

Using passive acoustics for monitoring seagrass beds

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Abstract—This paper discusses the ambient noise acquired during the period of one week, from May 8 to 15, 2013 over a *Posidonia oceanica* bed in the Bay of la Revellata, Calvi, Corsica. The acoustic receivers were moored at 3 locations with water depth ranging from 2 to 20 m. Simultaneously with acoustic measurements, the dissolved O₂ was measured by an array of optodes. Preliminary results have shown that the acoustic noise power measured at various locations in the meadow is highly correlated with dissolved O₂ (measured by other methods). Nevertheless, a close inspection of noise waveforms shows impulsive signals with shape similar to those produced by snapping shrimp and other shell fish. This work discusses the challenges faced on using these noise waveforms as ecosystem indicators and particularly to monitor the photosynthetic activity.

Index Terms—passive acoustics; seagrass meadow; oxygen production; ambient noise

I. INTRODUCTION

Despite accounting for only a relatively small area of the coastal ocean, seagrass-dominated ecosystems contain a large biodiversity, play a role in preventing erosion of the seabed, produce oxygen, and store large quantities of CO₂[1]. In the Mediterranean, *Posidonia oceanica* is an endemic seagrass that covers about 2% of the seafloor growing to considerable depths, up to 40 m. Healthy seagrass meadows are highly populated and the refuge of numerous marine species of fish and crustaceans. The seagrasses O₂ production and CO₂ storage capacity per occupied area is 20 to 30 times greater than that of forests[2]. But, like other coastal environments *Posidonia oceanica* meadows are threatened due to human activity, including marina and port construction, touristic developments, anchoring and mooring, waste water discharges and other types of pollution[2]. The health of seagrass meadows is primarily linked with their photosynthetic activity, therefore the amount of O₂ produced is an important indicator of the seagrass meadow status. Conventional methods accurately determine the amount of O₂ dissolved in sea water, nevertheless underestimates O₂ released as bubbles (see [3] and Refs. therein). Dissolved O₂ has little or no effect on underwater sound, but when sound travels through bubbly media it suffers attenuation due to scattering at high frequency or increased bottom interaction in the low frequency band. Several experiments where low frequency sound was emitted through seagrass meadows have demonstrated a significant release of O₂ as bubbles, suggesting that combining acoustic with conventional methods, one can attain more reliable

estimates of O₂ production. The sound sources used in these experiments, although applying low sound levels, do represent an intrusion in the environment. Fishes and crustaceans that leave in the seagrass meadows produce acoustic signals when moving, hunting, eating or even breathing, generally known as acoustic noise. A healthy seagrass environment is a noisy environment, and since the characteristics of the noise and its variability can be assigned to particular species and/or behavior, it can be used to estimate populations and their respective time and spatial patterns, therefore acting as secondary indicators of ecosystem status. Preliminary results of our research conducted in a pristine seagrass meadow in STARESO, Bay of La Revellata, Corsica, France in 2013, show that the noise power measured at various locations in the meadow is highly correlated with dissolved O₂ (measured by other methods) [4]. Nevertheless, a close inspection of noise waveforms shows impulsive signals with shape similar to those produced by snapping shrimp and other shelled creatures.

The overall noise variability in a seagrass meadow is intricate. Although, it can serve as an indicator of biological activity of the ecosystem, the noise sources are not well characterized and understood. The correlation between noise power and dissolved O₂ is evident, but its causality has not been demonstrated and deserves further investigation. In that sense, a possible path to be explored is the analysis of the echoes generated by single impulses. In underwater a signal propagates from a source to a receiver through different paths giving rise to various echoes. In general, at short ranges, one can differentiate echoes that have interaction with the bottom or surface and echoes that does not suffer from such interactions. The release of O₂ bubbles during photosynthesis can lead to changes in the characteristics of echoes arriving from different directions. One can expect that bottom reflected echoes, which cross the plant layer would be significantly affected by bubbles, therefore carrying information about their concentration. These issues will be studied during next 3 years under the project SEAFOX by a multidisciplinary team of acousticians and marine biologists from University of Algarve, Portugal with the objective to develop non-intrusive acoustic methods to monitor the status of seagrass.

