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# [Upwelling effect on acoustic propagation in the Cabo Frio island bay]

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**Abstract**

Coastal upwelling is an oceanographic phenomenon that challenges the understanding of acoustic propagation, especially when it extends to shallow water areas with complex geographic configuration. The data used in this paper was collected in a semi-enclosed bay filled by the upwelling stream through an inlet off the island of Cabo Frio, in the coast of Brazil. The experiment was carried out in January 2019, under the BIOCOM project, a joint initiative between the Brazilian Navy and the University of Algarve (Portugal). Broadband acoustic signals were transmitted over a 1.6 Km-long transect across the upwelling flow during five days. These signals were superimposed in a soundscape formed by a strong biological acoustic signature and boat engine noise due to close by recreation activities. Signals were received in two hydrophone arrays: one vertical and another horizontal, close to the bottom. Comparisons between the signal and noise power, during a period when the upwelling stream was present, indicates an increasing of the transmission loss about 10 dB. Besides, further modeling computations were carried out in order to support the understanding about the underwater acoustic propagation in this complex environment.

Keywords: Underwater acoustic propagation, acoustic monitoring, coastal upwelling

## 1 INTRODUCTION

Coastal upwelling [8] is an oceanographic phenomenon which consist typically in the motion of dense, colder and nutrient rich water towards the surface. This phenomenon challenges the understanding of acoustic propagation, especially when it extends to shallow water areas with complex geographic configuration.

The Cabo Frio upwelling system is an anomaly in Southeast Brazilian coast that influence ocean temperature stratification, sound wave propagation and biological activity [6, 3]. Upwelling in this region, especially during the spring and summer seasons, brings rich and colder waters to the surface. These conditions motivate the development of a large diversity of marine organisms which contribute and shape the underwater soundscape.

An initial acoustic propagation study about the considered region, was initiated in [1]. Although the contributions of this work, only modeled data were shown considering the upwelling phenomenon. Otherwise, this work presents a preliminary study regarding the influence of the upwelling phenomenon through the experimental comparisons of signal and noise power in a period when a highly dynamic system was formed.

The joint project ”BioCommunications” between Brazilian Navy Institute of Sea Studies and the University of Algarve-Portugal aims to acoustically characterize, in a long term, the biological activity and its correlation with the upwelling regime and other biotic and abiotic factors. In this sense, the channel characterization is a fundamental step performed by means of acoustic propagation monitoring to understand the related features that may influence this complex environment. The BIOCOM’19 experiment took place from 14-18 January, 2019, in the bay of the Island of Cabo Frio, where broadband acoustic transmissions were performed over a 1.6 km-long transect across the upwelling flow during five days. Signals were received in two hydrophone arrays: one vertical and another horizontal, close to the bottom. For acoustic monitoring purposes, only data collected for the vertical array was considered in this work. Previous long term soundscape recordings in this area [2] have shown a persistent biological acoustic signature reaching levels of 74 to 84 dB. It is anticipated that the transmissions during the BIOCOM’19 experiment will have low signal to noise ratio due to the biological noise and the variability due to abiotic factors such as the upwelling regime.

The experimental results indicate an increasing of transmission loss (TL) about 10 dB when the upwelling system is present. Besides, further modeling predictions were carried out, using the TRACEO Seismo-Acoustic ray based model [7], which provide additional support regarding the sound propagation.

## 2 THE BIOCOM'19 EXPERIMENT

The BIOCOM'19 experiment took place at a shallow water site, in Cabo Frio Island Bay, during Jan14-18, 2019. In a previous initiative the biological soundscape has been continuously monitored over a year using a four hydrophone array, disposed in a pyramidal shape, was placed close to the rocky shore, in an almost flat bottom location. During the BIOCOM'19 experiment, another four-hydrophone linear array was installed spanning 4.5m of an 8m water column and a vector sensor approximately 1m above the bottom, both located just a few meters on each side of the pyramid horizontal array, as shown in the diagram of Fig.1.

