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DEMASK: Assessing the ships energy budget in the North Sea

DATE: 31 October 2025

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DOCUMENT: 03943

VERSION: 1.0

Subject: Estimation of the total half-space energy for the ships in the North Sea

1. Introduction and scope of the work

The DEMASK project addresses the need to forecast and assess potential future effects of noise pollution in the North Sea, as well as to develop tools for its mitigation. JASCO Applied Sciences (JASCO) is tasked with evaluating the acoustic energy budget of the North Sea and developing a scoring system for ranking anthropogenic noise sources. JASCO's involvement includes particularly the estimation of sound energy contributions to be selected from shipping, operational offshore wind turbines and airguns. This work focuses on estimating the acoustic energy budget (distribution of sound energy by source type) generated by shipping activities in the North Sea, calculations for different sources and forecast scenarios will be addressed at a later stage.

In Section 2, the free-field and half-space sound energy concepts are introduced. The vessel categories and their numbers in the North Sea are given in Section 3. This dataset is used for subsequent modelling efforts. Section 4 then describes the methodology used to calculate the source levels for these specific vessel categories. Section 5 is dedicated to the mathematical derivation of half-space energy, outlining the formulas used throughout the calculations in this task. In Section 6, modelling results are presented, including the half-space energy for individual vessels and the annually averaged number of vessels in the North Sea. Finally, Section 7 includes our conclusions from the study, along with practical recommendations for future research and noise mitigation strategies.

2. Free-field and half-space sound energies

In recent years, sound maps have provided insight into the contribution from a single source or source type to the overall energy budget. However, comparing the distributions from different sound sources to the overall sound level has often been done using various metrics. A more unified approach would facilitate consistent comparison.

The introduction of "free-field energy" provides a step towards a unified metric (Ainslie et al. 2009). This quantity is the total acoustic energy that would exist in the water if the same source were placed in an infinitely deep ocean. It is proportional to the source power and inversely proportional to the absorption coefficient of seawater. To account for the effect of the sea surface, in this work, the "half-space sound energy" is used in place of the free-field energy. The two approaches are closely related, the only difference being that the half-space energy models the single ship as a dipole emitting source while the free-field energy treats it as a monopole source. These quantities provide a convenient way of ranking the contribution to the sound field from qualitatively different natural and anthropogenic sources using the same metric. Even though they don't account for detailed sound propagations properties (unlike, for example, a sound map), they still provide a useful result in the form of a ranking by source type (Sertlek et al. 2019). If desired, such ranking estimates can be followed by more detailed calculations tailored to specific local conditions and visualizations of variation in space, time and spectrum for the sound energy distribution in real-world applications. In this way, mitigation efforts can be focused where they are most needed.

The analysis presented in this report aims to assess the half-space sound energy per vessel category and to provide insights into different contributions to the overall underwater acoustic energy.

3. Number of ships by category

The acoustic output of an individual ship, characterised by its source level, depends on the vessel type. TNO provided data on the number of ships for different categories (as specified by the Jomopans-Echo model (MacGillivray and de Jong 2021) discussed in Section 4), that transited the North Sea region for each month in 2020. The annual average number of vessels per category was also calculated and used to estimate the total acoustic energy contribution. A summary of the vessel categories, their monthly counts (averaged over the monthly count of vessels every 10 minutes intervals), and the annual average for the year 2020 is showed in Table 1 and its graphical representation is provided in Figure 1.

