The influence of environmental parameters on the optimal frequency in a shallow underwater acoustic channel

Zarnescu George

Maritime University of Constanta, Str. Mircea cel Batran nr.104
Constanta, cod 900663, zarnescugeorge@yahoo.com

ABSTRACT

In a shallow underwater acoustic channel the delayed replicas of a transmitted signal are mainly due to the interactions with the sea surface and the bottom layer. If a specific underwater region on the globe is considered, for which the sedimentary layer structure is constant across the transmission distance, then the variability of the amplitude-delay profile is determined by daily and seasonal changes of the sound speed profile (SSP) and by weather changes, such as variations of the wind speed. Such a parameter will influence the attenuation at the surface, the noise level and the profile of the sea surface.

The temporal variation of the impulse response in a shallow underwater acoustic channel determines the variability of the optimal transmission frequency. If the ways in which the optimal frequency changes can be predicted, then an adaptive analog transmitter can be easily designed for an underwater acoustic modem or it can be found when a communication link has high throughput.

In this article it will be highlighted the way in which the amplitude-delay profile is affected by the sound speed profile, wind speed and channel depth and also will be emphasized the changes of the optimal transmission frequency in a configuration, where the transmitter and receiver are placed on the seafloor and the bathymetry profile will be considered flat, having a given composition.

Optimal transmission frequency, transmission loss, amplitude-delay profile, wind speed, shallow underwater acoustic channel.

1. INTRODUCTION

The optimal transmission frequency is the frequency that is the least attenuated by the underwater acoustic environment[1]. The value of this frequency is quite difficult to obtain in practice, but it is easy to estimate in certain cases. As we will show in the next section the optimal frequency is determined by two parameters: the transmission loss (TL) and the noise level (NL). The latter parameter depends on the wind speed. The transmission losses are obtained using the channel's amplitude-delay profile. It is worth mention that the variation of the impulse response, will determine the optimal frequency to change its value[2]. The shape of the impulse response is determined by the environmental parameters such as the SSP, the surface and bathymetric profiles or the surface and bottom reflection losses. If these parameters are known the channel's impulse response can be computed immediately using an underwater acoustic channel simulator. After that the estimation of the optimal frequency is a trivial step in the process of underwater acoustic simulation[3]. If the estimated temporal variation of the optimal frequency is very accurate, then it allows the evaluation of the quality of an underwater transmission or the design of an efficient analog transmitter for an underwater acoustic modem[4].

It must be specified that the underwater acoustic channel simulator used is described in detail in[5] and is based on the Bounce and Bellhop algorithms[6-8]. These algorithms have been used successfully in simulating a couple of amplitude-delay profiles and the results were comparable with the real ones[9, 10]. In[11-13] was evaluated the way in which the underwater communications are influenced by the environmental parameters and for this purpose the time variations of the channel's amplitude-delay profile were measured and estimated. The author of[14, 15] presents a statistical characterization of the impulse response for a shallow underwater acoustic channel using real data.

In this article the way in which the amplitude-delay profile varies will be highlighted for three SSPs, which are frequently encountered in a shallow underwater acoustic channel, for three wind speeds, for three channel depths and for a specific sedimentary layer composition. Next it will be emphasized the changes of the optimal transmission frequency as the environmental parameters introduced above will be varied, for specific simulation settings. Afterwards it will be presented the optimal frequency variations, for the same simulation configuration, emphasizing the effects on the transmission quality.

This paper is structured as follows. In section 2 the way in which the optimal transmission frequency is computed will be presented. In section 3 the environmental model construction and the simulation settings will be detailed. Afterwards in section 4 the results of the simulations will be presented, emphasizing the variations in the ray diagrams and in the amplitude-delay profiles as three important environmental parameters are changed. In section 5 the variation of the optimal transmission frequency and the effects on the quality of underwater transmissions are highlighted. Section 6 highlights the conclusions of this paper.

2. THE OPTIMAL TRANSMISSION FREQUENCY

In this section it will be presented the way in which the optimal transmission frequency was computed. This method is described in detail in[3].

The parameters in relation 1 depend exclusively on the characteristics of the underwater acoustic channel. They represent the part of the passive sonar equation that can't be controlled by the design engineer of the underwater acoustic systems, but can be estimated.

$$\mathrm{TFR} = \mathrm{TL} + \mathrm{NL} \tag{1}$$

where TFR represents the total frequency response. TFR, TL and NL are measured in dB and are functions of frequency.

