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Underwater Ambient Noise – An Estimation Methodology

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ABSTRACT

The use of the submarine weapon in the various naval operations has increased significantly in the last decades. Due to their tactical advantages over other vessels, it is necessary to create tools supporting sonar forecasting and enabling underwater acoustics modeling. One of the variables that limit sonars performance is the so-called spectral ambient noise. There is a need to study the way in which it masks or affects the signal coming from the targets to be detected or the signal emitted by the acoustic system itself. In order to assign adequate values to ambient noise levels, existing graphics were analyzed, having in account the meteorological and oceanographic conditions, and the area navigation density; however, those do not include all meteorological and oceanographic conditions. In order to interpolate or extrapolate the existing data, to overcome such limitation, a software was created, with the help of the MATLAB tool, for a least squares data fitting. It is only necessary to introduce the operating frequency of the acoustic system, the wave height or sea state, precipitation level (absent, weak, moderate, strong or very strong) and the navigation density (low, moderate or high). In the end, the program returns the value of spectral ambient noise.

Keywords: Noise, Underwater Acoustics, Sonar Forecasting
I-INCE Classification of Subject Number: 22

1. INTRODUCTION

In the scope of the naval military operations in order to warranty the use and control of the sea, in the context national and allied interest's defences and navies main missions, it becomes essential the knowledge and modelling of the submarine acoustics phenomena's improving the sonar forecasting capacity. One of these phenomena is the ambient noise, capable of reducing the probability of detection for half the distance in unfavourable conditions.

The underwater acoustics noise is classified taking into account the source which produces it. Due to the easiness with which sound waves propagate in this environment, through mechanical vibrations of the particles that constitute it, being able to reach large distances, along with the various existing sources, the underwater environment becomes quite noisy.

Ambient noise can be defined as the signal received by an acoustic system in the absence of signals that can be attributed to an individual source, such as ships, or resulting from the so-called self-noise, either from the system itself or from other sources related with the platform on which the hydrophone is installed.

The measurement or prediction of the ambient noise value is not an easy task, and it is necessary to remove the contribution of all sources of noise (propellers, auxiliary machines, generators and even the transducer itself) as well as the noise from individual ships that are navigating in the surrounding area. In other words, all sources that are identifiable must be removed, remaining only what we call background noise. This is the main challenge of this article, predict or estimate reliable values that can be attributed to ambient noise.

Several authors have studied this subject, with several measurements taken after World War II, when the submarine weapon became relevant to gain tactical advantage over the enemy. However, existing charts created after these measurements only apply to certain oceanographic and meteorological conditions. The final objective will be the construction of a software tool to allow the creation of functions to adapt existing values to any conditions that ships may encounter at sea, whit help of the least squares fitting.

2. SPECTRAL AMBIENT NOISE

The ambient noise level (ANL), used as a parameter in the sonar forecasting, corresponds to the sound pressure level, in dB, of ambient noise relative to a plane wave that has a pressure root mean square corresponding to 1 μPa. Although they are measured in different frequency bands, ambient levels are usually reduced to a 1 Hz frequency band or ambient noise spectrum levels (Urick, 1983, pp. 202).

The main sources of noise depend on the depth of the sea as well as the area being studied, therefore the need to distinguish shallow waters and deep waters[1]. The main shallow water sources correspond to: ship traffic, industrial activity (more significative in bays and ports), wind and sea life (Urick, 1983, pp. 211-215).

The influence of ship traffic depends directly on the area in which we are navigating, being more relevant in navigation routes, traffic separation schemes, straits or choke points, bays, ports or in coastal and inner waters. It is also more relevant for lower operating frequencies, namely up to 0.5 kHz. However, up to 100 Hz is the dominant source of noise, and is independent of Meteorological and Oceanographic (METOC) conditions encountered by ships (Hodges 2010, pp. 131).

In bays and ports, industrial activity is more relevant because of its proximity to ships, one of the main sources contributing to the noise level. Also the marine life, the tides and the turbulence that characterizes these areas leads to a very noisy environment. In coastal waters, the main sources are the waves caused by the wind that are felt in the area, the breaking waves, marine life and maritime traffic. Sometimes the noise here originates at long distances and can then be detected in deep water. In fact, if we eliminate the effect of marine life and maritime traffic, the values obtained will be in agreement with those found in deep waters (Urick, 1983, pp. 212).