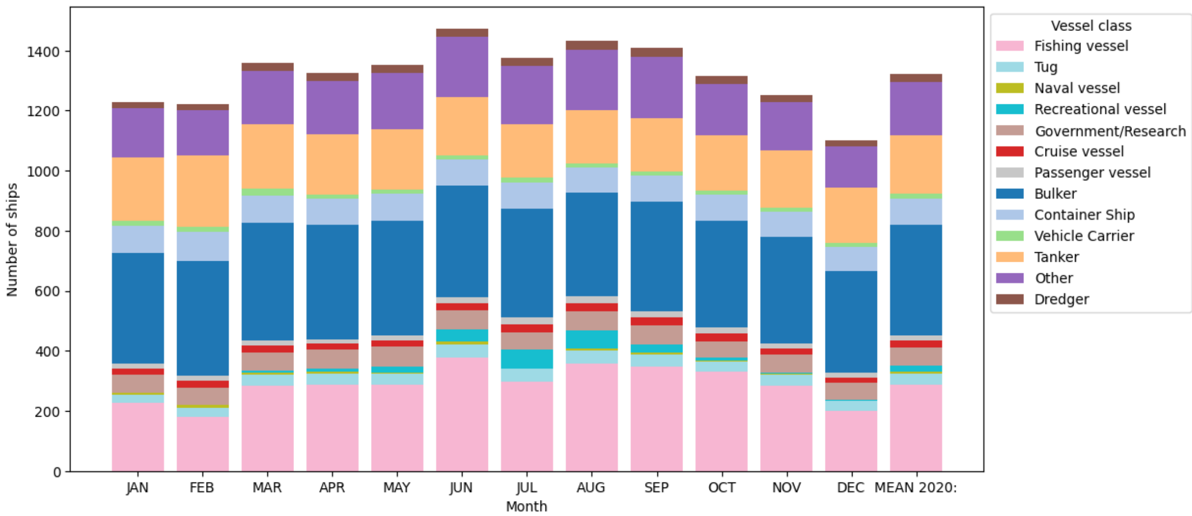

Figure 1. Cumulative bar representation of the monthly number of ships per category and corresponding average in 2020.

Table 1. Total monthly number of ships in the North Sea in 2020 and corresponding average

Vessel class	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	MEAN 2020
Fishing vessel	226	180	283	288	286	378	296	359	348	329	284	201	**288**
Tug	29	32	39	37	36	45	43	42	40	34	35	32	**37**
Naval vessel	4	7	6	4	5	8	3	6	7	5	4	2	**5**
Recreational vessel	3	3	5	11	22	40	61	60	26	10	5	3	**21**
Government / Research	59	55	62	63	66	65	59	65	62	55	58	54	**60**
Cruise vessel	21	25	23	19	20	22	27	27	27	26	21	20	**23**
Passenger vessel	16	16	15	14	16	20	23	24	21	18	17	15	**18**
Bulker	369	382	394	381	384	373	363	343	367	358	354	338	**367**
Container Ship	90	95	91	90	89	86	87	86	85	84	83	80	**87**
Vehicle Carrier	17	18	21	13	14	15	17	12	14	14	14	15	**15**
Tanker	211	237	215	199	202	194	177	177	178	184	192	183	**196**
Other	164	152	180	179	186	198	194	203	203	172	161	138	**178**
Dredger	19	19	25	26	28	29	27	30	31	28	24	20	**25**
TOTAL	1228	1221	1359	1326	1354	1474	1376	1433	1408	1317	1252	1102	**1321**

4. Source Levels

Source levels are estimated using the Jomopans-Echo model,(MacGillivray and de Jong 2021) which defines 13 different classes of vessels. Each class is associated with a reference spectrum, a reference speed, resulting from the best fit of the model over validation data, and a mean length of the measured ships for each class used for the development of the model. The reference speed and mean length values for each vessel class are listed in Table 2.

In the Jomopans-Echo article, vessel source levels are modelled as a function of vessel speed and length using the following equation:

$$L_{S,}(f,v,l,C) = L_{s,0}(f,C) + 60\log_{10}\left(\frac{v}{v_c}\right)\,\mathrm{dB} + 20\log_{10}\left(\frac{l}{l_0}\right)\,\mathrm{dB} \qquad (1)$$

where f is the frequency, v_c and l_0 are the reference speed and length shown in Table 2, v and l are the speed and length of the vessel, C is the vessel class. For the scope of this work, it was assumed that each ship from the same category had length and sailing speed respectively equal to the reference length (l_0) and the reference speed (v_c) associated to its category. $L_{s,0}(f,C)$ is the reference source level spectrum, in decibels, for vessel category C given by Equation (2), which is valid for all the categories except cargo ships

$$L_{S,0}(f,C) = K - 20\log_{10}(f_1)\,\mathrm{dB} - 10\log_{10}\left(\left(1-\frac{f}{f_1}\right)^2 + D^2\right)\,\mathrm{dB} \qquad (2)$$

Table 2. Summary of the parameters used in the Jomopans-Echo model for each vessel class. Vessel speeds are stated in knots (kn) and converted to metres per second (m/s). One knot is one nautical mile per hour = 1852/3600 m/s ≈ 0.514 m/s.

