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# New considerations regarding underwater noise in Black Sea

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**Abstract**. The development and standardization of measurement techniques for underwater noise sources are important to both military and civil fields regarding the reduction of sound emitted by commercial and military ships. This paper presents new analysis of the acoustic signature of a small vessel during a voyage in the Black Sea. The measurements were made when the ship was moored in shallow waters. The measuring system had 3 hydrophones that were positioned at different depths. Using the coherence function, it was determined the correlation between the recordings. The results were analysed to determine the acoustic signature of the ship. Thermal variations of sea water and effects of sound reflection from the bottom of the sea were taken into account. Conclusions have been made regarding the utility of this type of analysis and the levels of underwater noise in the shallow waters of the Black Sea.

## 1. Introduction

Measuring underwater noise and evaluating the noise level produced by various sources represents a helpful method of keeping underwater environment undisturbed. Shipping and other human activities increase each year and their concentration is especially in waters of small depths (< 50m). As a result, over the years, the species living in shallow waters have migrated from the areas where human activities exist. In order to preserve the nature, the effects of human activities must be reduced. One of the effects of these activities is the underwater noise produced by ships. Onboard ships are numerous sources that produced vibration and noise which are transmitted in water at various frequencies. With the help of technology, one can determine the acoustic signature of a ship.

Through the years many methods have been developed to measure and evaluate the underwater noise produced by ships in shallow waters. Farrokhrooz and Wage [1] made underwater noise measurements using a vertical line array of hydrophones in the North Pacific. After a year of measurements they reported that ambient underwater noise in the 50Hz SOFAR (Sound Fixing And Ranging) channel changed a little in comparison with measurements made in the FLIP 1973 experiment. Matsumoto et al [2] conducted an experiment using a vertical autonomous hydrophone array to record the seismic activity in the Lau Basin. For a four months period they measured underwater noise and made observations regarding the propagation of seismic waves taking into account the direct and reflected waves.

De Lorenzo et al. [3] reviewed the measurement techniques and underwater noise standards regarding the merchant ships. In their article, they summarized the current standards used to determine underwater noise produced by merchant ships. Although the standards have common methodology, the conditions for measuring underwater noise vary. For example, the minimum water depth for shallow water measurements varies from 30 meters to 300 meters. This being said, one can conclude that the determination of acoustic signature of a ship must be correlated with the natural conditions of the zone. Even if the seabed is flat, then the structure of the seabed is different from one measuring site to another.

In our paper, we have determined through existing models the underwater noise level from a moored ship and the transmission loss in the point where the hydrophones were deployed. Also, the correlation between signals was made to determine the acoustic signature of the vessel.

## 2. Measurements in the Black Sea (Romanian waters)

During RoNoMar project, in the Romanian area of the Black Sea were conducted a series of measurements and experiments in order to determine the level of underwater noise and its effects over the species living in this area. One of tests made in the Black Sea was conducted onboard vessel Mare Nigrum. With the ship moored, underwater noise was measured using a system of three hydrophones deployed at various depths. The system was launched from a small boat moored at various distances from the vessel. The hydrophones were connected to a data acquisition system and a laptop to record and analyze the signals. During each recording, sea water characteristics were determined – salinity, temperature, sea state (height of sea waves).

The characteristics of the area where the measurements took place are presented in table 1. The sound speed corresponds to observations made by Lurton [4] (figure 1).

Table 1

| | Depth | Temperature | Salinity (ppt) | Conductivity (ms/cm) | Sound speed (m/s) |
|---|---|---|---|---|---|
| 1. | 0.991 | 10.0217 | 17.3795 | 2.018430 | 1468 |
| 2. | 2.818 | 9.8157 | 17.3840 | 2.008454 | 1467 |
| 3. | 5.863 | 9.0502 | 17.4700 | 1.978618 | 1464 |
| 4. | 6.472 | 8.2620 | 17.5450 | 1.946343 | 1461 |
| 5. | 7.689 | 8.1461 | 17.8021 | 1.966571 | 1461 |
| 6. | 8.298 | 7.9899 | 17.8533 | 1.963742 | 1460 |
| 7. | 9.516 | 8.2833 | 18.0518 | 1.999013 | 1460 |
| 8. | 13.778 | 8.0295 | 18.0970 | 1.990514 | 1460 |
| 9. | 15.604 | 7.4378 | 18.0630 | 1.956511 | 1459 |
| 10. | 16.822 | 7.3002 | 18.0595 | 1.949095 | 1459 |
| 11. | 20.474 | 6.9353 | 18.0882 | 1.933229 | 1457 |
| 12. | 21.083 | 6.6737 | 18.0794 | 1.918950 | 1456 |
| 13. | 21.692 | 6.3373 | 18.0868 | 1.902441 | 1456 |
| 14. | 25.344 | 6.1557 | 18.0602 | 1.890699 | 1454 |
| 15. | 25.953 | 6.1520 | 18.0549 | 1.890023 | 1454 |

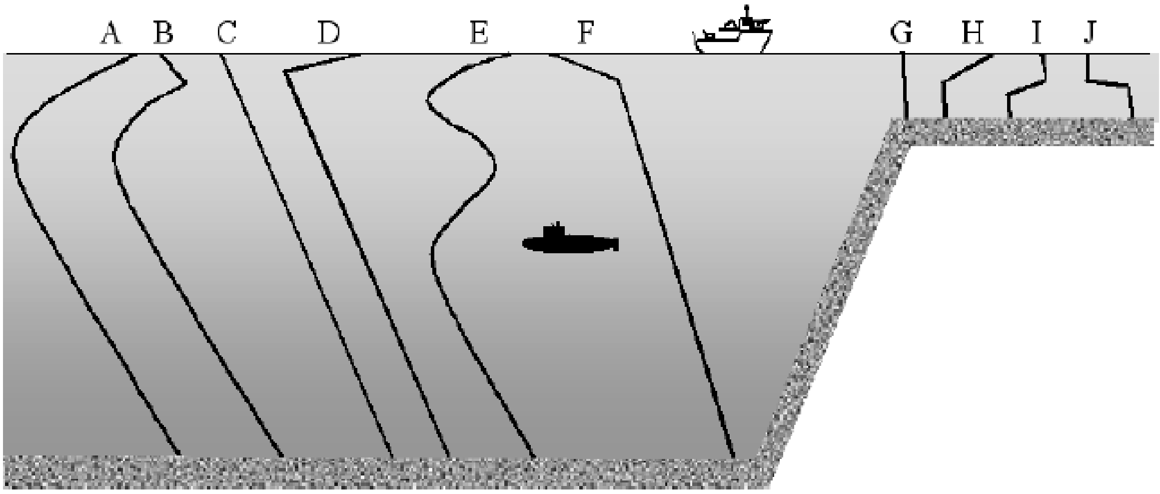

Figure 1 Generic sound-velocity profiles. Curve G corresponds to measuring conditions (winter-spring shallow waters) [4]

