detect and classify marine mammals, monitor migratory patterns and even for density estimation of different species. This discipline has gained popularity among marine biologists and other scientists in the last years. The procedure of PAM involves using recording devices and algorithms. Underwater passive acoustic sensors are also commonly used in other communities. Navies, for instance, have been using passive acoustics for a long time, but their systems are generally expensive, complex and their performance is usually classified. Biologists on the other hand, use small and simple recorders for PAM. These recorders are sometimes home-built, or purchased from small specialized companies. The devices typically employed fall into two different categories: towed array systems connected to a boat that record and process the data in a laptop/desktop computer, and standalone autonomous systems that remain underwater for long periods of time and have to be recovered in order to access the data. In this work, we are going to focus on these autonomous devices, study their performance, algorithms and compare them to the system developed at the Instituto de Telecomunicaciones y Aplicaciones Multimedia (iTEAM).

2. Passive acoustic monitoring devices

One of the most successful devices for PAM is the pop-up buoy developed at Cornell University [1]. The instrument consists of a small-scale recording device placed in a water-tight glass sphere. This system has been successfully employed to monitor the critically endangered northern right whale. Another well known autonomous system is the HARP instrument developed at Scripps Whale Acoustic Lab. This system was developed to record baleen whales that are known to emit low frequency calls (e.g. fin and blue whales [2], and beaked whales [3]). It is worth mentioning the C-POD as one of the first systems developed that makes some signal processing within the insides of the device. Although the C-POD does not record the raw data, it is capable of detecting cetacean clicks alongside with some variables such as center frequency, sound pressure level, duration and bandwidth. The C-POD works with all toothed cetaceans except sperm whales and has been recently used for beluga whale monitoring [4]. Some other devices typically used by biologists are the EAR [5] as well as other instruments with a limited number of publications. Table 1 shows a comparative study of the aforementioned devices.

At the present, the available systems cannot be programed to include specific algorithms for whale call de-

PAM devices	System frequency range	Hydrophone frequency range/ sensibility	Continuous recording/ Predetermined on/off schedule	Max. Deploym ent depth	System autonomy	Storage memory	Possibility of including automatic detection algorithms
EAR - Oceanwide Science Inst. Hawai	20Hz -30kHz	1Hz -28kHz (+/- 1.5 dB)	Predetermined on/off schedule	500m	Variable	160Gb	No
Pop-up MARU - USA Cornell University	Up to 200kHz	-	Continuous	6000m	90 days	120Gb	No
HARP	2KHz-200 KHz	10 Hz – 100 kHz	Both	N/A	54 days	16 x 120 GB (IDE)	No
AURAL-Canada Multi-Electronique	10 Hz - 16384 kHz	2 Hz - 30 kHz	Both	300m	162-208 days	64MB Flash card 320GB Hard Disk	No
SM2M – USA Wildlife Acoustics	4Hz-96 kHz	2-40kHz (+/- 1dB)	Both	150m.	62 days -Alkaline 104 days - Lithium	512GB SDXC card.	No
SM2M Ultrasonic Wildlife Acoustics	4Hz-384 kHz	2-40kHz (+/- 1dB)	Both	150m.	25 days -Alkaline 42 days- Lithium	512GB SDXC card.	No
mRADAR USA Cetacean Research	20 Hz – 96 kHz	20 Hz– 50KHz	Continuous	100m.	2 -3 days	16 Gb	No
C-POD Chelonia ltd. United Kingdom	20-160 kHz	20 Hz-160 kHz	Not raw audio, only events are available.	> 100m.	4 months D type Alkaline bat.	SD Card	Yes (only detects echo-location sounds from toothed cetaceans)
SAMARUC	20 Hz -96kHz	16Hz – 44KHz (+/- 3dB)	Both	1000m.	1 month D type Alkaline bat.	SD Card	Yes. Entirely programmable

Table 1. *Comparative specifications of the main PAM devices.*

tection and classification. Most of the systems work as digital recorders and the recorded sounds have to be processed afterwards in regular computers with signal processing software. Although this may add versatility to the process it can be a drawback when the system has to be used by researchers with limited knowledge of signal processing.