Vessel Class	v_c (kn)	v_c (m/s)	l_0 (m)
Fishing vessel	6.4	3.3	32
Tug	3.7	1.9	28
Naval vessel	11.1	5.7	79
Recreational vessel	10.6	5.5	45
Government/Research	8	4.1	58
Cruise vessel	17.1	8.8	268
Passenger vessel	9.7	5.0	52
Bulker	13.9	7.2	211
Container ship	18	9.3	294
Vehicle carrier	15.8	8.1	194
Tanker	12.4	6.4	186
Other	7.4	3.8	81
Dredger	9.5	4.9	128

Speed values in m/s are rounded to the first decimal place.

In Equation (2), $\mathrm{K} = 191\ \mathrm{dB}$, $f_1 = 480 \cdot \frac{v_{ref}}{v_c}\ \mathrm{Hz}$ with $v_{ref} = 1\ \mathrm{kn}$ and D = 4 for cruise vessels or D=3 for all the other categories. Vessels belonging to the category of cargo ships (ie, bulk carrier, container, vehicle carrier and tanker) undergo a different computation of the reference source levels spectrum at low frequencies to account for additional peaks that appear at frequencies < 100 Hz, and is described by Equation (3):

$$L_{S,0}(f < 100\ Hz, C) = K^{LF} - 40\log_{10}(f_1^{LF})\ \mathrm{dB} + 10\log_{10}(f)\ \mathrm{dB} + \\ -10\log_{10}\left(\left(1-\left(\frac{f}{f_1^{LF}}\right)^2\right)^2 + (D^{LF})^2\right)\ \mathrm{dB} \qquad (3)$$

Where K^{LF} = 208 dB, $f_1^{LF} = 600 \cdot \frac{v_{ref}}{v_c}\ \mathrm{Hz}$ and D^{LF} = 0.8.

In the end the source levels computed with Equation (1) are converted into decidecade source levels by adding the term $10\log_{10}\left(0.231\frac{f}{\mathrm{Hz}}\right)\mathrm{dB}$.

5. Mathematical derivation of the half-space energy

In this section we describe the methodologies for calculating the energy budget for anthropogenic noise caused by ships (Ainslie et al. 2009, Sertlek et al. 2019). We provide a brief extract, but a more detailed derivation can be found in the mentioned articles. In our implementation, we considered the effect of the critical surface angle on the average source power for the frequency f , which is expressed as (Ainslie et al. 2023)

$$W_f(f) = \frac{4\pi}{\rho c} F_{S,f}(f) \left[1 - \frac{\sin(2kz_s \sin(\psi))}{2kz_s \sin(\psi)}\right] \sin(\psi) \qquad (4)$$

where $F_{S,f}(f) = \frac{p_0^2 r_0^2}{\Delta f_0} 10^{\frac{SL(f)}{10\text{ dB}}} \left[\frac{\text{Pa}^2 m^2}{Hz}\right]$ is the source power spectral density calculated with reference values of $p_0 = 1\ \mu Pa;\ r_0 = 1\ m;\ \Delta f = 1\ Hz$, and with $SL(f)$ being the source level at frequency f; ψ is the critical surface angle set equal to $\psi = 0.2\ rad$; $k = \frac{2\pi f}{c}$ is the acoustic wavenumber; z_s the source depth; c the sound speed in water and ρ the water density. The source depth is assumed as 6 m for all vessel categories. The source power expressed in Equation (4), averaged over a frequency band, is used to calculate the sound energy radiated by *N* ships of same class. Equation (5) provides the formula for computing the half-space energy using the average source power at the central frequency f. We also denoted as $\alpha(f) = \alpha_{Thorp}(f) + \alpha_{min}$ the volume absorption coefficient given by the contribution of two terms: the first given by the Horton-Thorp formula (Urick 1975, Fisher and Simmons 1977), and the second of empirical nature to account for attenuation at frequencies smaller than 200 Hz and set equal to $\alpha_{min} = 0.3 \frac{Np}{Mm}$.

$$E(f) = N \frac{W(f)}{2c\alpha(f)}. \qquad (5)$$

6. Results

In this section, we present the results obtained by using Equation (5) for each vessel category. We begin by showing the half-space energy spectra for a single vessel in each category, followed by the total energy contribution based on the average number of ships in 2020.

