Tank and field experiments of short-range acoustic propagation through a seagrass canopy

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***Abstract*—Aiming at monitoring the bubbles released during seagrass photosynthesis in different conditions, three experiments were made: two in an outdoor tank and one in the field. The outdoor tank experiments were conducted in winter and summer conditions with *Cymodocea nodosa* plants transplanted from a nearby meadow. The field experiment took place in September 2018 on a *Posidonia oceanica* meadow, where bubbles formation due to plants photosynthesis has been reported. In all the experiments continuous wave pulses in the band 10–20 kHz were used to estimate the diel change of effective sound speed and the attenuation over the plants. Additionally, high frequency backscatter images at 0.5, 1, 2 and 4 Mhz were obtained to figure out bubbles signature. The results suggest that even in winter, the tank conditions, without water movement, allows for the formation of a small amount bubbles of small radii. In summer tank conditions, the bubbles formation due to photosynthesis of seagrasses significantly increases, but also algae may contribute for the bubbles formation in the environment. The field experiment was carried out after the peak of a bad weather event. There was no evidence of bubbles formation, what can be related to water movement and leaves stirring, that prevents bubbles formation.**

***Index Terms*—oxygen bubbles; seagrass meadow; oxygen production; acoustic monitoring**

I. Introduction

Under supersaturation, the oxygen released by seagrass during photosynthesis may lead to the formation of bubbles. Bubbly water forms a dispersive acoustic medium, where the sound waves are attenuated and the sound speed deviates from bubble free water depending on the bubbles population and the frequency of the signal. Thus, the occurrence of bubbles during photosynthesis should correlate with attenuation and travel time estimates of acoustic signals propagating throughout the seagrass canopy. Furthermore, these estimates can be used to invert for bubbles' populations.

The bubbles can not be readily estimated by conventional methods used to access the primary production of seagrass meadows and other marine environments. Therefore, acoustic methods can significantly improve these estimates, being an important tool for the study and management of these relevant coastal ecosystems.

During photosynthesis bubbles are released to the water column when supersaturation occurs, however, bubbles formation is less important when the water flow around leaves is high enough to reduce the thickness of the boundary layer and decrease the pressurization within the leaves[1].

This work investigates the bubbles formation in winter and summer tank conditions and in a meadow where a previous work suggested the presence of bubbles in the same period of the year. Low frequency (10–20 kHz) signals transmitted over the plants during periods of several days were used to estimate the instantaneous effective sound speed of the water and the attenuation of the signal. These are proxies of the presence of bubbles in the water column, and may be used for bubbles' population estimation (see [2] for an overview of acoustic methods for bubbles estimation). High frequency backscatter operating at 0.5, 1, 2 and 4 MHz were used to image bubbles signature in the water column, as bubbles should increase significantly the backscatter levels. For the tank experiments, *Cymodocea nodosa* plants, a common seagrass in the Ria Formosa Lagoon, south of Portugal, where collected from a nearby meadow. The field experiment took place in a pristine *Posidonia oceanica* meadow in front of Calvi in Corsica (France) after a bad weather event.

The results suggest the formation of bubbles in tank conditions, even in the winter. Nevertheless, the bubbles formation during the summer occurs at a much higher rate. In the field experiment there was no evidence of bubbles formation, what may be ascribed to water movements and stirring conditions due to the bad weather event.

The paper is organized as follows: section II describes the materials and experimental methods used during the tank and field experiments; section III reports and discusses the obtained results; finally section IV draws conclusions and suggests further lines of investigation.

