Acoustic Laboratory for Marine Applications: Overview of the ALMA system and data analysis.

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***Abstract*—The authors present a recently developed acoustic system (ALMA for Acoustic Laboratory for Marine Applications). ALMA was designed and used to address the topic of sound waves propagating in fluctuating oceans (especially coastal and shallow waters). Observing and understanding the underlying phenomena such as wavefronts fluctuations due to internal waves, scattering from the sea surface and/or bottom and their impact on sonar performance is the main long-term goal of this work. Several measurement campaigns were conducted and will be presented. They were carried out in the Mediterrannean sea in various conditions of water depth, season or type of emitted signals. An analysis of some of the acoustic and environmental data collected during the 2016 campaign will also be provided. The influence of temperature fluctuations is shown with calculation of the mutual coherence function and conventional beamforming.**

***Index Terms*—underwater acoustic measurements, signal coherence, fluctuation, at-sea measurement systems, observatories**

I. Introduction

Due to the increasing stealth of the classical threats in underwater acoustic (UWA) detection contexts, a corresponding improvement in sonar systems performance is required. The latter can be classically achieved by increasing the number of sensors, the size of the arrays and the frequency band of interest. Nevertheless, some counterparts are noticed with this increase in global system dimension: the sensitivity to the environment and its fluctuations is enhanced and can become a destructively interfering part of the process [1] [2]. Therefore, the topics of source depth discrimination, noise non-stationnarity and directivity and signal coherence have become of great interests [3]. In particular, the loss of signal coherence in fluctuating media such as the ocean is a major topic of interest in the field of underwater acoustics since the 1970s [4] [5] [6] [7] [8] [9]. This issue is also shared with other scientific fields, such as medical ultrasound imaging [10] and adaptive optics [11]. The inner objective of this study is to benchmark innovative signal processing techniques (not necessarily issued from the field of UWA detection) on sets of qualitative acoustic data. To reach this goal, we first studied the existing solutions for obtaining such datasets, with a ”free-user” requirement, so that the data can be shared with the scientific community. Acoustic observatories and long-term measurement systems such as those deployed in Fram strait [12] or by the CTBTO [13] allow scientific to access their data. These kind of systems permit long-term statistical studies, usually on a few hydrophones, and are a real chance for noise characterization and global observations studies. They nevertheless do not provide the high-number of sensors and frequency bands required by mid-frequency sonar studies. Other sources of data are experiments peformed during a short amount of time, usually once, focusing on one particular issue. Most cited examples are SW06 [14], AsiaEx [15], acoustics in the Yellow Sea [16] and the experiments cited in [5]. They constitute considerable amount of work and very useful conclusions for our topic of interest were drawn out.

However, the system that we present in this paper shows strong advantages, such as a vast modularity and an important capacity of fast deployment. One experiment per year was conducted since 2014, in various environments and with different objectives that will be discussed in more details. ALMA (Acoustic Laboratory for Marine Applications) consists of an active component (single or multiple broadband sources, either moored or towed) and a modulable passive array (64 then 128 hydrophones [17], with a surface buoy for data and energy storage). Our goal is to perform acoustic propagation experiments in specific locations, mostly shallow and coastal waters, subject to the presence of fluctuations in the water column (linear internal waves, turbulence). Environmental monitoring is also ensured, so that acoustic and environmental data analyses are coupled.

In section II, the system will be described into more technical details. Section III will provide a summary of the measurements conducted to this day, while a focus on the data analysis of a part of the 2016 experiment is given in section IV, including an evaluation of the mutual coherence function (and the array gain degradation associated with the decrease of the radius of coherence) and a study of the performance of conventional beamforming on data acquired in a fluctuating environment. The latter was characterized with measurements from a thermistor string. Finally, we will propose a conclusion with our views for future work.