Figure 2 shows the half-space energy spectra for a single ship from each category defined in the JOMOPANS-Echo model. This figure highlights container ships as having the highest individual energy contribution. However, when the average number of vessels per category in 2020 (as shown in Table 1) is considered, bulk carriers, container ships and tankers emerge as the dominant contributors to the overall acoustic energy budget. This is shown in Figure 3, which presents the energy spectra scaled by the average number of vessels in each category, as well as the total energy summed across all categories for each decidecade frequency band. The plot clearly shows that for vessels belonging to the Cargo category (bulkers, container ships, vehicle carriers and tankers), the frequency bands close to 40-50 Hz dominate the overall energy contribution, while for the remaining categories, the frequency bands close to 150-200 Hz give the strongest contribution to the energy levels. The characteristic hump in the source levels of cargo-type vessels (as expected due to Eq. (3)) is clearly reflected in the corresponding sound energy densities. The contribution to the energy from frequencies above ~600 Hz is small by comparison. However, when sediment and bathymetry are considered in the shallow water depths of the North Sea, the frequency distribution of sound energy will differ from calculations in a half-space that does not account for these factors. Sound energy contributions below the cut-off frequency could be small, as the seabed's properties and bathymetry affect how low-frequency sound propagates.

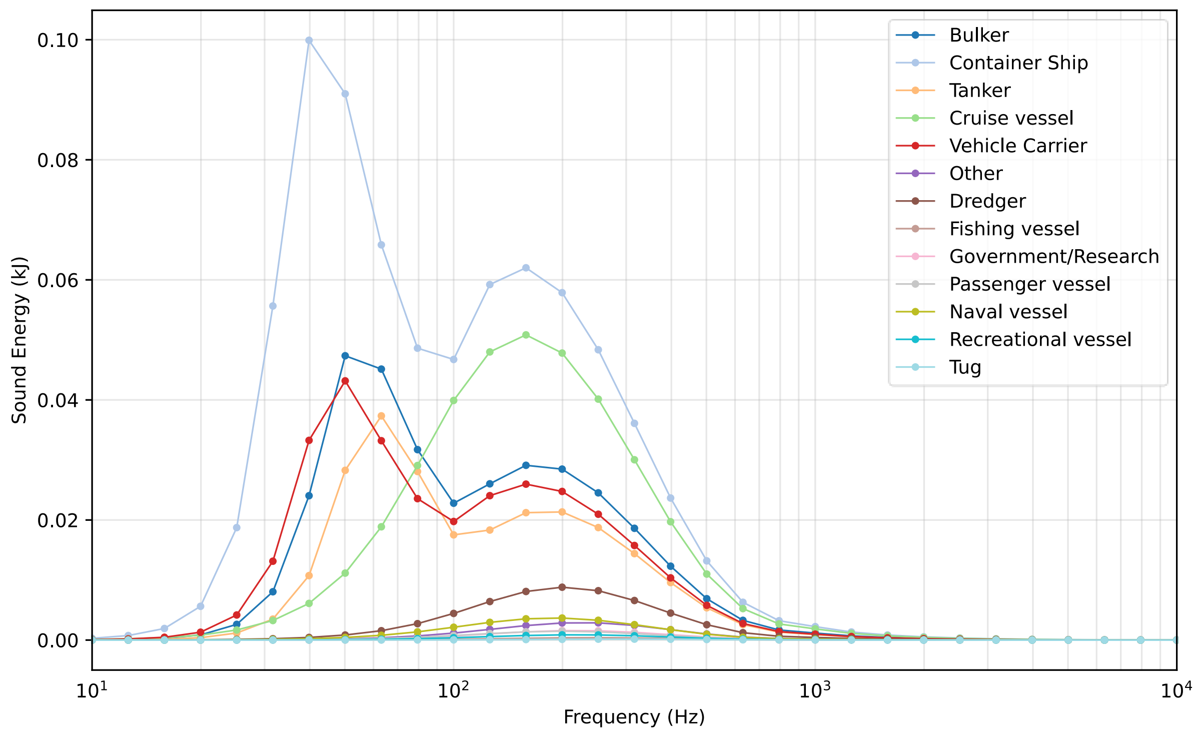

Figure 2. Decidecade half-space energy spectra for a single vessel of each vessel category from the Jomopans-Echo classification.

