AECOM

Shannon Technology and Energy Park (STEP) Power Plant

Appendix A7A.3: Noise Modelling Report

Shannon LNG Limited

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Vysus Group

Underwater Noise from Shannon Technology and Energy Park

Prediction of underwater noise

Report Information

Underwater Noise from Shannon Technology and Energy Park: Prediction of underwater noise

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Document control (Vysus Group internal use):

Release	Prepared by	Date	Comments
0	RSL	22 Oct 2020	First issue for client
1	RSL	6 Nov 2020	Included sea water pumps as noise sources
2	PTA, ASZ	23 Dec 2020	Update with FSRU data and a 5th scenario
3	RSL, PTA	21 May 2021	Included measurements and SEA modelling for FSRU source level
4	PTA, RSL	16 Jul 2021	Inclusion of AECOM comments, addition of extra construction scenarios, inclusion of more species
5	RSL	27 July 2021	Slight correction of intro and minor typos.
6	RSL	10 Aug 2021	Client's comments to descriptions of scenarios B and E, and App. B

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Executive Summary

In relation to a planned Liquified Natural Gas (LNG) import terminal and power plant at Shannon Estuary in Ireland, the Shannon Technology and Energy Park (STEP), the underwater noise was predicted by Vysus Group for the following scenarios in the construction and operation phases:

Construction phase:

- C1 Impact pile driving
- C2 Vibratory pile driving, including support vessels
- C3 Drilling for socket piles, including support vessels
- C4 Blasting – on land

Operation Phase:

- A FSRU (Floating Storage and Regasification Unit) as the only noise source
- B FSRU together with an offloading LNG carrier, including 1 tug in idling mode close to the carrier
- D FSRU together with approaching LNG carrier, including 4 sailing tugs
- E FSRU together with berthing LNG carrier, including 4 engaged tugs, a general cargo ship sailing in the middle of the Estuary, and ship moored at Moneypoint.

The noise was modelling along multiple transects in an “n x 2D” approach, using a Parabolic Equation (PE) model for low to medium frequencies as well as a Beam Tracing model for high frequencies. This approach accounts for range dependent bathymetry, multi-layered seabed, and frequency dependence. The predicted noise was compared to sets of acoustic criteria, relating to bottlenose dolphins, harbour & grey seals, harbour porpoises, salmon, twaite shads, marine and river lamp-rays, as recommended for the study by LGL Ecological Research Associates Inc. Evaluation of these criteria led to tables of distances (and corresponding areas) to threshold. These tables are presented in the report and have been passed on to LGL for detailed assessment of the potential acoustic impact on the listed species. This biological assessment follows in a separate report.

For the best possible estimate of the FSRU’s source level, underwater noise measurements were taken on the Golar Freeze FSRU on a site in Jamaica, and the corresponding source level was determined. Further, the underwater noise source level of an FSRU (Golar Igloo) was modelled using state-of-the-art Statistical Energy Analysis (SEA) software VAOne. Based on these, a conservative source level spectrum was derived and applied for the Shannon LNG terminal study

Furthermore, measurements of ambient noise were taken on-site on two days in May 2020 as spot-checks. Statistical analyses of the ambient noise are presented in the report and are used for coarse comparison with the predicted underwater noise. In particular, a measured event of a passing ferry was considered, and it was found that the predicted noise contribution from the FSRU on its own (scenario A) or with the offloading carrier (scenario B) was less than that of the ferry except for ranges within 1200 m.

Vysus Group and Lloyd’s Register

Following a strategic carve-out from the Lloyd’s Register (LR) Group, LR’s Energy business is now Vysus Group, a standalone engineering and technical consultancy, offering specialist asset performance, risk management and project management expertise across complex industrial assets, energy assets (oil and gas, nuclear, renewables), the energy transition, rail infrastructure, and marine.

The current study was initially awarded to Lloyd's Register Consulting – Energy A/S, and subsequently transferred to Vysus Denmark A/S, which is a subsidiary of Vysus Group.