3. Passive acoustic monitoring algorithms

It is possible to find in the bibliography a large number of PAM algorithms for specific applications. The majority of PAM algorithms are based on computing some kind of time-frequency representation of the acoustic recordings. The sound patterns or calls of the different species are searched in these time-frequency representations by means of various signal processing techniques: spectrogram correlation detector (XBAT) [6],[7], cross correlation with a matched filter kernel [7], [8], two-dimensional linear FIR filters [9], artificial neural networks [7], [10], and classification and regression tree classifiers [10] are the most representative techniques. Some authors propose using algorithms to remove undesired noise and enhance the spectrogram. Hussein used in [11] edge detection techniques to obtain enhanced spectrograms while preserving their temporal and spectral accuracy. Another example can be found in [12] where Baumgartner employed a Gaussian smoothing kernel and a tonal noise-removing algorithm to reduce ship generated noise.

In the last years, some software packages for PAM have have been developed. PAMGUARD (an open source project for semi automated real time detection), XBAT and Raven (from the Cornell Lab of Ornithology) are the most representative. These packages integrate most of the state of the art algorithms and provide a user-friendly interface for researchers. However, most of these packages are created as research laboratory tools and require high capacity processors. Additionally, the user needs to be familiarized with different signal processing concepts in order to achieve automatic detection of whale calls.

New technologies have begun to incorporate signal recognition algorithms for a reduced set of species to be used in real-time systems while devices are recording [13], [14]. In order to achieve real time monitoring, a two-stage process is normally employed. The first stage consists of an activity detector designed to detect any signal that is not background noise. The second stage is a spectral classifier designed to detect the desired whale vocalizations. Different approaches have arisen to design the optimum and with the lowest computational cost activity detector: matched filter detector [15], local max detectors [15], energy detector [16], [17], entropy detector [18], and power-law detectors [19]. In a similar way, efficient algorithms for classification based on principal component analysis (PCA) with discriminant analysis (DA) to feature space dimensionality reduction achieve the greatest separation of classes [20].

On the other hand, algorithms for automatic passive monitoring of anthropogenic noise have been almost restricted to underwater noise from ships [21]–[23]. It is very difficult to find any reference of algorithms for passive monitoring of underwater noise from seismic airgun surveys for petroleum [24], and naval sonars [25].

Beyond the state of the art of Passive acoustic monitoring algorithm

Even though there has been previous research on optimizing automatic detectors for specific calls or specific species, the real time detection of any type of call by a diversity of marine mammal species still poses quite a challenge. The development of detectors and classification algorithms becomes more complicated if we add the presence of underwater noise from sources such as ship-

ping, seismic airgun surveys, and naval sonars, that in some situations can be easily confused with some cetacean calls. This is of particular relevance if we take into account that underwater noise is growing at a rapid rate, with background noise levels doubling every decade over the last half century [26]. A feasible alternative for passive acoustic monitoring in the presence of noise consists of incorporating image processing algorithms based on mathematical morphology to clean up the time-frequency representation. An example can be found in [24] where the authors designed an automatic detector for fin whale calls. In this work, it was shown that time-frequency representations contaminated with tonal noise $P(n,k)$ could be cleaned up by filtering in the Discrete Cosine Transform Domain to obtain $P_{denoised}(n,k)$ as illustrated in Equation (1):