The depths for hydrophones are highlighted in table 1: upper hydrophone – line 6; middle hydrophone – line 10; lower hydrophone – line 14. The maximum depth in the mooring zone is 30 m.

The weather was nice: sea state 1, small waves (0.5m) and air temperature 22 $^{0}$C.

The measurements made near ship were conducted during the mooring and onboard ship all noise sources were functioning – main engine, diesel generator, pumps, propeller.

At 1.5 Nm (approximately, 2800m) the measurements were conducted from a small boat which had the engine stopped. Onboard ship only the diesel generator was functioning.

## 3. The results

Underwater noise analysis can be made using different functions. Usually it is used the FFT and CPB analysis to visualize the corresponding noise peaks according to frequency span. In this paper, we analyse the signals using FFT function and the coherence function. By using the coherence function, we want to get information regarding the correlation between hydrophones related to depth and to distance from ship.

From the FFT analysis we obtained the noise level in the frequency span of 6.4kHz with a sampling rate of 1Hz. The same sampling rate was used for coherence analysis, but in the frequency span of 1.6 kHz.

The 3 hydrophones were deployed at different depths: upper hydrophone – 8 meters depth; middle hydrophone – 17 meters depth; lower hydrophone – 25 meters depth. The system was anchored to the sea bottom and a buoy tied to the system was mounted at the surface of the sea. The ambient underwater noise was measured before trials. Due to sea-state (calm sea), there are no peaks in the broad spectrum of frequency and the interferences are small; the ambient underwater noise is approximately 80dBre1µPa.

The next figures represent the FFT analysis and the correlation between signals recorded by the hydrophones.

