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A study on spatial fading in a shallow water channel

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Abstract

A methodology to assess the spatial fading suffered by acoustic signals transmitted in a Underwater Acoustic (UWA) channel in Arraial do Cabo, Brazil, is provided. This study was necessary in order to predict how the nominal conditions of this shallow water environment impose spatial variations on the Transmission Loss (TL) of a propagating signal. A Ray Tracing model was used to predict the underwater acoustic wave field (frequency range from 5 kHz to 10 kHz). The numerical model takes into account the geometric and geo-acoustical properties of the bathymetry founded at the studied area. In addition, the influence of two distinct range dependent Sound Speed Profiles (SSP) on spatial fading is investigated. One SSP was measured during a coastal upwelling event and the other in regular sea conditions. The result is a methodology of analysis that not only estimates the TL due to geometrical spreading, sound absorption and multipath propagation, but also the signals intensity fluctuations along the channels range. Thus, this study allows a better understanding about the signal's behavior on this environment aiming the use of diversity techniques to lower the effects of signal fluctuations on a receiving system.

Keywords: Underwater acoustic communication, underwater acoustic channel modelling, spatial fading, coastal upwelling.

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1 Introduction

The Underwater Acoustic (UWA) communication channel is a complex media for performing digital wireless communication. According to [1], the transmission of an acoustic signal in an UWA channel is mainly affected by attenuation and multipath propagation. The attenuation of the signal, or path loss, occurs mainly due to spreading loss and sound absorption. Both are range dependent parameters but the latter is also frequency dependent, limiting the bandwidth available for communication systems. Multipath propagation takes place due to sound reflection in the channel boundaries, or in any objects. Also, the spatial variation of the sound speed causes sound refraction, which plays an important rule on multipath propagation since it bends a propagating wavefront. The consequence of multipath propagation is that an acoustic pressure signal is perceived by a receptor as the combination of multiple arrivals of the same signal.

Specially in shallow water environments, where a big interaction between a propagating signal and the channel boundaries happens, the effects brought by multipath propagation becomes relevant since it leads to spatial variations of the intensity of a transmitted signal. A moving receiver perceives these spatial variations as signals intensity fluctuations, whose will affect an established communication data link. Thus, when designing underwater communication systems, it's important to develop a representative channel model that allows us to predict how the propagation media affects the signal transmission.

The effects brought by path loss and multipath propagation combined can be estimated by deterministic propagation models, given the nominal conditions that can better model the channel in study. These conditions are described by the channel boundaries (bathymetry and surface) and their properties, along with a characteristic sound speed profile (SSP). Deterministic underwater propagation models are usually based on ray theory [2] or in the normal mode method [3] and their use is widespread in the available literature. However, these models are only able to predict a time invariant response of the channel since random channel variations (*e.g.* surface waves, internal tides, scattering, among other phenomena) are not taken into account. These random variations are often modelled using stochastic or statistical [4] approaches. Nevertheless, deterministic propagation tools are useful to provide an initial picture about the transmission of an acoustic signal in a UWA channel.

The motivation of this work is to provide an initial insight on the spatial fading of transmitted signals in an UWA channel in Arraial do Cabo, Brazil, a site where Brazilian Navy develops research on underwater communication. In this location, a phenomena called coastal upwelling [5] takes place recurrently throughout the year, modifying the characteristic SSP founded in the region. Thus, it's important to study how the occurrence of this phenomena affects the signal transmission. Towards this goal, section 2 describes the numerical model developed to predict the propagation of acoustic pressure signals in the UWA channel. Section 3 presents the proposed parameters to assess the spatial fading and section 4 shows and discusses the results obtained. In section 5, the final remarks on the present study are made.

2 Numerical model of the UWA channel

This section describes the numerical model developed to predict the sound propagation on the studied UWA channel. It was used a beam tracing tool called TRACEO [6], which is a two-dimensional propagation model based on gaussian beam approximations [7]. This simulation tool allows us to predict both sound attenuation and multipath fading effects on the sound propagation when given the boundary conditions and SSP that proper describes the scenario in study.

2.1 Study scenario

The site of interest is located in Arraial do Cabo coast, situated in Rio de Janeiro state, Brazil. The area presents peculiar oceanographic characteristics and wind patterns whose enable the occurrence of coastal upwelling, a complex phenomena characterized by the upwelling of deep water, cold and rich in nutrients. The occurrence of this phenomena impacts on the SSP since it changes the temperature and the salinity of the water column.

