

Article – Environmental Sciences

Assessment of Ship-Generated Underwater Noise in the Shallow Lithuanian Marine Klaipėda Port Through Measurements and Modelling

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HIGHLIGHTS

- Underwater noise measurements in the very shallow marine harbor.
- Application of underwater noise ships spectral source modelling in a very shallow marine environment.
- Comparison of underwater noise measurement and modelling results.

Abstract: Mapping of shipping underwater noise purposed for environmental impact assessments and to forecast noise effects on aquatic life incorporate source spectral models. These models published in scientific literature updated regularly, although these may have limitations and may depend on the variables stored in the ship's automated identification system data, tied to specific locations i.e., ship speeds and their lengths. Regarding these limitations, it is crucial to assess the possibility of model application in the research area. In this paper the results of evaluation of four different noise models in the shallow Lithuanian marine harbor presented. The results acquired using "ECHO-JOMOPANS" model and the updated "Research Ambient Directionality Model" revealed good correlation with measurement results, although these two models have a different dependency on the ships parameters. The benchmarked "ECHO-JOMOPANS" model incorporates the reference spectrum, having the dependency on the sound frequency, ship's speed, its length and ships database related reference speeds and ships lengths. In contrast, an updated "Research Ambient Directionality Model" is a modification of an original model, having the dependency only on the sound frequency, ship's speed, and length.

Keywords: Baltic Sea; Klaipėda Port; underwater noise; ships.

INTRODUCTION

Scientific studies focusing on the underwater noise emitted by the navigating ships have revealed its possible negative impacts, both short and long term, on marine life, especially marine mammals. These findings led to the adoption of the “Guidelines for the Reduction of Underwater Radiated Noise from Shipping to Address Adverse Impacts on Marine Life” by the Marine Environment Protection Committee of the International Maritime Organization [1].

The use of underwater noise models is a reliable and cost-effective way to estimate temporal and spatial underwater noise trends in the European waters [2]. Modelling of underwater noise trends requires input parameters such as ship source noise levels, vessel locations and types, environmental parameters relevant to acoustic propagation and statistical noise distribution. The description of radiated ship source levels is a crucial part of these modelling routines. Despite differences in the field measurement methodology, different studies have already been conducted to describe underwater noise radiated by individual ships [3, 4, 5]. These differences have led to the development of international standards ISO 17208-2 and ISO 17208-3 (under development). Scientific studies have focused explicitly on the empirical description of ship source levels, resulting in the development of published ship source spectral models. Although, using different ship source spectral models often leads to differences in the acquired ship source noise levels, as these models are based on different experimental data and datasets [6, 4]. Differences in ship noise modelling results raise the need to verify chosen models using ship noise measurement data collected in specific research areas, if available. To address this issue, underwater radiated noise (URN) levels of several types of ships: container, RO-RO, cargo, tanker, tugboats were measured and compared with the results acquired using a few most often used ship source spectral models, published in scientific literature. The URN measurement data comparison against the ship noise modelling results revealed a difference of up to six decibels between the modelling and measurement results.

The acquired results support the use of ship spectral source noise models, based on realistic shipping activity data in very shallow water environments, such as the Klaipėda Port, as well supports an option to assess the shipping noise as an environmental stressor and to provide the tools for future sustainable management of very shallow marine areas of interest.

MATERIAL AND METHODS

Underwater noise radiated by ships was measured in the Klaipėda Port area (Figure 1), using an underwater sound recording setup, positioned on the seafloor. An average depth in the noise measurement area equaled to 10.0 meters and the maximum depth equaled to 13.7 meters (the bathymetric data were analyzed using GIS), where the dominating bottom substrate in this area is fine sand [7].