II. Materials and methods

A. Experimental setups

1) Tank experiments: The tank experiments were carried out at the Aquaculture Research Station of Portuguese Institute for the Sea and Atmosphere (EPPO), Olhão, southern Portugal in an outdoor fiberglass tank with $5\,\mathrm{m}\times 2.5\,\mathrm{m}\times 1.8\,\mathrm{m}$ (length-width-depth). The data discussed herein were gathered from November 30 to December 3, 2017 and, from June 11 to July 13, 2018, hereafter called winter and summer experiment, respectively. *Cymodocea nodosa* shoots, including sediments of approximately 10 cm thickness were gathered from the seagrass meadow covering a pond in the research station[3]. The shoots were transplanted to a plastic box

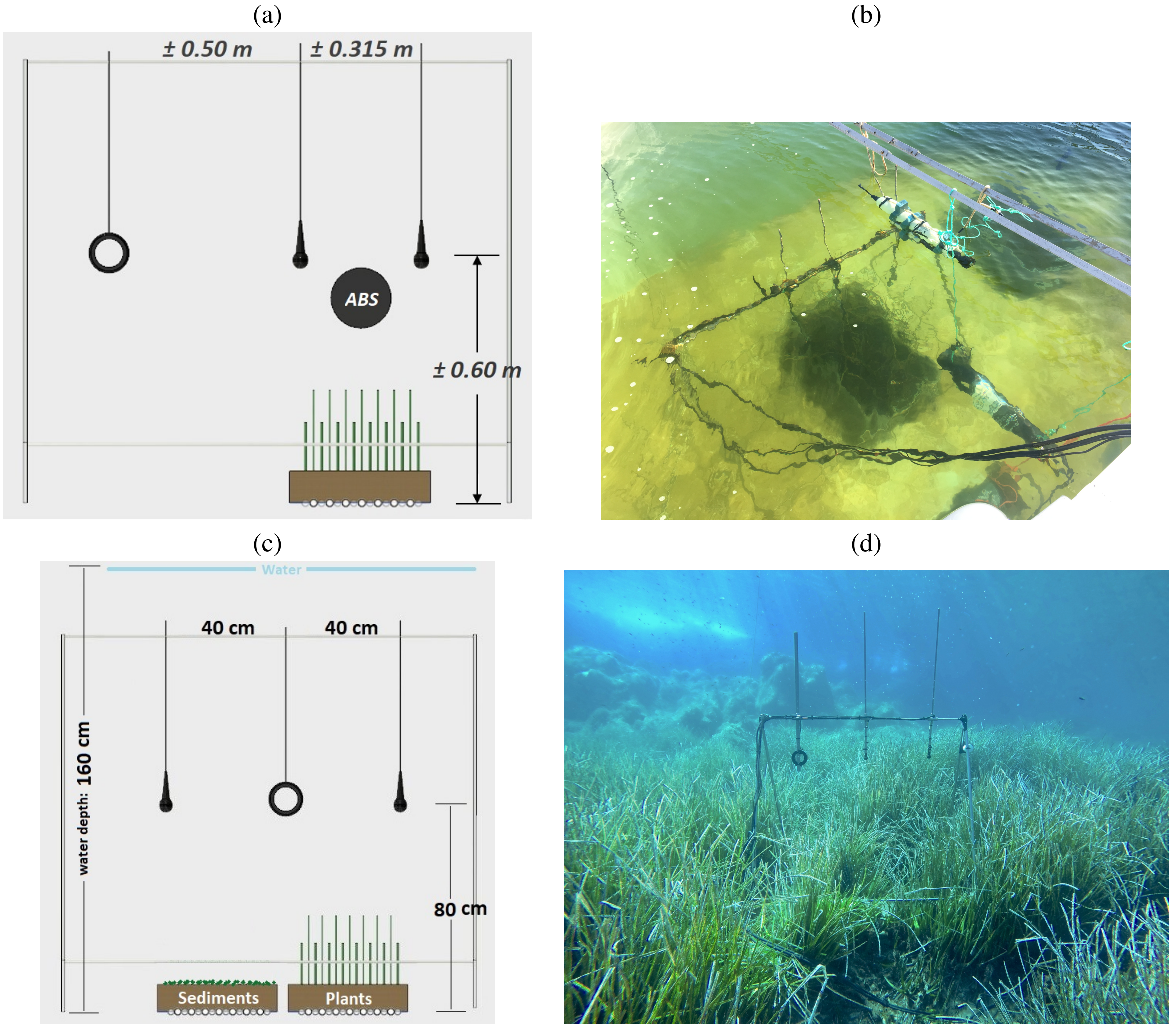


Fig. 1. Experimental setup where the ring represents the source (ITC-2044), the spheres represent the receivers (Reson TC4033) and the filled circle represent the Acoustic Backscatter (ABS): winter tank experiment (a), summer tank experiment (b). Pictures taken during recording: tank experiment (c) and field experiment (d). (The setup of the field experiment is similar to the winter tank experiment (a), but the source and hydrophones were fixed at 0.9 m from the bottom, the hydrophones were 0.5 m apart, the distance between the source and the nearest hydrophone was 0.4 m and the ABS was moored in a nearby location, pointing to the sea surface.)

with 67 cm×40 cm×15 cm (length-width-height). The box was deployed in the bottom of the tank, which was filled with salt water up to the maximum water height of 1.60 m, limited by an outlet. After reaching this value, a small flow of water was continuously maintained.

Figures 4(a) and (b) show a diagram and a picture of the winter experiment, where it can be seen the plants box deployed between two hydrophones, suspended on a steel structure at 60 cm from the bottom. The sound source was fixed at the same depth of the hydrophones, at a distance of approximately 0.5 m from the nearest hydrophone. An acoustic backscatter system (ABS) operating at 0.5, 1, 2, 4 MHz was used to image the bubbles in the water column. The ABS was mounted horizontally above the seagrass, pointing along the plants' box. Additionally, dissolved oxygen, temperature, salinity and depth were gathered by a RBR concerto CTD. The CTD is the white cylinder above the plants' box seen in Fig. 4(b). Meteorological data was acquired by a meteo station installed in the top of a nearby building.