Introduction

1 Introduction

In the context of the future construction of an LNG terminal and power plant in the Lower River Shannon Special Area of Conservation (SAC) and River Fergus Special Area of Protection, Shannon LNG Limited has requested Vysus Denmark A/S (hereafter VG) to perform prediction of underwater noise for a variety of noise source scenarios. The site considered is a Floating Storage and Regasification Unit (FSRU) nearshore terminal for Liquified Natural Gas (LNG), the Shannon Technology and Energy Park (STEP), located near Tarbert and Ardmore Point in the Shannon Estuary, County Kerry, Western Ireland.

This study concerns establishment of an FSRU, including construction of the associated jetty, as well as an approaching LNG carrier, and ships sailing and berthed in the Estuary.

This report presents methodology and findings of the underwater acoustic modelling, as well as on-site measurements of ambient underwater noise performed in May 2020 and source level measurements in Jamaica in March 2021. The modelling results have been transferred to VG's sub-contractor LGL Ecological Research Associates, Inc. (www.lgl.com, hereafter LGL) for subsequent, biological sound exposure assessment. LGL's assessment will follow in a separate report. Furthermore, the acoustic criteria applied in this report were prepared by LGL.

2 Site description

2.1 Location overview and bathymetry

Figure 1 and Figure 2 show location overviews of the section of the Shannon Estuary near the LNG terminal. The indicated positions A, B, C and M are those assumed as noise source positions in this study.

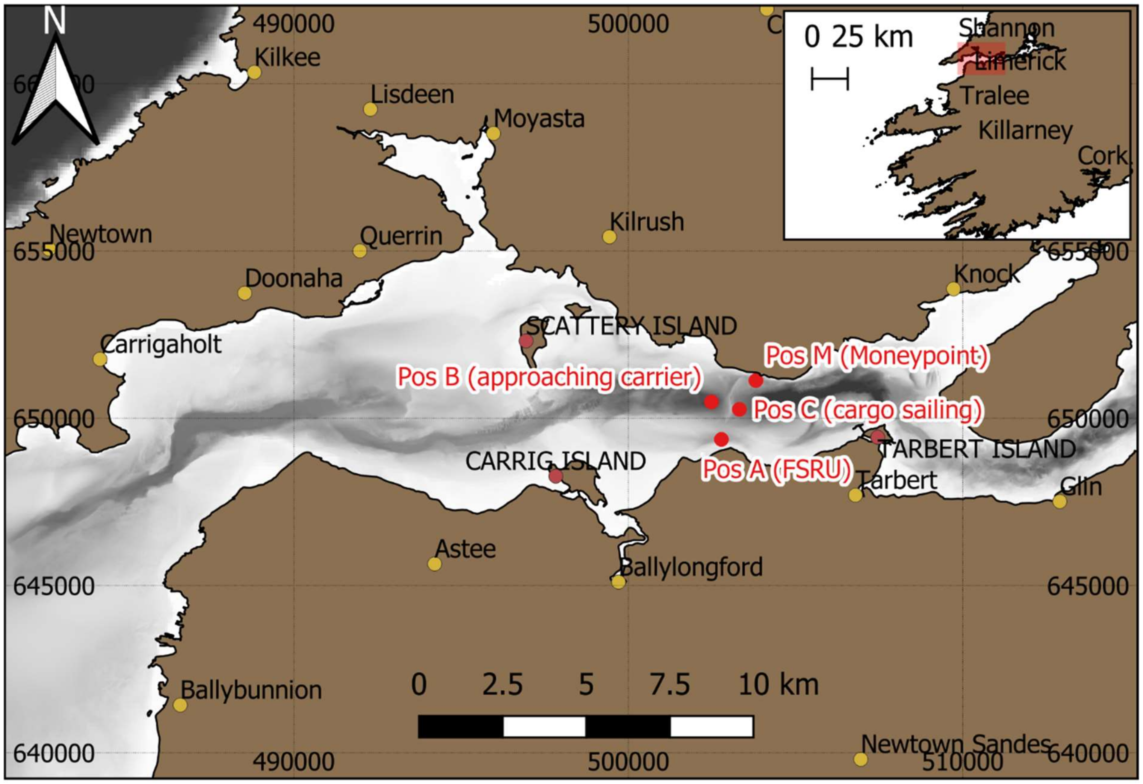

Figure 1. Situation map and location of main noise sources. Projection is IRENET95/Irish Transverse Mercator. Land polygons ©OpenStreetMap contributors [1]. Placename data from OSi [2] under standard CC license [3].