The noise level parameter, NL, is used in a compact form and is highlighted in relation 2. We note that this parameter depends on the frequency and the wind speed at the surface.

$$\mathrm{NL}(\mathrm{f},\mathrm{v}) = 50 + 7.5\mathrm{v}^{0.5} + 20\log_{10}\mathrm{f} - 40\log_{10}(\mathrm{f}+0.4) \tag{2}$$

where v is the wind speed measured in m/s and f is the transmission frequency measured in kHz.

The relation 3 shows the way in which the frequency response of the underwater acoustic channel can be obtained. It is necessary to know the weighted function in a certain frequency band in order to compute the frequency response. The amplitude-delay profile is considered to have a finite length and to vary with transmission frequency. The amplitudes of the delayed impulses are determined by the attenuation at the surface, the attenuation in the sedimentary layer and the absorption coefficient. This last parameter determines the amplitudes of the impulses based on the traveled distances between the transmitter and receiver. Each delayed impulse has a different trajectory and this is due to the sound speed profile, the sea surface profile and the bathymetric profile. The delays of the impulses are considered to be discrete. The way in which the weighted function was estimated is described in the following section.

$$\mathrm{H}(\mathrm{f},\mathrm{l}) = \sum_{\mathrm{k}=1}^{\mathrm{n}} \mathrm{A}_{\mathrm{k},\mathrm{l}}\, \mathrm{e}^{-\mathrm{j}2\pi \mathrm{f} \mathrm{t}_{\mathrm{k},\mathrm{l}}} \tag{3}$$

where $\mathrm{A}_{\mathrm{k},\mathrm{l}}$ is the amplitude of the impulse k, $\mathrm{t}_{\mathrm{k},\mathrm{l}}$ represents the delay of the impulse k for a transmission distance l and n represents the number of impulses. All these parameters are finite positive integers.

From the above relationship it can be noted that the frequency response depends on the transmission distance. In the simulations performed for this study it was considered a fixed distance between transmitter and receiver.

Using the absolute value of the frequency response, the transmission losses can be obtained. This is highlighted in the relation 4.

$$\mathrm{TL}(\mathrm{f}) = 20\log_{10}|\mathrm{H}(\mathrm{f},\mathrm{l})| \tag{4}$$

The optimal transmission frequency is computed using the relation 5.

$$f_o = f[\max(\mathrm{TFR})] \qquad (5)$$

where f[ ] is considered an array of frequencies and f_o represents the optimal transmission frequency.

3. ENVIRONMENTAL MODEL AND SIMULATION PARAMETERS

As it was mentioned above the amplitude-delay profile was estimated using the underwater acoustic simulator described in detail in[5]. The values of the simulation parameters have been specially chosen in order to better describe a connection between two underwater acoustic modems being part of an underwater sensor network placed on the seafloor. The environmental model of the underwater channel is based on three SSPs frequently recorded in the shallow regions of the sea. These profiles are shown in Figure 1 for a channel depth of 20 meters. A profile with a constant velocity can be found frequently, Figure 1 a). For these simulations the value of the underwater sound speed was chosen to be the mean value on the globe, which is equal to 1500 m/s. The thermocline, Figure 1 b), could be encountered when the temperature of the water column decreases with depth. The mixed layer could also be encountered, Figure 1 c), where the temperature is constant throughout the water column. This is due to the harsh weather conditions and in particular to the great wind.