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II. The ALMA system and its objectives

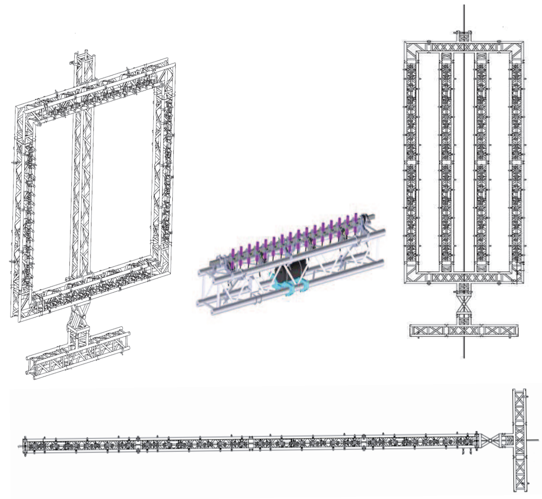
A. Objectives and philosophy

The system was designed in order to gather experimental data representative of the main problems encountered by scientists in the UWA field. In particular, acoustic fluctuations due to oceanic phenomena typical of shallow and coastal waters represent a topic of great interest [18] [19]. Several criteria are required to achieve the objectives aforementioned: first, a high level of modularity and capability of evolution of the passive acoustic array is needed to cover the wide range of applications (from sonar performance to inverse problems). Then an important autonomy and data storage are needed to ensure the consistent gathering of long-term acoustic data. On this aspect, ALMA consists in the embryo step of an ocean observatory (usually cabled to shore). The ability to transmit the recorded acoustic data using WIFI is also aimed, for command and control of the acquisition process. The choice of COTS (Commercial off-the-shelf) over specifically developed technology is made here. The system must be deployable in any coastal waters environment (water depth less than 200m for the system anchoring). The impact of the various at-sea campaigns using ALMA on the environment is minimized since neither any anchoring nor any part of the system is left on the sea floor. Given the core objective of the system, the data recorded are not defense-protected and are hence shareable with the scientific community.

B. Equipment

1) Passive acoustic array : The acoustic array is composed of 2.70m-long rigid arms (16 hydrophones each), assembled together. Originally, 4 arms were designed, but the current system consists of 8 arms, 128 hydrophones. These rigid arms can be assembled in order to generate various array geometries (line, plane, volume). Fig. 1a displays examples of array geometry and a zoomed-in rigid arm. Each arm carries the acquisition system for its 16 hydrophones (tunable sampling frequency from 7.5 to 48kHz). The recorded data are then transmitted using an electro-optical cable to the surface buoy, show in Fig. 2. The latter is used for data storage (2 TB hard drive) and energy (9.6 kWh. rechargeable electric battery providing approximately 70 hours autonomy in continuous recording mode). The acoustic sensors of SENSORTECH SQ01 hydrophones (characteristics can be found in [20]). Attitude sensors provide the 3D orientation of the array in water. 3 anchors are deployed (2 for the array orientation and 1 reinforced anchor).

2) Active acoustic pinger : Although multiple sources of sound can be used during an at-sea experiment (as well as sources of opportunity), an active acoustic component is included in the development of ALMA. It is an omnidirectional wideband transmitter (PGS05, manufactured by ALSEAMAR) with emission capability from 1 to 14kHz. The source level (SL) is tunable up to 160 dB ref Pa @1m. The emitted signals are programmed onto the acoustic pinger before deployment in water. In continuous transmission, with maximum SL, the autonomy of the source is approximately 20 hours. 2 of these sources are available to this day. In the case of the use of other acoustic sources, the latter will be described in section III.



(a) Possible arrangments of the passive array

(b) Picture of the deployment of the passive acoustic array on the deck of the M/V JANUS.

Fig. 1: ALMA: Passive array

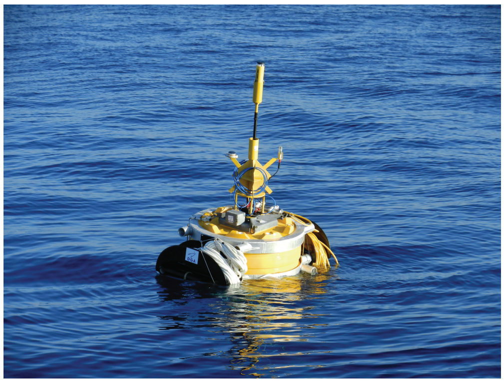


Fig. 2: Picture of the deployed surface buoy.