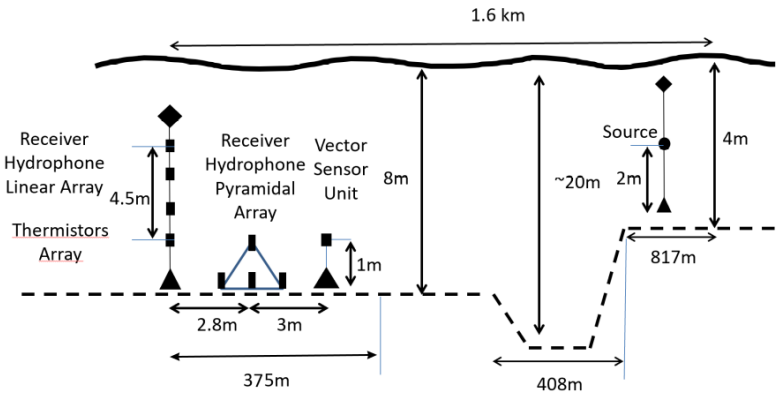



Figure 1. Diagram of the BIOCOM'19 experimental setup (not to scale)

The recording system was configured with sampling frequency of 52734Hz, a quantization of 24 bits, where each hydrophone has a sensitivity of -174.9 dB re 1V/1microPa and a frequency response between 0.1 and 40 kHz. For acoustic monitoring and communication purposes, an omnidirectional acoustic source, ITC 1001, was located approximately 1.6 km from the receivers, as shown in Fig.2.

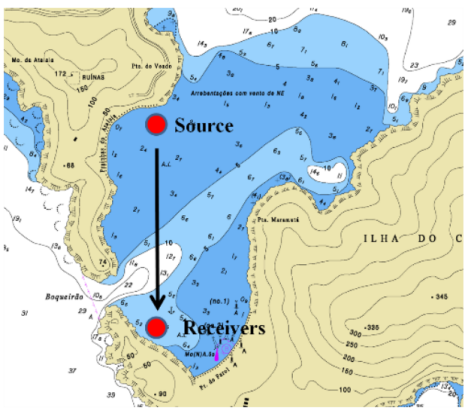



Figure 2. Position of source, receivers and propagation line across the bay of Cabo Frio Island during the BIOCOM'19 experiment.

The source was placed in the middle of the 4m deep water column, hardwired to the transmission system on shore. The bathymetry changes strongly along the propagation path. Most part of the path has an almost flat 5m deep bottom. However, in its deepest part, the propagation path crosses the entrance of the bay. Pointing to Southwest/South, the entrance connects the bay to the region off the Cabo Frio Island where upwelling occurs (see bathymetry and bay geo-morphology in Fig.2).

During the experiment, several sound speed profiles (SSP) and temperature recordings were collected along track, variably spaced between acoustic source and receivers, reaching depths in the interval 4-20m. Such measurements allowed observations of short-term drastic temperature changes of about 10 degrees Celsius in a few hours (Fig.3), possibly due to the upwelling regime occurring off the southern side of the bay rocky shore, and the cold water sipping through the narrow entrance termed as Boqueirão in Fig.2.