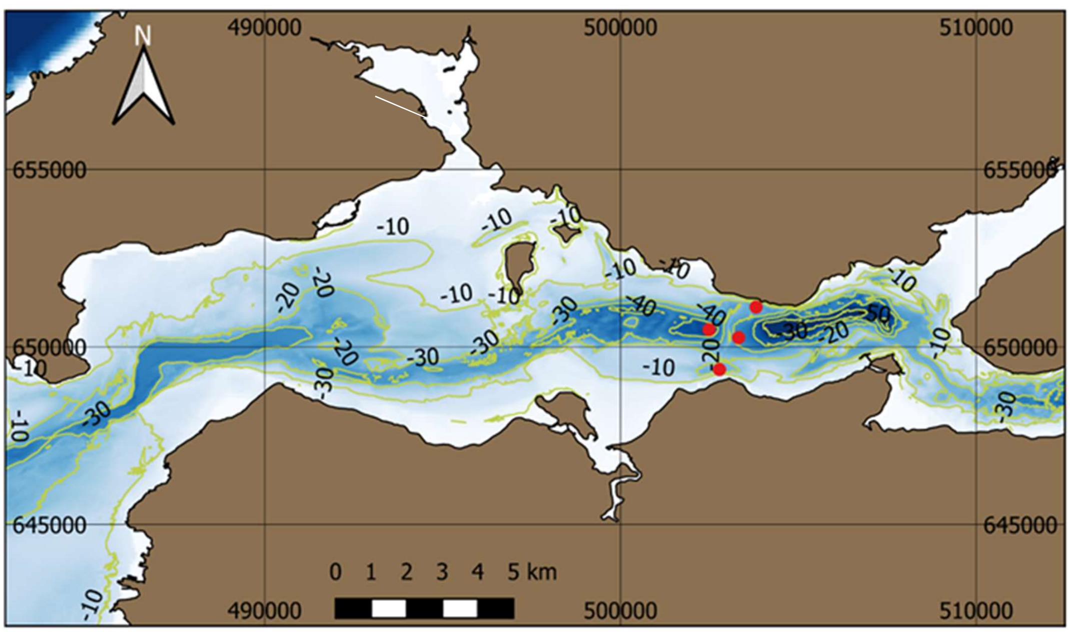

Figure 2. Location water depths overview, red spots indicate source locations. Projection is IRENET95/Irish Transverse Mercator, and water depth is referred to LAT. Land polygons ©OpenStreetMap contributors [1]. For bathymetry sources, see main text.

Position A is at the FSRU location of the jetty, while Position B is in deeper water and used for the source location of the approaching LNG carrier. Position C is the position used for the general cargo ship sailing in the middle of the estuary and position M is the location of the berthed ship at Moneypoint Power station. It is seen from Figure 2 that the water depth is generally within approximately 50 m, with the deepest region in the middle of the estuary.

The digital bathymetry data was obtained from:

- EMODnet: As NetCDF file with horizontal resolution of one sixteenth arc minute, which is approximately 115 m [1]
- INFOMAR/Geological Survey, Ireland (GSI): Merged GeoTiff files[1)] with horizontal resolution 5 and 10 m, respectively [5]

Bathymetry data was obtained as referenced to LAT, but converted to MHWS for use in the project, see Section 2.3.

A drawing of the LNG import jetty is shown in Figure 3. The jetty extends approximately 320 m out from the shore, to reach local deep water in the order of 20 m depth. As seen, the FSRU is moored at dolphins at a platform located at the end of the jetty, with an orientation nearly parallel to the shore.