Figure 4(c) show a diagram of the setup used during the summer experiment, where the source is fixed in between two boxes, one with plants and another with only sediments. The sediments were collected from an uncovered area of the same pond. The source and the hydrophones were fixed at 0.6 m from the bottom, the distance between the hydrophones and the source is 0.4 m. Similarly, to the winter experiment, dissolved oxygen, temperature, salinity and depth were gathered by a RBR concerto CTD. An additional optode was installed in the steel structure about 60 cm from the bottom in the plants box side. Unfortunately, the ABS device was malfunctioning and no data is available.

2) Field experiment: The field experiment was carried out in a *Posidonia oceanica* bed in front of the STARESO research station, in the Bay of la Revellata, Calvi in Corsica (France), from September 26t to 30, 2018, but due a bad weather event only the last 2 days of measurements are available. A previous field experiment carried out in October 2011 in the same meadow suggested the occurrence of bubbles [4].

Posidonia oceanica covers almost completely the bottom of the place where the equipment was anchored, as shown in Fig. 4(d). Visual inspection of the plants shows long leaves and short roots. The bottom parameters are unknown, but visual inspection shows that it appears to be sandy. The plants have a white coloration, which is due to limestone. The equipment was anchored in a location where the water depth is about 5.5 m. In this area of the Mediterranean water depth variation due to tide is insignificant (fraction of a meter, at maximum).

The source-hydrophones setup used in the field experiment is similar to Fig. 1(a), but the hydrophones and the source were fixed at 0.9 m from the bottom, the distance between the hydrophones was 0.5 m and the distance between the source and its nearest hydrophone was 0.4 m. The ABS was moored in a nearby location in the canopy, pointing to the sea surface. An optode device measuring dissolved oxygen and temperature was fixed to the steel structure approximately one meter from the bottom. In this experiment the CTD was used for profiling, i.e. measuring along the water column, dissolved oxygen, temperature, salinity and sound speed, a few times a day in a nearby location. The meteorological data, provided by STARESO station, were recorded by a meteo station installed in the station building.