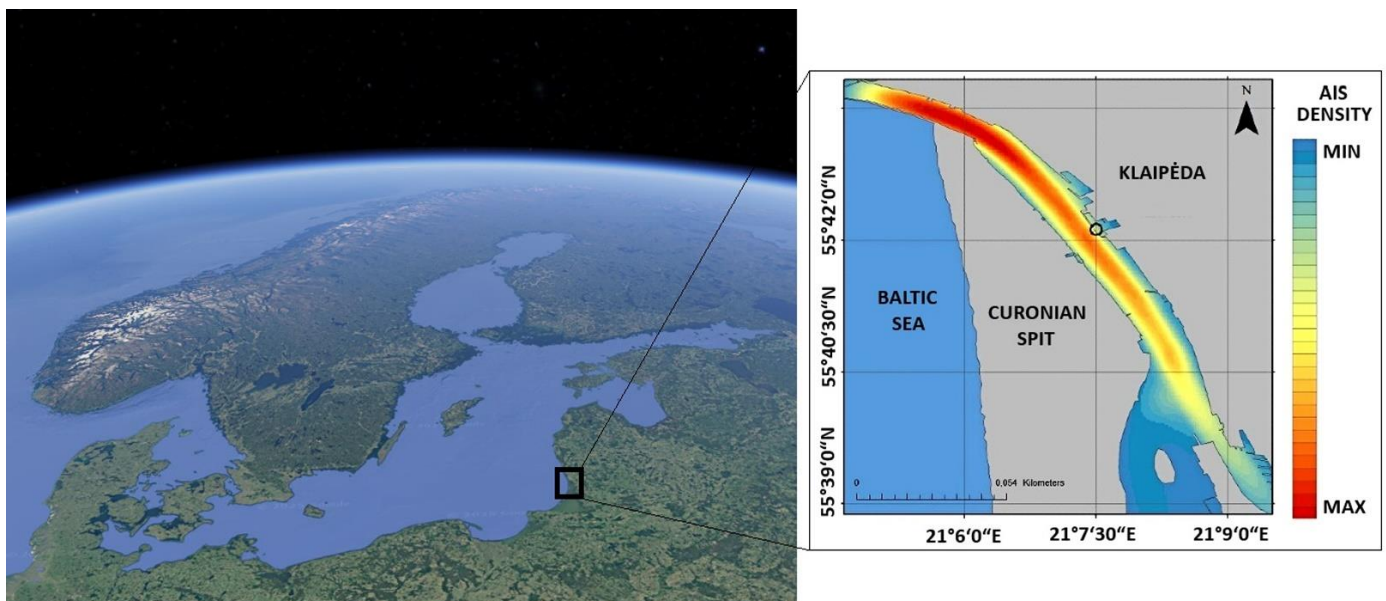


Figure 1. The research location (picture Google Earth V7.3 2023, Baltic Sea 56°30'38"N, 19°09'06"E, Eye alt. 200 Km, DigitalGlobe 2023. <https://earth.google.com>). Right panel shows the AIS ships density in the research area (the black circle marks the location of the resting hydrophone on the seafloor)

During the signal processing and analysis, the sound pressure levels (SPL) of ships were obtained in the central point of approach (CPA) in 1-second time windows. The URN measurement geometry used in the water column during the measurement campaign is shown in Figure 2, where the slant range from the hydrophone to the noise source varied from 121 to 251 meters and the angle between the water surface and the line of site connecting the hydrophone and noise source varied between 1.1° and 2.4° .

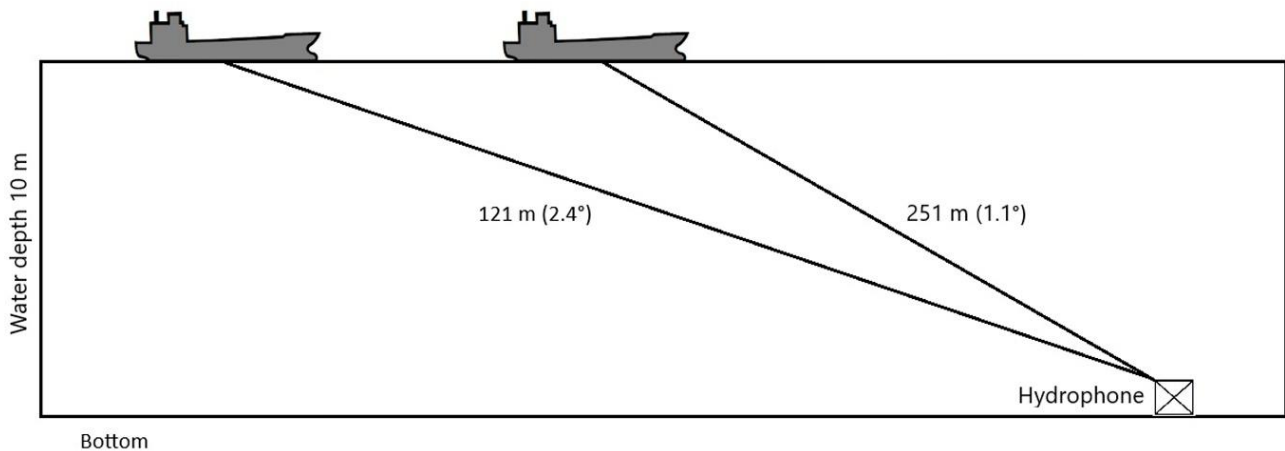


Figure 2. Measurement geometry used for ship URN measurements in the research area

The hydrophone angle, sustained between the source-to-hydrophone line during noise measurements changed with the value equal to 1 degree, while ships under analysis passed the measurement site with a slightly varying distance from the hydrophone setup. This geometry angle may have a significant effect on the measured source levels, when the ships pass the hydrophone location at the equal slant range from the hydrophone i.e., the change of 50 times of the hydrophone angle, sustained between the source-to-hydrophone line, would lead to a 5.0 to 10.0 dB SPL change, due to sound surface-image reflections [3]. Although, when measuring in the Klaipėda Port, the hydrophone angle differed by only two times during ship passages through the measurement site, leading to an assumed negligible change in the source level for comparison purposes.

