Variability of the ambient noise in a seagrass bed

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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. The noise field in the band 2-7 kHz was dominant. The noise directionality and bottom reflectivity estimated using a short vertical array show a diurnal variability pattern. The mean noise power measured at all receivers shows also a diurnal variability pattern, which is negatively correlated with the O2 dissolved in the water. Changes in noise power between the night (highest noise power) and day period (lowest noise power) as high as 5 dB were observed at the various locations. These results suggest that the ambient noise power and directionality are correlated with the photosynthetic activity of the seagrass meadow and that a passive acoustic system can be used to monitor the O2 production of the meadow.**

Keywords*—passive acoustics, seagrass meadow, oxygen production, ambient noise, posidonia oceanica.

I. Introduction

Posidonia oceanica meadows cover large areas of the Mediterranean and are known as blue lungs of the earth due to their important photosynthetic activity. The effect of photosynthetic activity on acoustic transmissions has been already demonstrated [1], [2]. It was shown that the attenuation of low frequency signals (<15 kHz) transmitted through the meadow and the diel cycle of photosynthesis were significantly correlated. The signals were highly attenuated during the daylight period. The attenuation was negatively correlated with dissolved O2 measurements carried out simultaneously with acoustic transmissions. It was hypothesized that the attenuation is due to the O2 produced by the photosynthetic activity of plants. The factors that influence the acoustic response of a seagrass are not well established, but it is considered that free gas bubbles emanating from the plants and the pressurization of the aerenchyma by photosynthetic O2 production are the most relevant ones. At frequencies well below the bubbles resonance frequency, both factors influence the acoustic compressibility and, thus, the effective sound speed of the medium [3], [4], [5], [6]. This suggests that during the photosynthesis a low sound speed channel forms at the plant bed giving rise to an increased bottom attenuation of the propagated acoustic signals. The attenuation of the acoustic signals can be used as a proxy of the photosynthetic activity of the meadow and to estimate the O2 produced. In spite of the difficulties faced to calibrate an O2 measurement system based in low frequency acoustic transmissions, the acoustic experiments conducted so far suggest a significant production of O2 as bubbles. Therefore, the primary production of a seagrass meadow is underestimated by methods that rely in the mass balance of dissolved O2, which are not capable of quantifying the production of O2 bubbles. Combining acoustic with dissolved O2 methods might allow to developing a more robust and accurate system for estimating productivity of seagrass meadows. The experiments

Fig. 1. Overview of the experiment area. Labels *Optodes*, *DA-1* and *DTU* indicate the locations of the array of optodes, the DA1 single-hydrophone and the 8-element Short Hydrophone Array, respectively. Labels *SR-1 2013*, *SR-1 2011* indicates the location of the 2 SR-1 hydrophones at 10 m and 20 m water depth, respectively.

conducted until now considered only active acoustic systems. Active acoustic systems, where a controlled source is used to transmit probe signals, suffers from various drawbacks: the transmitted probe signals might disturb the environment, the acquisition of source systems and their maintenance is in general expensive (when compared with simple acquisition systems) and power consuming what limits the autonomy of the system when powered by battery (usual condition at sea). In recent years passive methods that use ambient noise to infer properties of the ocean have been subject of growing interest [7]. The applicability of passive methods to bottom characterization has been demonstrated by several works[8], [9], [10], [11]. In opposite to active methods, passive methods are environmental friendly and might sample the ocean for long periods with high time resolution. As a first step to develop a passive acoustic system to monitor the O2-based productivity of a seagrass meadow at the ecosystem level, this work analyzes the variability of the ambient noise in a seagrass meadow. The data presented herein were acquired in May 2013 during a period of one week in the Bay of Revellata, Calvi, Corsica over a *P. oceanica* bed by various hydrophones and a short vertical array. The noise power was analyzed at various locations in the meadow. Using the vertical array