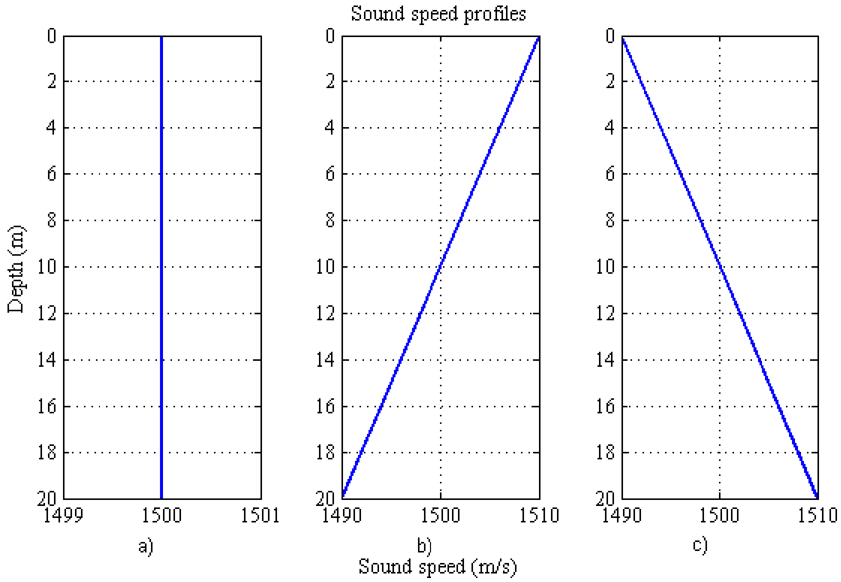

Figure 1. Three sound speed profiles recorded frequently in a shallow underwater acoustic channel.

The simulator that was used allows the modeling of the sea surface using a single parameter, namely the wind speed. The simulator considers a fully developed sea having a sinusoidal shape on the entire transmission distance. The wave height is computed using the relationship 6 and the wavelength is obtained with the relation 7. These equations are the result of the study conducted by Pierson and Moskowitz, measuring the wave heights in the North Atlantic.

$$h = \frac{0.14784\, v^2}{g} \qquad (6)$$

$$\lambda = \frac{2\pi\sqrt{gzv}}{0.877g} \qquad (7)$$

where h is the wave height in meters, v represents the wind speed in m/s, g is the gravitational acceleration in m/s^2, z is the depth of the water column in meters and λ represents the wavelength in meters. Three values for the wind speed, namely 0, 2.5 and 5 m/s were considered. The sea surface was considered flat when the wind didn't blow.

In addition to the sea surface profile the simulator takes into account the reflection coefficient at the surface and computes it with the relation 8. This relationship is based on the Pierson and Moskowitz spectrum and is described in detail in[16] together with other surface attenuation models.

$$\mathrm{RL} \approx 8.6 \times 10^{-9} f^2 v^4 \theta^2 \tag{8}$$

where RL is the reflection loss at the surface measured in dB/bounce, f is the transmission frequency measured in Hz, v is the wind speed in m/s and θ is the grazing angle measured in degrees.

It must be emphasized that the bathymetric profile is considered flat over the transmission distance. The characteristics of the sedimentary layer are shown in Table 1. These data were used by the simulator to compute the reflection coefficient of the bottom layer. These environmental values are representative to a region near the Danube Delta in the Black Sea.

Table 1 – The properties of the sedimentary layer.

Properties	Silty-Clay	Silt	Sand
Depth (m)	0.15	0.05	> 1
Sound speed (m/s)	1485	1575	1800
Density (kg/m^3)	1300	1700	2000
Attenuation (dB/λ)	0.1	1	0.9

The simulations were performed for three depths 20, 40 and 80 meters. These depths are specific to a shallow underwater acoustic channel.

The values of the simulation parameters are shown in Table 2. The transmitter and receiver are placed one meter from the seafloor. The transmission distance is equal to 500 meters. The range of frequencies for which the amplitude-delay profile was obtained is 0.1 – 100 kHz.

Table 2 – The values of the simulations parameters.

Properties	
Depth (m)	20, 40, 80
Tx Depth (m)	19, 39, 79
Rx Depth (m)	19, 39, 79
Transmission distance (m)	500
Range of frequencies (kHz)	0.1 – 100
Wind speed (m/s)	0, 2.5, 5

4. SIMULATION RESULTS

With the help of the underwater acoustic channel simulator, the configurations highlighted in the previous section where created. After considering each channel configuration, the obtained data were processed and there resulted two products of simulation. Those are the ray tracing diagram and the amplitude-delay profile for a particular frequency.

The ray tracing diagram is very helpful in finding the way in which the energy of the transmitted acoustic signals propagate in the underwater channel. Told in a different way the ray diagram shows each arrival and how they interact with the sea surface and sea floor.