In this study we focus on the impulsive waveforms present in the ambient noise. We show the multipath structure of the recorded waveforms and analyze the diurnal variability of the frequency (number of peak events per time unit) and



Fig. 1. Overview of the experimental area, STARESO, Bay de La Revellata, Corsica, France. Label "Optodes" indicates the dissolved O₂ measurements. Labels "DA-1", "DTU", "SR-1" indicate the hydrophone moorings

the amplitude of the noise pulses at the 3 moorings. Using a short vertical array data we show the diurnal variability of the direction of the noise pulses along the water column. It is also discussed the diurnal variability of the bottom grazing angle that could be linked with photosynthesis.

The paper is organized as follows. The experimental setup is described in the next section. The correlation between noise power and O₂ measurements is discussed in Section III. Section IV addresses the impulsive nature of the noise and analysis the variability patterns of the frequency (number of events per time unit), amplitude and directionality of noise pulses. Section V discusses how to invert for bottom properties from the noise pulses. Finally, Section VI draw some conclusions.

II. EXPERIMENTAL SETUP

The acoustic data were gathered during one week period, from 8th to 15th May 2015, in front of the Station de Recherches Sous-marine et Océanographiques (STARESO), Bay of Revellata, Calvi, over a *Posidonia oceanica* meadow. The area is classified as a pristine site, where a healthy and dense *P.Oceanica* meadow extends from shore to approximately 30m depth over a sandy bottom with a few rocky patches.

The acoustic signals were recorded every 10 min by 2 SR1 self-recording hydrophones, and continually by the DA1 single-hydrophone and the DTU 8 hydrophone short array (see equipment positions in Fig. 1 and mooring schemes in Fig. 2). The DA1 single-hydrophone was moored in the STARESO harbor 1.5 m above the bottom (Fig. 2(a)). Initially deployed at 2.3 m water depth, the DA1 was redeployed at 5.8 m water depth on May 13, at 7 am. The Short Hydrophone Array (DTU/SHA) is a vertical array of 4 hydrophone pairs 10 cm apart that is functionally equivalent to a vector sensor array [5], herein used as a 4-hydrophone pressure array (1 hydrophone from each pair). The array was deployed 4 m above the

bottom at 10 m water depth, the deepest hydrophone is labeled "Hyd 1"(Fig. 2(b)). The SR-1 self recording hydrophones [6] were fixed to a rope 4 m and 6 m above the bottom (Fig. 2(c)) acquiring 3 min of signal every 10 min. From May 9 to 13, the SR-1 hydrophones were deployed at location labeled *SR-1 2013* in Fig. 1 at 10 m water depth. Then, the SR-1 hydrophones were recovered for maintenance and redeployed at the location labeled *SR-1 2011* in Fig. 1 at 20 m water depth.

Simultaneously with acoustic measurements environmental data were gathered. Temperature-conductivity profiles acquired at various locations during the period of the experiment showed that temperature ($\sim 17^\circ$) and salinity (~ 38 ppt) were virtually constant with depth and time giving rise to a sound speed of approximately 1517 m/s. The dissolved O₂ concentration was measured by 2 Aanderaa optodes (3835) moored at 10 m depth. The optodes acquired data hourly at 7.0 and 9.5 m depth as part of a permanent mooring installed in August 2006 [7] (see label "Optodes" in Fig. 1 for location).

III. NOISE POWER VARIABILITY

The power spectral density of the ambient noise and its diurnal variability from blocks of 30 s acquired every 5 min has been presented in a previous work [4]. Figure 3 presents the power spectral density of the ambient noise acquired at DA1 hydrophone. The noise field in the band 2–7 kHz was dominant and it is clearly seen a diurnal variability pattern, where noise power is higher overnight than during daylight. Similar power spectral characteristic and its diurnal variability was observed at other coastal locations[8], [9]. Since the various hydrophones were not calibrated, the absolute sound power levels are not available. In May 13 (julian day 133), the DA-1 and SR-1 moorings moved from a shallow locations (2.3m and 10m water depth, respectively) to deeper locations (5.8m and 20m water depth, respectively). The absolute magnitude of the ambient noise decreased at deeper locations (see Fig. 3), but the day-night variability pattern and relative day-night magnitude of the noise power did not change significantly in the considered band.