The ships parameters and the URN measurement geometries used in this study are summarized in Table 1.

Table 1. Properties of the ships that passed through the measurement site

Ship type	Ship length	Ship width	Ship speed at CPA	Distance to ship	Source-to-hydrophone angle, α
Container	168.0 m	26.0 m	7.8 kn	251.0 m	1.14°
RO-RO	150.0 m	23.0 m	4.6 kn	215.0 m	1.59°
Cargo 1	100.0 m	15.0 m	8.1 kn	224.0 m	1.28°
Cargo 2	90.0 m	13.0 m	5.9 kn	203.0 m	1.41°
Tanker	51.0 m	8.0 m	7.3 kn	121.0 m	2.37°
Tugboat	29.0 m	9.0 m	4.9 kn	212.0 m	1.35°

The source depth of all ships measured and modelled was assumed to be 5 meters, which was chosen as the average draft of a standard mid-size cargo ship with a length between 90 and 135 meters [7]. This reference depth represents half of the waveguide depth in the underwater environment at the measurement site.

The recording setup and signal processing software used in this study were developed for a measurement campaign conducted in 2021. The ships' URNs were recorded using a bottom-resting hydrophone system with a 16-bit resolution and a 44.1 kHz sampling frequency [8]. To collect the true noise levels the recording equipment was calibrated using a comparison method (black box method) using the environmental noise meter and the loudspeaker generating narrow band tones in the 1/3 octave bands [9, 10]. The noise data were collected in the period from August 14, 2021 to August 16, 2022. The signals were processed using MATLAB scripts specifically developed for underwater noise analysis by authors of this study, applying the Fast Fourier Transformation (FFT) with a Hanning window and 50% overlap. Acoustic

data were analyzed in 1-second time resolution using an FFT size of $n = 4,096$ points. The analysis was performed in 1 Hz frequency bins in the frequency range of 0.01–10 kHz.

The ship's spectral noise levels were modelled using four different models published in scientific literature. While the modelling of ship sources was completed using the ECHO-JP spectral model, the ship reference parameters were adjusted to reflect the local ship AIS data collected in the research area. The reference speed of the ships was set to the speed limit for ships in this area and the reference length was set to the average length of ships registered in the local AIS data. The summarized information about source spectral ship noise models applied in this study are shown in Table 2.

Table 2. The background information on ship URN spectral models used in the study

Model	Reference	Source	Parameters required	Vessel classes	Comments
ECHO-JP	MacGillyvray & de Jong 2021	Monopole	Frequency (Independent variable) Ship speed Ship length Reference speed* Reference length*	Oil/chemical tankers Cargo ships Passenger ships Fishing vessels Dredgers, Tugs Other classes	Extension of the RANDI 3.1 model
RANDI 2017	Chion et al. 2017	Dipole ¹	Frequency (Independent variable) Ship speed Ship length	Oil/chemical tankers Cargo ships Bulk carriers Container ships	Update of the RANDI 3.1 model
RANDI	Chion et al. 2017	Dipole ¹	Frequency (Independent variable) Ship speed Ship length	Merchant ships Tankers Fishing vessels	Known as the RANDI 3.1 model
SONIC	Liefvendahl et al. 2015	Monopole	Frequency (Independent variable) Ship speed Ship length Reference speed*	Oil/chemical tankers Cargo ships Passenger ships Fishing vessels & other classes	Extension of the Wales-Heitmeyer model

*Reference parameters that depend on the ship databases used for development of models
¹Chion et al. 2019

The ECHO-JP ship source spectral model described by [4]:

$$L_{S,J-E} = L_s(f, C) + 60 \log_{10} \left(\frac{V}{V_0} \right) + 20 \log_{10} \left(\frac{l}{l_0} \right)$$

The baseline spectrum $L_s(f, C)$ is found using:

$$L_s(f, C) = K - 20 \log_{10}(\hat{f}_1) - 10 \log_{10} \left(\left(1 - \frac{\hat{f}}{\hat{f}_1} \right)^2 + D^2 \right) \quad (1)$$

Where V_0 is the reference vessel speed per vessel class, V is the vessel speed (kn), l_0 is the mean ship length per vessel class, l – the ship length (m); $\hat{f} = \frac{f}{f_{ref}}$; $\hat{f}_1 = 480 \text{ Hz} \times \frac{V_{ref}}{V_c}$; $f_{ref} = 1 \text{ Hz}$; f – frequency (Hz); $V_{ref} = 1 \text{ kn}$; $K = 191 \text{ dB}$; $D = 3$ for all ship classes, except for cruise ships $D = 4$.