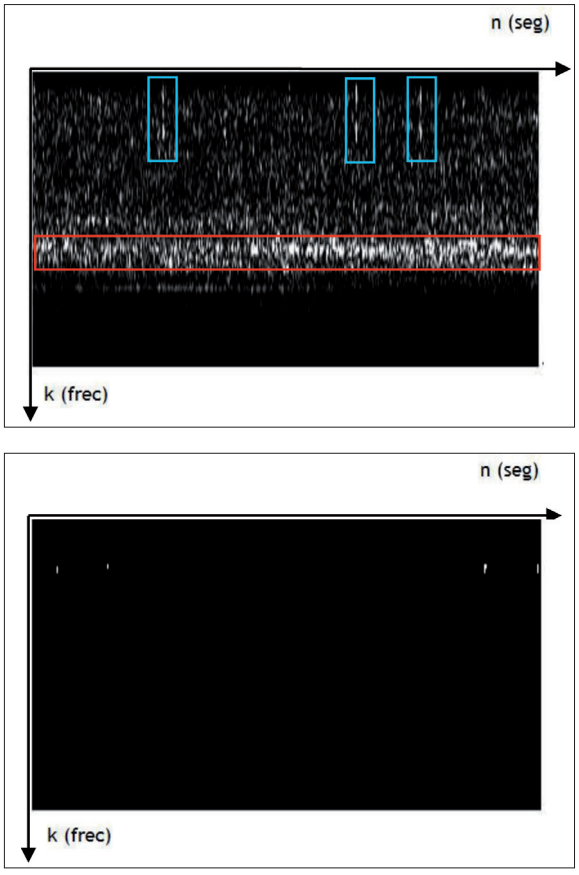

Figure 1. *Top figure: time-frequency representation contaminated with airgun explosions (blue rectangles) and ship noise (red rectangles). Bottom figure: Time-frequency representation after applying the technique described in [24].*

Advanced techniques employed in voice activity detection of human speech can also be used in the detection of cetacean calls.

$$P_{denoised}(n,k)=P(n,k)-P_r(n,k). \quad (1)$$

Where $P_r(n,k)=DCT_{un}^{-1}[DCT_{nu}[P(n,k)]\cdot W(u)]$ with DCT_{nu} and DCT_{un}^{-1} the direct and inverse Discrete Cosine Transform and $W(u)$ the cosine domain filtering window. Posterior processing of the time-frequency diagram using row-wise Otsu´s thresholding as well as statistical information of fin whale calls allows to distinguish whale calls from seismic acoustic explosions (see Figure 1).

Advanced techniques employed in voice activity detection of human speech can also be used to improve the detection robustness and performance of cetacean call detection in noisy environments [27]. Some examples are: the use of Empirical Mode Decomposition (EMD) and variance-of-instantaneous-frequency detection, that seem to be adequate tools to separate the target echo signal from the reverberation [28] and the use of Mel-frequency cepstral coefficients (MFCC) have shown to be very valuable in information retrieval and audio similarity measurement.

The mel scale approximates many animals' auditory system response in a closer manner than the linear-spaced frequency bands and gives, in some species, superior classification percentages to some other features' extraction techniques. Following this idea, the authors have studied an algorithm that applies the MFCCs for classification and detection of cetacean sounds, particularly to the right whales [29].

MFCCs are the results of a cosine transform of the real logarithm of the short-term energy spectrum expressed on a mel-frequency scale (Figure 2). The main coefficients are obtained using Equation (2),

$$c_n=\sum_{k=1}^{K} log(S_k)\, cos\left[\frac{n(k-0.5)\pi}{K}\right] \quad n=0,1,\ldots,L \quad (2)$$

where n represents the MFCC coefficient number. Furthermore, the static MFCC vector at frame t, has 13 delta (d_t) and 13 acceleration coefficients (a_t) appended to yield a 39-dimensional feature vector (Figure 3), where d_t and a_t are respectively obtained by Equations (3) and (4):

$$d_t=\frac{\sum_{p=1}^{P} p(c_{t+p}-c_{t-p})}{2\sum_{p=1}^{P} p^2}, \text{ where } P=2 \quad (3)$$