In Figure 2 are shown the eigenrays obtained for the isovelocity profile from Figure 1 a). The eigenrays are those rays of energy that propagate from the transmitter to the receiver. In Figure 2 it can be seen that in half of the cases at the receiver two types of rays arrive. Some denoted with red that propagate on a direct path and some denoted with blue that interact once with the bottom. It can be seen that for each category there are two rays. These will be additively combined at the receiver and the amplitude-delay profile will have one impulse for the direct path and one for the bottom path. These impulses will have approximately the same amplitude because the sound velocity underwater is constant from top to bottom. Also enough transmitted energy is concentrated in these two impulses.

This kind of impulse response is obtained for two conditions, when the depth is 80 m and the wind speed is 0, 2.5 and 5 m/s or when the wind speed is 5 m/s and the depth is 20, 40 and 80 m. Therefore when the modems are on the sea floor and the surface conditions are harsh or the water depth is high, the underwater channel can be characterized by a simple impulse response.

In the remaining cases it can be seen that the energy is spread on different paths in the channel. There are rays that interact with the sea surface. Also it can be seen that there are rays that interact many times with the two limits of the underwater acoustic channel. Therefore when the conditions are calm and the channel has a small depth it can be expected an impulse response with low amplitude impulses that are spread in time within several milliseconds.

It must be emphasized that for this case study the channel can be considered narrow band, if the duration of one symbol is greater than the total delay of the impulse response.

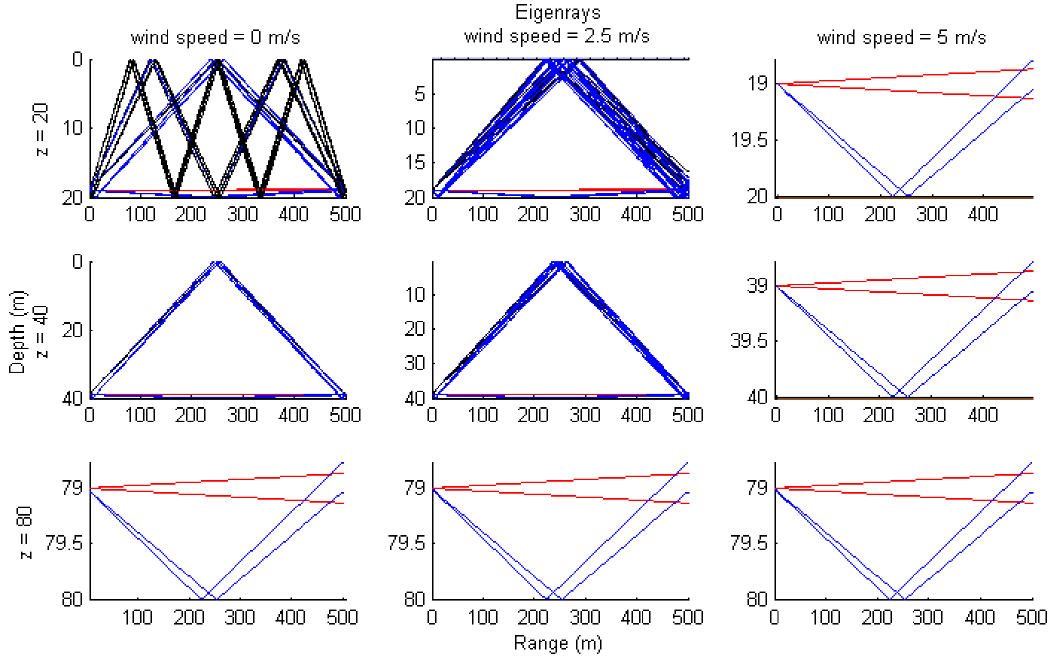

Figure 2. Simulated eigenrays obtained for isovelocity sound speed profile, for three depths and for three wind speed values.

For the following case study the simulated eigenrays, highlighted in Figure 3, were obtained using the thermocline profile. As expected the rays are bended towards the sea floor and this is because of the shape of the sound speed profile. Told in a different way the sound likes to travel underwater at the smallest speed. In this case the rays are heading towards the seabed were it is the smallest sound speed.

It can be observed that for a sea depth of 20 m and for each wind speed value, the direct path is missing. For the rest of the depths the direct path appears. It will be shown at the end of this section that this will increase the capacity of the channel because the optimal transmission frequency and the bandwidth will be larger.