In order to compare the noise power variability with the dissolved O₂ measurements, the total power in the band 2–7 kHz was computed from each 30 s long block of data. These "instantaneous" values of the noise power and respective half-hour averaged values are presented in Fig 4 by dots and solid lines, respectively. The colors are assigned to the hydrophones as follows: green to the DA1 hydrophone, blue to the hydrophone n.8 of the SHA/DTU, magenta to the SR1 hydrophone installed 4m above the bottom and cyan to the SR1 hydrophone installed 6m above the bottom. Since the various hydrophones are not calibrated and have different gains, for comparison proposes the mean noise power of each hydrophone was removed in the presented data. The black lines superimposed in the figure represent the dissolved O₂ measurements at 7 m depth (solid line) and 9.5 m (dash-dotted line). Please note that mean values were also removed in plots of the O₂ data. Moreover, the scale is different for the two depths. In fact the variability, the mean and the peak measured

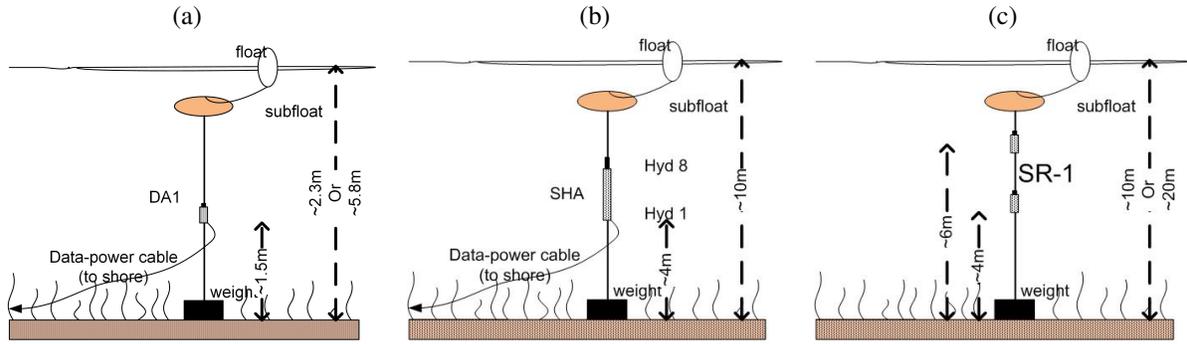


Fig. 2. Schematic of the moorings: DA1 single-hydrophone (a), Short Hydrophone Array (b) and SR1 self-recording hydrophones (c)

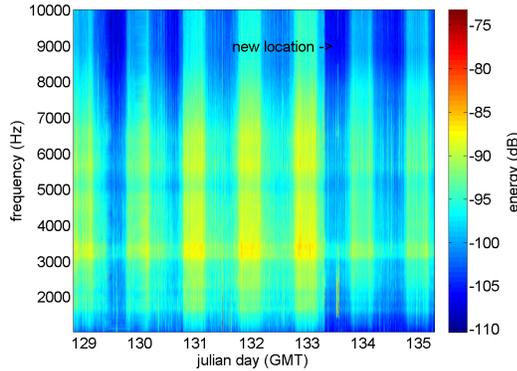


Fig. 3. Power spectral density of the noise acquired in DA-1 hydrophone during one week period. The arrow indicates when the hydrophone mooring was moved from the 2.3m to the 5.8m water depth location.

at the deeper optode, which is within the plant's layer are larger than the corresponding values at the shallowest optode, installed 3 m above the bottom [4].