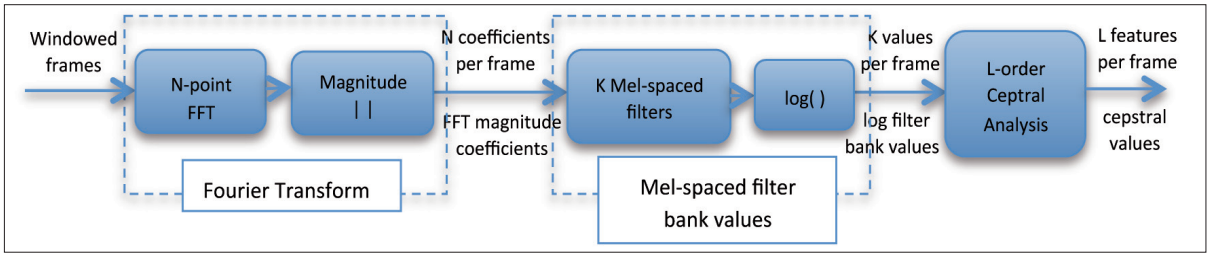

Figure 2. *Block diagram to obtain de MFCC.*

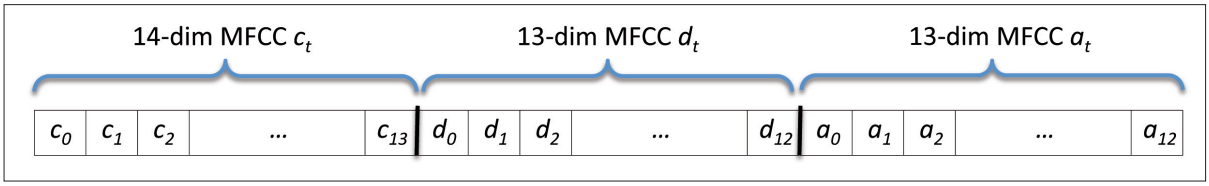

Figure 3. *Feature vector.*

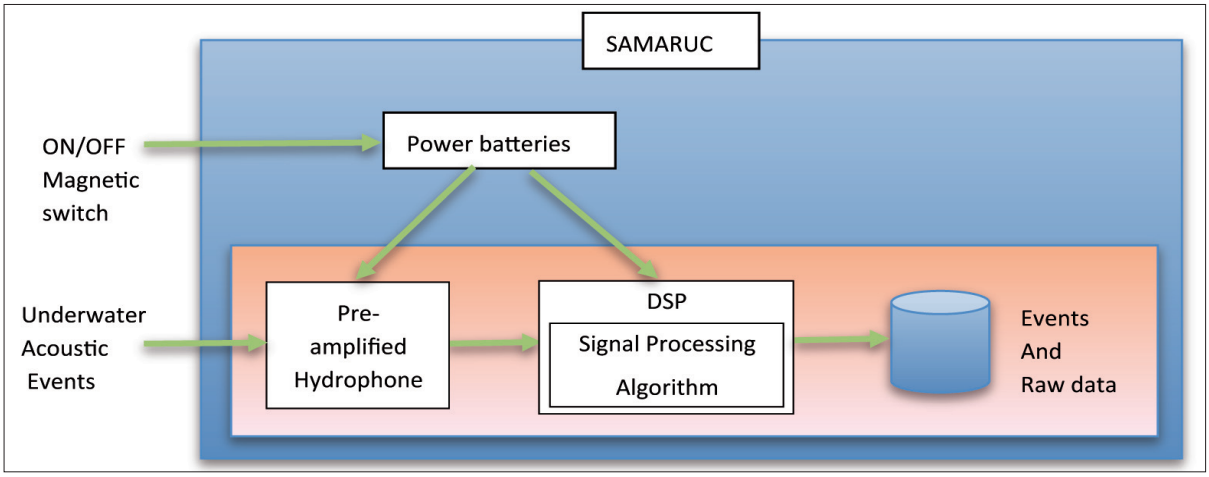

Figure 4. *General block diagram of the SAMARUC system.*

$$a_t = \frac{\sum_{p=1}^{P} p(d_{t+p} - d_{t-p})}{2\sum_{p=1}^{P} p^2}, \text{ where } P=2 \qquad (4)$$

The choice of this approach is motivated by a desire to obtain a more accurate detection and classification of a given whale species sound in low Signal to Noise Ratio (SNR) recordings. Additionally, using MFCCs makes it not necessary to compute spectrogram related features making these algorithms more appropriate to work in real time automatic detection systems.