The bathymetric map of the area is shown in Figure 1, where the black line illustrates the bathymetric profile considered in this work. The profile total range is 25 km, and its maximum depth is 115.5 m, representing a shallow water environment.

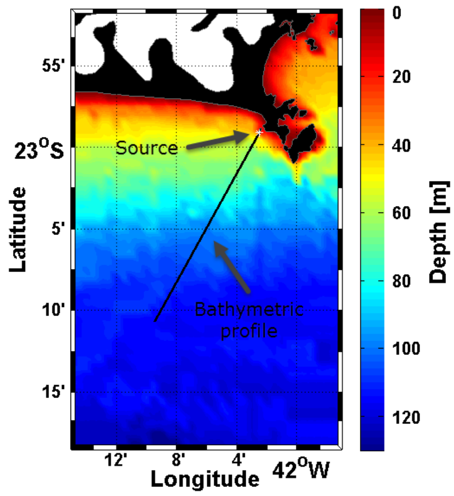
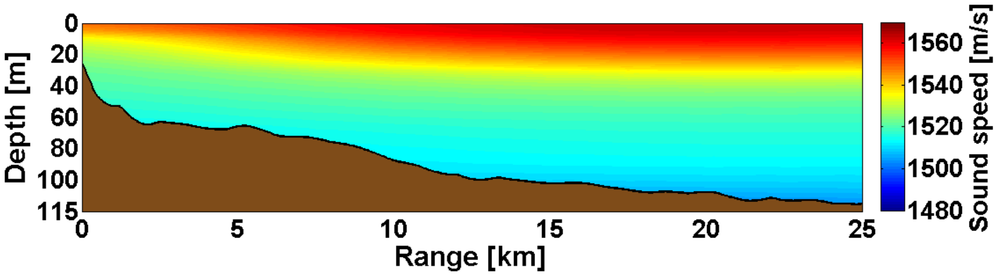


Figure 1: **Arraial do cabo coast bathymetric map**

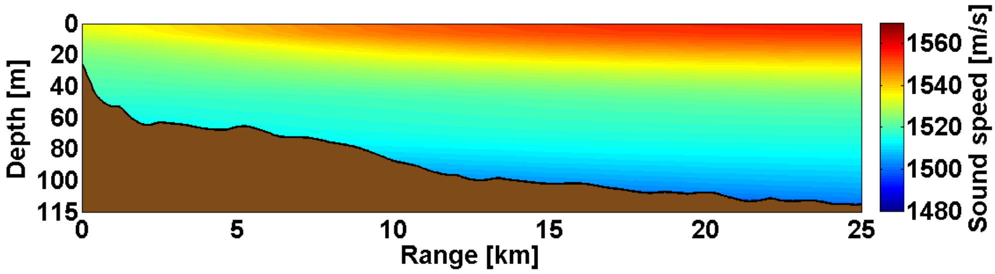
The geoacoustics properties of the seabed in the area were estimated by previous work [8], where it was found that it is mainly composed of fine sand. Based on this study, the bathymetric profile is modeled as an elastic and homogeneous sediment, with compressional sound speed, $v_p = 1684$ m/s, compressional attenuation, $a_p = 0.6$ dB/λ and density, $\rho = 1.99$ g/cm^3. The sea surface is modeled as a flat, homogeneous and completely reflexive interface.

2.2 Sound speed profile

In order to assess how the occurrence of a coastal upwelling event impacts on the signal transmission, the influence of two range dependent SSPs on sound propagation is investigated. One was measured during a coastal upwelling event and the other in regular sea conditions. The SSPs were estimated using data of temperature, salinity and pressure, collected along the water column by [9], and the equation provided by [10]. Figure 2 shows the range dependent sound speed profiles used in this work.



(a) Regular sea conditions



(b) Coastal upwelling event

Figure 2: **Range dependent sound speed profiles**

3 Assessing spatial fading

The Transmission Loss (TL), which is a parameter that expresses the magnitude of the overall loss suffered by a propagating acoustic signal, is used to assess the spatial fading of acoustic signals within a bandwidth of 5 kHz to 10 kHz. First, the entire channel is discretized by a grid of receivers and the acoustic pressure, for each receiver, is obtained. Thus, the analysis is carried out on an acoustic pressure grid, $\hat{\mathrm{P}}_{i,j,k}$, with i rows discretizing the channel's depth, z, in 1115 points (resolution of 0.1 m), j columns discretizing the range, r, in 500 points (resolution of 50 m) and k dimensions (analyzed frequency components). The sound pressure is obtained in TRACEO by the coherent sum of all rays that intercepts one receiver. Figure 3 illustrates the pressure grid and its relation with the channel dimensions.