3) Environmental sensing: The main topics of study and objectives of such an experimental system necessarily involve an accurate knowledge of the environment. In addition to the various models available in the literature [21], environmental sensors are used to assess the fluctuations encountered by the propagating sound waves. A Valeport SVP 500 Profiler is deployed from the ship for daily sound speed profile measurements. Moreover, since 2016, a thermistor string (RBR Concerto) consisting of 24 temperature sensors (sampled every 6.25m; the total length of the thermistor string is 150m) is deployed within a few hundred meters of the passive array location. Temperature data are recorded every 3s from beginning to end of the experiment. Occasionally, sea gliders (SEAEXPLORER from ALSEAMAR) with CTD payloads are deployed during the acoustic experiments.

III. Performed Experiments

We detail in this section the various experiments carried out since 2014. To this date, measurement campaigns were solely conducted in the Mediterranean Sea. Fig. 4 displays a map of all the explored locations. The 2014 campaign actually consisted in the system qualification. The passive array, consisting of 64 hydrophones arranged in a comb-like configuration (2.5m$\times$2.5m array) was deployed in a shallow water environment (D = 100m) with a sandy bottom 5km from the shores of north eastern shores of Corsica. A moored pinger transmitted sequences composed of LFM, CW and white noise signals in the pinger frequency band ($1 - 14$kHz). A structural evolution was validated in 2015, with the deployement of the passive array in Marseilles (shallow water environment, sandy bottom, $D = 100$m). The 64 hydrophones were arranged in the form of a vertical line array of 10m height. The emitted signals were identical as those used in 2014. The number of hydrophones was doubled in 2016. A 128-hydrophone comb-like array was deployed close to the location of ALMA2014. A moored pinger transmitted the sequence displayed in Fig. 3. A towed source also transmitted various signals at lower frequencies (down to a few Hz). Finally, the same array was deployed in 2017 in the canyon of St Florent, Corsica. The passive array and the moored pingers (two different pingers on the same mooring) were placed each on one side of the canyon, in order to explore deep water

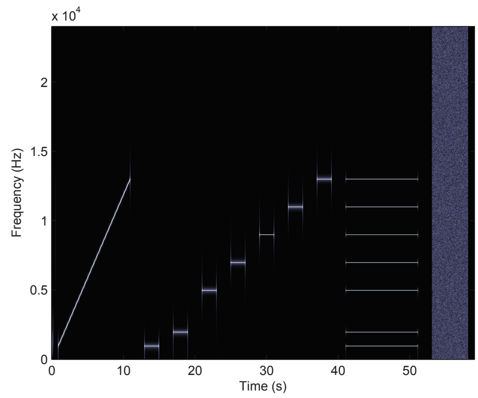


Fig. 3: Emission sequence.

TABLE I: Summary of the ALMA campaigns

Year	***2014***	***2015***	***2016***	***2017***
Nb sensors	64	64	128	128
Configuration	Comb	VLA	Comb	Comb
Moored Sources	1	1	1	2
Towed Sources	0	0	1	1
Water Depth (m)	100	100	100	$<$ 2500
Month	sept.	nov.	nov.	oct.
Location	E. Corsica	Marseilles	E. Corsica	NW Corsica

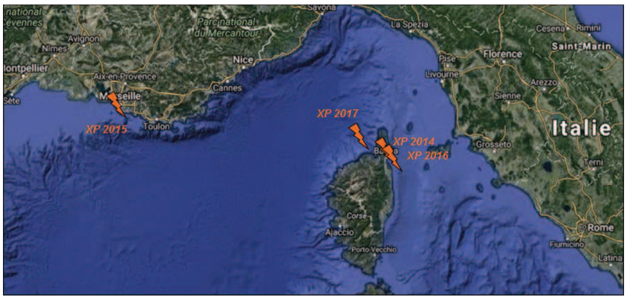


Fig. 4: Locations of the ALMA measurements campaign conducted in the Mediterrannean Sea.

propagation. The emitted sequence was the same as in 2016. Similarly to what was done in 2016, a towed source was used. Table I gathers the main details of the aforedescribed experiments.