Other techniques being studied by the authors, and whose application has been never, or very little, studied in cetaceans are the signal modality characterization [30] and the analysis / synthesis techniques modeling whale sound production mechanisms. These techniques may provide important information when trying to understand the nature of the signals and may yield new features related to the presence of nonlinearities, chaos dynamics and whale anatomy of the structures responsible for sound production.

4. Brief description of the SAMARUC signal processing and recording system for PAM

The SAMARUC system is a PAM device that can run real time signal processing algorithms for detection and classification of underwater sounds. The major component of the system is a general purpose ultra low power consumption Digital Signal Processing (DSP) board. The board is configured in DMA Ping-Pong mode so that signal processing algorithms can run simultaneously without sample loss while the system is recording acoustic information. A general overview of the system can be seen in Figure 4.

The electronics of SAMARUC can be activated by means of a magnetic relay switch so that no waste of energy occurs while the system is being transported to the deployment location. Additionally, the magnetic switch serves as trigger to start recording and processing the data. The battery block provides more than 30 days of autonomy to the pre-amplified hydrophone and to the DSP board. To do this, a highly efficient DC-DC regulator is employed. The acquisition subsystem is composed of a hydrophone with specific electronics that adequate the output to the Analog to Digital converter of the DSP board.

All these electronic components are placed inside of a pressure housing with underwater connectors. The system was conceived with the requirement that it has to be able to operate in up to a 1000 meter depth in the sea. To face this, the housing of SAMARUC was made of stainless steel (Figure 7). First designs of the structure of the buoy are shown in Figure 6. Figure7 shows the housing as it was built in the prototype.

The Ping-Pong configuration is suitable to include signal processing algorithms for detection and classification of underwater sounds (see Figure 8). These algorithms can be programmed by the user, using the time slot shown in Figure 8. The DSP chip employed provides computational power enough to run in real time the majority of the algorithms currently employed for PAM and described in Section 3. As examples of applications we can mention,

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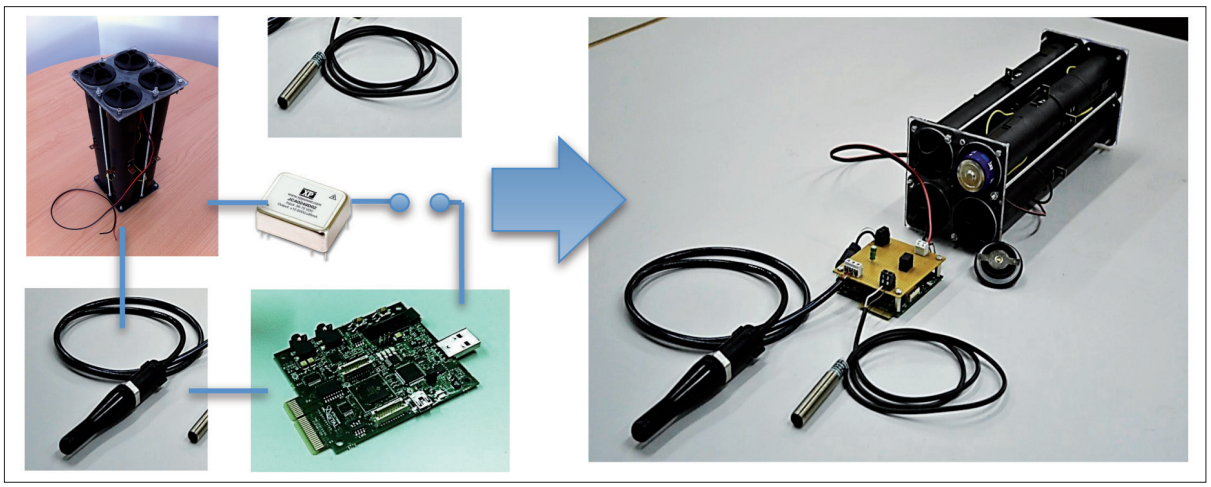