Concerning to biological noise, its influence was discovered during measurements in coastal areas, where marine life has a more significant presence.

[1] Shallow waters, in general, refer to bottom depths less tan 200 meters, and deep waters to waters whose depths are greater than 200 meters (Richardson et al., 2013, pp.96)

However, there are species that most affect the sound received by hydrophones, to emphasize cetaceans, crustaceans and some larger fish (Varela, 2001, pp. 2-25).

In deep waters, there is a greater diversity of sources that depend directly on the frequency spectrum. With increasing frequencies, we have: tides and hydrostatic effect of waves, seismic disturbances, oceanic turbulence, nonlinear interactions between waves, waves generated by the wind and thermal noise (Urick, 1983, pp. 203-209). There are also environmental phenomena that do not occur permanently, but which significantly influence environmental noise, such as rainfall.

Not always the sonars sensed pressure differences have a sound source, such as the tides and the hydrostatic effects of the waves, capable of causing large amplitude differences in the lower frequencies of the spectrum, reducing the useful signal received in the transducer. The surface waves also cause changes in the pressure, being this phenomenon more visible in places of smaller depth. The currents, in turn, cause changes in the temperature of the water, being this change felt in very low frequencies (Varela, 2001, pp. 2-25).

The noise resulting from the seismic activity presents greater variability and can result from earthquakes or volcanic eruptions whose origin is at the bottom and sub-bottom of the sea. Occurring quite frequently and with variable magnitude they affect, in a remarkable way, the lower spectrum of the frequencies, in deep waters. (Hodges 2010, pp. 128).

The turbulence associated and resulting from prevailing or transient currents (that may arise during a certain time) and the large-scale motion of the oceanic water masses, creates a background noise too. That turbulence will create pressure differences detectable by the sensors (Urick, 1983, pp. 205).

Surface waves are one of the main phenomena that affect ambient noise and their influence can be detected up to 25 kHz, i.e. not only in the lower range of the spectrum. In the sonar operating frequencies still have very high values for the waves originated noise. There are charts that match the state of the sea to the noise value in dB, and this is one of the subjects that will be solved in this article. (Hodges 2010, pp. 131).

Assigning a value to the ambient noise level is not an easy task. There are charts that consider some of the aforementioned sources, taking into account the frequency of the acoustic system operation, wind, precipitation and navigation density, an example of these graphs is presented in figure 1:

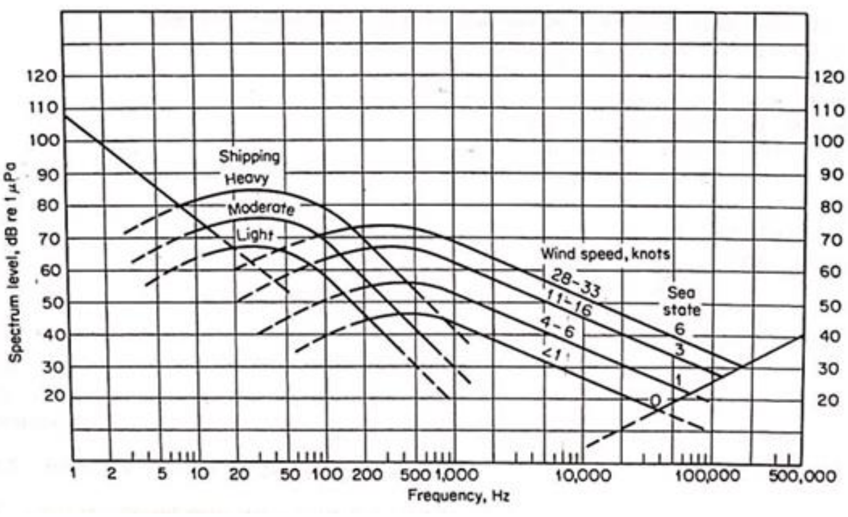

Figure 1: Spectral ambient noise for the ship traffic and wind speed of Urick 1983 (fig 7.5, p.210).

3. METHODS

3.1 Interpolation and Extrapolation

From the graphs of Urick 1984 (Figure 2-10, page 2-20), Urick 1983 (Figure 7.5, page 210), Kinsler *et al.* (1982, Figure 55.8, page 413) and Waite (2002, Figure 5.3, page 88), data interpolation and / or extrapolation was performed for all sea-state or wind, precipitation and shipping traffic values, for frequencies between 100 Hz and 10 kHz.

