THE INFLUENCE OF UPWELLING IN UNDERWATER COMMUNICATION OFF CABO FRIO ISLAND

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Abstract: *This work aims at understanding the influence of upwelling in underwater acoustic communications as observed in a shallow water environment on the coast of Cabo Frio Island, Rio de Janeiro, Brazil, during the BIOCOM'19 experiment in January 14-18, 2019. This sea trial is part of the project "Building of signalling with bioacoustic noise characteristics for underwater communications" (BIOCOM) whose objective is to characterise biological acoustic signals and, based on such information, to transmit communication signals compatible with the characteristics of the studied bioacoustic signals. The scope of the experiment is to perform frequency modulated transmissions during 4 days from a source at 2.6m depth to a 4-hydrophones tetrahedron-like receiver array, located 1600m away in a range-dependent transect with depth between 3 and 22m. The deeper part of this transect is subject to sudden water column temperature change due to upwelling, therefore the study of its effect on communication performance is of interest for eventual adaptation and improvement. The project goal is to develop signalling technique that use the biological information of the soundscape to then establish communications with low signal to noise ratio in this environment, in an attempt of hiding, at some degree, the message in the noisy soundscape. A modulation scheme based on hyperbolic frequency swept chirps is used, aiming to increase detection capability at the receiver. The results indicate that upwelling can deteriorate the communications link due to the occurrence of severe refraction caused by the rise of cold water, that change significantly the water sound speed profile and potentially increase the number of bit errors. The present work indicates that the upwelling phenomenon significantly affects the acoustic channel and the underwater communication performance causing fluctuation of the signal level at the receiver. The development of techniques that efficiently compensate, or at least overcome the main effects of, the upwelling in shallow water acoustic propagation is still an open field of research.*

Keywords: *Underwater acoustic communications, upwelling, shallow water propagation*

1. INTRODUCTION

Upwelling is an oceanographic phenomenon that involves motion of cooler, dense water toward the sea surface, changing the water sound speed profile structure and ambient noise level [1]. The rise of nutrient-rich water stimulates reproduction of phytoplankton and high concentration of clorophila, causing increased biological activity [2,3]. A communication link can be potentially damaged by upwelling effects because the sound speed profile can be changed by cold water motion. Such motion can cause a mixture layer in the water column or also can induces the formation of waveguide duct with excessive energy interaction with the seabed and increased transmission loss. The upwelling phenomenon can occur in a shallow environment between source and receiver, potentially making message recovery to be significantly more challenging. Shallow water acoustic channels are characterized by time-frequency doubly dispersion, frequency selective attenuation, phase fluctuation and fading, features that make it difficult to achieve message recovery in underwater acoustic communications [4,5].

Underwater acoustic communications in shallow water requires the usage of a robust modulation scheme, capable to offer enough robustness against the above described channel distortions. The well-known uncoherent scheme Frequency Shift Keying (FSK) may be an attractive choice, in comparison to coherent schemes, because carrier frequency detection in underwater communications is easier than carrier phase detection. A disadvantage is the modest capacity of data throughput, which, however, can be tolerated in cases when high data rate is not a strong requirement. Furthermore, considering communications with low Signal to Noise Ratio (SNR), some action should be taken to improve signal detection and assure message recovery. In this sense, we propose in this work to test underwater communications applying a procedure that consists in substituting the frequency orthogonal tones from FSK by hyperbolic frequency swept chirps whose central frequencies are the same of the orthogonal tones, in a scheme hereafter named Hyperbolic Chirp Shift Keying (HCSK). It is expected to improve symbol detection capability with HCSK relying on the well-known good autocorrelation properties of frequency swept chirps in comparison to frequency tones, assuming that we use a matched filter based receiver. Also, the hyperbolic chirps are preferred to linear chirps because the former is more robust to Doppler effect [6].

The HCSK scheme was used in the BIOCOM’19 sea trial, employing signal frequency bandwdith empirically chosen, after observing the Cabo Frio Island soundscape during a three month period. Thus, an acoustic signature of that zone was statistically characterized before the experiment period, collecting data mainly of biological origin, and from this information the frequency band of communication was chosen to coincide with the noisiest part of the band, in an attempt of mixing messages in the environmental soundscape. Figure 1 shows the spectral characterization of a long term 89-days observation of the underwater environmental noise in the site where the experiment took place.