The ECHO-JP ship source spectral model for the vessel classes of container ships, vehicle carriers, bulkers, tankers have an additional spectral peak in the frequencies below 100 Hz expressed by:

$$L_s(f, C) = K^{LF} - 40 \log_{10}(\hat{f}_1^{LF}) + 10 \log_{10}(\hat{f}) - 10 \log_{10} \left(\left(1 - \left(\frac{\hat{f}}{\hat{f}_1^{LF}} \right)^2 \right)^2 + (D^{LF})^2 \right) \quad (1.1)$$

Where $K^{LF} = 208 \text{ dB}$; $\hat{f}_1^{LF} = 600 \text{ Hz} \left(\frac{V_{ref}}{V_c} \right)$; $D^{LF} = 0.8$ for container ships and bunkers; $D^{LF} = 1.0$ for vehicle carriers and tankers.

The updated RANDI-2017 ship source spectral model described by [11]:

$$L_s(f) = L_{s,0}(f) - \left[\frac{144.7}{V - 12} \right] \log_{10} \left(\frac{V}{V_0} \right) + 20 \log_{10} \left(\frac{l}{l_0} \right) + df \times dl$$

The baseline spectrum $L_{s,0}(f)$ found using:

$$\begin{aligned} L_{s,0}(f) &= -10 \log_{10} (10^{-1.06 \log_{10}(f) - 14.34} + 10^{3.32 \log_{10}(f) - 21.425}) && \text{if } f \leq 500 \text{ Hz;} \\ &= 173.2 - 18.0 \log_{10}(f) && \text{if } 500 < f < 2000 \text{ Hz} \\ &= 219.2 - 32.0 \log_{10}(f) && \text{if } f > 2000 \text{ Hz} \end{aligned} \quad (2)$$

The correct values for df and dl found using:

$$\begin{aligned} df &= 8.1 && \text{if } f < 28 \text{ Hz;} \\ &= 22.3 - 9.77 \log_{10}(f) && \text{if } f > 28 \text{ Hz;} \end{aligned}$$

and,

$$dl = \frac{l^{1.15}}{3643.0}$$

Where V_0 – ship reference speed equal to 12 kn; l_0 – ship reference length equal to 91.44 meters (in Equation 300 ft);

The RANDI 3.1 ship source spectral model described by [3]:

$$L_s(f) = L_{s,0}(f) + 60 \log_{10} \left(\frac{V}{V_0} \right) + 20 \log_{10} \left(\frac{l}{l_0} \right) + df \times dl + 3 \quad (3)$$

Where the baseline spectrum $L_{s,0}(f)$ (except 2nd term of the baseline spectrum, that extends > 2 kHz) and the correct values for df and dl found as in equation 2.

The SONIC ship source spectral model described by [6]:

$$L_s(f) = L_{s,0}(f) + 60 \log_{10} \left(\frac{V}{V_0} \right) + 8$$

The baseline spectrum (Wales-Heitmeyer ensemble spectrum) $L_{s,0}(f)$ found using: (4)

$$L_{s,0}(f) = K - 10 \log_{10}(f^{3.594}) + 10 \log_{10} \left[\left(1 + \frac{f^2}{340^2} \right)^{0.917} \right]$$

Where the $K = 230$ dB; V_{ref} – ship reference speed, based on AIS data (in the model applied for tankers, cargo ships $V_{ref} = 14$ kn; passenger ships = 22 kn; fishing and other vessels = 10 kn, as assumed these categories of vessels generate most of the ship noise in the open Baltic Sea).

For modelling of the sound propagation losses, a Normal Mode (NM) approximation model was utilized [12]. The analysis was performed using 1 Hz frequency bins in a frequency range of interest. Custom sound speed profiling (SSP) data were obtained using a CTD probe by the Environmental Protection Agency on August 12, 2021 and had a positive slope of approximately 0.65 m/s⁻¹. Sound propagation losses were modelled using a constant water depth and sediment thickness, following the assumption applied in other sound propagation models [13].

For the purposes of comparison, the modelled ship source noise spectral levels were converted to sound pressure levels (SPLs) of decidecade bands, using the following equation:

$$\begin{aligned} L_E &= L_s + 10 \log_{10} \left(0.231 \times \frac{f_i}{1 \text{ Hz}} \right) \\ f_i &= 10^{\frac{i}{10}} \times 1000 \text{ Hz} \end{aligned} \quad (5)$$

Where L_E is the decidecade SPL, dB; L_s – source level spectral density level, dB; f_i – frequency in Hz; i – band index from -11 to 10 [4]. The measured source level spectral density levels were back-computed to 1 m distance from the source, using sound propagation loss modelling and converted to decidecade SPLs

using Equation 5, while averaging the measured levels in the range of upper and lower edges of the decade bands [14].