Figure 5. *Hardware components of the SAMARUC system.*

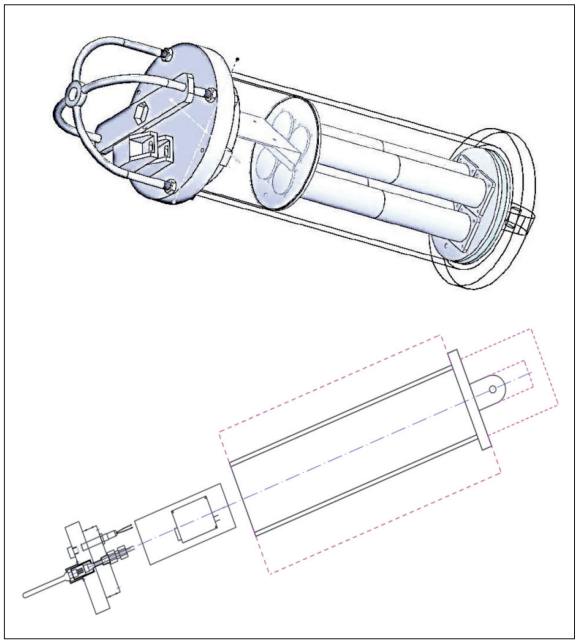

Figure 6. *CAD drawings of the SAMARUC system.*

are the use of algorithms for noise control of seismic explosion boats or to simply count echolocalization signals produced by a species of cetacean that could be user programed and included as plugins into the system.

5. Monitoring dolphin sounds with SAMARUC.

The SAMARUC system is relatively new. In its first weeks the system has been utilized in different environments, and for different applications. The system was employed to record the audio information from the risso's dolphin (Grampus griseus) that arrived on March 30, 2013 to the Valencia harbor. Unfortunately, the risso´s dolphin was in very poor physical condition and died a few days after despite all the veterinarian expert efforts. The SAMARUC system was placed in the security perimeter to monitor and check if any sounds could indicate any change in the dolphin´s health.