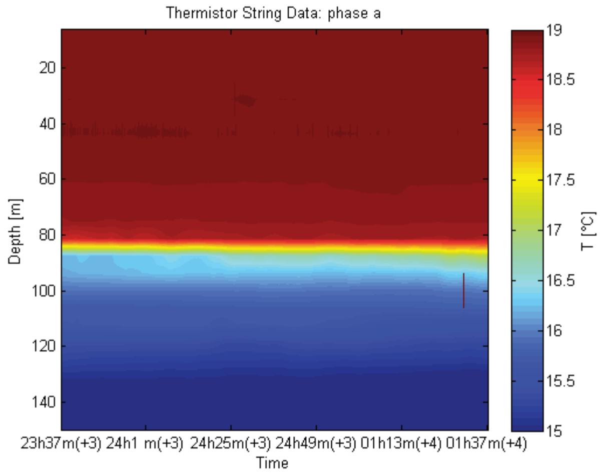
IV. Data Analysis: Sonar Performance in a Fluctuating Medium

A. Environmental Data

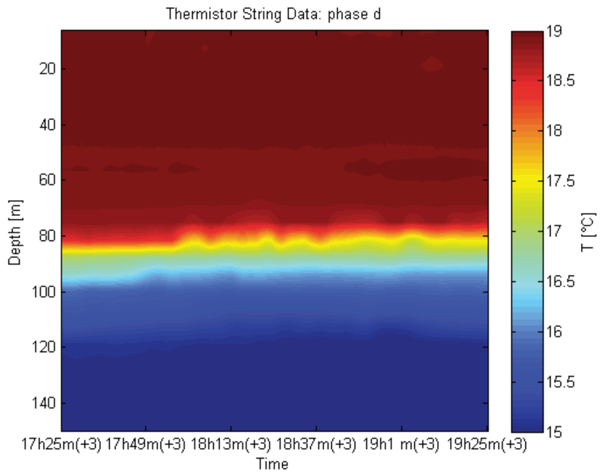
The analysis provided here focuses on two specific time period during the ALMA2016 recordings. These time periods were identified by detecting temperature fluctuations on the data recorded by the thermistor string. Hence, we will be able to compare features of the acoustic signals acquired in a relatively stable environment and in a perturbed medium. Fig. 5a displays a 2 hours period recording of the temperature data. As depicted, the temperature is almost constant down to a depth of 80m, where a strong thermocline is observed down to a 120m depth. The temperature profile is stationnary during this time period. On the contrary, Fig. 5b shows the appearance of temperature fluctuations in the thermocline, starting at approximately $18h13m(+3)$. The period of theses temperature oscillations was estimated to be around 10 minutes, which makes internal waves a probable candidate for their source. Although the amplitude of the fluctuations seem quite small, they have a major impact on the sound wave propagated throughout.

B. Coherence and Estimated Array Gain Degradation

As shown in [22] [23] [24], one can estimate the correlation of the signal received along an array by calculating the Mutual Coherence Function (MCF), which provides the correlation coefficient as a function of the sensor separation. It is classically defined as follows:



(a) Unperturbed case.



(b) Perturbed case.

Fig. 5: Temperature data recorded by the thermistor string

$$\Gamma(l) = \left\langle\left\langle \frac{\Pi(n)\,\Pi^*(n+l)}{|\Pi(n)|\,|\Pi(n+l)|} \right\rangle_{N_r}\right\rangle_N, \quad (1)$$

where Π is the spectrum of the received signal at the frequency of interest, l is the discrete sensor spacing, $.^*$ denotes the complex conjugate, $< \ . >_N$ is the ensemble average over the array (variable n) and $< \ . >_{N_r}$ is the ensemble average over the number of independant realizations. The calculation of the MCF leads to the estimation of the radius of coherence, defined by Carey [1] as the sensor spacing l that verifies:

$$\Gamma(l = \rho_C) = e^{-\frac{1}{2}}. \quad (2)$$

Moreover, from the calculation of the radius of coherence, a parameter that we will refer to as the "array gain degradation" parameter, denotes δAG can be obtained [25] [26] [27] by weighting the theoretical array gain ($G_{Th} = 10log(N)$) by the MCF:

$$\delta AG = G_{Th} - 10\ \log\left(1 + \sum_{l=1}^{N} \frac{2(N-l)}{N} |\Gamma(l)|\right). \quad (3)$$