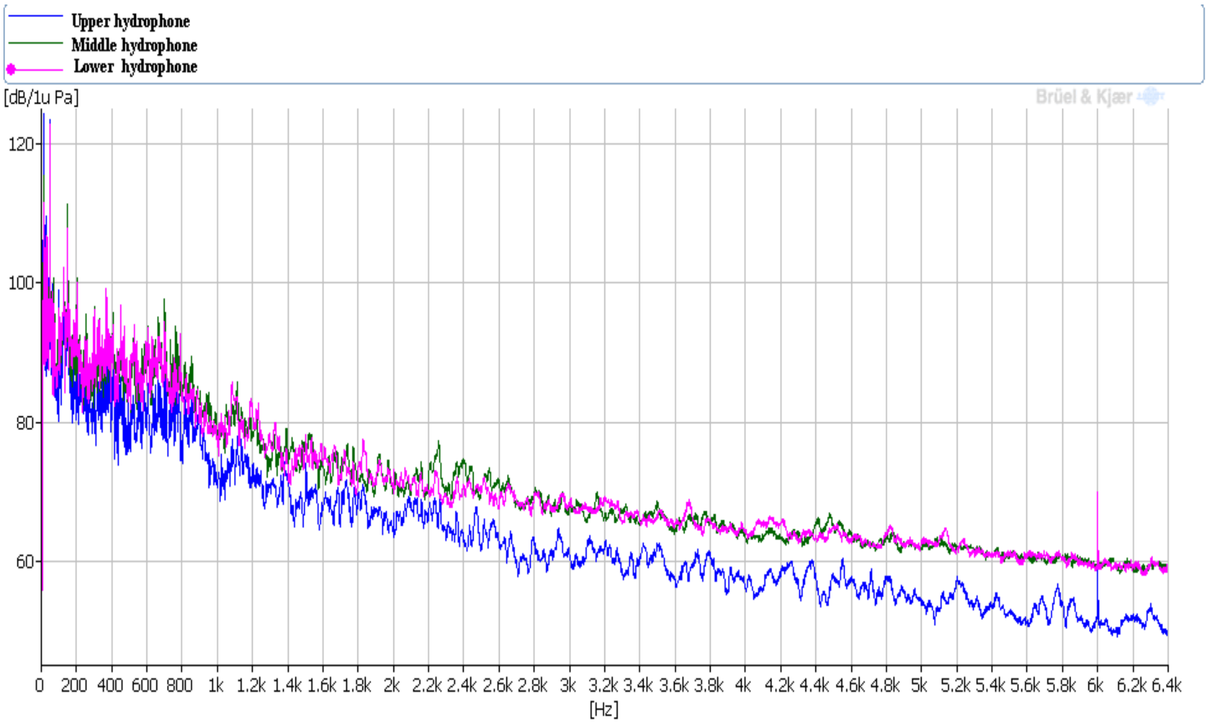

Figure 2 Underwater noise spectra measured near ship

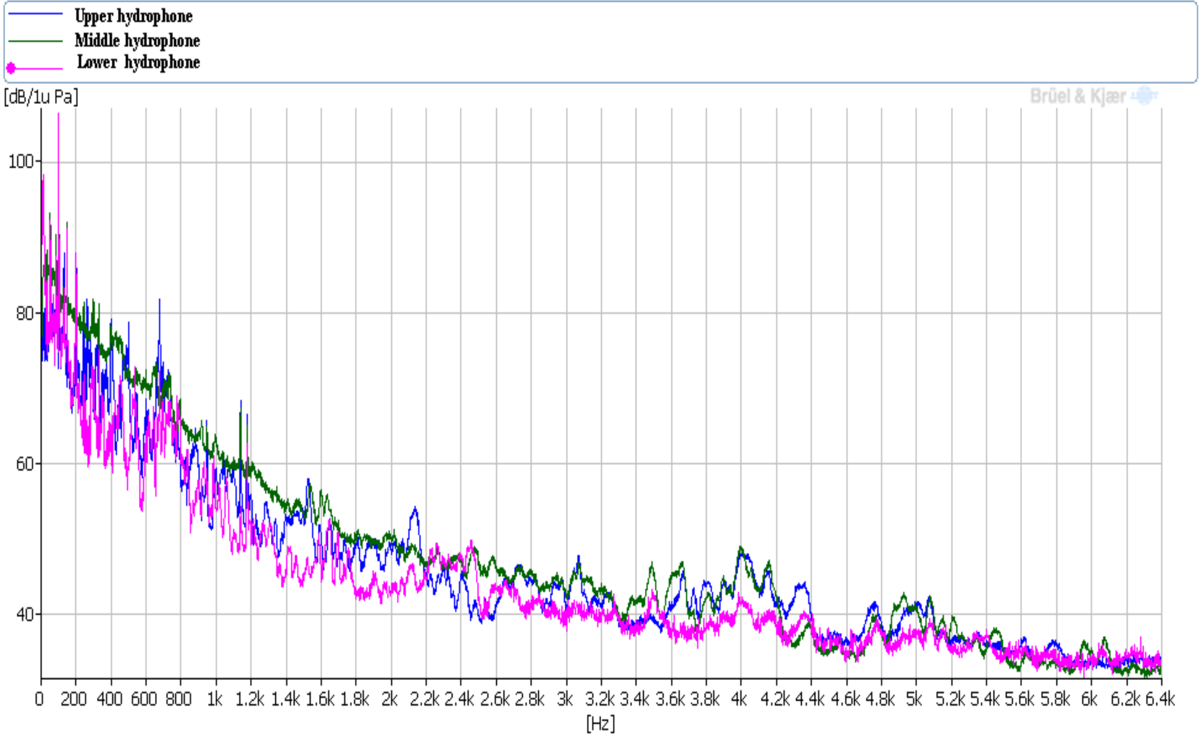

Figure 3 Underwater noise spectra measured at 1.5Nm from ship

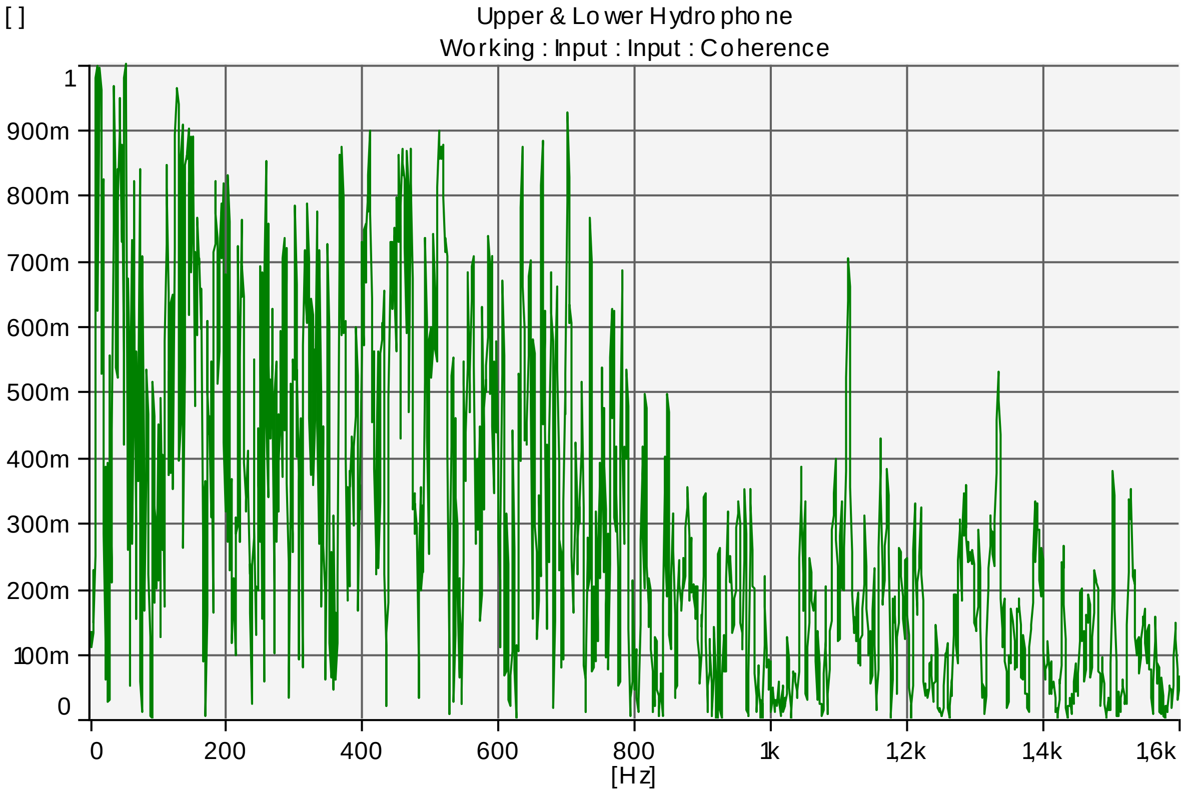

Figure 4 Correlation between upper and lower hydrophones (near ship)