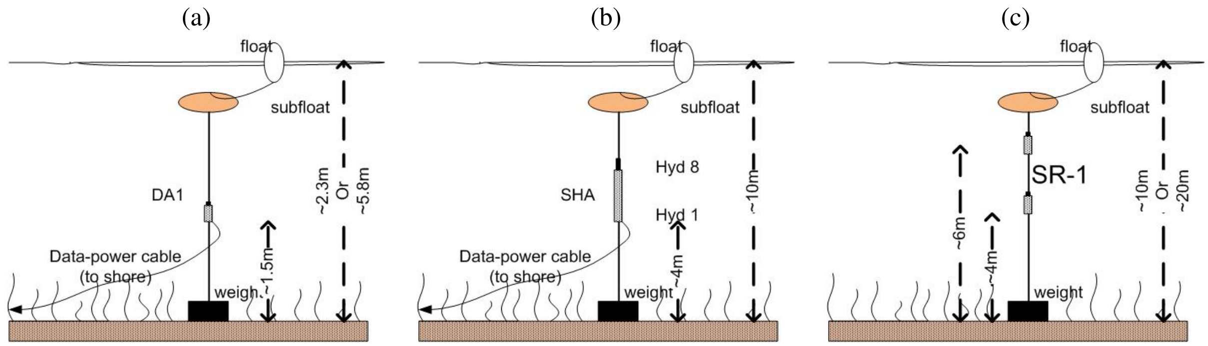

Fig. 2. Schematic of the moorings: DA1 single-hydrophone (a), Short Hydrophone Array (b) and SR1 self-recording hydrophones (c)

data, the directionality of the ambient noise was estimated using the Bartlett processor, then the bottom reflection loss and the bottom grazing angle was deduced from the down-up ratio of the beam power [8], [12]. The results show that the ambient noise variability is also affected by the photosynthetic activity as the noise power is significantly correlated with dissolved O2 measurements conducted simultaneously with acoustic data acquisition. Also, the noise directionality and the bottom reflectivity show a variability with time consistent with the expected photosynthetic activity of the plants.

This paper is organized as follows. The experimental setup is described in the next section. The analysis of the ambient noise power is presented in Sec. III, whereas the noise directionality and bottom reflectivity is analyzed in Sec. IV. Finally Sec. V draws some conclusions.

II. Experimental setup

The data were gathered from May 8 (julian day 128) to 15 (julian day 135), 2013 in front of the Station de Recherches Sous-marine et Oceanographiques (STARESO). STARESO is a research center of University of Liège (Belgium) located in the Bay of Revellata, Calvi, on the northwest coast of Corsica in the Mediterranean Sea (8°45 E, 42°35 N), Fig. 1. The area is classified as a pristine site, where a dense *P. oceanica* meadow extends from shore to approximately 38 m depth over a sandy bottom with few rocky patches. The temperature-salinity profiles acquired by a RBR Concerto instrument at various locations during the period of the experiment showed that temperature ($\sim 17°$)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 an array of 3 Aanderaa optodes (3835) moored at 10 m depth. The optodes acquired data hourly at 4.5, 7.0 and 9.5 m depth as part of a permanent mooring installed in August 2006 [13]. Unfortunately the optode at 4.5 m was malfunctioning and the data were lost. During the experiment a sound source transmitted 2 min long sequences of low frequency signals (< 10 kHz) followed by a 3 min period of silence. The acoustic data presented in this study was acquired during the period when the source was not transmitting. A previous experiment was conducted in the area in October 2011 [2], but the acoustic data was acquired only during transmissions. In the present experiment the acoustic signals were recorded continuously by the DA1 single-hydrophone moored in the STARESO harbor and by the Short Hydrophone Array (DTU/SHA) moored at 10 m depth (Fig. 1). Both systems were connected to shore by a data-power cable allowing for real-time data monitoring. The DA1 single-hydrophone was moored at $\sim$2.3 m water depth from May 8 to 13 (7h00), when it was redeployed at a deeper location ($\sim$ 5.8 m). The hydrophone was 1.5 m above the bottom (Fig. 2(a)). The Short Hydrophone Array was moored May 9, and recovered May 15 at $\sim$10 m water depth, 4 m above the bottom (Fig. 2(b)). The Short Hydrophone Array is an array of 4 hydrophone pairs 10 cm apart that is functionally equivalent to a vector sensor array [14]. However, in the present study the array is used as a 4-hydrophone pressure array (1 hydrophone from each pair). The deepest hydrophone is labeled ”1”. In addition to continuously data acquisition, a mooring composed of 2 digitalHyd SR-1 self recording hydrophones [15] installed 4 m and 6 m above the bottom (Fig. 2(c)) acquired 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. This location is the same location as in October 2011 experiment[2].