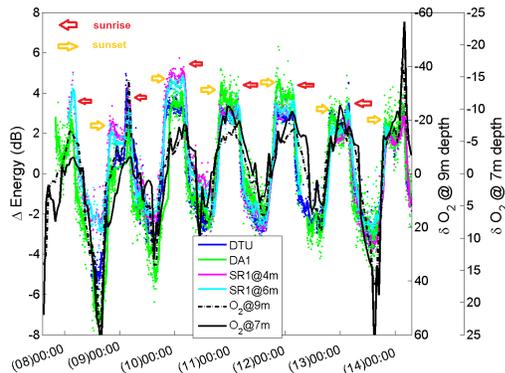


Fig. 4. Comparison between changes of the noise power at DA-1 hydrophone (green), DTU/SHA hydrophone 8 (blue), and SR-1 hydrophone 4 m (magenta) and 6 m (cyan) above the bottom (blue dots represent the instantaneous values, blue solid line the half-hour moving average) and the changes of dissolved O₂ measured by the optode at 7m (black solid line) and 9.5 m (black dashed line). The mean values were removed from the plots. The arrows represent sunrise and sunset events.

Figure 4 shows a significant (negative) correlation between the noise power at the various locations and the changes in dissolved O₂ measured by optodes. In an earlier experiment conducted in the same area[4], similar correlation have been observed between the attenuation of active signals transmitted through the meadow and the dissolved O₂ measurements. These variability patterns were ascribed to the photosynthetic activity of the meadow. Like with active signals it can be observed that at sunset the increase of noise power occurs simultaneously with the decrease of the dissolved O₂ in the water column, but at sunrise the high gradient of change appears earlier in noise power than in dissolved O₂ (the arrows in Fig. 4 indicate sunrise and sunset). For the active signals it was ascribed to the air in plant tissues (aerenchyma) as a signature of photosynthetic activity. The link between ambient noise power and photosynthetic activity has not been established so far. The correlation between the noise power and the measured O₂ is evident. The attenuation of acoustic signals due to O₂ bubbles released by photosynthesis can contribute for the lower noise power observed during daylight. However, seagrass meadows are populated by numerous species of fishes and crustaceans that produce sounds when moving, hunting and eating and are particularly active during the night. Therefore, it is expected an increase of biological noise during the night with local peaks at dusk and dawn[8] as observed in our data. The study of the different contributions to the ambient noise deserves further attention in order to develop passive tools to long time assessment of seagrass meadows.

IV. ANALYSIS OF IMPULSIVE NOISE SOURCES

The analysis presented in the previous section gives an ensemble average characterization of the noise. The inspection of the time series shows an important contribution of impulse like noise sources to the noise field. Next, we show the time series and estimate the variability of the number (frequency), the amplitude and the elevation direction of the impulses along time.

A. Noise time series

Figure 5 shows one minute period and half second detail of the ambient noise recorded at the DA1 hydrophone, where the red line represents daylight data and the superimposed

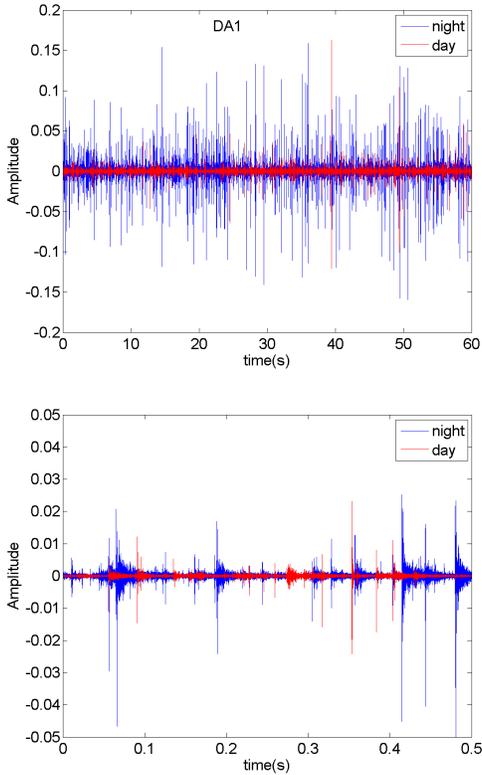


Fig. 5. One minute long time series of ambient noise at the DA1 hydrophone (upper panel), and a 0.5 s detail (lower panel) . The blue line shows daylight data and the red line night data

blue line represents night data. It can be noticed the prevalent impulsive nature of the noise. The presented data suggests a higher frequency of impulsive events during the night than during the day. It can be also observed that various waveforms overlap in time.