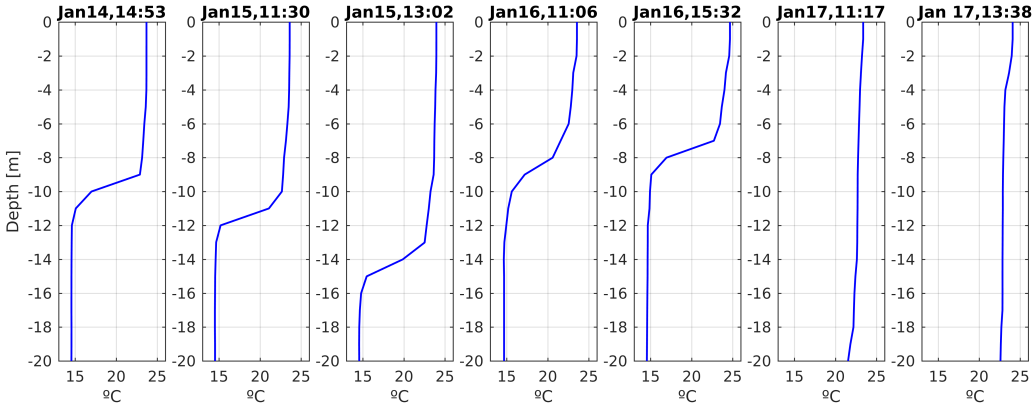



Figure 3. Temperature profiles collected at the Boqueirão narrow inlet bay entrance.

Different signal schemes were transmitted in this upwelling environment for specific purposes according Table 1. The data block is composed of four codes and each code is preceded by a silence guard time of 5s. After code 4, there is a final guard time of 40s. Therefore, the total duration of the data block is 4min20s. The data block was transmitted once every 5 minutes during the experiment (Fig.4), but with different source power level (SL). The transmission and recording systems were synchronized at minute 45. Therefore, from minute 45 to minute 10 of next hour, the blocks were transmitted with constant SL, to check codes consistency. Next, from minute 15 to 40, the SL was reduced in 1dB after each transmission, to reduce the SNR and allow performance analysis.

Table 1. Data block: Binary Phase Shift Keying, CHSK: Chirp Shift Keying, LFM: Linear Frequency Modulation, CW: Continuous Wave, FSK: Frequency Shift Keying.

| Code | Modulation | Bandwidth (kHz) | Duration(s) |
|---|---|---|---|
| - | Silence guard time | - | 5 |
| 1 | BPSK | 5-10 | 60 |
| - | Silence guard time | - | 5 |
| 2 | 8-CHSK | 4.5-12.2 | 60 |
| - | Silence guard time | - | 5 |
| 3 | LFM/CW | 2-9/2-12 | 60 |
| - | Silence guard time | - | 5 |
| 4 | 8-FSK | 5-10 | 20 |
| - | Silence guard time | - | 40 |

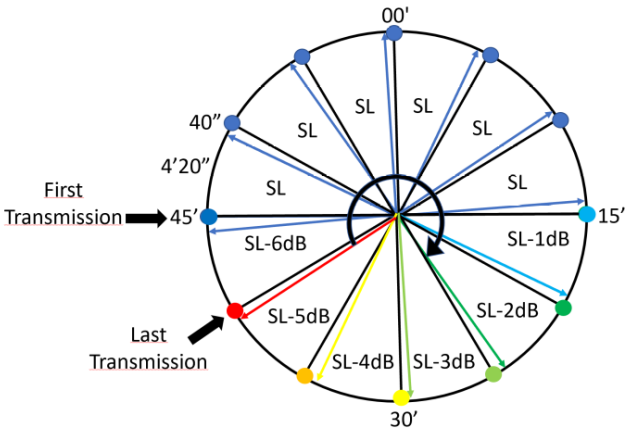



Figure 4. One-hour diagram of different SL transmissions, once every 5 minutes, during the experiment. First transmission at minute 45 with SL. Last transmission at minute 40 with SL-6dB. Total duration of data block: 4min20s.

## 3 PRELIMINARY RESULTS AND ANALYSES

To investigate this complex regime of acoustic propagation, a four-hydrophone linear array was considered to record received acoustic pressure at various depths. Among the signals transmitted for several purposes, a parabolic linear frequency modulation (LFM) with band between 8.75kHz and 9.25kHz was chosen to perform a study combining the sound pressure level (SPL), TL and SNR levels. The source level (SL) was calculated based on the transmitting voltage response of the acoustic source, considering the LFM band frequency, which corresponds to 135.4 dB plus 32 dB regarding a estimation of 40Vrms. Thus, the SL corresponds to a fixed value of 167.4 dB. The estimated TL and SNR were calculated as TL = SL - Sl (dB) and SNR = Sl - NL (dB) [4], where