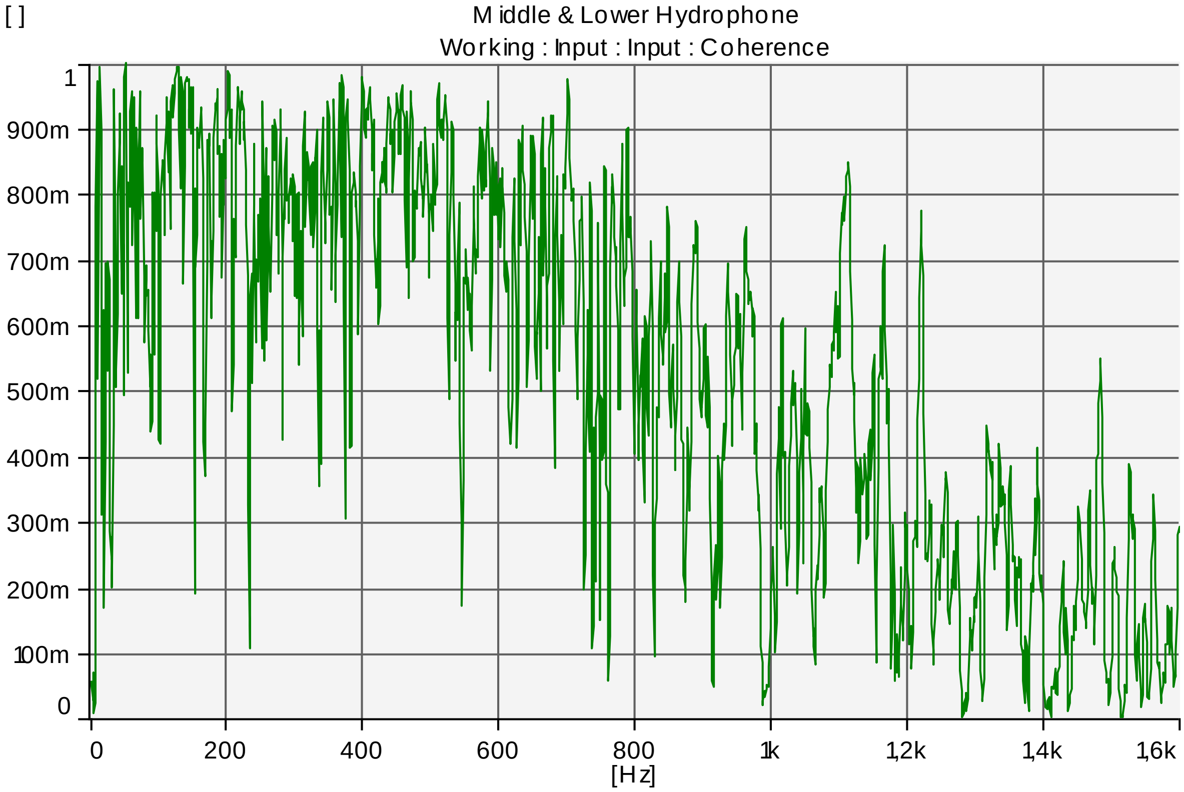

Figure 5 Correlation between middle and lower hydrophones (near ship)

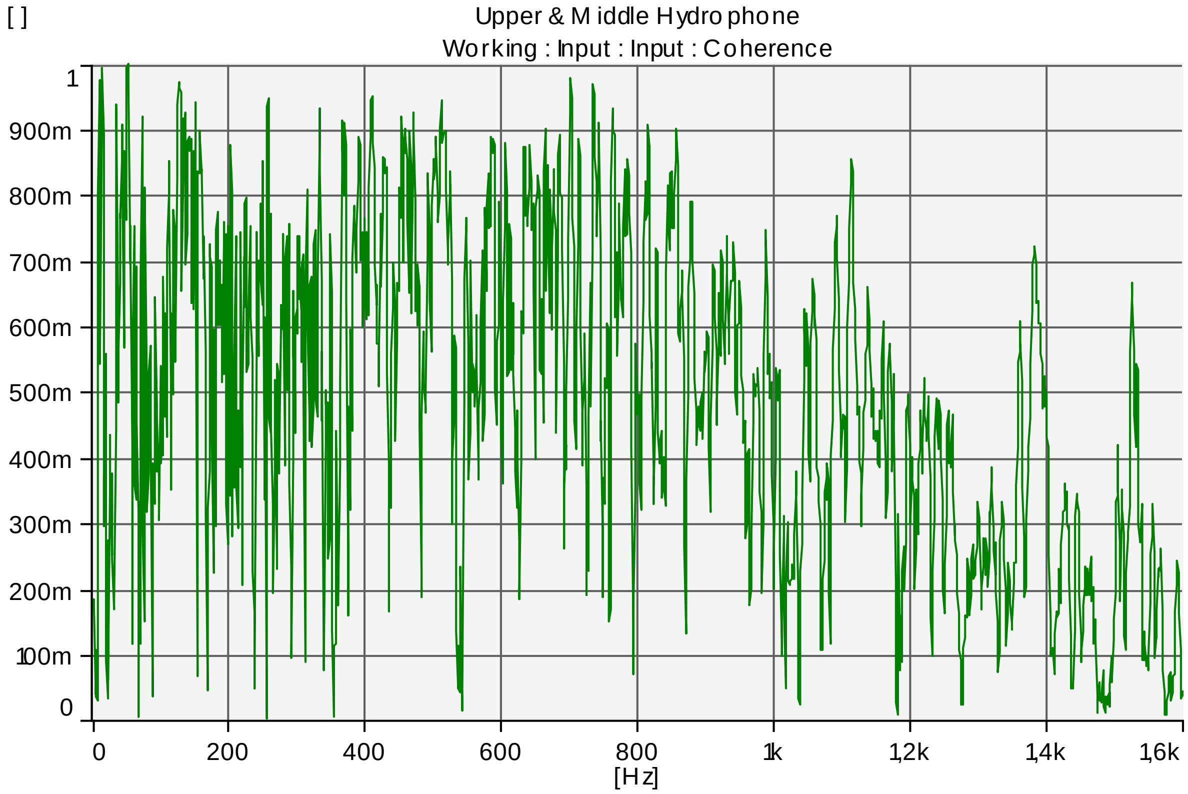

Figure 6 Correlation between upper and middle hydrophones (near ship)