This paper presents results of the BIOCOM’19 experiment, occured off Cabo Frio Island, in Arraial do Cabo, Rio de Janeiro, Brazil, during January 14-18, 2019. Several HCSK modulated data set were transmitted in shallow water, from a source at 2.6m depth to a 4-hydrophones tetrahedron-like receiver array, located 1600m away in a range-dependent transect with 3 to 22m water depth. The transmissions analized in the present work were performed during the occurrence of upwelling, during the first three days, and during its absence in days January 17 and 18. Thus, we expect to achieve a fair comparison of communication results between these two scenarios.

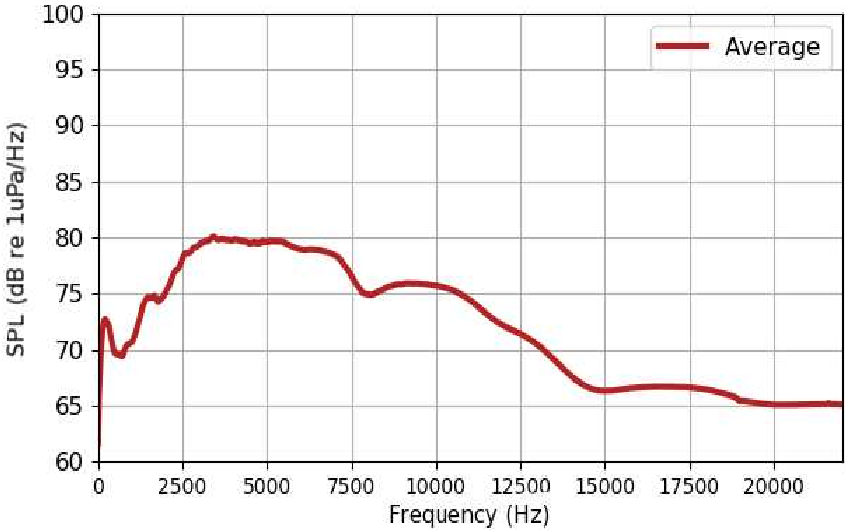

Fig.1: Soundscape observed during 89 days in the BIOCOM'19 experiment, forming an average characterization of an small underwater zone off the Cabo Frio island.

2. THEORETICAL BACKGROUND

Assume a M-FSK incoherent modulation, where the prefix M denotes the symbol map size. The method for generating this scheme is to gate M oscillators with the modulating signal:

$$x_m(t)=A\cos(2\pi f_m t+\theta_m);\quad m=1,2,\dots,M;\quad 0\le t\le T_b \tag{1}$$

where the m-th carrier frequency is denoted f_m, the constant amplitude is A and the m-th carrier phase is θ_m, noting that the phases need not be the same in this uncoherent system. Furthermore, the frequencies f_m are chosen so that the signals $x_1(t)$ to $x_M(t)$ are orthogonal to each other over the time interval [0, T_b], as follows

$$\int_0^{T_b} x_m(t)x_n(t)\,dt = 0;\quad m=1,2,\dots,M;\quad n=1,2,\dots,M;\quad m\neq n \tag{2}$$

The proposed HCSK assumes that the set of orthogonal frequencies f_m are used respectively as the central frequencies of a set of hyperbolic frequency swept chirps, whose bandwith are two times the pulse bandwidth for better correlation results while also using large enough frequency guard intervals to avoid significant intercarrier interference. Thus, driven by the hyperbolic frequency swept chirp (HFM) definition [7], the M-HCSK signal is

$$s_m(t)=rect\left(\frac{t}{T_b}\right)\cos\left(\frac{2\pi}{k}\ln(1+k f_m t)\right)+\theta_m;\quad k=\frac{f_0-f_{end}}{T_b f_0 f_{end}}\quad m=1,2,\dots,M;\quad 0\le t\le T_b \tag{3}$$

where f_0 and f_{end} are respectively the starting and ending frequency of the HFM pulse.

The HCSK transmitted signal propagates through the shallow water channel that is assumed linear time-invariant since the transmission time is small enough and is contaminated by additive noise that has the non-flat power spectrum shown in Fig. 1, yielding the received signal. The received chirp symbols are then sequentially identified by a matched filter detector that decides for maximizing the signal to noise ratio in reference to symbols contained in the symbol map.