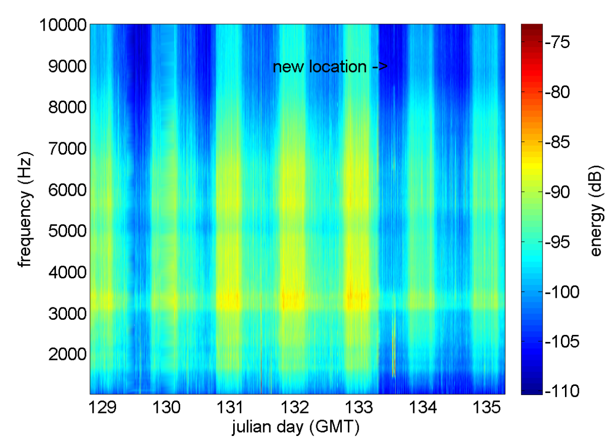

Fig. 3. Power spectral density of the ambient noise acquired in DA1 hydrophone. The arrow indicates when the hydrophone mooring was moved from the 2.3 m to the 5.8 m water water depth location.

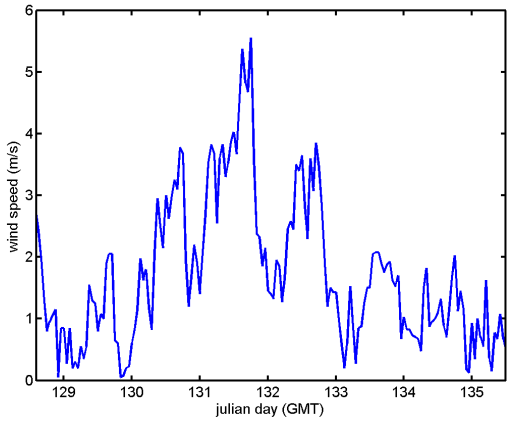

Fig. 4. Wind speed measured during the experiment.

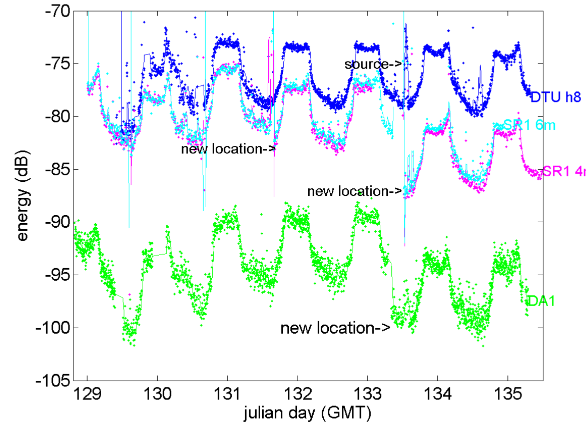

Fig. 5. Noise power in the band 2000-7000 Hz at the various receivers: dots represent instantaneous values, solid lines represent moving average values