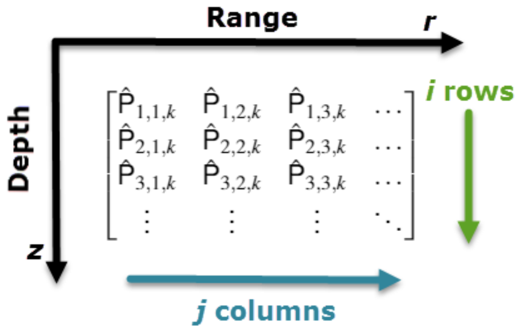


Figure 3: **Pressure grid illustration**

According to [11], the calculation of the sound pressure in TRACEO already takes into account a reference pressure value, $P_o = 1/(4\pi)$. Thus, the TL can be obtained by equation (1):

$$\mathsf{TL} = -10\log_{10}\left|\hat{\mathsf{P}}_{i,j,k}\right|^2. \tag{1}$$

In order to study signal loss fluctuations along channel's depth, first, a parameter called Vertical Transmission Loss is derived from equation (1) by:

$$\mathsf{TL}_{\mathsf{V}_{j,k}} = -10\log_{10}\left|\hat{\mathsf{P}}_i\right|^2, \tag{2}$$

assessing all i row values of $\hat{\mathsf{P}}_{i,j,k}$, in fixed j and k components. We are interested in obtain two parameters from the vertical transmission loss. First, the mean value of TL_V is obtained by:

$$\overline{\mathsf{TL}}_{\mathsf{V}_{j,k}} = -10\log_{10}\left(\frac{1}{N}\sum_{i=1}^{N}\left|\hat{\mathsf{P}}_i\right|^2\right). \tag{3}$$

The second information refers to the maximum fluctuation of the TL along the channel depth. Thus, a parameter called peak-to-peak Vertical Transmission Loss is obtained by equation (4):

$$\mathsf{TL}_{\mathsf{VPP}_{j,k}} = \max(\mathsf{TL}_{\mathsf{V}_{j,k}}) - \min(\mathsf{TL}_{\mathsf{V}_{j,k}}). \tag{4}$$

Both $\overline{\mathsf{TL}}_\mathsf{V}$ and TL_VPP are scalars, for each range, j, and frequency, k, increments. Figure 4 gives an illustration of the proposed parameters.

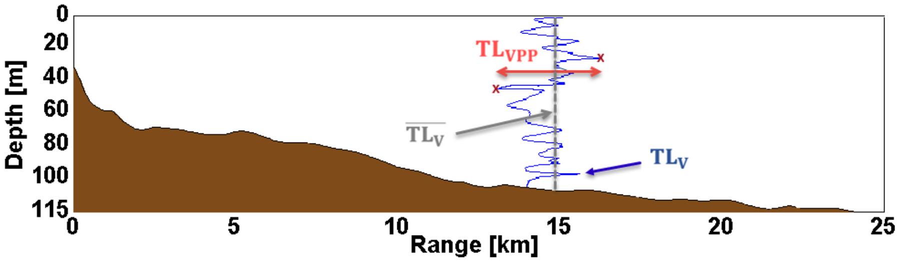
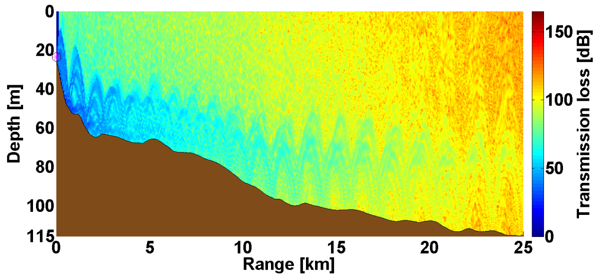