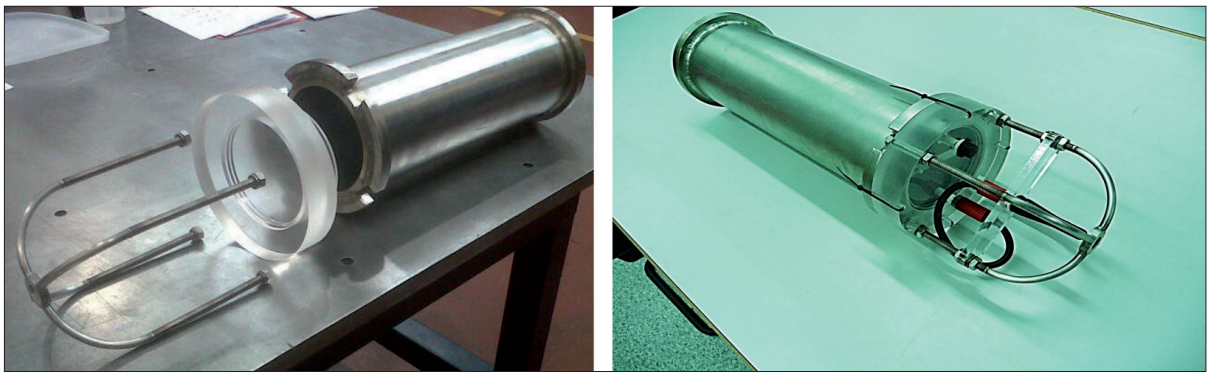

Figure 7. *SAMARUC housing (left). Complete SAMARUC prototype (right).*

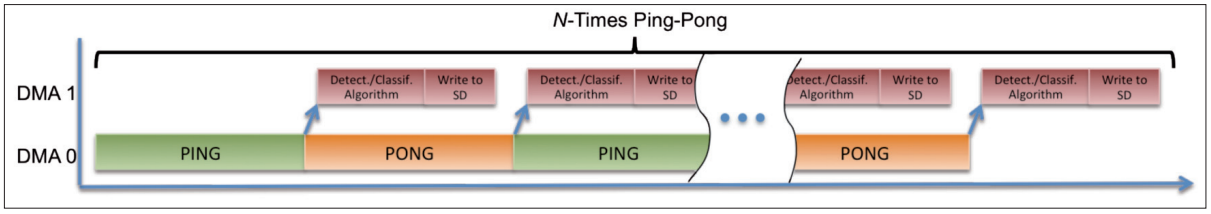

Figure 8. *Chronogram of the DMA Ping Pong Configuration.*

The possibility of programming specific automatic detection algorithms that run within the SAMARUC system can be very valuable and offers great usability.

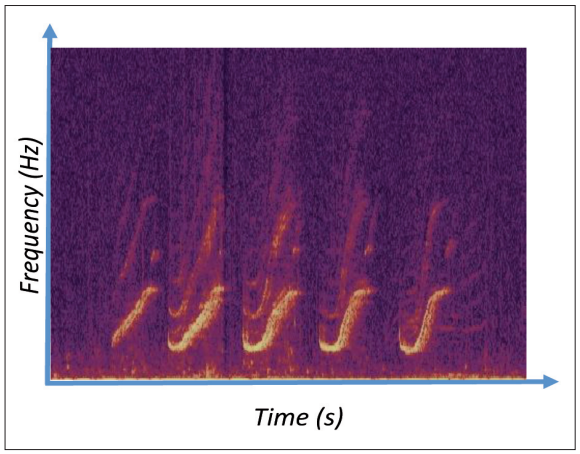

Figure 9. *Time frequency representation of bottlenose dolphin sounds recorded with SAMARUC.*

The system is also being employed to record audio information produced by the bottlenose dolphins (Tursiops truncatus) located at the dolphinarium of the Oceanografic of Valencia. In fact, more than 150 vocalizations have been stored (see Figure 9). The purpose of these recordings is to prepare and test the system for a more intensive recording campaign that will be done in the next months in the Mediterranean Sea. These tests serve also to check the usability of the system by biologists and non-technical personnel.

Typical operation of the SAMARUC system in measurement campaigns is illustrated in Figure 10. The SAMARUC system is transported to the location where it is going to be deployed and dropped to the seafloor. The system sinks and remains firmly moored on the seafloor by means of an anchor weight and is also equipped with an acoustic release transponder (EdgeTech). A flotation device is used to keep the system in vertical operational mode (Figure 10a). The system is moored for a period of time, recording and processing all the sounds from different species (Figure 10b). At the recovery phase, the control station issues an acoustic command. The control station is typically on a boat, but may also be a device operated by a diver or mounted on a remotely operated underwater vehicle. Upon receipt and verification, the acoustic release triggers a mechanism that drops the anchor weight. The SAMARUC is carried back to the surface by the flotation device for recovery (Figure 10c).

6. Conclusions and future work

A new PAM system called SAMARUC has been developed to register and do in-situ processing of sounds. The possibility of programming specific automatic detection algorithms that run within the system can be very valuable and offers great usability. Additionally, the system has comparable (and in some aspects superior) technical specifications with respect to the rest of systems. On the other hand, the system is at its early stage and much more testing has to be done in the future. In the next months, a long measuring campaign is planed. SAMARUC is going to be deployed in the Cabrera Archipelago Maritime National Park, in the Balearic Islands (Spain), a protected area with enough presence of cetaceans. With these measurements SAMARUC will be ready to be marketed and begin its expansion strategy.

Future applications of the algorithms and the system include expansion to automatically detect different species such as the sperm whale (Physeter macrocephalus) or Cuvier's beaked whale (Ziphius cavirostris). Future enhancements of the system include a higher bandwidth A/D converter that will allow SAMARUC to be used to monitor the noise level in our seas and oceans as well as to monitor underwater detonations during prospection. Another future development will be including a compact hydrophone array into the system. This will allow some localization capabilities as well as taking advantage of spatial diversity signal processing algorithms to obtain a more robust PAM device.