This parameter was calculated in the two temporal windows described earlier on: the unperturbed case and the fluctuating case. Fig. 6a and 6b display the results of this calculation on each of the four subarrays of the comb-like 128-hydrophone array, respectively at 1 and 2kHz during the two time windows. The acoustic data used to calculate the MCF and δAG are CWs at 1 and 2kHz, integrated over their total duration ($\tau = 10s$).
The influence of the temperature fluctuations can be observed on the quantities represented here: in the non-fluctuating case, δAG is of the order of 0.5dB at 1kHz and of the order of 1.2dB at 2kHz, while in the perturbed case, those values increase up to 1.5 dB and 2dB respectively. Note that other factors, such as the sensor dispersion can affect the parameter calculated here, are not considered in this study. Furthermore, the integration time of the considered acoustic signals plays a filtering role regarding the phenomena of interest. By integrating over 10s, we disregard the potential influence of small time scale fluctuations such as turbulence. The aim of this study is more to underline the influence of environment fluctuations on array gain than to precisely quantify it.

C. Influence on Conventional Beamforming

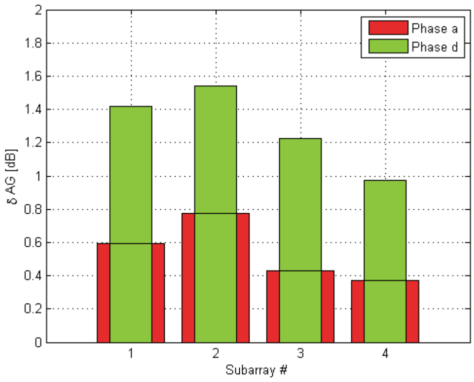
In this section, we confront the conclusions of the coherence study to the practical case of Direction Of Arrival (DOA) finding using conventional beamforming. The latter is applied to the two data sets studied earlier on (acquired in non fluctuating and fluctuating environments). We recall the general method used for conventional beamforming, where the output power is given by [28]:

$$\tilde{P}(\hat{\mathbf{r}}) = \left| \frac{\mathbf{x}_m^H(\hat{\mathbf{r}})}{|\mathbf{x}_m(\hat{\mathbf{r}})|} .\mathbf{x} \right|^2 \quad (4)$$

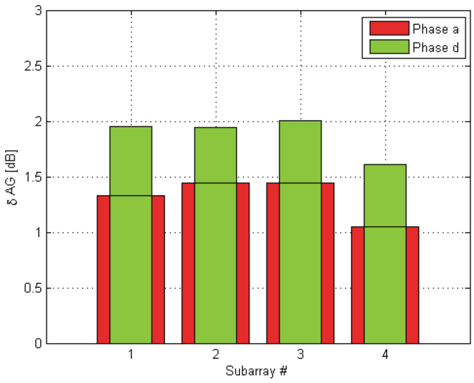
where $.^H$ is the Hermitian operator and $\hat{\mathbf{r}}$ is the estimated parameters of the source location (here the elevation angle of arrival). $\mathbf{x}$ is the vector containing the received signal x on each receiver. For the n-th receiver:

$$x_n(t) = \sum_{n=1}^{N} h_n(t) * s(t-\tau_n) + n_n(t) \quad (5)$$

where $h_n(t)$ is the impulse response of the $n-$th sensor, $s_n(t)$ is the signal radiated from the source, $n_n(t)$ is additive white Gaussian noise (AWGN), with power σ_N^2 and τ_n is the delay associated with the $n-$th sensor. The AWGN is supposed to be uniform along the array and uncorrelated between sensors.