The cut-off frequency for the very shallow research area in the Klaipėda Port, while at 10 m depth, described by [15]:

$$f_c = \frac{C_w/4H}{\sqrt{1 - C_w^2/C_s^2}} \quad (6)$$

Where f_c is the cut-off frequency in Hz; H – water depth (m); C_w – sound speed in water (m/s); C_s – sound speed in sediments (sound speed in water 1,500 m/s; sound speed in sediments 1,700 m/s).

The statistical goodness of fit of modelled ship source spectral noise levels against the measured spectral levels was assessed fitting the statistical 1st degree polynomial regression model using the MATLAB software. The polynomial model expressed using the following equation:

$$y = \sum_{i=1}^{n+1} P_i X^{n+1-i} \quad (7)$$

Where X , Y – independent and dependent variables; $n + 1$ – the order of the polynomial, n – the degree of the polynomial. The order gives the number of coefficients to be fit, and the degree gives the highest power of the predictor variable.

The analysis of ship movement was conducted using the Automatic Identification System (AIS) data, which was provided by the Lithuanian Transport Safety Administration.

RESULTS

The results of the measured underwater radiated noise of ships revealed the presence of strong surface effects on sound wave propagation in the shallow marine environment of the Klaipėda Port area. The surface effects (known as “Lloyd mirror” effects) alter the propagating sound waves [5] and are evident in the ship spectrum shown in Figure 3, recorded as a 168-meter-long containership passed the recording station at a 251-meter distance at its CPA.

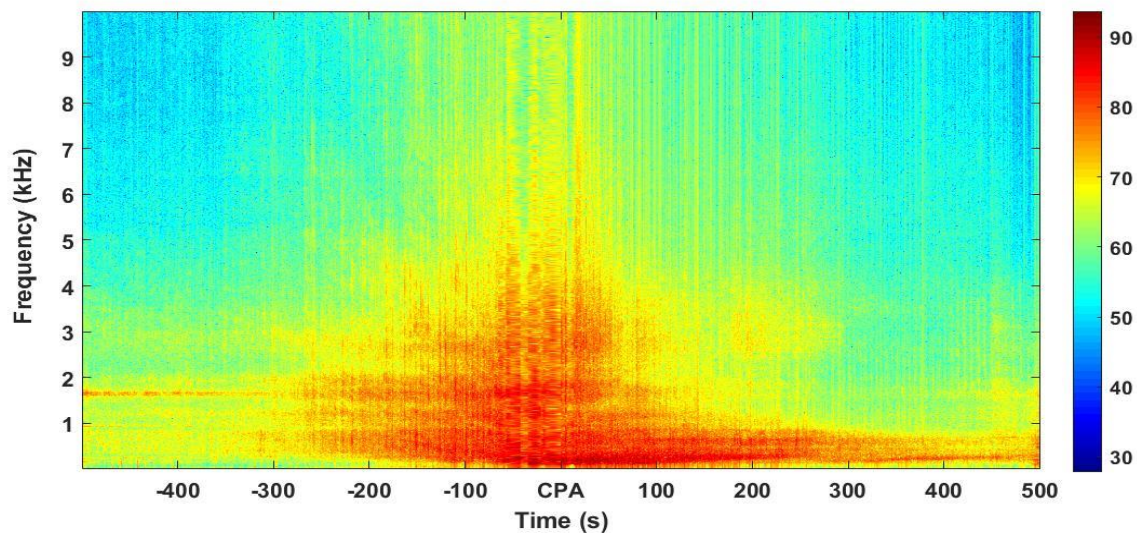


Figure 3. The radiated ship source spectra of the 168 m length containership at its CPA, 251 meters from the hydrophone setup in the Klaipėda Port on August 14, 2021, 09:40 (GMT+3) (ship speed – 7.8 knots). Color bar – units dB re 1 μ Pa/Hz

The use of the Normal Mode approximation model helped to accurately model the sound propagation losses in the shallow research area, considering the surface effects that were affecting the sound wave propagation. An example of modelled sound propagation losses in the 1 kHz frequency band, with the custom sound speed profile and the constant water depth of 10.0 meters (constant sediment thickness) depicted in Figure 4.