It is called interpolation the method that allows obtain a new set of data from a discrete set of previously known values. Extrapolation is the process of estimating, in addition (out of the range but nearby) to the original observation interval, the value of a variable based on its relation to another variable, which allows to estimate the values for sea state 7, 8 and 9.

This was achieved by reading the spectral noise level for the various frequencies, whose data are available, and it was necessary to carry out this process for the four mentioned sources. One limitation of these graphs is that only exist the curves for certain sea state (SS) or wind speed, which makes it impossible for the user to select the existing METOC conditions.

To solve this problem the interpolation or extrapolation of known values was used. For this purpose, a table was created for each graph used, where the dB value of the ambient noise was inserted for each frequency and known sea state. For the missing curves it was considered that the variation between each one will be the same for close SS, and thus the tables were completed.

The final values used in the program correspond to an average of the data obtained from all the constructed tables. In the case of precipitation and density of the navigation not all the authors mention their influence, reason why we only considered those that present values for those sources of noise. From it resulted the graphic in figure 2:

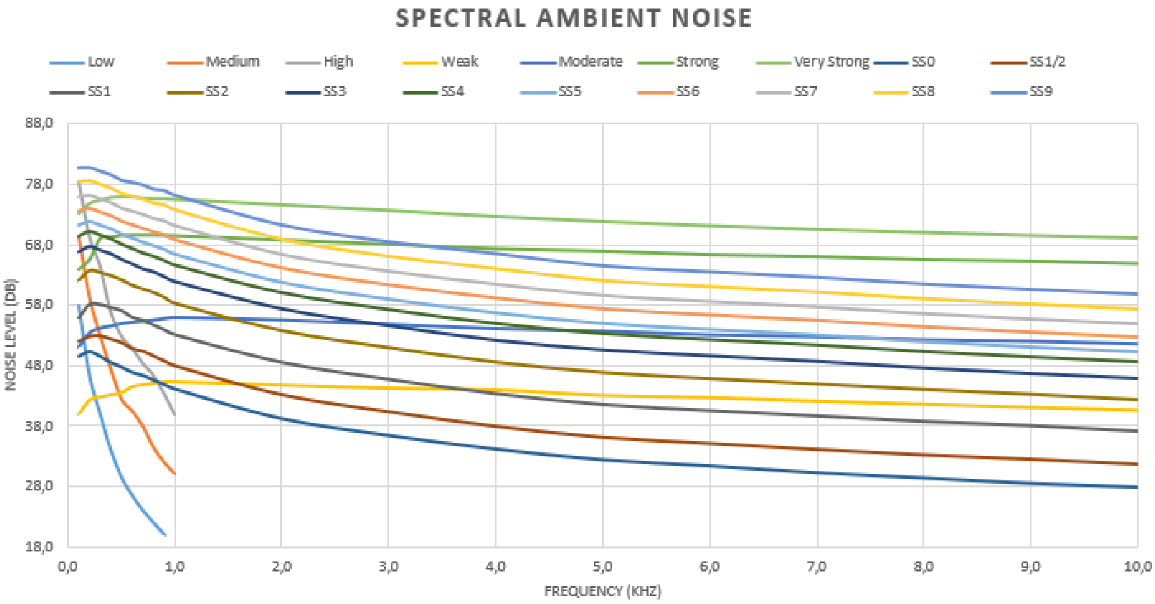

Figure 2: Spectral Noise Environment resulting from the extrapolation of the five sources mentioned for navigation density, sea state and precipitation.

In the Matlab program the interp1 function was used for the interpolation of the final table or graph data for the whole spectrum, so that the software user introduces the frequency of the acoustic system instead of an approximation.

3.2 Hodges Data

The aforementioned process is subject to several errors, either due to misreading of the graphs and non-use of discrete data, or by the interpolation and extrapolation method used are not the most reliable. Thus, another process, by the least square fitting technique, was used. From discrete data (at given frequencies), allows to obtain functions, in this case as an independent frequency variable, allowing the user of the software to use the frequency value of the sonar in question, obtaining the ambient noise value for the various conditions that can be encountered in operations at sea.