Figure 6 show samples of noise pulses recorded at the various acquisition systems. These very short impulses compares with shrimping noise and other biological noise reported in the literature [9], [10], [11], [12]. The shape of the sample recorded at the DA-1 is significantly different of the waveform recorded at SR-1. It may suggest that different species contribute for the sound scape of the area.

A zoomed view of the sample recorded at DA1 (Fig. 7), suggests the occurrence of multipath, where we can identify the direct and the surface reflected arrivals. It is clear seen that the leading oscillations of the first (direct) and second (surface reflected) arrival are inverted (180 degree phase shift). A similar multipath structure can be identified in the SR-1 sample, between 0.005 and 0.125 s. Figure 7 shows the expected multipaths for an impulse source within few meters from the receiver. Apart of the direct and surface reflected arrival, one should also expect a bottom reflected arrival. However, the bottom reflected arrival suffer from bottom attenuation and is not clearly seen in Fig. 7. A possible location of the bottom arrival is indicated in the figure. In the sample data recorded at DTU array (Fig. 6 lower panel) it is impossible by eye

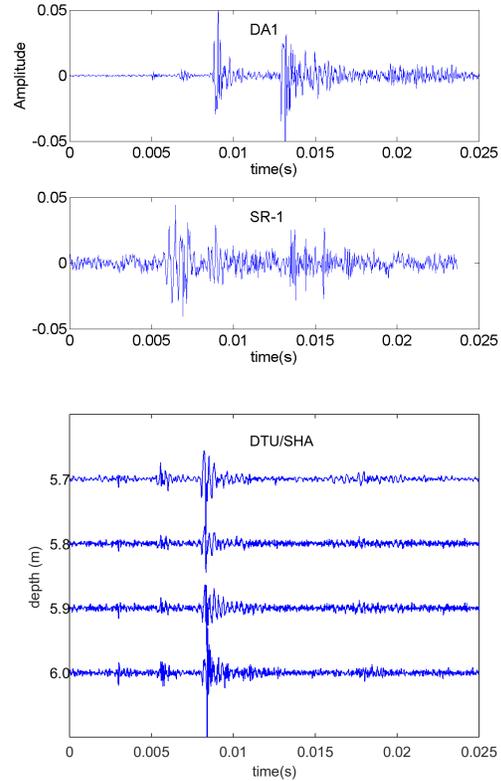


Fig. 6. Samples of impulse waveforms recorded at the DA1 (upper panel), the SR1 hydrophone (middle panel) and along 4 hydrophones 10cm apart of the DTU array (lower panel)

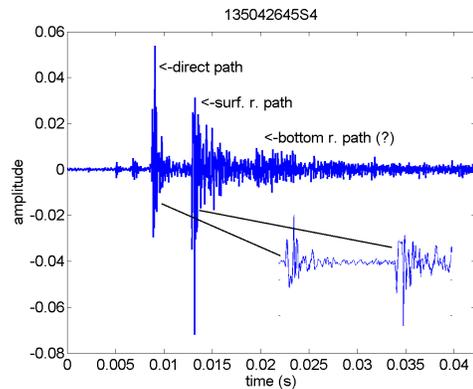


Fig. 7. Multipath structure recorded at DA1 hydrophone

to identify nor the bottom reflected arrival, nor the surface reflected arrival. The reason for the lack of the bottom reflection was explained above. For the surface reflected arrival, most likely the impulse's source is close to the surface and this arrival overlap with direct arrival (increased surface attenuation can also play a significant role). Figure 7 shows also the occurrence of a small amplitude pulse (precursor) before the louder direct arrival. A precursor signature was also observed in the snapping shrimp *Synalpheus parneomeris* samples by [11]. The precursor can be seen in the upper and lower panels

of Fig. 6, but not in the middle panel.