III. Ambient noise power

For ambient noise processing acoustic data sets acquired at the various acoustic receivers after the signal transmissions were selected. The data sets of noise from the single-hydrophone (DA1) and short hydrophone array (DTU/SHA) were 60 s long acquired every 5 min, whereas the sets of noise data from the 2 SR-1 self-recording hydrophones were 30 s long, acquired every 10 min. A first inspection in the spectrograms of these data showed that during the experiment the noise field in the band 2-7 kHz was dominant at the various locations. For noise power estimation the acoustic data acquired at the various receivers were down sampled to 20 kHz and components below 50 Hz removed by high-pass linear filtering. Next, for each data set the power spectral density was estimated by the averaged periodogram (Welch) method using blocks of 2048 samples with overlapping of 512 samples and 2048-points Hamming window. The FFT length was 2048 (same as the block size) giving rise to a frequency resolution of approximately 0.5 Hz. Figure 3 shows the power spectral density of the ambient noise acquired at the DA1 hydrophone along a period of approximately one week. The noise in the 2-7 kHz band is generally associated with wind and surface agitation. However, the variability of noise power spectral density with time does not show a visible correlation with the wind speed measured at the top of the STARESO building presented in Fig 4. On the other hand it is straightforward to see that the diurnal cycle of the noise power spectral density follows the day-night cycle, where noise power level is significantly higher during the night period. Please note that in May 13 (julian day 133) the DA1 hydrophone mooring was moved from the 2.3 m water depth location to the 5.8 m water depth location, what influenced the magnitude of the noise power but not the variability pattern. Similar patterns of diurnal variability of the power spectral density were observed at the other locations. As a next step to compare the noise variability among receivers/locations and with dissolved O2 measurements, for each data set the mean noise power in the band 2-7 kHz was computed by averaging the power spectral density estimates obtained by the procedure described above. The mean noise power of a single data set will be from now on designated as instantaneous noise power. In Fig. 5 dots represent the instantaneous noise power at the various locations, where the colors are assigned to the different receivers as follows: green to the single-hydrophone (DA1), blue to the hydrophone n. 8 of the short hydrophone array (SHA), magenta to the SR1 self-recording hydrophone installed 4 m above the bottom and cyan to the SR1 self-recording hydrophone installed 6 m above the bottom. The solid lines in Fig. 5 represent a half-hour moving average of the instantaneous values. The instantaneous and half-hour moving average environmental noise power in the band 2-7 kHz show a diurnal pattern, where the energy sudden decreases at sunrise and increases at sunset. The magnitude of the variability observed during the period of one week was similar at the various receivers/locations. This behavior suggests that variability of the ambient noise power is linked with plants photosynthetic activity. Due to different system gains and location of the receivers, the absolute values changed among hydrophones and/or periods. After May 13 (julian day 133), when the DA1 and SR-1 moorings moved from a shallow location (2.3 m and 10 m water depth) to a deeper location (5.8 m and 20 m water depth) the absolute magnitude of the ambient noise decreased, but the day-night variability pattern and relative day-night magnitude of the noise power did not changed significantly. It is expected that a deeper locations the photosynthetic activity of the plants is smaller because of the light availability, therefore the similar relative day-night noise power variability observed among different water depth locations deserves further investigation. From SR-1 moorings, one should remark that noise power did not depend significantly on the depth of the receivers, since the magnitude of noise power at the receivers installed 4 m and 6 m above the bottom are superimposed. It suggests that under the experimental conditions (constant temperature and salinity with depth) the noise field was homogenous distributed in the water column. Figure 6 shows the comparison between noise power and the changes in dissolved O2 measured by the optodes at 7 m and 9 m depth, where one can notice a high correlation between the noise power and the dissolved O2, suggesting the close relation between acoustic data and photosynthetic activity of the meadow. Nevertheless, at sunrise the high gradient of change occurs earlier in acoustic data than in dissolved O2, what could suggest that the air in plant tissues (aerenchymas) plays a major role in the acoustic

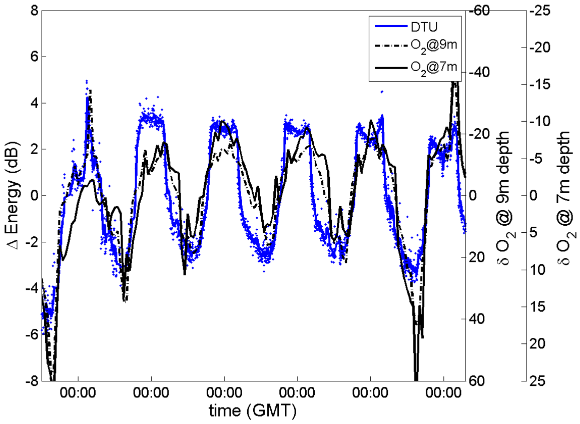

Fig. 6. Comparison between changes of the noise power at DTU hydrophone 8 (blue dots represent the instantaneous values, blue solid line the half-hour moving average) and the changes of dissolved O2 measured by the optode at 7 m (black solid line) and 9 m (black dashed line).