B. Attenuation and travel time measurements

The acquisition process (signal generation, recording and storage) of the acoustic data was performed by a Red Pitaya board controlled by a laptop computer. A PA1001 amplifier from ETEC (Denmark) was used for driving the acoustic transducer (ITC-2044) and for conditioning and amplifying the signal from the hydrophones (Reson TC4033). Further details of the acquisition system and acoustic elements can be found in [6]. During the field experiment the Red Pitaya board, the amplifier and the batteries were installed in a buoy anchored on the site. The control of the acquisition and the data storage was performed by a laptop installed at the STARESO buildings through an wifi connection.

The transmitted signals were sequences of continuous wave (CW) pulses. In order to avoid overlap of the direct acoustic path by bottom and surface echoes, even in the case of effective sound speed of the bubbly water reaches 1900 m/s, the number of cycles in a CW pulse was adjusted depending on the setup and the lowest frequency was limited to 10 kHz [6]. Due to the frequency response of the acoustic transducer, the highest frequency was 20 kHz, so the frequency of CW pulses was between 10 and 20 kHz at 1 kHz increment. The waveforms at both hydrophones were acquired simultaneously at a sampling frequency of 1.9 MHz and both data streams were stored in a single file for each transmitted CW pulse. The repetition rate of a CW pulse of a given frequency was approximately 3 minutes. The travel time/effective sound speed and the attenuation were estimated using the approach described in [5].

III. Results and discussion

A. Winter tank experiment

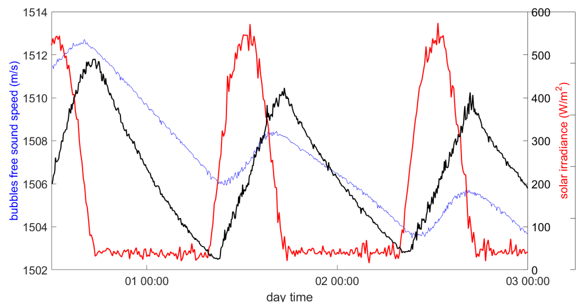
Figure 2(a) shows the variation of the environmental data gathered during the winter experiment. It can be seen that the solar radiation (red curve) has an expected repetitive behavior during the experiment, with a peak of approximately 550 W/m^2 at noon. The days were sunny, nevertheless the peak values and sunny hours are significantly lower than those observed in the summer (the peak of solar radiation in summer is around 1000 W/m^2). The sound speed (blue curve) measured by CTD shows a typical diurnal pattern with the daily peak in the afternoon and a decreasing trend along the experiment. During the experiment the total sound speed variation measured with the CTD was about 10 m/s. As already mentioned the sound speed obtained from CTD does not depend on the amount of bubbles in the water (bubbles free sound speed), but on the water temperature, salinity and depth. The saturation level of dissolved oxygen (black curve) also shows a diurnal pattern with peaks in the afternoon, at the time of sound speed peaks (blue curve). The increase of temperature (or sound speed) leads to a decrease of solubility of the oxygen, and therefore an increase of the saturation level. Supersaturation of the dissolved oxygen occurs as during part of the day the values are above 100 %, with peaks around 115 %. As expected the "valleys" of dissolved oxygen are below 100 % and occur early morning, when the sunrises, the solar radiation increases.

Figure 2(b) shows the sound speed obtained from the estimates of travel time between the two hydrophones (effective sound speed) at frequencies of 10, 15 and 18 kHz. It can be seen that the effective sound speed is similar to the bubbles free sound speed (blue curve in Fig. 2(a)). (The local variance of the estimates of the effective sound speed is due to technical/physical constraints, which are discussed in [5]).