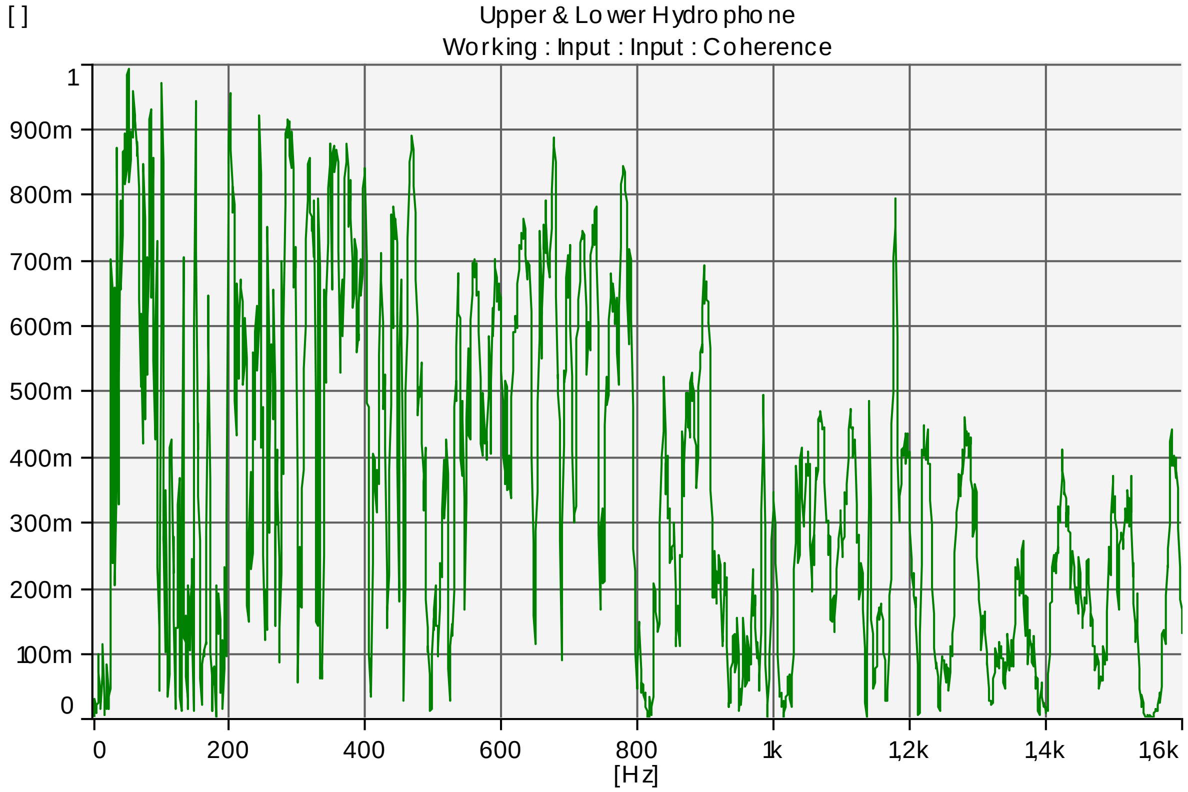

Figure 7 Correlation between upper and lower hydrophones (1.5Nm from ship)

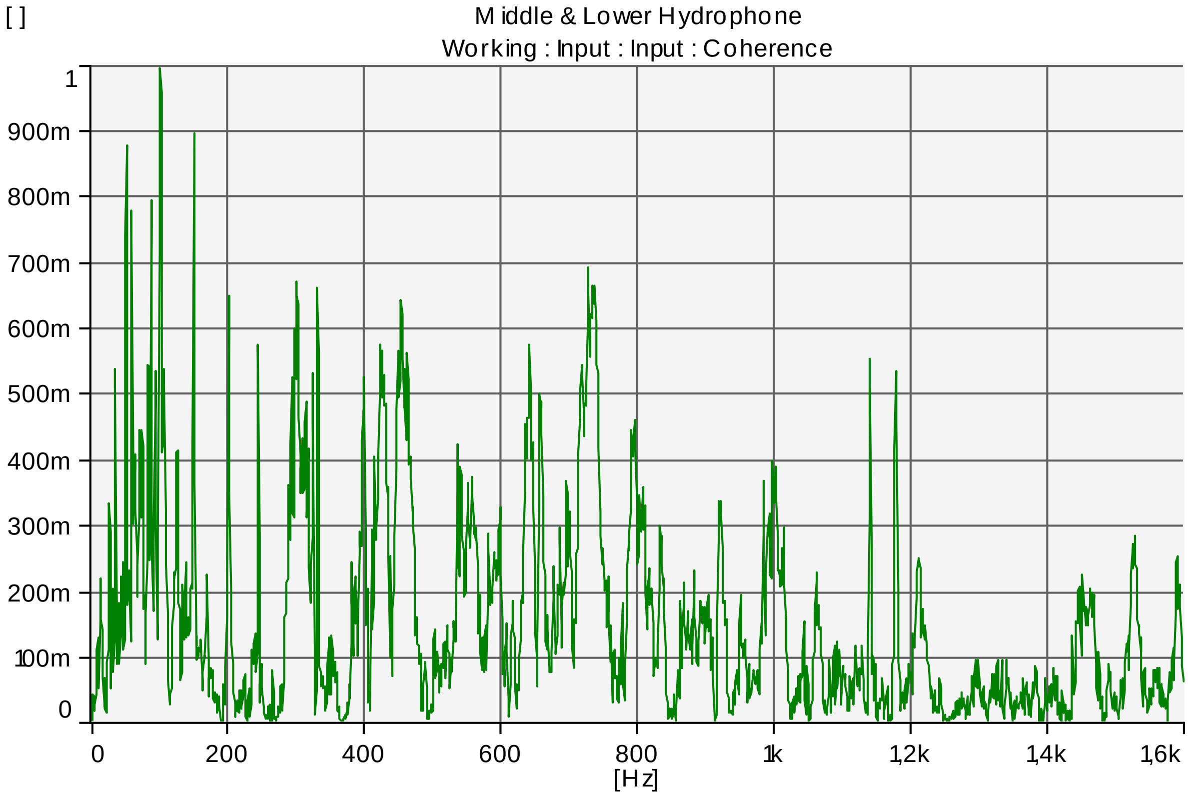

Figure 8 Correlation between middle and lower hydrophones (1.5Nm from ship)