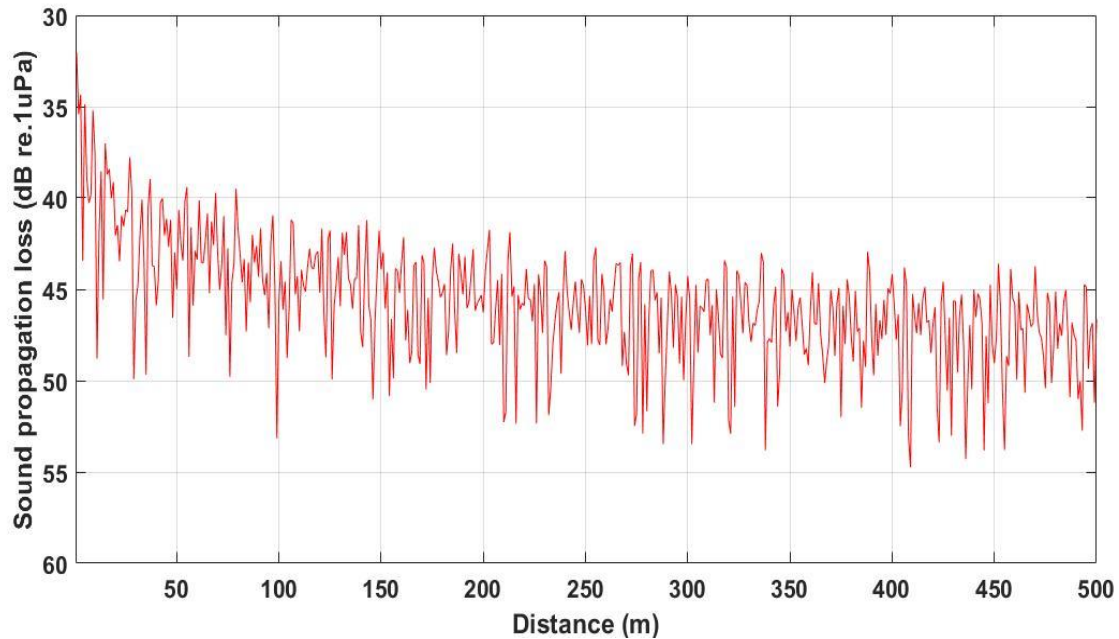


Figure 4. Sound propagation losses computed in 1 kHz band for the shallow marine environment of the Klaipėda Port area (source depth 5 m; water depth 10 m), with a measured positive sound speed profile

The source spectral density levels were back-computed to 1 meter distance from the sound source using the sound propagation model. Measured and back-propagated ship spectral source levels were compared to the modelled source levels, using different ship source models: ECHO-JP; RANDI-2017; RANDI and SONIC.

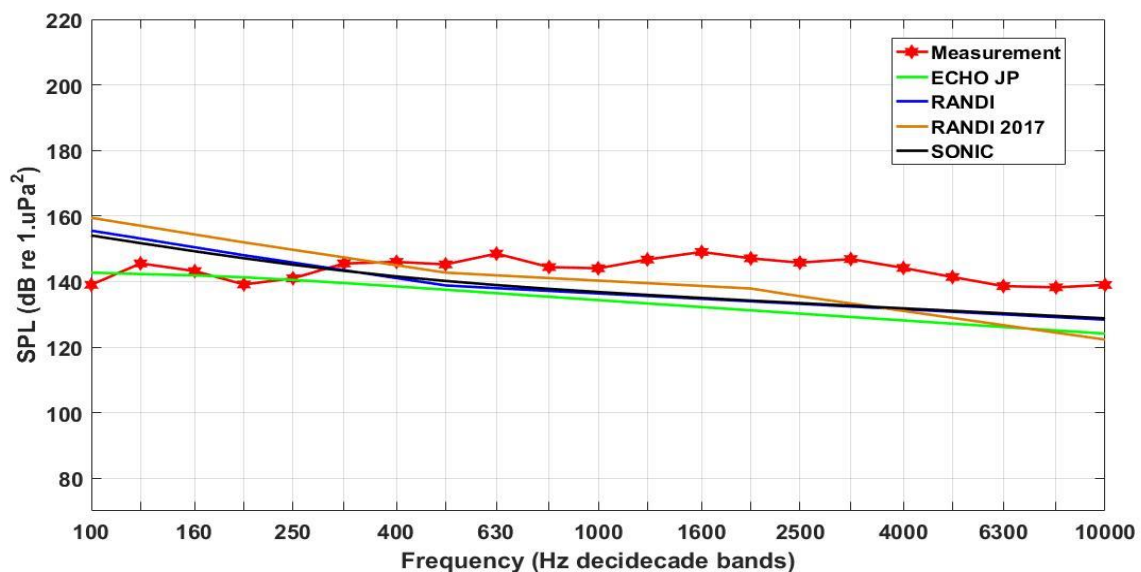


Figure 5. A comparison of the modelled and measured ship source spectral levels (CPA) in the decade frequency bands. Noise source – cargo vessel, 100 m LOA, speed 8.1 kn

The comparison between the measured and modelled spectral levels of a mid-size cargo ship (100 m LOA) at its CPA shown in Figure 5. The ship source models applied to model cargo ship spectra slightly underestimated the higher frequency spectral levels, while overestimating the noise levels in the lower frequency end of the spectra, except for the tugboat. The source spectral levels modelled using the ECHO-JP model overestimated the ship spectral noise levels significantly. The reference length and speed of the ships for the ECHO-JP model were then modified to reflect the data of the most prominent ship sizes in the local Automatic Identification System (AIS) data, where the 8.0 kn reference speed is the limit within this area. The obtained results compared in Table 3.