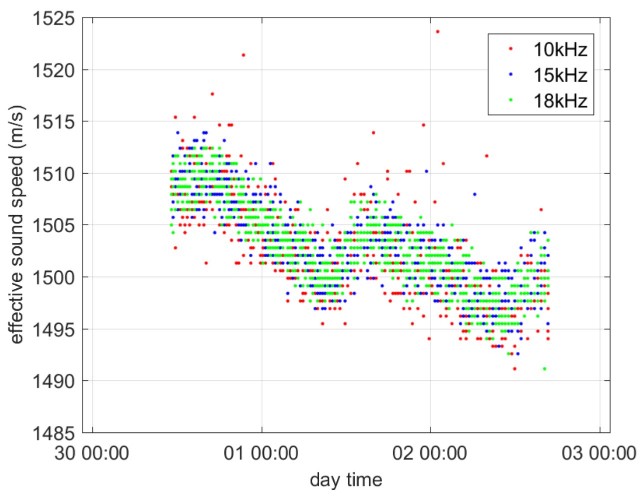
In the winter tank experiment, the energy of the signal (Fig. 2(c)) varied up to 0.5 dB at the receiver located before the plants box (blue) and up to 2 dB at the receiver located in the other side of the box (red). There is no significant correlation with the diel cycle of the dissolved oxygen (Fig. 2(a) black line), nevertheless it is observed a wider spread of the instantaneous measurements during the day. The backscatter image (Fig. 2(d)) shows increased levels around noon from ranges where the plants box is located (indicated by circles), what suggests bubbles production during daylight hours.

The observations suggest that the amount and radius of bubbles released to the water column are small. The frequencies used (10-20 kHz) in the experiment correspond to the resonance frequencies of bubbles with radius between 0.168–0.336 mm. Even a small amount of bubbles with radius in this range would lead to a significant variation of the energy/attenuation (and sound speed) of the acoustic signals used in the experiment along the day. Moreover the attenuation and the effective sound speed would be frequency dependent.

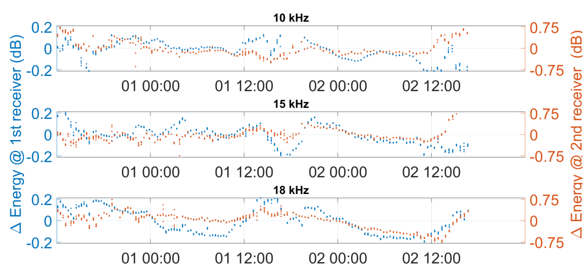
(a)



(b)



(c)



(d)

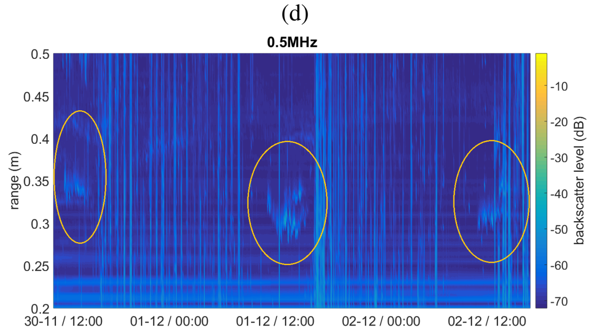


Fig. 2. **Winter tank experiment**. Environmental data (a): solar radiation (red), sound speed (blue), dissolved O2 (black). Acoustic data: (b) sound speed estimated from the travel time between receivers, relative signal level at both receivers (c), backscattering level (the circles indicates possible bubbles' signature) (d).

A large amount of small bubbles, i.e bubbles with radius well below 0.100 mm might not lead to significant attenuation in the range of used frequencies, but the sound speed would decrease significantly. Since, the backscatter images suggest the signature of bubbles, the saturation level of dissolved oxygen is a slightly above 100 % and the attenuation and the variability of signal that propagates over the plants box increases during the daylight hours one may conclude that bubbles concentration is formed by a small amount of small bubbles that are produced by plants photosynthesis in this winter tank conditions.