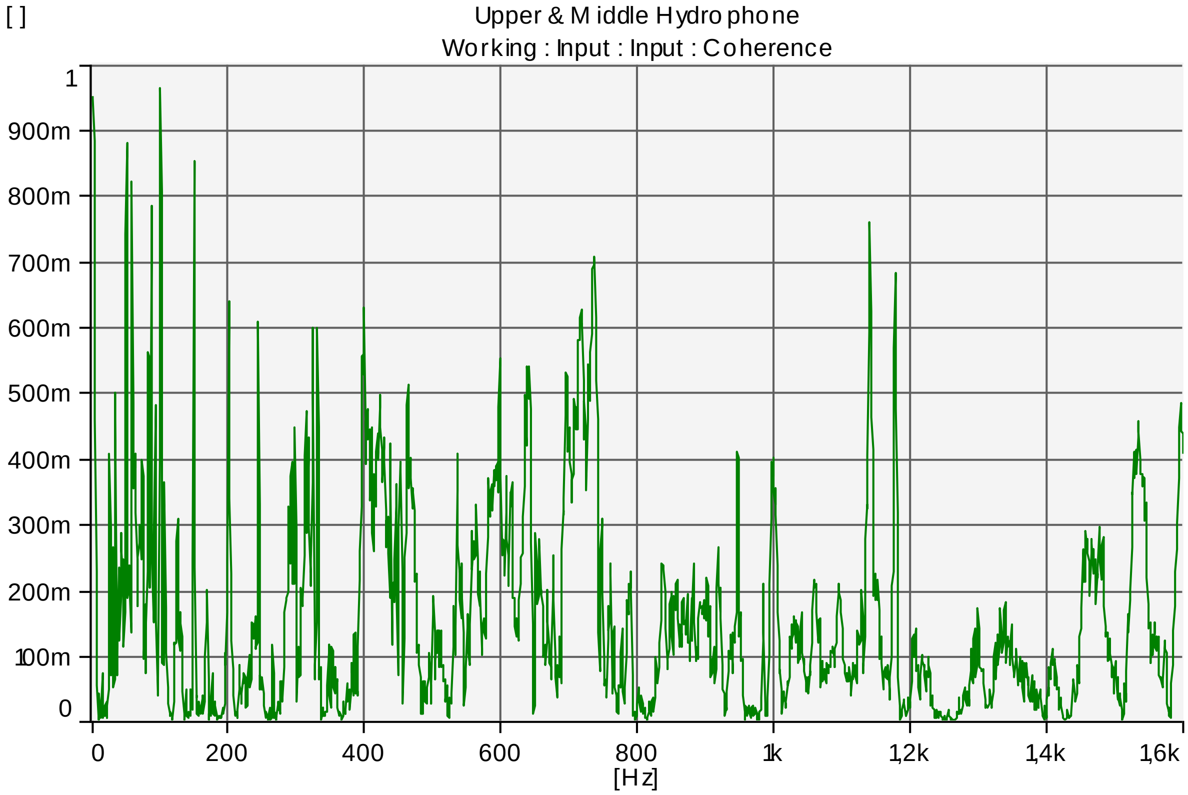

Figure 9 Correlation between upper and middle hydrophones (1.5Nm from ship)

Transmission Loss represents the sum of all losses caused by the propagation path and physical phenomena: Spreading Loss (SL) – spherical propagation or cylindrical propagation; Attenuation Loss (AL) – absorption losses (due to viscosity, ionic relaxation, heat conduction) and scattering losses; Bottom Loss (BL) – reflection and refraction of the waves when interact with the seabed [14].

$$TL = SL + AL + BL \tag{1}$$

In our measurements, the depth of water was small, approximately 30 meters. In such conditions of shallow waters, we considered that sound waves propagate cylindrical.

The Attenuation Loss is calculated with this equation:

$$AL = \alpha\left(r \times 10^{-3}\right) = \left(0,003 + \frac{0,1f^2}{1+f^2} + \frac{40f^2}{4100+f^2} + 2,75\times10^{-4} f^2\right)\left(r\times10^{-3}\right) \text{ dB} \tag{2}$$

where α is the attenuation coefficient, *r* is the distance source – receiver and *f* is the frequency.

Below 10kHz, the attenuation coefficient is less than 1dB per thousand yards [15]. So, in general, this factor can be neglected at any frequency below 10kHz.

In table 2 are presented the values of the Sound Pressure Level (SPL, dB re1μPa). Also, it is calculated the simple attenuation of noise generated by ship's sources.

Table 2

| | Sound Pressure Level (dB re1μPa) | | |
|---|---|---|---|
| | Upper hydrophone | Middle hydrophone | Lower hydrophone |
| | SPL (total) | | |
| Measurements near ship | 128 dB | 125 dB | 125 dB |
| Measurements at 1.5 Nm from ship | 103 dB | 109 dB | 110 dB |
| Propagation Loss (simple difference) | 25 dB | 16 dB | 15 dB |
| | SPL @ 50Hz | | |
| Measurements near ship | 124 dB | 123 dB | 123 dB |
| Measurements at 1.5 Nm from ship | 93 dB | 93 dB | 92 dB |
| Propagation Loss (simple difference) | 31 dB | 30 dB | 31 dB |
| Propagation Loss with relation (1) | 34 dB | 34 dB | 34 dB |

These attenuation values can be compared with the values computed with formula (3).

$$PL = 10\log r + \beta \cdot r \tag{3}$$

where PL represents the Propagation Loss or the Spreading Loss (due to cylindrical propagation), *r* is the range from ship to hydrophones and β is a frequency function (dB/km).

Vadov [5] have obtained for the Black Sea this value for α: $\alpha = 0,06\ dB/km$.

Relation (3) is derived from equation used by Al-Aboosi et al [6] where $k=1$ (cylindrical propagation). Near ship, underwater propagation is considered spherical ($r < 1000\,meters$), and away from the ship the sound waves propagate cylindrical ($r > 1000\,meters$) [4].