3. THE ACOUSTIC PROPAGATION SCENARIO IN CABO FRIO ISLAND

The shallow water noisy channel in Cabo Frio Island can be represented by the impulse response of a LTI channel, assuming an invariant channel for the short time of few symbols (*e.g.*, ~50 miliseconds), as shown in Fig. 2, where pulse compression is used to capture the Channel Impulse Response (CIR) estimate. It was obtained by averaging the cross-correlation envelopes of eight chirp successively received with the emitted chirp, showing the channel main features.

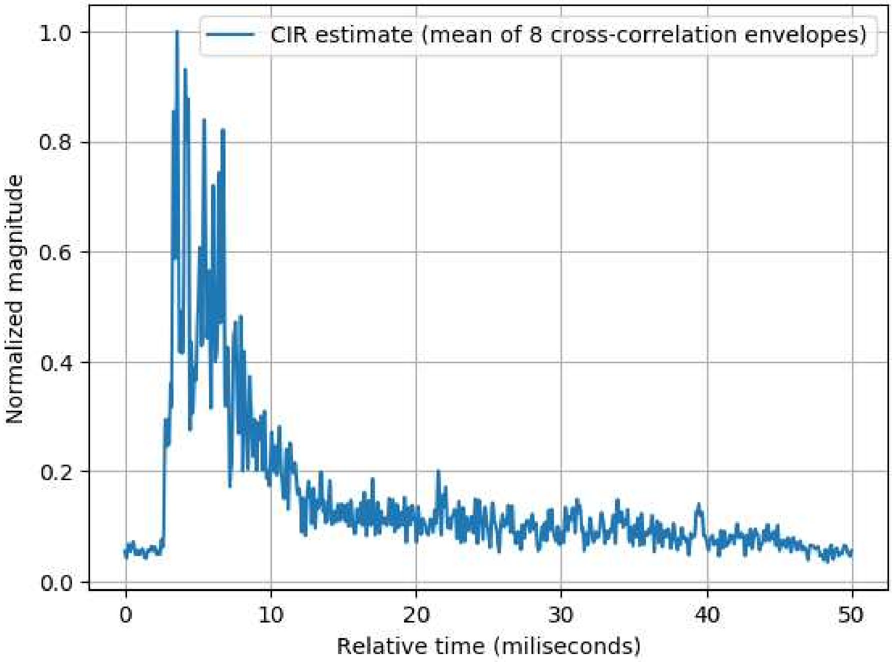

Fig.2: Channel Impulse Response (CIR) normalized estimate for the source-receiver transect of the BIOCOM'19 sea trial at time 10h20m on January 18, 2019.

Observing figure 2 we note that CIR delays spread significantly, indicating severe noise and multipath effect distortion along the whole CIR estimate.

The underwater communication transmissions were done in an environment where stratified water column occurs due to upwelling-driven cold water entering in the site of the experiment bellow the warm water. This stratification, a side effect of upwelling, occured on January 14-16, and was absent on January 17-18. Figure 3 shows the Sound Speed Profiles (SSP) recorded at afternoon of days 14 to 17, making it clear that there are a severe change in water sound speed for depths greater than 7 meters starting on January 17. In the first three days there are abrupt sound speed changes in the low part of the SSP profiles (decrease to about 1507 *m/s*), forming an acoustic propagation duct due to upwelling and this effect vanishes on the last day, presenting nearly isovelocity sound profile (with approximately 1530 *m/s*).