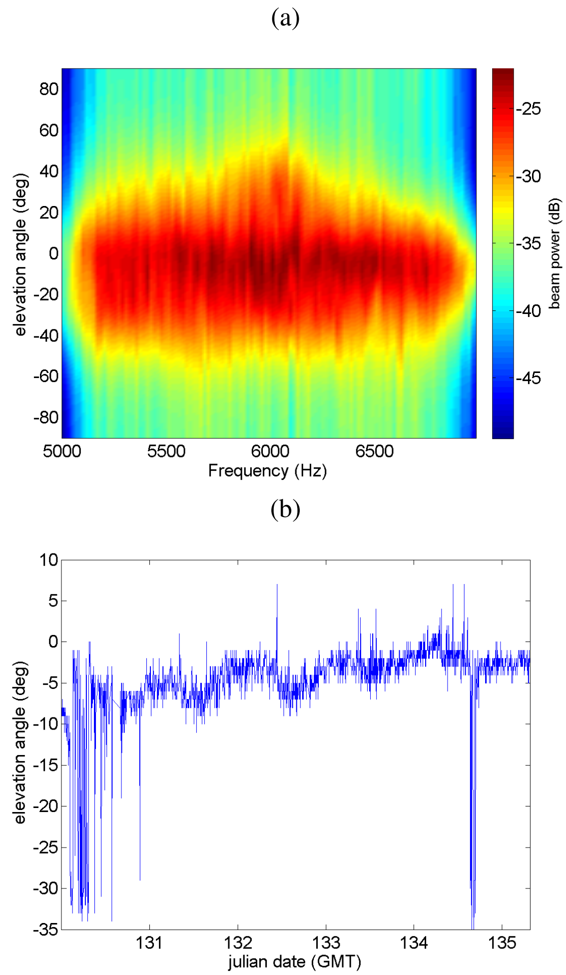

Fig. 7. Noise directionality: noise elevation angle at a given instant (a) and its variability with time (b)

signature of photosynthetic activity. This behavior could be related to the pressurization of the aerenchyma at sunrise, and it might suggest that photosynthetic activity affects the acoustic noise field even in the absence of conditions (O2 super-saturation) that allow the significant release of free bubbles. These measurements of environmental noise have confirmed the correlation between active acoustic signals transmitted through a seagrass meadow and the photosynthetic activity of the plants observed in the October 2011 experiment[2]. However, during the daylight period at the present experiment the local variance of instantaneous noise power (Fig. 5 and 6) is smaller than the local variance of the signal power at the October 2011 experiment. At daylight the curves of the moving averaged acoustic power in Fig. 5 and 6 are smooth and present a well defined valley (in line with the maximum of the dissolved O2), whereas similar curves in the October 2013 experiment presented several large peaks and valleys. The noise power estimates integrates the noise field contributions from all directions, but the signal power estimates in the October 2011 experiment accounts for signals arriving from one particular direction (from source to receiver), therefore more susceptible to the variability due to increased leaf buoyancy at daylight, currents or local transient O2 flows.

IV. Noise Directionality and Bottom Reflectivity

The directionality of the ambient noise was determined by plane-wave Bartlett beamforming from the same acoustic data sets acquired by the short hydrophone array (DTU/SHA) used for noise power estimation (see previous section). Only 4 hydrophones out of 8 were used (hydrophones n. 2,4,6,8), therefore the array acts as a 30 cm aperture array with working frequency 7.5 kHz. The data set of each hydrophone acquired at instant t_i (timestamp of the file) were down sampled by a factor of 3 (from 52 to $\sim$ 17 kHz), then the data set was segmented in blocks of 1024 samples with 512 samples overlapping and a FFT was applied to each block. The frequency resolution is ~17 Hz. Considering $Y_{n,j}(f_k)$ the frequency bin at frequency f_k, block n and hydrophone j, $(j = 2,4,6,8)$, the estimate of the correlation matrix at instant t_i is given by

$$\hat{\mathbf{R}}(t_i, f_k) = \frac{1}{N}\sum_{n=1}^{N} \mathbf{Y}_n(t_i, f_k)\mathbf{Y}_n^H(t_i, f_k) \qquad (1)$$

where $\mathbf{Y}_n(t_i, f_k)$ is the column vector $[Y_{n,8}(f_k), Y_{n,6}(f_k), Y_{n,4}, Y_{n,2}(f_k)]^T$, T and H are the transpose and Hermitian transpose operators respectively and N is the number of blocks. Then, the beamformer output at instant t_i, frequency f_k and direction (elevation angle in respect to the horizontal) ϕ ($\phi \in [-90^\circ, 90^\circ]$) given by

$$B(t_i, f_k, \phi) = \mathbf{u}^H(f_k, \phi)\hat{\mathbf{R}}(t_i, f_k)\mathbf{u}(f_k, \phi) \qquad (2)$$

where $\mathbf{u}(f_k, \phi)$ is the plane wave steering vector. Assuming the origin at hydrophone 8 (the shallowest), then the steering vector can be written as

$$\mathbf{u}(f_k, \phi) = \begin{bmatrix} 1 \\ \exp(j2\pi f_k d \sin(\phi)/c) \\ \exp(j2\pi f_k 2d \sin(\phi)/c) \\ \exp(j2\pi f_k 3d \sin(\phi)/c) \end{bmatrix} \qquad (3)$$

where d is the inter-element spacing ($d = 0.1\,m$) and c is the sound speed at the receiver ($c = 1517\,m/s$).