The difference between the calculated values of the propagation loss and the measured ones can be explain with the seabed reflection loss [7,8]. Muzi et al estimated the bottom reflection loss using the correlation between the signals from hydrophones mounted in a vertical line array.

The bottom loss (for angles $\theta_b > 0$) is defined as [9]:

$$BL\left(\theta_b, \omega\right) = -10\log_{10} R\left(\theta_b, \omega\right) \tag{4}$$

where $R\left(\theta_b, \omega\right)$ is the plane-wave power reflection coefficient of the bottom, ω is the angular frequency and $\theta_b$ is the grazing angle.

The plane-wave power reflection coefficient of the bottom is defined as [10]:

$$R(\theta_b,\omega)=\frac{Z(\theta_b,\omega)\sin\theta_b-1}{Z(\theta_b,\omega)\sin\theta_b+1} \tag{5}$$

where $\omega=2\pi f$ and $f$ is the frequency.

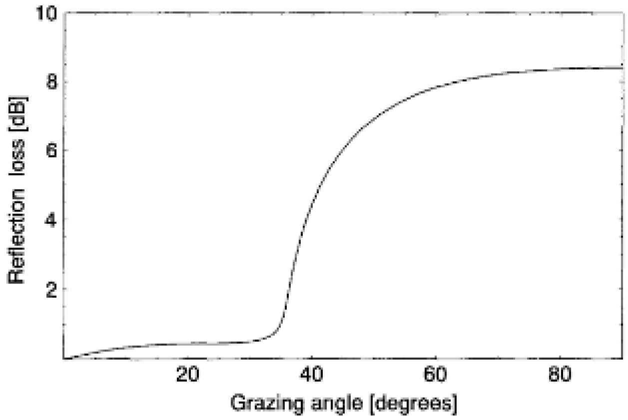

Figure 10 Reflection loss for a homogenous seabed of coarse sand [10]

$R$ can be defined also as:

$$R=\frac{\rho_2 c_2\sin\delta-\rho_1 c_1\sin\varphi}{\rho_2 c_2\sin\delta+\rho_1 c_1\sin\varphi} \tag{6}$$

$\delta$ – the incident angle

$\varphi$ – the reflection angle

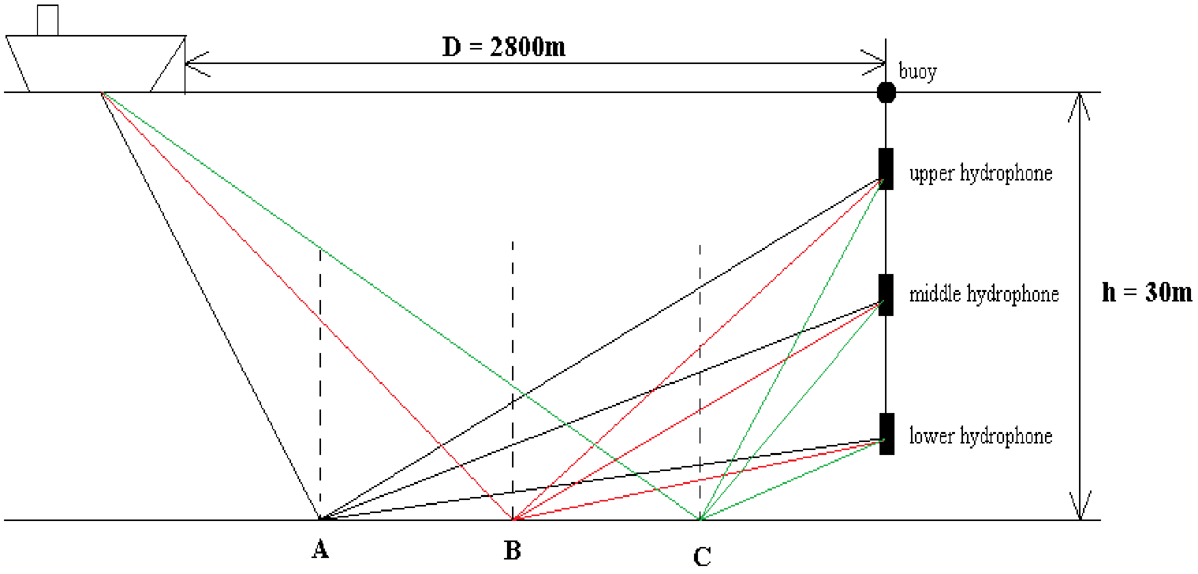

Figure 11 Reflection of sound waves generated by the ship

A – reflection point at 925m from the ship
B – reflection point at 1400m from the ship
C – reflection point at 1850m from the ship

In table 4 are presented the incident and reflection angles for each incident points calculated with ship-hydrophones distance and depth.

Table 3

| Incident position | Incident angle | Reflection angle 1 | Reflection angle 2 | Reflection angle 3 |
|---|---|---|---|---|
| A | 88,14 | 89,31 | 89.59 | 89.84 |
| B | 88,77 | 89,09 | 89.46 | 89.79 |
| C | 89,07 | 88,63 | 89,19 | 89,69 |

The grazing angles calculated using the distance ship – hydrophones vertical array (D) and depth (h) are:

Table 4

| | $\theta_b$ | | |
|---|---|---|---|
| | Upper hydrophone | Middle hydrophone | Lower hydrophone |
| Position A | 0,69 | 0,41 | 0,16 |
| Position B | 0,91 | 0,54 | 0,21 |
| Position C | 1,37 | 0,81 | 0,31 |

Because the grazing angles are very small ($\theta_b \to 0$), the impedance $Z$ approaches a limiting value, $Z_0$ [10]. It will be considered that the seabed is a homogeneous viscoelastic layer. Also, because the water characteristics (temperature, salinity, sound speed) present small variations versus water depth, the water column will be considered homogeneous. This means that the water has density $\rho_1$ and sound speed $c_1$, and the seabed has density $\rho_2$ and sound speed $c_2$. Due to the lack of data regarding the composition of the seabed, the impedances will be approximated here by $Z_1 = \rho_1 c_1$ and $Z_2 = \rho_2 c_2$. So, the plane-wave power reflection coefficient will be written:

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \tag{7}$$

For the calculus of $R$, we used the next values:

$\rho_1 = 1{,}015\, g/cm^3$ [11], $\rho_2 = 1{,}45\, g/cm^3$ [12], $c_1 = 1460\, m/s$ [our measurements], $c_2 = 1554\, m/s$ [13].