In order to collect data, Hodges 2010 book "Underwater Acoustics" was used, in which there are three tables: ship traffic (table 7.1, pp. 132), precipitation (table 7.3, pp. 136) and sea state or wind velocity (table 7.2, pp. 134). The tables provide for specific given frequencies the corresponding ambient noise spectrum levels. Since only a specific band of the spectrum is required for the operation of the sonars, only the values of interest for the scope of the work (from 0.1kHz to 10kHz) have been used.

Although we have discrete values, being less subject to errors, we want the user to use any frequency value and not an approximation, so we need to create functions using the least square fitting method.

However, in the case of sea state or wind speed, Hodges (2010) does not present data for all possible conditions to be found, hence an interpolation and extrapolation process has been applied to the existing values, similar to that explained in the previous subchapter.

3.3 Least Squares Fitting

Fitting requires a parametric model that relates the response data to the predictor data with one or more coefficients, in this case with four coefficients. The result of the fitting process is an estimate.

To obtain the coefficient estimates, the least-squares method minimizes the summed square of residuals. The residual for the data point is defined as the difference between the observed response value and the fitted response value, and is identified as the error associated with the data, which corresponds to the difference between the data measured by Hodges and those obtained by the approximation of a third-degree polynomial to those values.

Basically, the polynomial we want to get is the following, in which f means frequency:

$$y = a_0 + a_1 f + a_2 f^2 + a_3 f^3$$

Equation 1: Third dregree polynomial.

Placing the matrix problem:

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} = \begin{bmatrix} \mathbf{1} & \boldsymbol{f_1} & \boldsymbol{f_1^2} & \boldsymbol{f_1^3} \\ \mathbf{1} & \boldsymbol{f_2} & \boldsymbol{f_2^2} & \boldsymbol{f_2^3} \\ \vdots & \vdots & \vdots & \vdots \\ \mathbf{1} & \boldsymbol{f_n} & \boldsymbol{f_n^2} & \boldsymbol{f_n^3} \end{bmatrix} \begin{bmatrix} \boldsymbol{a_0} \\ \boldsymbol{a_1} \\ \vdots \\ \boldsymbol{a_n} \end{bmatrix}$$

Equation 2:The least square fitting in matrix.

In the above matrix we have:

- a is the vector of the coefficients of the third-degree polynomial to be obtained;
- F is the matrix that has as lines the value of the frequencies for which we have the ambient noise values, and as columns the frequencies raised to 0, 1, 2 and 3;
- y is the vector with known ambient noise values.

To solve this problem, it is necessary to transpose F matrix, so the equation is:

$$F^T y = F^T F a$$

Equation 3: The prolem with F transpose.

Isolating vector a, which corresponds to the coefficients, we get:

$$a = (F^T F)^{-1} F^T y$$

Equation 4: Vector a.

The residual is given by:

$$R^2 = \sum_{i=1}^{n} [y_1 - (a_0 + a_1 f + a_2 f^2 + a_3 f^3)]^2$$

Equation 5: The residual.

3.4 The problem in MATLAB

In order to do the calculations mentioned in the previous subchapter it was necessary to create a code through Matlab. To avoid in this article the complete code of all the programming carried out, we just show the part to obtain the third degree polynomial for sea state 0 in the following lines.

```
freq=[0.1; 0.125; 0.16; 0.2; 0.25; 0.32; 0.4; 0.5; 0.64; 0.8;
1; 1.25;...
1.6; 2;2.5; 3.2; 4; 5; 6.4; 8; 10];
dim=size(freq);
f_0=zeros(dim(1,1),1);

%SS=0
for i=1:1:dim(1,1)

x=freq(i,1);
A_0=[1 0.1 0.1^2 0.1^3;...
1 0.125 0.125^2 0.125^3;...
1 0.16 0.16^2 0.16^3;...
1 0.2 0.2^2 0.2^3;...
1 0.25 0.25^2 0.25^3;...
1 0.32 0.32^2 0.32^3; ...
1 0.4 0.4^2 0.4^3; ...
1 0.5 0.5^2 0.5^3; ...
1 0.64 0.64^2 0.64^3; ...
1 0.8 0.8^2 0.8^3;...
1 1 1^2 1^3; ...
1 1.25 1.25^2 1.25^3; ...
1 1.6 1.6^2 1.6^3; ...
```

```
1 2 2^2 2^3; ...
1 2.5 2.5^2 2.5^3; ...
1 3.2 3.2^2 3.2^3;...
1 4 4^2 4^3; ...
1 5 5^2 5^3; ...
1 6.4 6.4^2 6.4^3;...
1 8 8^2 8^3; ...
1 10 10^2 10^3];
B_0=[50.9; 50.9; 50.8;
50.6;50.2;49.7;49;48.2;47.3;46;44.8;43.4;41.6;39.8;...
38.1;36.2; 34.3;32.6;30.8;28.9;27.1];
X_0=(A_0'*A_0)^(-1)*(A_0'*B_0);
f_0(i,1)=X_0(1)+X_0(2)*x+X_0(3)*x^2+X_0(4)*x^3;
end

disp(X_0)

Residuo_0=norm(f_0-B_0);
```