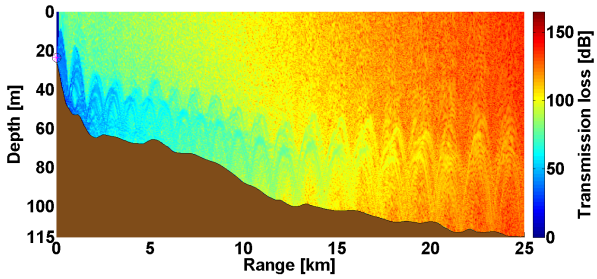
Figure 4: **Illustration of a TL_V generic curve, computed at r=15 km, and derived parameters**

4 Results

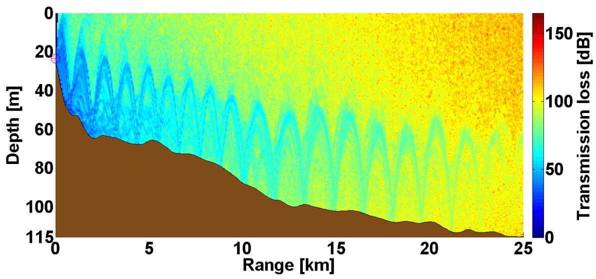
In this section, the spatial fading of transmitted signals (from 5 kHz to 10 kHz) is analyzed from the numerical model results. For all simulations, the source was situated at $r = 0$ m, with depth of 23.5 m. Figure 5 shows the transmission loss results.



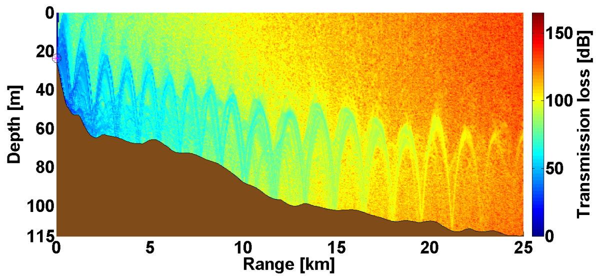
(a) Regular sea conditions: 5 kHz



(b) Regular sea conditions: 10 kHz



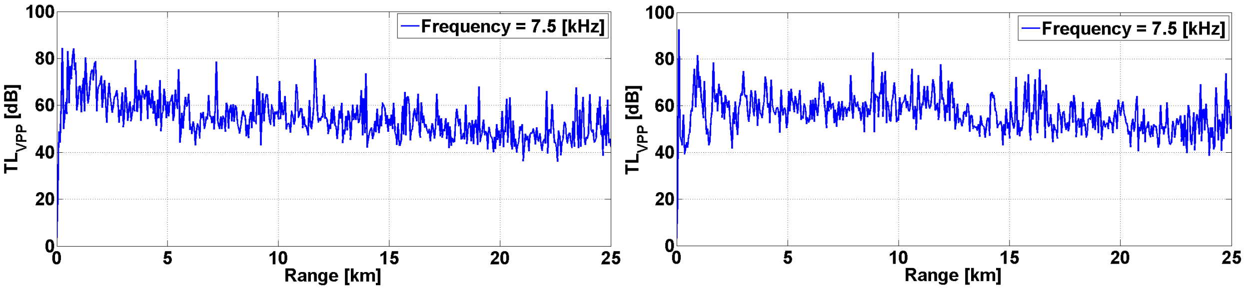
(c) Coastal upwelling event: 5 kHz



(d) Coastal upwelling event: 10 kHz

Figure 5: **Transmission loss along the channel**

Figure 5 allows to have an overall picture about the signal fading along the channel. In general, it's possible to verify that the TL is range and frequency dependent, mainly due to geometrical spreading and sound absorption. Notwithstanding, the influence of the SSP in multipath propagation is noticeable. The high sound speed gradient from the surface to the sea bottom forms a propagation duct towards the channel bottom, where a considerable part of the acoustic energy is trapped due to sound refraction. Consequently, the intensity of the signal along the water column suffer fluctuations. Figure 6 shows the maximum signal fluctuations along the channels depth for the central frequency of the analyzed bandwidth.



(a) Regular sea conditions

(b) Coastal upwelling event

Figure 6: **Peak-to-peak vertical transmission loss results**

The results shown in Figure 6 indicates that the signal fluctuation levels happens in a similar way for both SSPs. Table 1 shows the mean value and standard deviation of the peak-to-peak vertical transmission loss, for all frequencies.