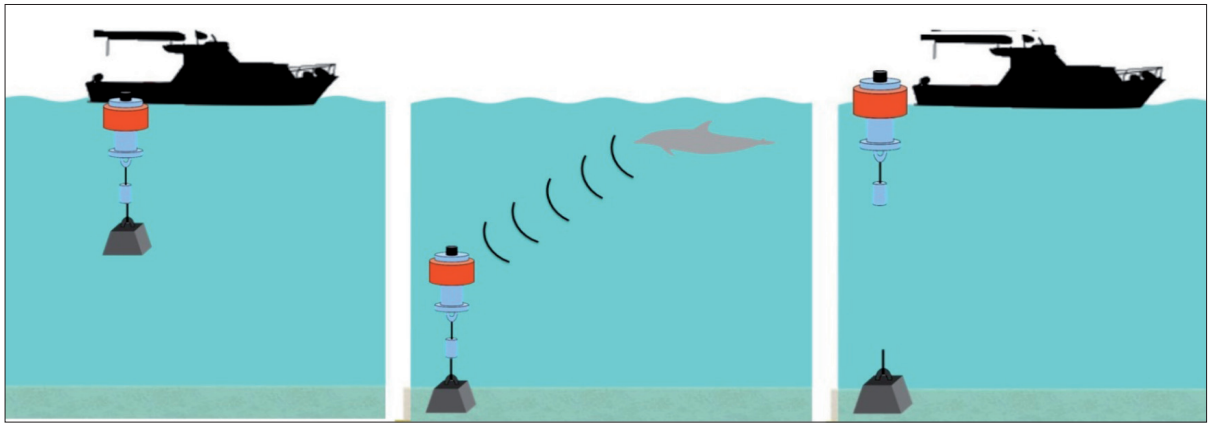

Figure 10. *a) The system sinks by means of an anchor weight, b) The system remains moored recording and processing acoustic information, c) An acoustic command is employed to release the SAMARUC.*

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Biographies

R. Miralles was born in Valencia (Spain) in 1971. He received the Ingeniero de Telecomunicación and the Doctor Ingeniero de Telecomunicación degrees from the Universidad Politécnica de Valencia (UPV) in 1995 and 2000 respectively. In 1996 he became a lecturer in the Departamento de Comunicaciones at the Escuela Politécnica Superior de Gandía. From 2000 until now he has been working as an Assistant Professor in the Escuela Técnica Superior de Ingenieros de Telecomunicación (Valencia). He is member of the management team of the Institute of Telecommunication and Multimedia Applications (iTEAM).

His research focuses in signal processing for passive acoustic monitoring as well as in signal processing for industrial applications, where he has been responsible of developing systems and algorithms for quality control in the food industry. He is co-author of more than 22 journal papers and 50 international conferences.

G. Lara was born in Valencia. He has received the Ingeniero de Telecomunicación degree from the Universidad Politécnica de Valencia (UPV) Spain in 2010. He is currently a Ph.D. student in the Institute of Telecommunication and Multimedia Applications (iTEAM) of UPV.

His research interest is focused in pattern recognition and statistical processing applied to submarine acoustics. Currently, he is involved in the development of a submarine buoy capable of recording cetacean sounds without sample loss, programming the electronics and the internal hardware.

A. Carrión was born in Lorca (Spain). She received the Ingeniero de Telecomunicación degree from the Universidad Politécnica de Valencia (UPV) in 2011, her Master Thesis was carried out at Fraunhofer Institute IOSB, Karlsruhe (Germany). Currently, she is a Ph.D. student in the Institute of Telecommunication and Multimedia Applications (iTEAM) of UPV. Her research interests include nonlinear signal processing and signal modality characterization in different fields such as submarine acoustics, construction and food industry.