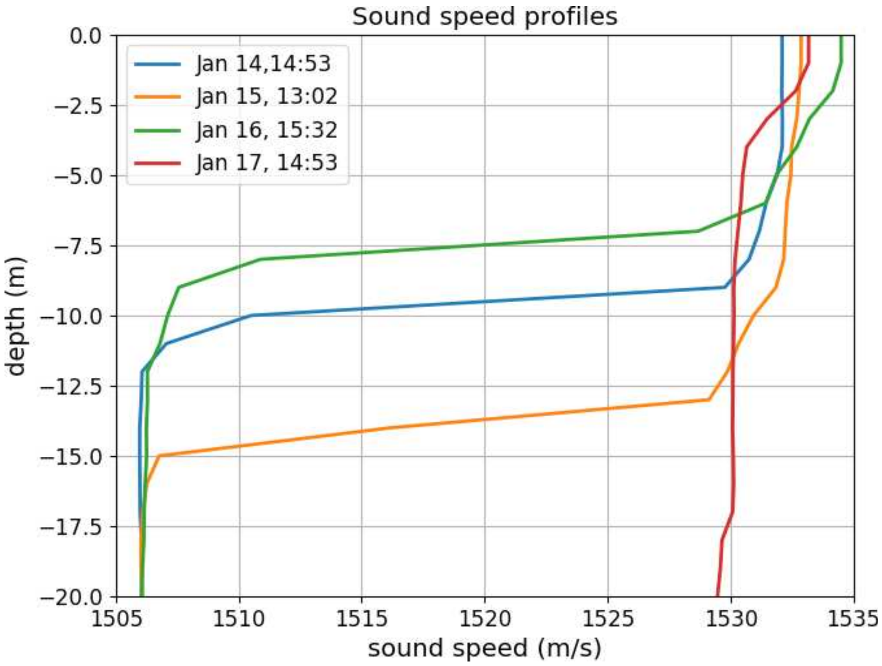

Fig.3: SSP at afternoon on January 14 (blue line), 15 (orange line), 16 (green line) and 17 (red line). Note the severe change of water sound speed occuring at depths greater than 7 meters before January 17. The acoustic duct that exists on the three ealier days vanished on the last day, presenting after 3 meters depth a nearly isovelocity sound profile.

In addition, in order to present a visualization of the acoustic propagation in the above scenarios of the BIOCOM’19 sea trial, a ray trace acoustic propagation model (Bellhop [8]) is used to compute the transmission loss in the scenario without upwelling effect (using isovelocity SSP with 1530 *m/s*), as shown in Fig. 4, and with upwelling effect (using the SSP of the day 15), as shown in Fig.5. The seabed is mainly formed by a sand half-space and its bathimetry is visualized by the upper limit of the blue part of plot in Fig 4. The source, a ITC-1001 omnidirecional transducer, is at 2.6 meters depth and the 4 hydrophones of the tetrahedron-like receiver array are at 7.5 meters depth (upper single hydrophone) and at 8.4 meters (three hydrophones at the bottom tips of the structure), with the tetrahedron edges separating each sensor being 0.9 meters. Eight carrier frequencies are distributed between 4520*Hz* and 12200*Hz* with separation of 960*Hz*, spreading the symbols in a noisy frequency band of the soundscape of the Cabo Frio Island shown in Fig. 1. The transmission loss simulation was done using the central frequency (8360*Hz*).

Observing the transmission loss figures it becomes clear that the energy level arriving on the receiver at the non-upwelling scenario (Fig. 4) is much better distributed, and probably higher due to increased bottom reflection, than the energy level arriving when in presence of upwelling (Fig. 5). In the latter, there is severe interaction with the seabed, indicating interference in terms of transmission loss. This effect is caused by the severe downward refraction in the SSP profile recorded in a zone influenced by the upwelling phenomenon off Cabo Frio Island.

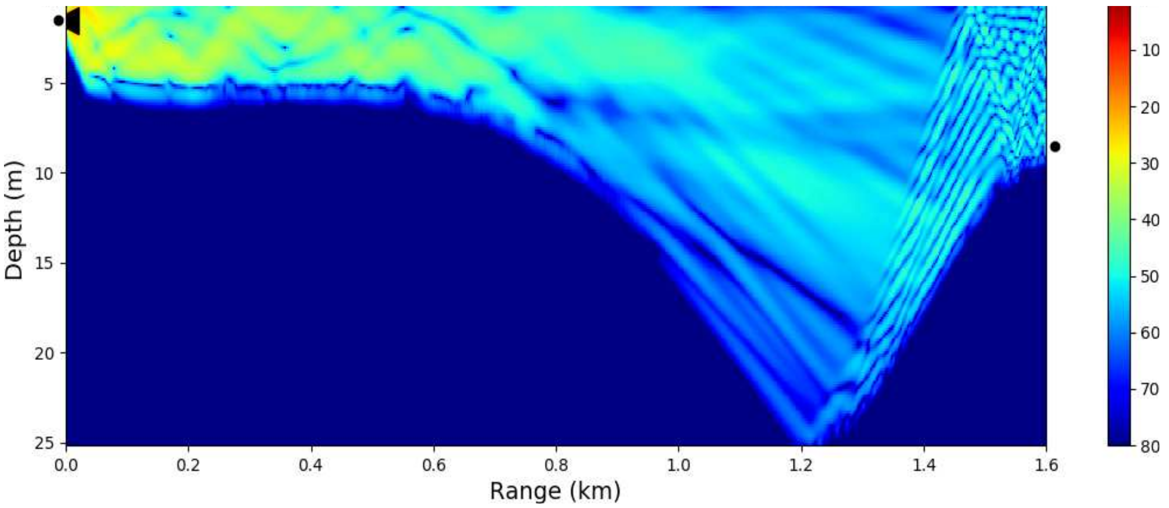

Fig.4: Transmission loss simulation at frequency 8360Hz with the environmental characteristics of the site of BIOCOM'19 sea trial using isovelocity sound speed profile.