So $R$ is 0,206.

This is an approximate value since the exact composition of the seabed is not well known.

In the end, the bottom loss $BL$ is:

$$BL = -10\log_{10} R = -10\log_{10}(0{,}206) = -10\cdot(-0{,}686) = 6{,}86$$

Finally, the Transmission Loss is:

$$TL = SL + BL = 34{,}5 + 6{,}86 = 41{,}26 \cong 41 dB \tag{8}$$

By comparing the calculated TL value with the simple TL value obtained from measurements, will result a difference of 10dB.

It is not a small difference, but it can be explained by the lack of information regarding the structure of the seabed. De Jong et al [16] specify that in order to get comparable values between measurements and calculus, the natural conditions must be known: seabed density, sound speed through the seabed, geometry of the seabed. Also, the bottom hydrophone must be placed close to the seabed (between 3 to 5 meters from the seabed) [17]. Because the geometry of the seabed it was unknown, one can conclude from the measurements the bottom of the sea is not flat; another explanation is that possibly, the sound waves are absorbed better than expected. In conclusion, the calculated Bottom Loss can be neglected.

From the measurements, the difference between calculated PL and measured PL is 3dB at 50Hz. In Bureau Veritas standard [17] it is specified that for measurements in shallow waters a 4dB correction must be taken into account. So, it can be concluded that the difference in propagation loss corresponds to this correction factor. This means that the underwater sound waves propagation in this area of the Black Sea is cylindrical and the model used to calculate the transmission loss depends only by the distance between ship and hydrophone.

From figures 2 and 3 it can be observed that noise decrease according to frequency span. The dominating levels are from the sources onboard ship. The peaks are related to diesel generators and main engine, but the dominating ones are related to diesel generators (see the peaks at 50Hz, 100Hz etc.) – fundamental and harmonic values.

In figure 3 it can be observed that the noise spectra measured by the these three hydrophones are different up to 4kHz. For upper and lower hydrophones the shape of spectra is almost the same, with noticeable peaks. The noise spectra of middle hydrophone is „smoother" – the height of the peaks is smaller. It can be concluded that the attenuation of sound waves at that depth is much uniform than the attenuation at the other depths.

Figures 4, 5 and 6 show a very good correlation between measured signals by the hydrophones, no matter the depth of the hydrophones. These high values of correlation, between 0,7 and 1, are found in the low frequency domain (0 – 1kHz). Above 1kHz, the peaks of the correlation begin to decrease and the peaks reach only 0,7.

In the figures 7, 8 and 9 the density of correlation peaks decreases in the low frequency band. There is a good and a very good correlation only at frequencies (fundamental and harmonics) associated with the noise sources onboard ship. In figure 7, the number of peaks in 0 – 1kHz domain is bigger than the one in figures 8 and 9. These additional peaks can be associated with the interference of the reflected waves from seabed and sea surface. In the figures 8 and 9 it is observed a very good correlation only for the frequencies corresponding to diesel generators and other installations. Thus, it can be concluded that the recordings from the middle hydrophone give the best spectra of the noise sources from the ship. So, the influence of interferences is reduced when the hydrophone is placed at mid-depth.

## 4. Conclusions

Underwater noise produced by ships and other human activities represent a constant preoccupation for scientists who must determine the effects on sea and ocean environment. These analyses provide an estimation of the modifications made to the environment over the years. Since the first investigations made to the impact of artificial noise over marine flora and fauna, a large amount of data was gathered. This data is an instrument to evaluate the changes in the environment and to propose measures to minimize the negative effects and to protect the environment. Human activities do not influence only the near areas, but the noise produced by these activities propagate over long distances in the low frequency domain. This represents an increase of underwater ambient noise level. Over small distances high frequency noise affect the fish. The noise in the low frequency band affects communication between mammals.

The observations made in this paper are an addition to the conclusions made in the RoNoMar project. The distribution of noise level radiated from Mare Nigrum ship is analysed. Special propagation of the noise produced by ship's installations contribute to ambient noise level. By using the coherence function it is estimated the distribution of noise related to water depth. Also the noise is correlated to sea water characteristics: salinity, temperature etc.

A first observation is that the underwater noise level measured near ship do not vary with depth. Due to proximity to ship, sound propagates spherically and noise is radiated almost uniform. The correlation between hydrophone signals has high values in low and broad spectra. Even so, it can be noticed that the peaks are associated to the noise sources onboard ship like diesel generators and main engine. These peaks can also be found in the spectra of the noise measured 1.5Nm from the ship. In this measuring point, a very good correlation for the noise sources exists between signals. The broadband frequency span doesn't show the same correlation at large distance from ship compared to the measurements near ship.

The correlation between upper hydrophone and lower hydrophone (figure 7) shows a greater number of peaks by comparing with the correlation between middle and lower hydrophone (figure 8), upper and middle hydrophone (figure 9). The density of the peaks in the figure 7 can be explained by the physical phenomena – reflection, refraction, interference of the sound waves over long distances.

In figures 8 and 9 these peaks are more refined and they can be easily associated with the sound sources onboard ship: engine, generators.

The acoustic signature of the ship from signals correlation is better obtained for hydrophones placed at bigger depths, away from sea surface. When the hydrophone is placed close to sea surface, the sea state and reflection from sea surface influence the noise level measured by the hydrophone. In shallow waters, where sound propagation is cylindrical, it is formed a sort of a sound duct. This means that sound waves are better received by hydrophones placed away from sea surface and sea bottom.

Finally, these measurements in situ depend on the information regarding seabed geometrical shape and seabed physical properties. The authors are determined to make future investigations of the underwater radiated noise from ships in the Black Sea. Future collaborations must be made with the specialists from INCDM „Grigore Antipa", national authority for exploration of marine environment, in order to obtain precise results regarding the underwater noise in the Black Sea.

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