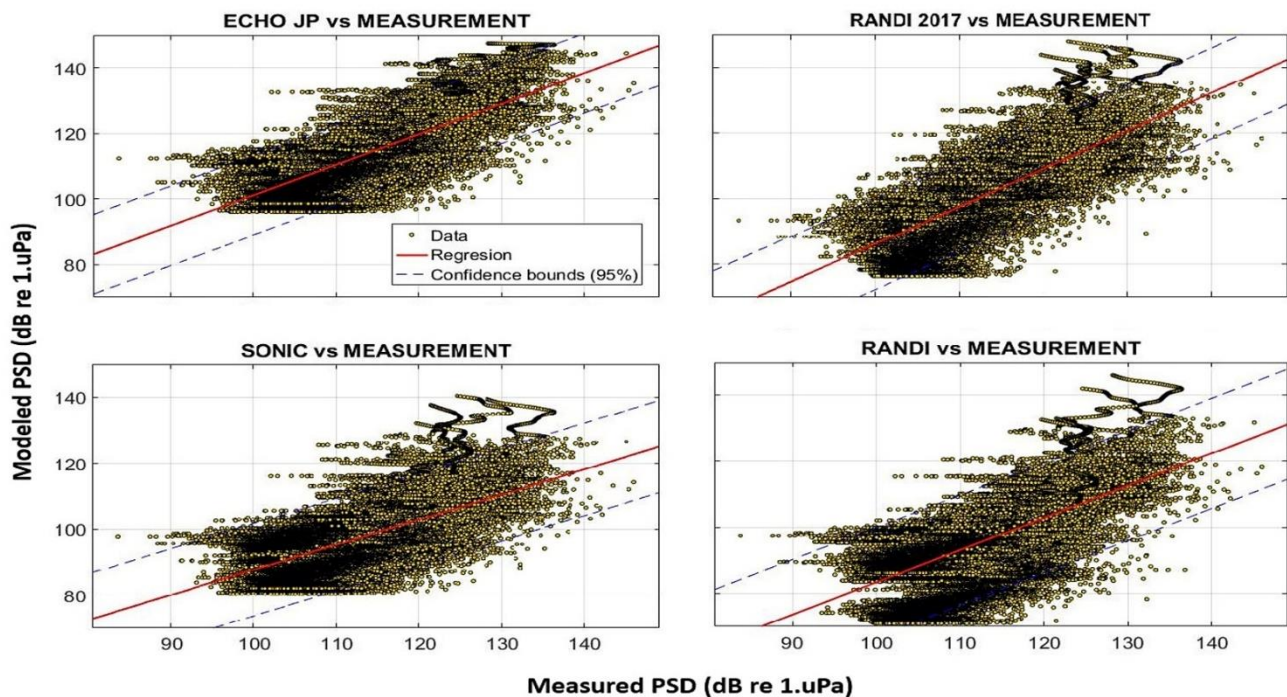
Table 3. Modelled and measured broadband SPLs of passing ships at CPA (0.1–10 kHz frequency range)

Ship type	Modelled / measured				
	ECHO-JP	RANDI 2017	RANDI	SONIC	MEASURED
Container	144.5 dB	166.7 dB	162.0 dB	156.2 dB	165.4 dB
RO-RO	136.6 dB	164.0 dB	147.2 dB	142.4 dB	159.3 dB
Cargo 1	150.3 dB	162.0 dB	158.2 dB	157.1 dB	158.0 dB
Cargo 2	141.1 dB	160.1 dB	149.0 dB	148.9 dB	154.3 dB
Tanker	145.6 dB	155.8 dB	149.5 dB	154.4 dB	153.3 dB
Tug	174.8 dB	149.5 dB	134.1 dB	144.0 dB	154.8 dB

The differences between the measurements and the RANDI 2017 model were found to be the smallest, with a variation between 1.0 to 6.0 dB depending on the type of ship. The regression analysis was conducted to compare the measurement results with the ship source spectral density levels in the broadband frequency (0.1–10 kHz). The obtained regression analysis results summarized in Table 4; the regression graphs for all ship types shown in Figure 6.

Table 4. Regression fit coefficients for the ship noise source spectral data for all ships under analysis

Model	No. of coefficients	Sum of squared error (SSE)	R-square	Root mean square error (RMSE)
ECHO-JP	2	2.277e+06	0.5945	6.191
RANDI 2017		2.981e+06	0.6287	7.084
RANDI		4.264e+06	0.4608	8.472
SONIC		3.038e+06	0.4249	7.151

**Figure 6.** The regression plots for the ship noise source spectral data for all ships under analysis (broadband levels 0.01–10 kHz)

The regression analysis of measured URNs of ships and modelled noise source spectral levels proves that two models had the best statistical characteristics for the shallow research area: the updated “Research Ambient Noise Directionality” model and the and the ECHO-JP model [11]. The regression analysis found the best fit (as measured by the R-squared value) between the measurement data and the RANDI 2017 model, but the lowest root mean square error (RMSE) found for the ECHO-JP model.