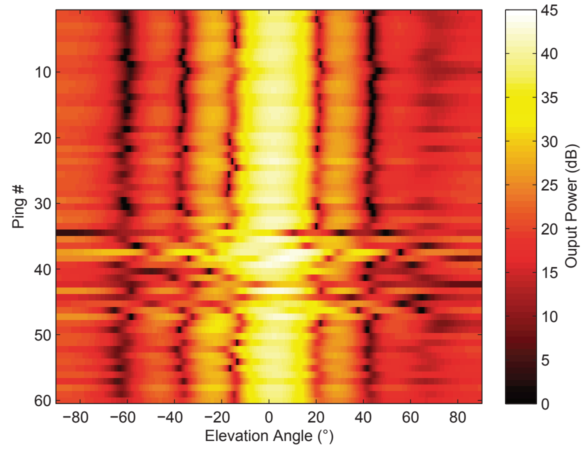


(a) δAG - f=1kHz.

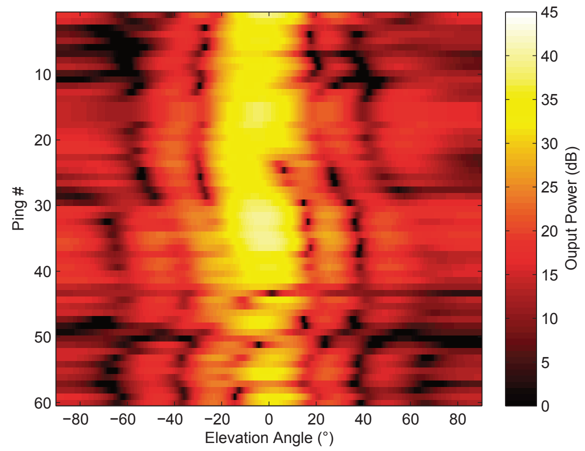


(b) δAG - f=2kHz.

Fig. 6: Array gain degradation



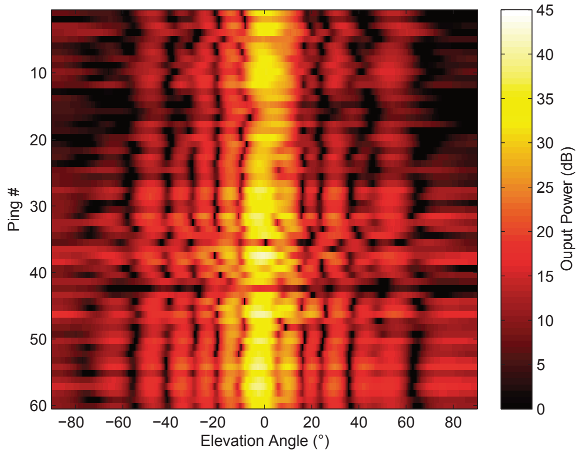
(a) Unperturbed case.



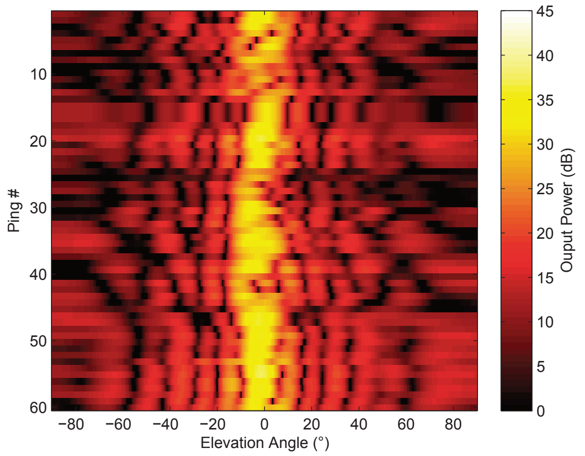
(b) Perturbed case.