B. Frequency and amplitudes of the impulses

In order to count the noise pulses a power law detector was applied in a first step. The integration time was set to ~ 3 ms. Since the various hydrophones were not calibrated, have different gains, and self-noise levels, the integration time and decision level (threshold) were adjusted by trial and error for each acquisition system. Therefore, care should be taken when comparing values among hydrophones. To eliminate very short pulses, only peaks lasting at least 1 ms were selected. For each selected peak the maximum amplitude and corresponding time was found. Figure 8 shows some basic statistical parameters obtained after the detection/selection procedure for each 30 s block of data (see Sec. III): for the frequency of pulses (upper), mean pulse amplitude (middle) and mean time difference between pulses (lower), for the DA1 and SR1 hydrophones left and right columns, respectively.

The number of pulses per second (frequency) and the mean time interval between pulses shows a marked diurnal pattern. Similar to the noise power (Fig. 4), the frequency of pulses is anticorrelated with O₂ measurements. This pattern can be explained by an increased biological activity during the night and similar behavior has been reported for other coastal ecosystems [8], [9]. We should notice that the frequency of pulses decreases at deeper locations, but the diurnal pattern does not change, as can be seen when the SR1 and DA1 moved to a deeper location (after julian day 133). As expected the mean time interval between pulses has an inverted trend with the frequency of impulse, increases during the day and decreases during the night. The mean amplitude of the impulses shows high variability along the all day and the diurnal variability pattern is not so evident, particularly when the hydrophone moved to a deeper water column. The threshold used in the single sensor detection scheme most likely rejects weak impulses that interact with bottom which in principle are the most affected by the O₂ produced by the seagrass. Although not shown similar results have been obtained for the hydrophone 8 of the DTU array.

C. Direction of arrival of impulses

The direction of arrival (DoA) from the single peaks where determined from DTU array data using a time domain beamformer, where negative angles indicate pulses coming from surface layers. Due to technical problems the gain of the various acquisition channels are different and some electronic spikes occurs. To minimize the effect of these problems in the results, before beamforming the single pulses where detected using hydrophone 8 (almost free of electronic spikes) and the amplitude of the various hydrophones where equalized. The later procedure allows to keep the phase information among channels, therefore minimizing biases in the direction of arrival estimates. The individual vertical DoA estimates from 30 s block of data were binned in equispaced bins with 5 degrees width. Then for a block of data the relative frequency of each bin direction was computed.

Figure 9 shows the variability of the relative frequency of the vertical DoA of impulses along time, where the diurnal variability pattern can be seen. These results are in line with noise (ensemble data) directionality estimates from the same dataset reported in [4], indicating that the impulsive noise has the major contribution for the noise field of the area. It can be also seen that the number of arrivals coming from steeper directions is small.

V. INVERTING PROPERTIES FROM NOISE PULSES

The main objective of this analysis is to estimate the amount of O₂ produced by the seagrass meadow during photosynthesis. Part of the O₂ produced diffuses to the rhizomes, roots and to the bottom, therefore the bottom sound speed decreases. Felisberto et al. [4] estimated the critical angle of the bottom from the same dataset. Notwithstanding the high variance of the results, it was observed a diurnal variability pattern where critical angle decreases during the daylight reaching the minimum of 22° at noon, and increases during the night reaching the maximum of 26° at midnight. Assuming perfect reflection, the critical angle ϕ_c is given by [13]

$$\phi_c = \arccos(c_w/c_b) \quad (1)$$

where c_w is the sound speed in the water and c_b is the sound speed in the bottom. Considering that $c_w = 1517$ m/s the bottom sound speed varies between 1636 m/s during the day and 1687 m/s during the night. Although, these results were not validated by independent methods and may be significantly biased (for example due to the bubbles the sound speed of the water at the water-bottom interface may be lower [3]), the trend is as expected during the photosynthesis (day) the bottom sound speed decreases.