When the conditions at the surface are harsh, meaning the wind speed is 5 m/s, for all the depths, the sea surface scatters the acoustic energy of the transmitted signal through the entire channel, but away from the receiver. When the sea is calm or almost calm and for depths of 20 and 40 m there are rays that travel by interacting with both limits of the underwater channel. It is expected that the amplitude-delay profile to be spread in time and the delayed impulses to have small amplitudes. Also it should be mentioned that for the thermocline scenario, it can be expected that the first arrival will not be the strongest one. This situation makes it difficult to synchronize the transmission.

For a depth of 80 m and for each wind speed the modems will see the same amplitude-delay profile, so the conditions at the surface will not disrupt the bottom transmission. Also because almost all the rays travel through bottom interactions there will be impulses with small amplitudes scattered very close to each other and after these in time the highest impulse, corresponding to the direct path, will appear. This happens because the direct path travels more at a higher speed than the other impulses that travels a lot less at a lower speed.

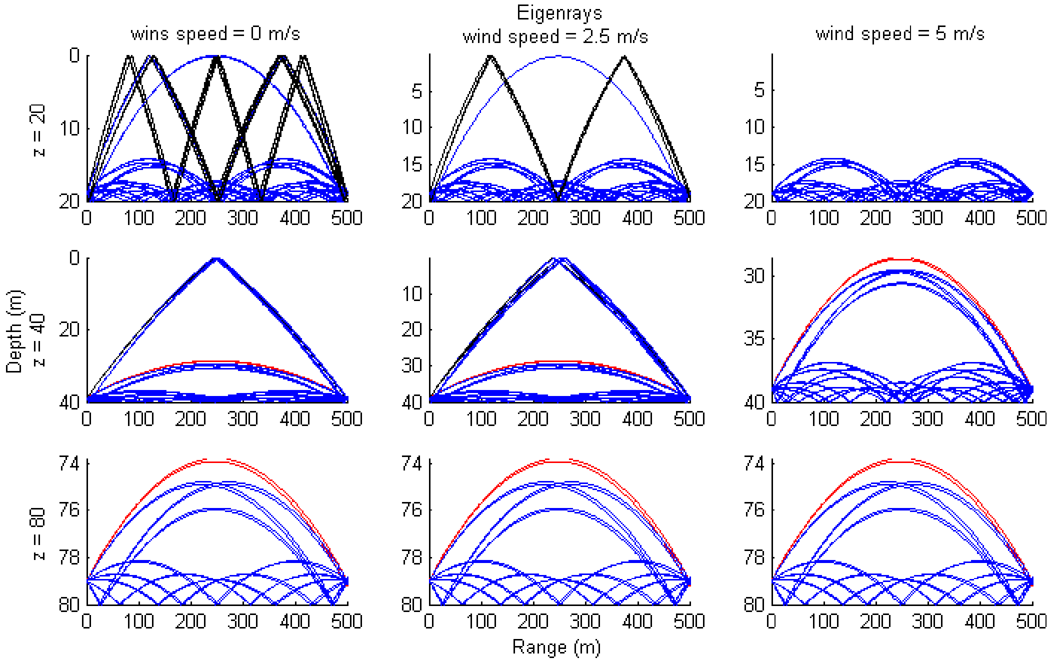

Figure 3. Simulated eigenrays obtained for termocline sound speed profile, for three depths and for three wind speed values.

For the last case study the simulated eigenrays, highlighted in Figure 4, were obtained using the mixed layer profile. From the beginning it is worth mention that the bottom communications aren't suited for this profile.

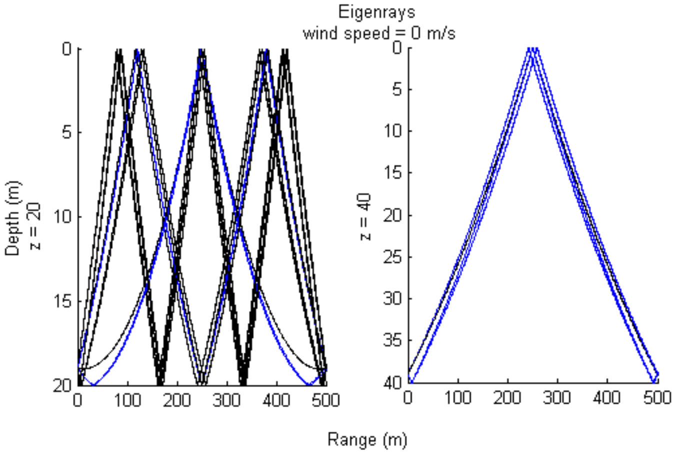

Figure 4. Simulated eigenrays obtained for mixed layer sound speed profile, for only a couple of conditions.