B. Summer tank experiment

Figure 3 shows the environmental data gathered during the summer tank experiment. The bubbles free sound speed estimated from temperature, salinity (blue curve) varies between 1524-1538 m/s with an increasing trend at the beginning of the period and a diurnal pattern with peaks in the afternoon and valleys at night. The saturation level of dissolved oxygen was measured by an optode installed at the plants (green curve) and the CTD optode (black curve). It follows a diurnal pattern with peaks in the afternoon and valleys around sunrise. The high peaks (more than 400 % of dissolved oxygen) occurring on June 12 and 13 are due to a bubble diffuser that was inadvertently switched on. Nevertheless, in the rest of the period the peak values are always above 200 %, thus large supersaturation occurs during the day. These conditions favor bubbles formation during photosynthesis. Apart of the bubble diffuser event, the dissolved oxygen at the plants level (green curve) decreases to values below 100 % every day, sometimes even below 50 %, what maybe linked to plant respiration. The saturation level of dissolved oxygen measured by the optode above the plants box (black curve), show minima in coincidence with the measurements at plants level(green curve), but the values do not decrease significantly below 100 %. The meteo data is not available for this period of the experiment, but solar radiation measurements gathered after this period with similar weather conditions reached constant peak values of the order of 1000 W/m^2. Figure 3(b) shows the variability of the effective sound speed estimated from the travel time perturbations between the source and the hydrophone installed in the plants box side (upper panel) and the source and the hydrophone installed in the sediments box side (lower panel) at frequencies of 10, 15 and 18 kHz. Herein, the effective sound speed perturbation were estimated instead of the effective sound speed as the former estimator is more robust when using a single hydrophone due to the unknown transient characteristics of the source (see [5]). It can be seen that the perturbation of the effective sound speed are similar to expected bubbles free sound speed as shown with the blue curve of Fig. 3(b). Nevertheless, the instantaneous variance of the effective sound speed perturbation is higher at the plants box hydrophone. This may be linked with the increased attenuation in this hydrophone (see below), which decreases the Signal-to-Noise ratio and therefore the variance of the travel time/effective sound speed estimator.

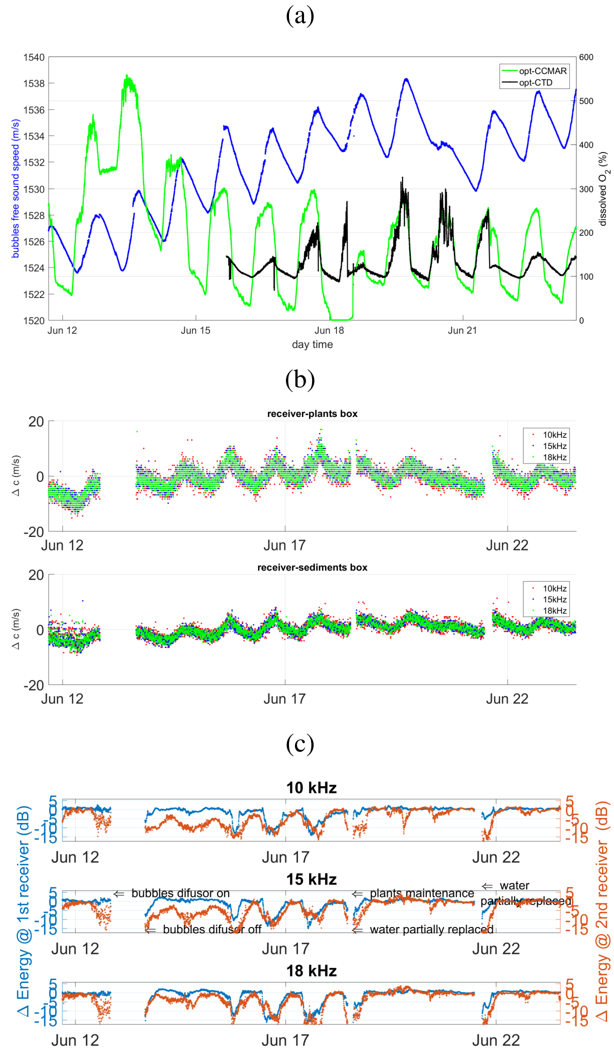


Fig. 3. **Summer tank experiment**. Environmental data: (a) sound speed from CTD (blue) and dissolved O2 from the CTD optode installed above the plants (black) and from the optode fixed at plants' level (green). Acoustic data: (b) relative sound speed estimated at the plants box receiver (upper) and sediment box receiver (bottom), (c) relative energy of the signals received throughout the sediment box (blue) and the plants box (red).