$$\mathrm{Sl} = \text{signal level (dB)}$$

$$\mathrm{NL} = \text{noise level (dB)}$$

Acoustic data and environmental information were selected for a period of Jan 16, 13:02 to Jan 17, 09:02. These period shows a strong temperature gradient, probably because the upwelling effect (see Fig.3). Data time for all results in this paper correspond to UTC-2. Received signals were filtered in the same frequency band of the transmitted signal to compute signal and noise power. The SPL were calculated based on the power spectral density estimate, regarding the LFM frequency band, considering a time window containing the LFM signal and a subsequent one, in the silence guard time, for the noise level.

Signal and noise power are presented in Fig.5 where thick lines correspond to the average values, calculated using a average filter, and peaks presented in the signal curve were related to the SL variation, as explained in section 2. In Jan 16 afternoon, all curves presented a low SPL level, which coincided to when the water temperature was colder. About Jan 16, 15h, the signal energy almost decreases below the noise energy, which will probably hamper the signal detection. Actually, during the analysis of this period, some files did not present any signal in this band, which is believed to be due to the upwelling interference. Conversely, on Jan 17, an increasing in the SPL levels can be noted which coincided with a increase of temperature. Therefore, SPL decreases during upwelling events (lower temperatures) and increases when a downwelling (the opposite of upwelling) occurs. Furthermore, TL and SNR curves are shown in Fig.6 (a) and (b), respectively. The TL curve was calculated based on a fixed SL minus the signal level received at the hydrophones. Overall, the difference