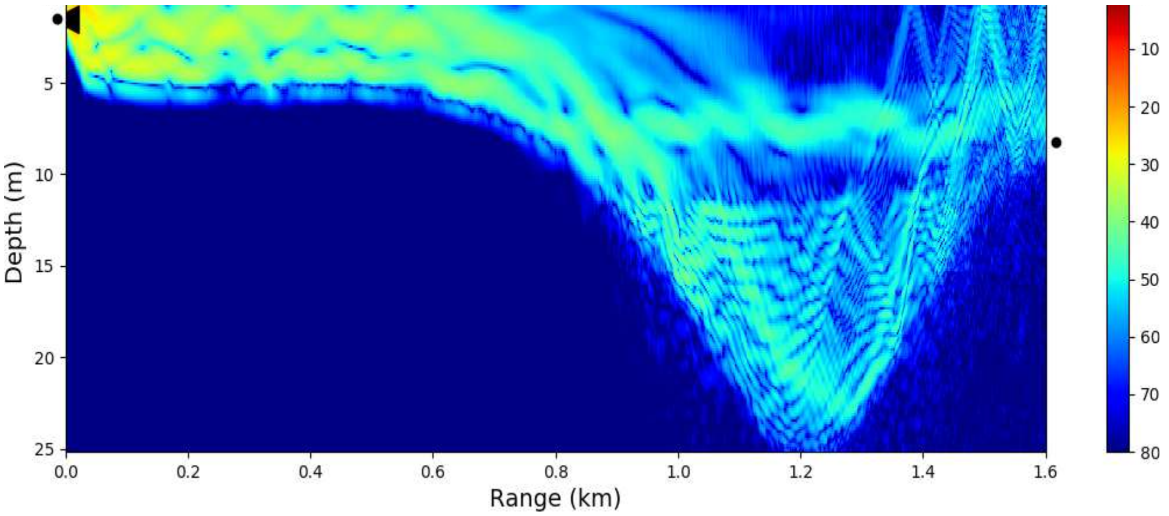

Fig.5: Transmission loss simulation at frequency 8360Hz with the environmental characteristics of the site of BIOCOM'19 sea trial using the sound speed profile captured on January 15, with severe downward refraction due to upwelling.

4. THE BIOCOM'19 SEA TRIAL RESULTS

The results are presented for the HCSK-modulated message transmitted repeatedly for 246 times during the days 15 and 18, and received at the 4-hydrophone array generating the total of 984 received messages by all channels together.

Figure 6 shows the Bit Error Rate (BER) of the processed messages received in each channel during the days 15 and 18 sequentially, where the result of each message (named as packet) is denoted by a blue star for data of day 15 and green star for day 18. This figure has the goal of presenting the performance variance of the results for all packets sequentially (blue/green stars) as well as their trend (red line) along those two days, in order to observe how the results are influenced by the SSP variations induced by upwelling. The vertical dashed line also marks the separation from one day to another. The red line is made by joining the points determined by the average of every 20 consecutive packets, thus representing a general trend of the results.

The upwelling effect is indirect in the BIOCOM'19 sea trial because the site of the experiment had entering of cold water through a passage between the Cabo Frio Island and the main land, causing SSP stratification with cold water bellow warm water. The strong stratification observed is not due to surface agitation but due to the sipping of cold water underneath the warmer water due to the combined effect of upwelling and tide. The stratified SSP versus nearly isovelocity SSP is the main cause of the variation between results from days 15 and 18.