The bottom may also be characterized through the reflection coefficient estimated from the amplitude of direct arrivals and the bottom reflected arrivals of the impulses. To do so, apart from the amplitude of the various arrivals (direct, and bottom reflectd) the location of the impulse must be know to determine de grazing angle of reflected arrival and path lengths. This can be accomplished using the image method. This is a work on progress.

VI. CONCLUSION

The overall noise variability in a seagrass meadow is intricate. Although, it can serve as an indicator of the biological activity of the ecosystem, the noise sources are not well characterized and understood. The correlation between noise power and dissolved O₂ is evident, but its causality has not been demonstrated and deserves further investigation. In that sense, a possible path to be explored is the analysis of the echoes generated by single impulses. In the ocean a signal propagates from a source to a receiver through different paths giving rise to various echoes. In general, at short ranges, one can differentiate echoes that have interaction with the bottom or surface and echoes that does not suffer from such interactions. The release of O₂ bubbles during photosynthesis can lead to changes in the characteristics of echoes arriving

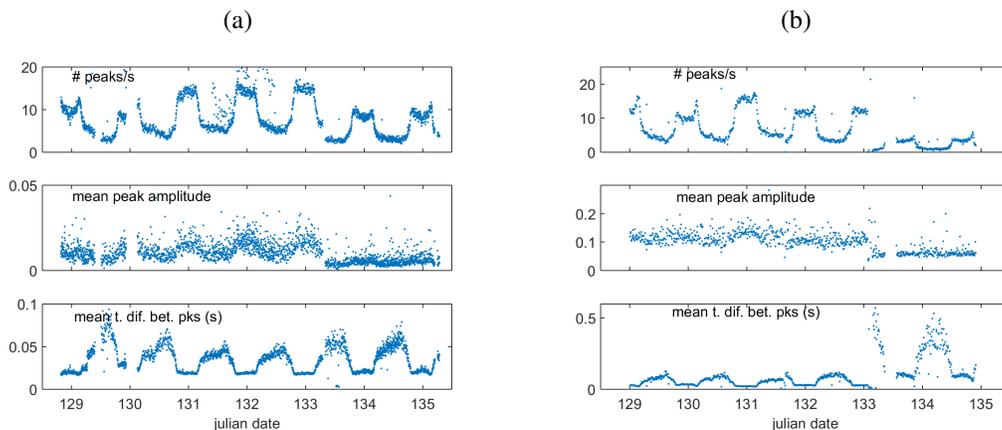


Fig. 8. Noise pulses variability at (a) DA1 hydrophone, (b) SR1 hydrophone 4 m above the bottom: (b) frequency of mpulses (upper panel), mean amplitude of the pulses (middle panel) and mean time interval between pulses (lower panel). Please not that since the hydrophones are not calibrated, the amplitudes are not comparable

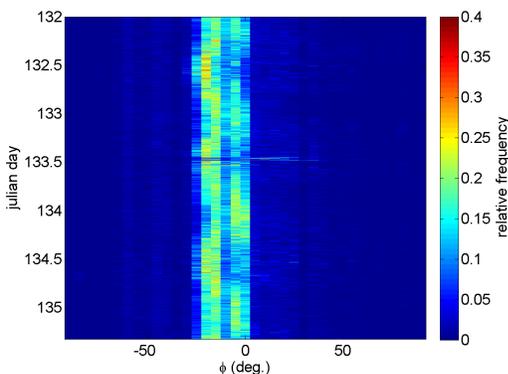


Fig. 9. Relative frequency of impulses as function of vertical DoA at any given time (negative angles indicates downward direction, i.e. impulses coming from shallowest/surface layers).

from different directions. One can expect that bottom reflected echoes, which cross the plant layer would be significantly affected by bubbles, therefore carrying information about their concentration. This is work is being pursued under the framework of project SEAFOX funded by FCT under contract PTDC/EEI-PRO/2598/2014.

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