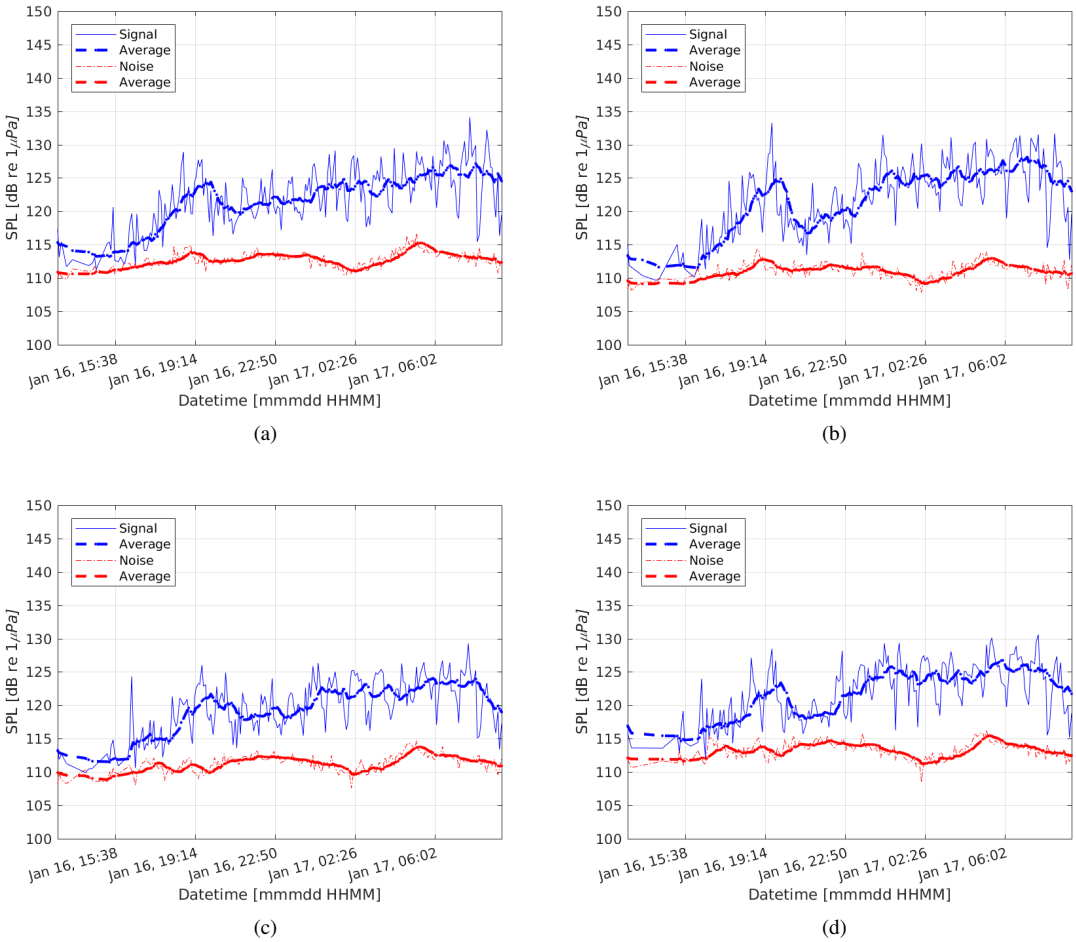



Figure 5. Signal and noise power and its corresponding average values (thick lines) in frequency band 8.75kHz-9.25kHz. Peaks presented in the received signal were due to the SL variation, as explained in section 2. Hydrophones depths are: $\approx$ 2.5m (a), 4.0m (b), 5.5m (c), and 7.0m (d).

in energy loss was about 10 dB from Jan 16 afternoon to Jan 17 morning. As explained above, the experiment was planned for a environment with low SNR and, around Jan 16, 15:38, the SNR presented a mean value of 3dB and, after that, it was increasing as explained above, up to 10 - 15 dB, depending on the considered array channel.

Further simulations were performed to support the evidence about the upwelling effect on sound propagation. In this sense, two sound speed profiles were used. One collected at Jan 16, 15:32, and the other at Jan 17, 11:17 (see Fig.7). A sea bottom with sand dominate the experiment site. Thus, it was assumed a sediment (compressional) sound speed of 1650 m/s, a density of 1.9 g/cm$^3$ and an attenuation of 0.8 dB/$\lambda$ [5]. For modeling purposes, was considered the geometry as depicted in Fig.1. The TRACEO model was used to calculate predictions, taking into account the source/receiver line (see Fig.2) and a central frequency of 9kHz was considered. The result presented in Fig.7(a) suggests that the acoustic signal crosses the entrance of the bay and reaches the receivers with much lower energy than that obtained in the case of a decreasing upwelling scenario