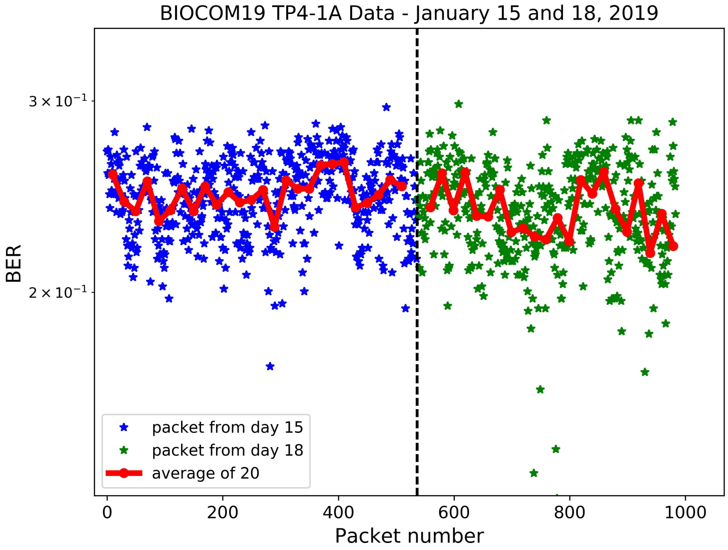

Fig.6: BER resullts of packets sequentialy received on January 15 (blue stars) and 18 (green stars). The vertical dashed line denotes the date change from one day to another. The red line is made by joining the points determined by the average of every 20 consecutive packets.

The data presented in this work have poor BER performance because of excessively low SNR in the receiver. Despite of that, these data is useful to analize communication degradation induced by the upwelling phenomenon observed in the experiment site. Figure 7 shows a comparison between the trend observed in the results obtained from data recorded on January 15, when the environment is under effect of upwelling, and the trend observed in the results obtained on January 18, without upwelling, also in terms of BER.

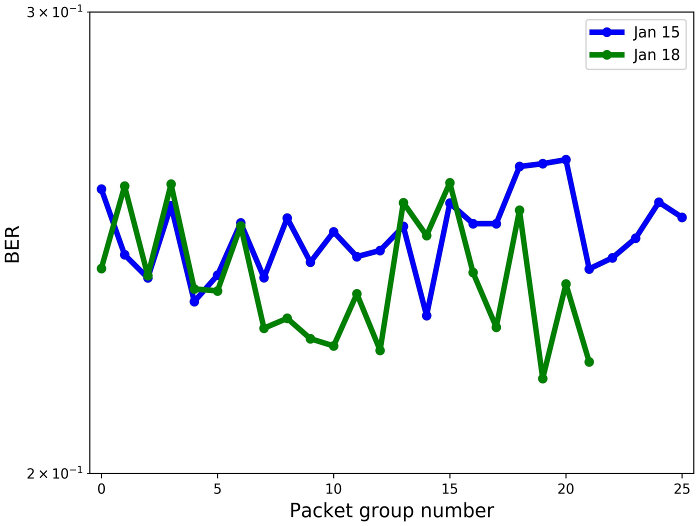

Fig.7: Average of each consecutive 20 packet results of data received on January 15 (with upwelling) and January 18 (without upwelling).

Results of figure 7 indicate that there are lost of communications performance for the data received in an environment under upwelling phenomenon, as expected, given the effects of the stratified SSP. This confirms that upwelling can significantly deteriorate an underwater acoustic comunication link, even using the HCSK modulation scheme in an atempt of reach robust detection in a shallow water noisy environment.

5. CONCLUSION

The performance of underwater acoustic communication systems is frequently affected by channel conditions. Variations in the underwater acoustic channel, such as those caused by upwelling phenomenon, can generate shadow zones due to high gradient of water density. Moreover, this gradient can improves the multipath effect in shallow water potentially making it worse for the intersymbol interference. The BIOCOM'19 results show this relationship between upwelling and bit error rate. The analyzed data indicated that there are a positive and linear relation, *i.e.*, the errors increase when upwelling is more severe. These results presented at very particular conditions encourage further studies in order to develop techniques to mitigate the upwelling effects in order to preserve acoustic communication links in shalow water.

6. ACKNOWLEDGEMENTS

The authors are grateful to the Brazilian Navy and to the *Conselho Nacional de Desenvolvimento Científico e Tecnológico* (CNPq)/*Ciências Sem Fronteiras* (Contract No. 401407/2014-4) for all the support given to BIOCOM Project. This work is also part of the effort developed for project 2DeepScape (contract MITEXPL/IRA/0070/2017) FCT program MIT-Portugal.

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