Figure 3(c) shows the relative energy/attenuation perturbations measured at various frequencies (upper panel 10 kHz, middle panel 15 kHz, lower panel 18 kHz) at the plants box (red curve) and at the sediments box (blue curve) hydrophones. The high supersaturation conditions observed during the summer experiment favors bubble formation, and the diel variability of the attenuation rises up to 15 dB. The signal received throughout the box with plants (red) shows higher attenuation and instantaneous variability than the signal received throughout the box with sediments (blue), in particular immediately after tank maintenance/water renewal (indicated by labels and arrows in the Fig. 3(c)). Note that during this period, algae, which also release O2, rise rapidly in the water, maybe boosted by the presence of the sediments. Latter on, and after algae in tank walls were cleaned, the box with sediments removed and the water completely renewed, the attenuation of the signal received throughout the plants box was much higher than the other receiver [5]. Unfortunately, due to the malfunction of the ABS, backscatter images are not available for this experiment.

Nevertheless, the results show a large signal attenuation in the band 10-20 kHz in summer conditions, that can be ascribed to bubbles released by the photosynthesis of seagrass and algae that grow in the tank environment.

C. Field experiment

Figure 4(a) shows a summary of the environmental data gathered during the field experiment at the *Posidonia oceanica* meadow. As stated above this experiment took place at the end of bad weather event. The solar radiation (red curve) reaches peaks of approximately 800 W/m^2, of the same order of those observed on a experiment conducted in the same meadow in October 2011 [4]. The saturation level of dissolved oxygen (black curve) shows peaks of the order of 110 % that are slightly above the supersaturation threshold. These peaks are lower than those observed in the already mentioned previous experiment. The bubbles free sound speed (blue) estimated from temperature, salinity and depth increases continuously along the duration of the experiment from 1550 to 1565 m/s. It does not show any diurnal pattern which maybe related to water mixing due to the bad weather event.

The effective sound speed obtained from travel time estimates between the two hydrophones presented in Fig. 4(b) for 10, 15 and 18 kHz signals follows, in average, the bubbles free sound speed in Fig. 4(b)(blue curve). Also, the energy perturbation for 10, 15 and 18 kHz signals presented in Fig. 4(b) are much smaller than 1 dB, does not show a diurnal pattern correlated with dissolved oxygen measurements and there is no significant difference between hydrophone closer to source (1st receiver, blue curve) and the farthest hydrophone (2nd receiver, red curves) as it would be expected in case of bubbles in the water column. The backscatter level presented in Fig 4(d) does not show signature of bubbles, neither. The experiment was performed the day after the peak of a bad weather event, thus water movement and leaves stirring does not allows for bubbles' formation.

IV. Conclusion

The experiments described in this study show that seagrasses release a large number of bubbles in calm and sunny summer days, as observed during the summer tank experiment. Moreover, in the summer tank experiment algae grow rapidly and release bubbles to the water column. During sunny winter days and calm environment the seagrasses may also release a small amount of bubbles to the water column, as suggested by the winter tank experiment. Nevertheless, the bubbles radii should be small and difficult to detect using signals in the band 10–20 kHz. The bubbles signatures are detected in high frequency backscatter images. The field experiment shows that water movements and stirring conditions might significantly reduce the bubbles production, as the field experiment conducted in this study does not show signature of bubbles