DISCUSSION

In this study, four well-known empirical models, purposed for predicting ship underwater radiated noise levels were compared, with an aim to evaluate their applicability in very shallow marine environments, such as the Klaipėda marine Harbor area. The obtained research results suggest that the ECHO-JP and RANDI-2017 models have the best correlation with the measured spectral noise levels of ships. The regression analysis showed the best fit of the RANDI-2017 model (R-square 0.63), although the smallest root mean square error (RMSE 6.2) was observed using the ECHO-JP model. It is notable that the ECHO-JP model was designed using ship data of 12 different classes of vessels, representing a wide range of vessel sizes, speeds, and types, while in contrast, the RANDI-2017 model relies on a smaller selection of vessel types [4, 11].

The ECHO-JP model has an additional term for the baseline spectrum determination in the low frequency bands below 100 Hz, although in our analysis due to the very shallow marine area the spectral levels were analyzed in the frequency bands above 100 Hz. The sound wave cut-off frequency phenomenon in this very shallow area, having a sandy seafloor, had a significant impact on the sound propagation losses in the frequency bands below 80 Hz (Equation 6). All four tested models tended to underestimate the high-frequency spectral levels, while slightly overestimating the sound levels of low frequencies. This difference could be attributed to the unique characteristics of sound propagation in the very shallow environment of the research area with the depth of 10 meters. The variability of the modelled sound spectral density levels in the high end of the spectra can be explained by the variations of the measured ship radiated noise levels, attributable to the individual ship sound signatures and their different noise directivity.

The ship source spectral model, ECHO-JP, in addition to individual ship parameters, relied on the specific ship parameters, such as reference speed V_0 and reference length l_0 . Another model, SONIC, relied only on reference speed V_0 . These parameters are linked to the AIS data. As a result, the spectral levels obtained using the ECHO-JP model had the smallest RMSE in regard to ship noise measurement data, after the adjustment of these reference parameters to align with the local AIS data in the research area. Although, the ECHO-JP model, even after the adjustment of its reference parameters, still overestimated the SPLs of the tugboat, with the difference reaching up to 20.0 decibels. According to [6], the SONIC model can be applied effectively in the Baltic Sea region, although the reference speeds of cargo ships may not be accurately determined due to a shortage of AIS data for this type of ships in the Baltic Sea basin.

The determination of ship URN source levels, using the noise measurement data can be compromised by an experimental design and data processing approach, i.e., with a distance of CPA to a sound receiver less than a few hundred meters can have an impact on the resulting broadband sound levels, as the point source approximation is no longer valid. In the case of the recording setup location in proximity to the ship, underwater noise would originate from a number of point sources located in the ship's hull, having different separation distances from source to recording setup. On the other hand, with the larger distances from a recording setup to a CPA, the use of geometrical sound spreading laws without the consideration of surface effects during the estimation of source levels can result in substantial discrepancies whilst determining ship SPLs [3]. In this study, the CPA of all vessels varied between 203 and 251 meters, except for a small tanker having a length of 51 meters, where the CPA reached a distance of 121 m. To avoid compromising the acquired URN measurement results, the Normal Mode (NM) approximation model was used instead of geometrical sound propagation laws to model sound propagation losses and back-compute ship source levels. Although, the applied models are distinguished (Table 2) as underwater radiated noise source (URN) and monopole source level (MSL) models: ECHO-JP (MSL); RANDI-2017 (URN); RANDI (URN) and SONIC (MSL), the results show a good correlation between the measurement and modelling results (Table 3).

Uncertainties can also arise from determining the depth of the ship source, as a difference of 2 meters in the source depth can result in a difference of approximately 10 decibels in SPLs in low frequency bands [16]. It is noteworthy that the research area was of very shallow environment, where the source depth of 5.0 meters, used as the main origin of the ships noise, is located at the half of the waveguide depth.

The accuracy of the hydrophone calibration can affect the results of the measurements, and the precision of the calibration can vary depending on whether it was performed in field or laboratory conditions, in addition [3].

CONCLUSION

Evaluated different ship source spectral models in the very shallow marine environment reveal that source spectral models effectively can be applied in such marine environments.

The main conclusions of this study are:

- The best correlation between modelled and measured ship noise spectral levels was achieved with the ECHO-JP and the updated RANDI-2017 models.
- Assessed ship source models demonstrate a slight underestimation in their noise level predictions in the research area.
- Reference parameters of source models should be evaluated, using actual local ship AIS data before modelling noise levels.

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Conflicts of Interest The authors declare no conflict of interest

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