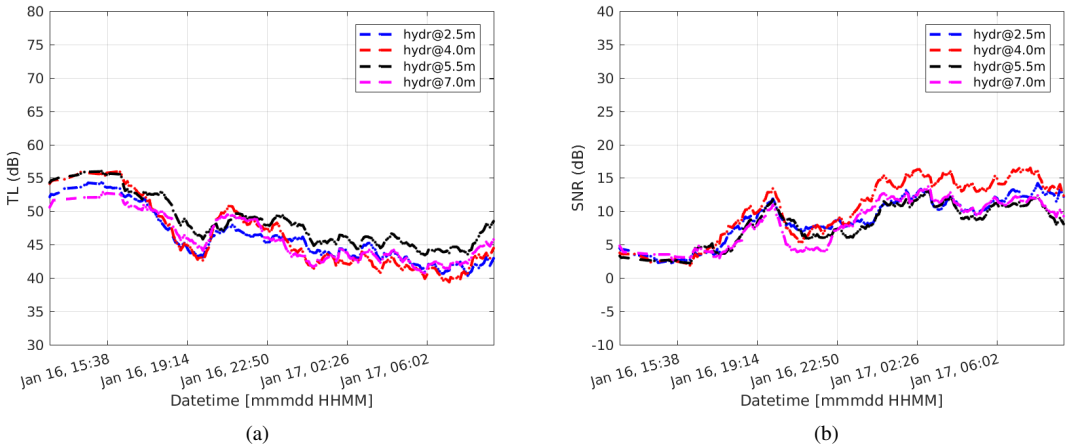


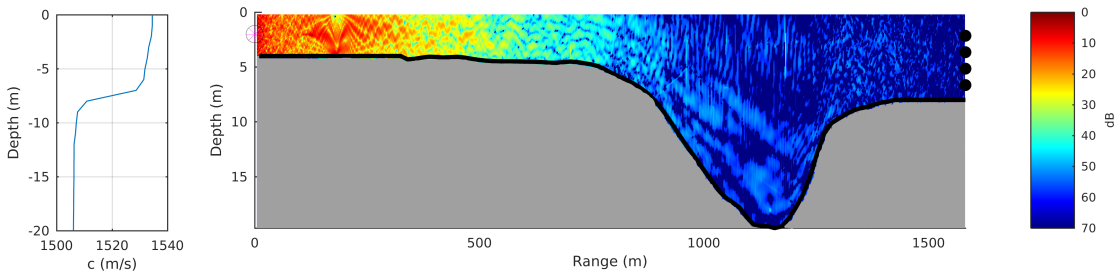

Figure 6. Estimated transmission loss (TL) and signal to noise ratio (SNR) in dB for each array hydrophone.

(Fig.7(b)). Numerical predictions also show that the difference of the mean values at the hydrophone line array is about 10dB, which corresponds approximately to a propagation loss of 55dB and 45dB comparing Figs.7(a) and 7(b), respectively.

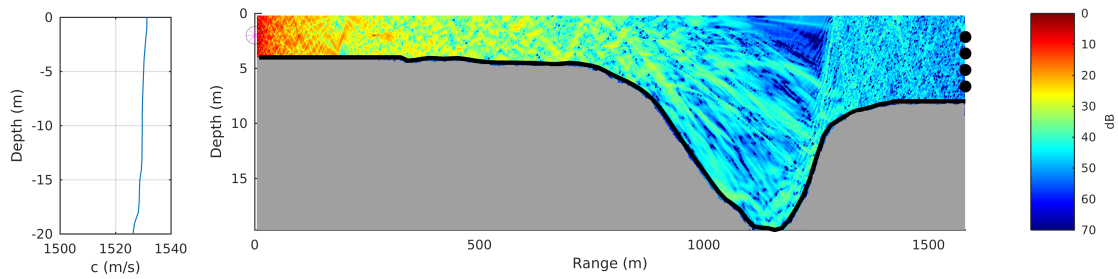
Additional perspective is presented in Fig.8, which shows experimental estimated against predicted arrival patterns. Received signals at the vertical array were selected in two different moments: Jan 16, 18:06 and Jan 17, 08:12, considering upwelling Fig.8(a) and downwelling Fig.8(b), respectively. To account properly with amplitudes, data were normalized for its maximum value considering the vertical array in both moments (Jan 16, 18:06 and Jan 17, 08:12), for experimental and modeling result separately. During the intense upwelling, the amplitude of all channels seems weaker than those received when the water was warmer. Furthermore, the number of arrivals presented in Fig.8(a) are lower in all channels than those presented in Fig.8(b). Although some discrepancies presented in the model predictions, channel 3 (5.5m depth) presents a good agreement regarding the time of arrivals and amplitude. The discrepancies found in the comparisons are believed to be related to water depth, frequency and SNR levels. Yet such discrepancies do not invalidate the evidence regarding the upwelling effect on sound propagation.

## 4 CONCLUSIONS

This work presented a preliminary study of the upwelling effect on acoustic propagation in the Cabo Frio island bay. The study was performed through comparisons of the experimental result regarding the SPL, TL and SNR. A strong correlation between the presence of the upwelling events (lower temperatures) and the decreasing of signal power, consequently, an increasing of TL values were showed which certainly will impact in the communications performance and biologic monitoring. Experimental results of TL show a difference of more than 10dB from Jan 16, afternoon to Jan 17, morning. Furthermore, modeling results suggests that the cold and dense water from the upwelling stream have behaved like a filter for the sound propagation, at the entrance of the bay. Results also suggests that the number and amplitudes of arrivals are reduced when the upwelling effect is present. Future works will be oriented to use LFM signals, in the same band of the biological noise, to analyze signal and noise power, as well as TL and SNR. Moreover, it is intended to perform a water column properties inversion in these highly dynamic system to track temperature changes and its corresponding effect in acoustic propagation.