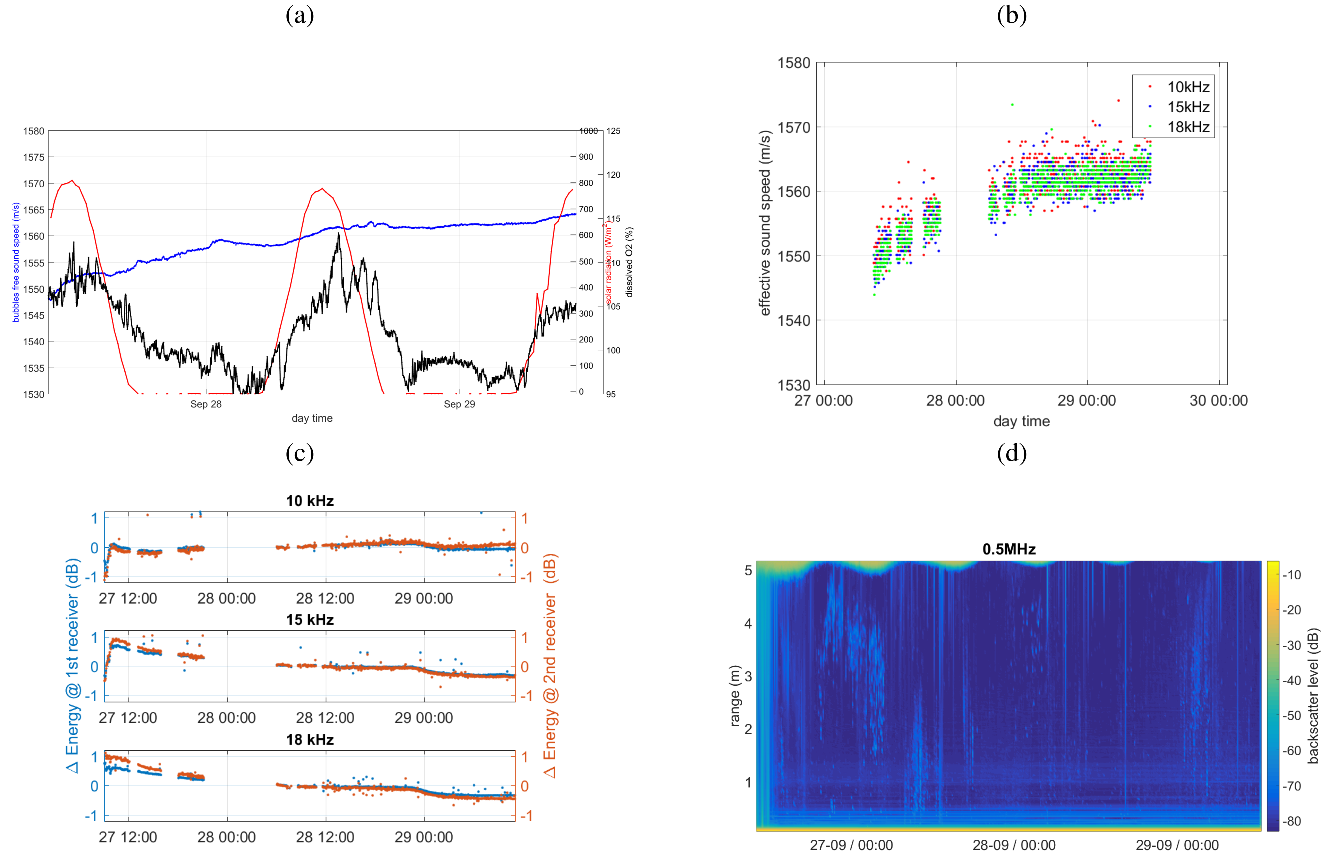


Fig. 4. **Field experiment**. Environmental data: (a) solar irradiation (red), sound speed (blue) and dissolved O2 (black). Acoustic data: (b) sound speed estimated from the travel time difference between receivers (upper), (c) relative energy of the signals at 1st receiver (blue) and 2nd receiver (red), (d) backscattering level.

neither in the 10–20 kHz pulses, nor in the backscatter images, where a previous experiment conducted in the same meadow with similar solar radiation levels suggested the presence of bubbles in the water column correlated with the diel cycle of photosynthesis.

Detailed analysis of the data presented herein is in progress and it will contribute to improve the bubbles monitoring system for seagrass ecosystems under development.

Acknowledgment

This study received Portuguese national funds from FCT - Foundation for Science and Technology through project PTDC/EEIPRO/2598/2014 (SEAOX) and project UID/Multi/04326/2019.

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