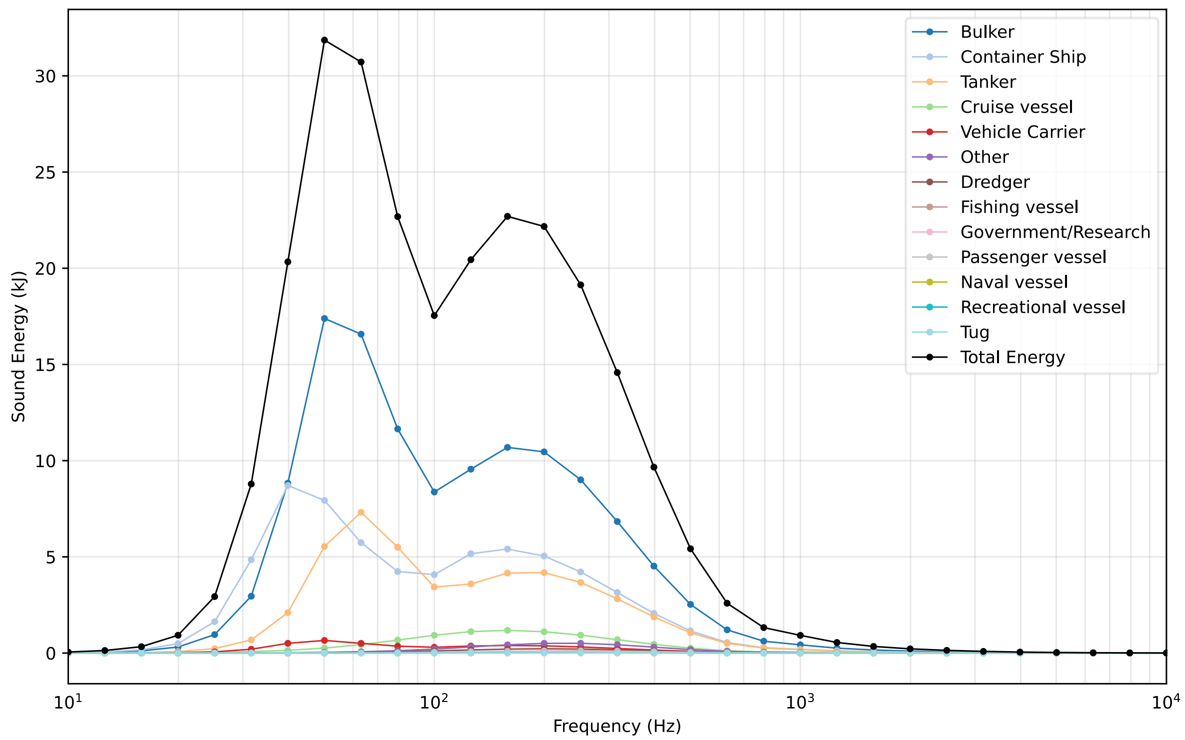

Figure 3. Decidecade half-space energy spectra of the annual average number of ships for each vessel category from Jomopans-Echo classification.

Table 3 summarizes the broadband levels extracted from Figure 2 which include the energy spectra generated by a single ship for each category, while Table 4 summarizes the broadband levels extracted from Figure 3 which includes the energy levels when taking into account the total number of ship for each category. The sound energies are listed for different decade band based on (ISO 7605:2025).

- Band B: 8.9 Hz to 89.1 Hz
- Band C: 89.1 Hz to 891.3 Hz
- Band D: 891.3 Hz to 8912.5 Hz

Table 4 shows that bulk carriers, container ships, and tankers contribute an order of magnitude more energy than the other vessel categories.