Table 1: Mean value and standard deviation of peak-to-peak vertical transmission loss

	Regular sea conditions		**Coastal upwelling event**	
Frequency [kHz]	$\overline{TL}_{VPP}$ **[dB]**	$\sigma_{TL_{VPP}}$ **[dB]**	$\overline{TL}_{VPP}$ **[dB]**	$\sigma_{TL_{VPP}}$ **[dB]**
5	52.9	8.6	56.4	8.7
6	53.8	8.4	56.5	9.0
7	53.9	8.8	56.4	8.3
8	54.1	9.0	56.8	8.5
9	54.3	9.1	56.7	8.4
10	54.4	9.1	56.9	8.2

By comparing the results obtained for the two cases in Table 1, it's possible to verify that the signal fluctuations during a coastal upwelling event are slightly bigger than in regular sea conditions. Besides that, the fluctuations happens in a similar way for all frequencies. For regular sea conditions, the fluctuations oscillates between 54 dB, with an average deviation of 8.9 dB. In the case of a coastal upwelling event, the mean value of the signal fluctuations is 56.7 dB, with an average standard deviation of 8.6 dB.

Figure 7 compares the mean signal loss, $\overline{TL}_V$, along the channel, for each case.

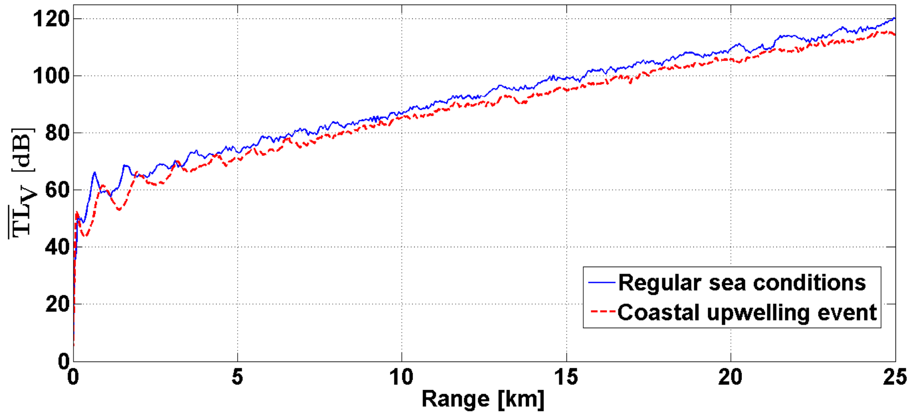


Figure 7: **Mean vertical transmission loss results for 7.5 kHz.**

Figure 7 shows no significant difference of the mean signal loss along the channel. The transmission loss observed at 25 km is 120 dB for a regular sea condition SSP while during a coastal upwelling event is 114 dB.

5 Conclusions

In this work, a numerical model was developed to study the signal fading along a UWA channel. The propagation model uses ray tracing theory to predict the overall transmission loss of acoustic pressure signals, taking into account path loss and multipath propagation. From the simulation results, was possible to assess how different SSPs affects the spatial fading of signals transmitted in the studied channel.

It was possible to observe that the multipath propagation impose fluctuations on the signal intensity along the channel. This fact is mainly due to sound refraction, which is caused by the SSP variation along the channel, but also due to sound reflection in the channel boundaries. By computing the maximum signal fluctuation along the channels depth, was possible to conclude that the fluctuations are slightly bigger during a coastal upwelling event. Nevertheless, the difference is never bigger than 3.5 dB. Thus, in the worst case, the signal fluctuation along the channel is 23.4 dB. Besides that, the fluctuations happens in a similar way for all frequencies. As a final investigation, the mean transmission loss along the channel observed by both SSPs showed similar results. In fact, the difference is not bigger than 6 dB, for a distance of 25 km. The signal loss is bigger in regular sea conditions, showing a TL of 120 dB for the maximum transmission range.

As a general remark, this study allowed a better understanding about the influence of the channel in the signal transmission. Multipath propagation plays an important rule in the signal spatial fading since it leads to big fluctuations of the signal intensity. When aiming to develop a robust communication system, is important to have an insight about the signal fluctuation perceived by an receiver so techniques that can lower these effects can be developed. Among others, spatial diversity promoted by using an array of receivers or frequency diversity, where the same information is transmitted in different frequency carriers, could be beneficial techniques to spatial fading mitigation.

Acknowledgements

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