4. RESULTS

After applying the programming previously presented to all possible conditions, whether at the level of sea state or wind speed, ship traffic and precipitation, was obtained a set of functions, which are intended to be used in the acoustic model software project. The functions obtained are as follows:

For the sea state or wind speed:

- SS0, wind 1.5 knots, wave 0 meters:
$$y = 51.8285 - 7.6227f + 0.9717f^2 - 0.0459f^3$$
- SS1/2, wind 3.5 knots, wave 0.1 meters:
$$y = 55.0614 - 6.7208f + 0.8106f^2 - 0.0373f^3$$
- SS1, wind 5 knots, wave 0.15 meters:
$$y = 58.262 - 5.7971f + 0.6462f^2 - 0.0285f^3$$
- SS2, wind 8.5 knots, wave 0.46 meters:
$$y = 63.0914 - 4.6787f + 0.4188f^2 - 0.0154f^3$$
- SS3, wind 13.5 knots, wave 0.91 meters:
$$y = 65.929 - 3.9829f + 0.2826f^2 - 0.0077f^3$$
- SS4, wind 19 knots, wave 1.8 meters:
$$y = 67.6311 - 3.4708f + 0.1813f^2 - 0.002f^3$$
- SS5, wind 24.5 knots, wave 3.6 meters:
$$y = 69.3144 - 3.1646f + 0.1114f^2 - 0.0023f^3$$
- SS6, wind 37.5 knots, wave 5 meters:
$$y = 71.8288 - 3.0857f + 0.094f^2 + 0.0034f^3$$
- SS7, wind 51.6 knots, wave 7.6 meters:
$$y = 74.3443 - 2.9611f + 0.0632f^2 + 0.0053f^3$$
- SS8, wind 59.5 knots, wave 11.4 meters:
$$y = 76.8575 - 2.9279f + 0.0591f^2 + 0.0055f^3$$
- SS9, wind 64 knots, wave 13.7 meters:
$$y = 79.3719 - 2.849f + 0.094f^2 + 0.0065f^3$$

For the ship traffic:

- Low:
$$y = 50.7034 - 21.3545f + 3.5545f^2 - 0.1954f^3$$

– Medium:

$$y = 64.5478 - 21.3145f + 3.3387f^2 - 0.1795f^3$$

– High:

$$y = 77.9369 - 22.423f + 3.7548f^2 - 0.2043f^3$$

For the rain:

– Weak (1mm/h):

$$y = 51.0769 + 1.4687f - 0.5232f^2 + 0.0335f^3$$

– Moderate (5mm/h):

$$y = 61.5358 + 1.0147f - 0.4255f^2 + 0.0277f^3$$

– Strong (10mm/h):

$$y = 65.1107 + 0.8226f - 0.3825f^2 + 0.0251f^3$$

– Very Strong (100mm/h):

$$y = 74.3464 + 1.0131f - 0.4258f^2 + 0.0277f^3$$

With these functions that have been introduced in the main sonar prediction software, the user is able to select the current conditions without the need to approach them, reducing the errors that the modelling is subject to. Showing the results on a graphic we have:

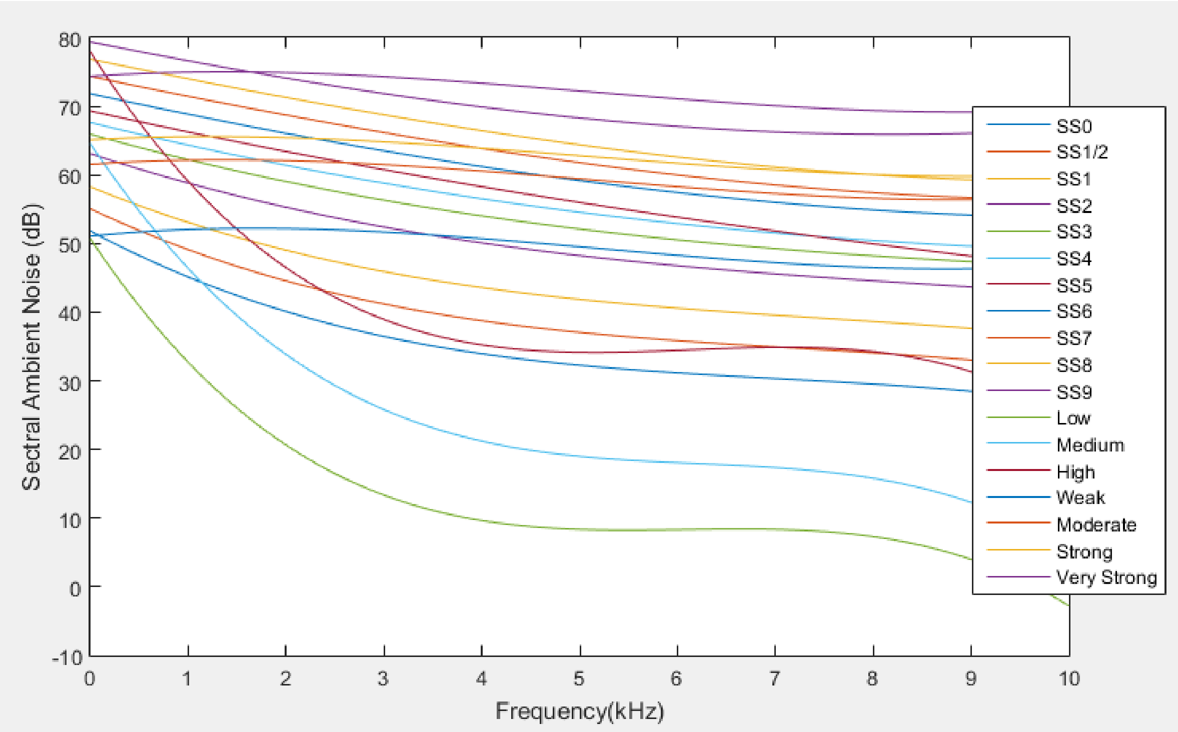

Figure 3: Spectral Noise Environment resulting from the functions created with the least square fitting.

Comparing the two graphs obtained by the described methods, we can conclude that the values are close, although in the case of the least squares method there are no abrupt variations of the data, since it becomes a function that describes them, besides the interpolation and extrapolation carried out from several sources, whose data are taken from different areas of the world, leading to greater variations.

It is also possible to observe in both graphs that the main source is the rain, followed by the state of the sea and finally the density of navigation. It should also be noted that by the first method the data on ship traffic exist only up to the frequency of 1 kHz, with the creation of functions it was possible to extend the data up to 10 kHz. In both cases the presence of noise is less noticeable to the upper part of the spectrum.

5. CONCLUSIONS

Thus, the spectral ambient noise presents a high variability, due mainly to the predominant source, be it density of navigation, precipitation, wind or sea state. In general, shallow waters may present a greater diversity of values due to the intermittent nature of the sources in these waters, being higher or lower depending on the time and area under study. In deep water there will be a tendency for spectral levels to be less variable.

The existing values for ambient noise already date back to the 80's, so today the reality may already be something different. Undoubtedly, the technological developments that have taken place in recent years contribute to the greater number of ships circulating in the various oceans, as well as their size, thus contributing to an increase in noise. The other sources mentioned, namely rainfall and sea state, have a great seasonality, but the different conditions that can be found are already described.

Due to the high variability of the ambient noise, in time and space, it is impossible to use a value that represents the reality found, being only possible to make an approximation.

Comparing the two methods used, in the first one only the interpolation and extrapolation of several sources was done, it has the disadvantage of comparing data from different areas of the world, however it allows to obtain an average value for all the oceans, still to mention that the data taken are graphs which implies more errors, since it does not allow a reliable reading of them.

Hodges comes to solve this question, since it presents discrete data, however these values measured in a certain area are then transposed to all the navigable areas. In addition, the use of the method of least squares presents greater reliability, since it allows the creation of functions, being not so subject to punctual variations of frequency.

In the final program the least squares method was used with discrete data presented by Hodges.

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