Figure 7(a) presents the magnitude of the beamformer output for frequencies between 5 and 7 kHz at a given instant. The main lobe at the various frequencies shows that the noise field impinges the array close to the horizontal slightly from upward. The direction of the noise field during the whole experiment were estimated at the various instants by averaging over all frequencies the direction pointed out by the main lobe of the beamformer. These estimates are presented in Fig. 7(b). Notwithstanding the high variance of these preliminary results, it can be seen a diurnal pattern, where at daylight the angle is wider, suggesting a higher contribution of the noise field impinging the array from upward during the photosynthetic active period. Using the beamformer output presented above, the bottom reflection loss versus grazing angle for the noise in the band 5-7 kHz was estimated by the method proposed in [8]. The reflection loss at instant t_i,frequency f_k and bottom angle θ_0 was estimated by the ratio between the downward and upward beamformer output

$$R(t_i, f_k, \theta_0) = \frac{B(t_i, f_k, -\theta_0)}{B(t_i, f_k, +\theta_0)}. \quad (4)$$

One should remark that: 1)θ_0 is the angle complementary to angle ϕ, 2) it is assumed an isovelocity sound speed profile,therefore it is not necessary to correct the bottom angle (eq. (32) in [12]). Figure 8(a) shows a bottom reflection loss image, where the fringe indicates a bottom grazing angle consistent with a sandy bottom. Figure 8(b) presents the time evolution of the grazing angle (average over frequencies at a given instant) showing a diurnal pattern, where the bottom grazing angle decreases at daylight consistent with a decrease of the bottom sound speed. This behavior suggests the variability of the bottom parameters is linked with plants photosynthesis.

V. Conclusions

This paper shows that the directionality and particularly the power and of ambient noise are significantly affected by the photosynthetic activity of marine vegetation. It is shown that the variability of the ambient noise power is highly correlated with measurements of dissolved O2 by optodes. The results suggest that acoustic noise can be used as a proxy for the photosynthetic activity of a *Posidonia oceanica* meadow. Therefore, this work is a contribution for the development of a low cost passive acoustic system to assess the O2 based productivity of a seagrass meadow.

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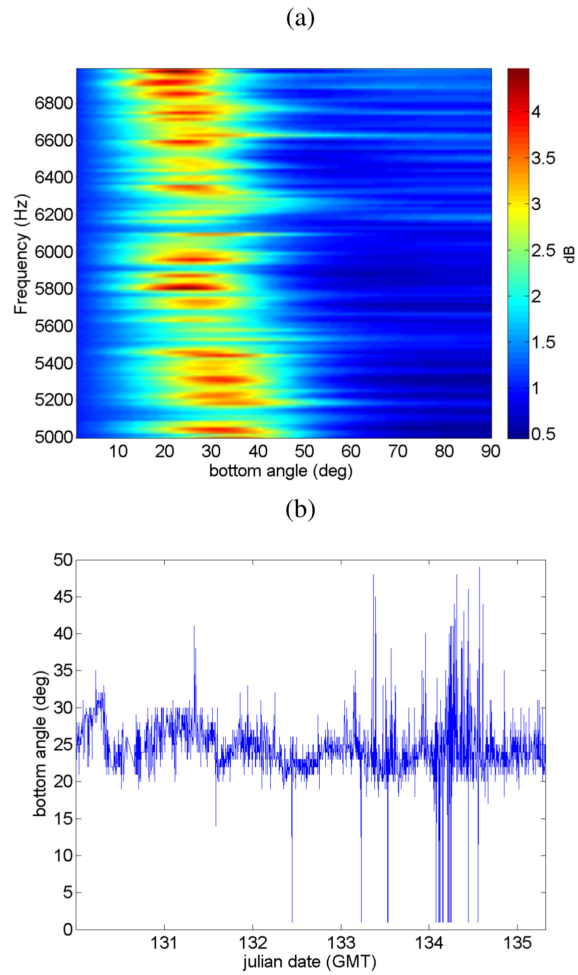

Fig. 8. Bottom reflection loss deduced from the down-up ratio of the beam power showing the bottom grazing angle (a), and its variability with time

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