The rays of energy will propagate towards the surface layer because there is the smallest speed in the SSP. It can be seen that for almost all the situations the energy is scattered away from the receiver, so this device is in a shadow zone. When the sea is calm and for small depths, 20 and 40 m, there will be rays that arrive at the receiver through interactions with both limits of the channel. The amplitude-delay profile will have impulses with small amplitudes that will be scattered far away from each other, and the total delay will be on the order of several milliseconds. In the next section an analysis of the variation of the optimal transmission frequency is presented.

5. OPTIMAL FREQUENCY ANALYSIS

In Table 3 are highlighted the optimal frequency values obtained for the isovelocity profile, for each water depth and for each wind speed. With the help of Table 3 and Figure 2 it can be seen that when the energy is scattered throughout the underwater acoustic channel, the optimal transmission frequency is quite small. This implies a small bandwidth and of course a small channel capacity. On the other hand, when the signal energy is concentrated in a few rays, it can be obtained a high enough optimal frequency. This implies a high frequency band and an increase in the channel capacity. From Table 3 it can be noticed that when the channel depth is high or the conditions at the surface are harsh the highest optimal frequency can be obtained.

Table 3 – Optimal transmission frequency analysis for the isovelocity profile.

Optimal frequency (kHz)	v = 0 m/s	v = 2.5 m/s	v = 5 m/s
z = 20 m	24.5	16.3	89.7
z = 40 m	24.5	16.6	89.7
z = 80 m	89.7	89.7	89.7

In Table 4 are presented the optimal frequency values obtained for the thermocline profile. With the help of Table 4 and Figure 3 it can be seen that when the first arrival is present the optimal frequency is high and when is missing has small values. When the first arrival is present it can be noticed that the optimal frequency is approximately half of the maximum frequency obtained for the isovelocity profile. This is because in the latter case there are many more rays that travel through bottom interaction than the first case.

Table 4 – Optimal transmission frequency analysis for the thermocline profile.

Optimal frequency (kHz)	v = 0 m/s	v = 2.5 m/s	v = 5 m/s
z = 20 m	11.4	11.4	11.6
z = 40 m	39.5	39.6	44.6
z = 80 m	42.6	42.6	42.6

In Table 5 the values of the optimal frequency obtained for the mixed layer profile are presented. In all but two situations the receiver is in a shadow zone, therefore a connection between the transmitter and receiver isn't possible. In the situations where a connection is possible, it can be observed that the underwater channel exhibits a low optimal transmission frequency; hence the channel capacity is low.

Table 5 – Optimal transmission frequency analysis for the mixed layer profile.

Optimal frequency (kHz)	v = 0 m/s	v = 2.5 m/s	v = 5 m/s
z = 20 m	21.8	-	-
z = 40 m	21.3	-	-
z = 80 m	-	-	-

6. CONCLUSIONS

In this article it was presented an environmental model for the underwater acoustic channel and the way in which the optimal transmission frequency changes its value as certain parameters are varied. The channel was characterized by three typical sound speed profiles, the isovelocity, the thermocline and the mixed layer profile. The profiles were entered in an underwater acoustic channel simulator along with three wind speed values, 0, 2.5 and 5 m/s, three water depths, 20, 40 and 80 m, corresponding to the shallow water channel and a real sedimentary layer structure. The channel was simulated using a bottom transmission configuration and the estimated data were processed. For the conditions mentioned above it was observed, using ray diagrams, that when the direct path exists the optimal transmission frequency is high which means that the bandwidth and the channel capacity will be high. The highest optimal frequency was obtained for the isovelocity profile, when the depth of the channel was high and the conditions at the surface were harsh. For the same conditions, when the thermocline profile was considered, the value of the optimal frequency was approximately equal to the half of the maximum one. This is because almost all the rays travel through bottom interactions. When the direct path is missing or the profile corresponds to the mixed layer, the value of the optimal frequency is low, which means that the conditions in the channel degrade the bottom transmission.

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