(a)




(b)

Figure 7. Numerical predictions of TL, calculated with TRACEO [7], using a transect based on source/receiver line (see Fig.2). Calculations were performed for two different regimes of temperature: upwelling (a) and downwelling close to the deepest site (b). Data time regarding the sound speed measurements corresponds to Jan 16, 15:32 and Jan 17, 11:10, respectively.

## ACKNOWLEDGEMENTS

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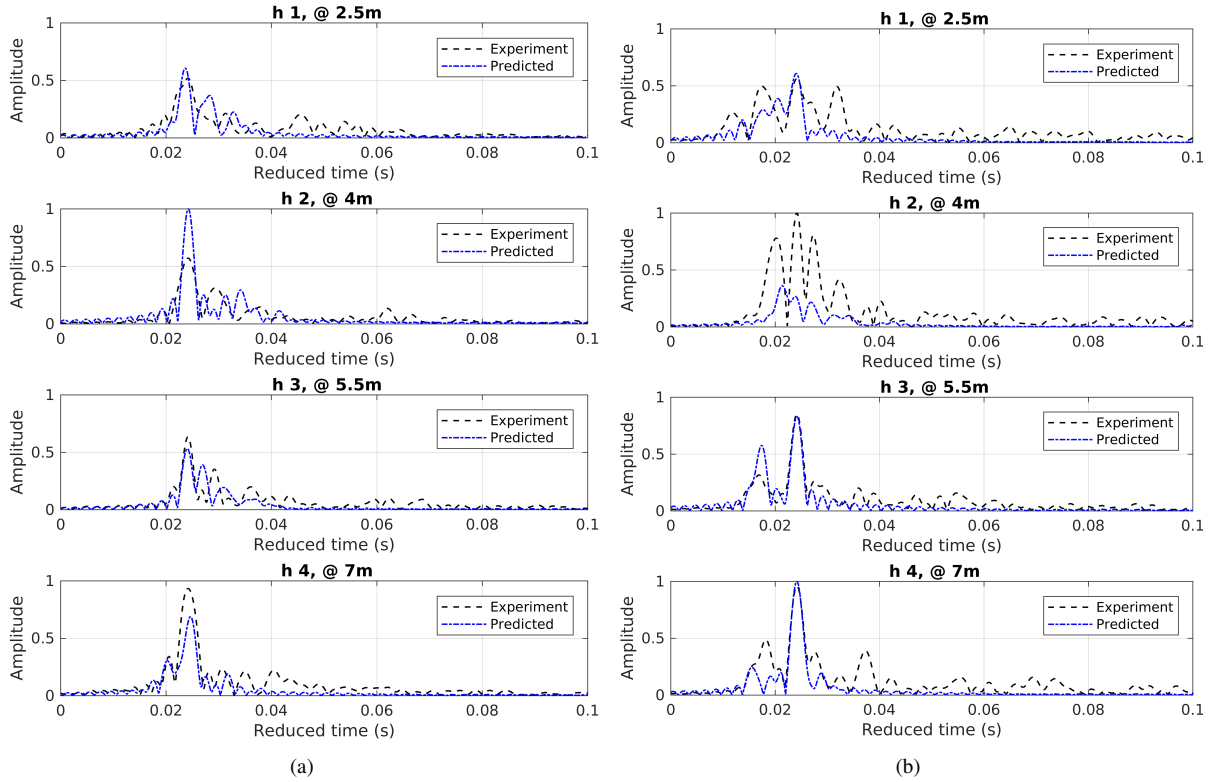


Figure 8. Experimental data against predicted arrival pattern, calculated with TRACEO [7]. Received signals at the vertical array were selected in two different moments: Jan 16, 18:06 (a) and Jan 17, 08:12 (b).


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