Table 3. Broadband energy levels (expressed in J) of a single ship for each vessel category

Ship category	Sound energy (J)			
	8.9 Hz to 89.1 Hz (Band B)	89.1 Hz to 891.3 Hz (Band C)	891.3 Hz to 8912.5 Hz (Band D)	8.9 Hz to 8912.5 Hz (Band BD)
Bulker	160	174	3.01	337
Container Ship	388	357	5.78	751
Tanker	110	130	2.35	242
Cruise vessel	71.7	295	4.81	372
Vehicle Carrier	153	152	2.53	307
Other	1.49	17.0	0.46	19.0
Dredger	6.02	51.5	1.12	58.6
Fishing vessel	0.17	2.32	0.07	2.57
Government/Research	0.89	9.31	0.23	10.4
Passenger vessel	1.03	8.62	0.19	9.84
Naval vessel	3.06	21.6	0.43	25.1
Recreational vessel	0.52	5.20	0.14	5.86
Tug	0.04	0.93	0.06	1.03

Table 4. Broadband energy levels (expressed in kJ) of the monthly average number of ships for each vessel category

Ship category	Sound energy (kJ)			
	8.9 Hz to 89.1 Hz (Band B)	89.1 Hz to 891.3 Hz (Band C)	891.3 Hz to 8912.5 Hz (Band D)	8.9 Hz to 8912.5 Hz (Band BD)
Bulker	58.8	63.8	1.11	124
Container Ship	33.9	31.1	0.51	65.5
Tanker	21.5	25.5	0.46	47.5
Cruise vessel	1.66	6.86	0.11	8.63
Vehicle Carrier	2.32	2.31	0.04	4.67
Other	0.26	3.02	0.08	3.37
Dredger	0.15	1.31	0.03	1.49
Fishing vessel	0.05	0.67	0.02	0.74
Government/Research	0.05	0.56	0.01	0.63
Passenger vessel	0.02	0.15	<0.01	0.18
Naval vessel	0.02	0.11	<0.01	0.13
Recreational vessel	0.01	0.11	<0.01	0.12
Tug	<0.01	0.03	<0.01	0.04
Total	118.76	135.57	2.37	256.70

7. Conclusions and future works

The largest contribution to the half-space sound energy budget of the North Sea is from bulk carriers, container ships and tankers, in decreasing order. Variations in AIS data quality and coverage directly influence the number of vessels, which is a critical parameter for half-space sound energy calculations.

Analysis also indicates that most of the broadband sound energy originates from Band B and C. For vessels classified as “cargo” (bulk carriers, container ships, vehicle carriers and tankers), frequency Bands B and C give similar contributions to the overall sound energy. In contrast, non-cargo vessels present a dominant contribution in Band C. This pattern is reflected in the spectra showed in Figure 3 where a hump is visible for cargo vessels. This hump would likely be less visible if the energy were calculated from the sound maps using more detailed source inputs such as the distribution of vessel speeds and lengths, along with environmental factors that influence acoustic propagation. None of which are accounted for in the energy formulas used for the scope of this work.

Across all vessel categories, Band D has the least amount of sound energy, typically accounting for less than 2% of the total broadband energy, while frequencies above 10 kHz account were excluded from the analysis because they accounted for less than 0.02% of the total energy.

In future work, this analysis can be expanded taking into consideration the following points:

- To verify the ranking resulting from the analysis, the dominance of vessel categories to the overall acoustic energy should be confirmed by computing shallow water energy associated to each category.
- To assess the biological implications of these acoustic contributions, it is essential to consider the hearing sensitivity of aquatic animal groups. Vessels with significant energy contribution in frequency band B may affect low-frequency hearing marine mammals, as classified by (Southall et al. 2019). Conversely, greater Band C emissions are more likely to impact high-frequency hearing species. However, further analysis using hearing weighting curves is advisable to accurately evaluate the relative contributions of each frequency band across vessel categories.
- The sound energy densities can be calculated for other anthropogenic sound sources (e.g., seismic airguns, offshore wind farms) and compared with these results.
- Sound energies could be also used to quantify the effect of mitigation measures for the forecast modelling scenarios.

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