Fig. 7: Conventional Beamforming - f=1kHz

Fig. 7a and 7b display the temporal evolution of the output power of the conventional beamforming (one output per considered ping) for the 1kHz CWs, in the case of stationary and fluctuating media (respectivelly). The features of the output of the beamforming in Fig. 7a are stable: a main detection lobe occurs at a slightly positive elevation angle and is constant over the total duration of this phase (60 pings 2 hours). Between Ping 35 and Ping 42, some distortions occur but they are related to a sudden drop in SNR due to an undetermined event. On the other hand, the pattern displayed by Fig. 7b shows clearly different features: while the platforms (source and receiving array) are motionless, the main detection lobe occurs at an arrival angle that varies significantly over time. While fairly idientifiable in Fig. 7a, the arrivals related to multipath propagation are diffuse and their direction of arrival varies over time in the fluctuating case.
Similarly, the 2kHz case (Fig. 8a and 8b) exhibit the same features: in the unperturbed case, the main detection lobe as well as the arrivals associated with multipath propagation does not vary much over the total length of the observation time window. The fluctuating case (Fig. 8b), on the other hand, displays a slight narrowing of the various directions of arrival at the beginning of the time window (Ping 8 to Ping 15) and a less dominant central lobe. The influence of the fluctuations of the propagation medium is here also observed.
It is however interesting to notice some promising properties, such as the increase in output power near Ping 35 in Fig. 7b (fluctuating environment, 1kHz). This could be a preliminary evidence of the potential use of processing techniques known as "Lucky imaging" [29] to make the most of the received signal, even in usually difficult propagation environment.
We provide in Fig. 9a and 9b some complementary results obtained with the same method on 5kHz CW. A remarkable property is observed in the non-fluctuating case: Fig 9a displays the separation of two rays with a direction of arrival close to $0\,\mathrm{deg}$. However, fluctuations of temperature in water column seem to completely disable the separation of these two rays. This results highlights another source of degradation of sonar performance by fluctuations in the ocean: the loss of resolution (and more specifically here, spatial resolution).

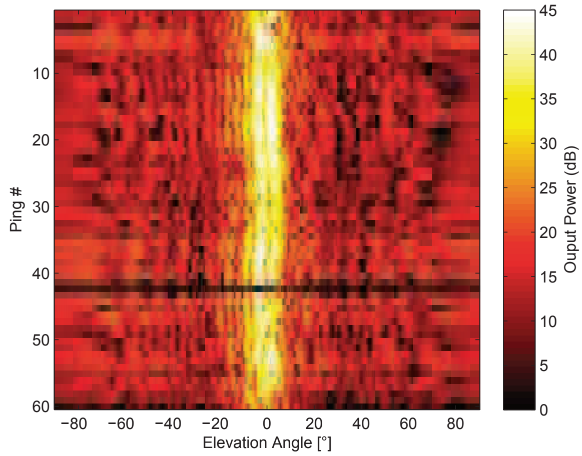


(a) Unperturbed case.

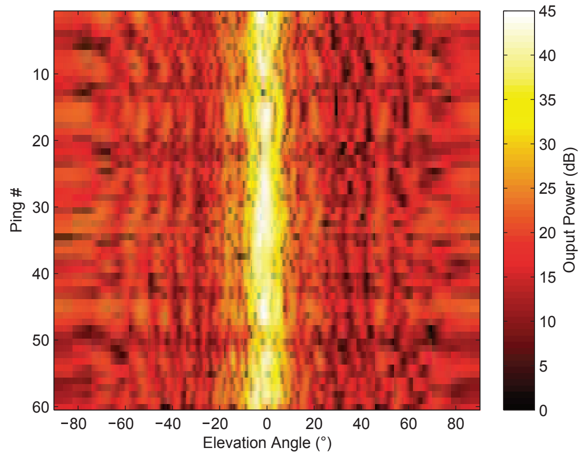


(b) Perturbed case.

Fig. 8: Conventional Beamforming - f=2kHz



(a) Unperturbed case.



(b) Perturbed case.

Fig. 9: Conventional Beamforming - f=5kHz

V. Conclusion

In this paper, we presented a deployable acoustic measurement system that we personnaly see as an embryo for an acoustic observatory. Its capability to be deployed in various environments at numerous occasions was demonstrated. Moreover, a considerable amount of acoustic data (gathered on either 64 or 128 hydrophones), complemented with environment assessment in various environments (shallow water, canyons) was recorded and is available for scientists who may find an interest in this work. A set of data analysis was presented, emphasizing on the loss of detection gain, accurate multipath description and resolution of the sonar processing chain. We wish for the collected datasets to be useful for benchmarking corrective robust sonar processing techniques to mitigate the effects of the environmental fluctuations. Some promising early work was already conducted [30] [31] [32] and is to be validated on data issued from ALMA campaigns. Advances in other fields such as adaptive optics [33] or other studies in underwater acoustics [34] are also under study.

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