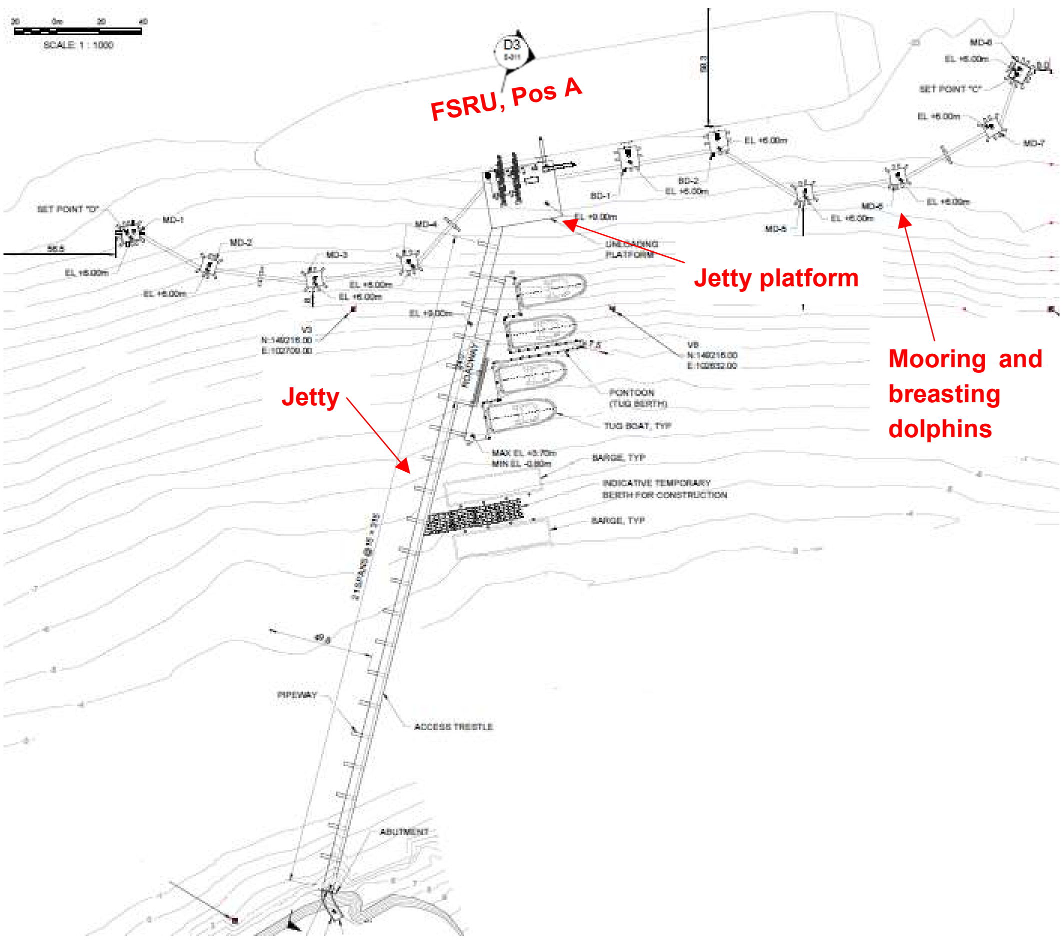

Figure 3. LNG import jetty and Floating Storage and Regasification Unit (FSRU). Pos A, corresponding to the FSRU location, is the source location used for the acoustic modelling, see Figure 1.

1) Contains Irish Publish Sector Data (Geological Survey) licensed under a Creative Commons Attribution 4.0 International (CC BY 4.0) license [3].

2.2 Bathymetry

Range-dependent bathymetry can strongly influence the sound transmission loss over range. Bathymetry slope (either downward or upward) affects the horizontal sound propagation in shallow water mainly by two features:

- Change in water column height
- Change in the grazing angles of sound rays with the sea bottom and sea surface

These features combine with the shallow water low-frequency cut-off phenomenon (Section 2.3) and the bottom loss dependency on grazing angle. The consequence is a general tendency that downward slopes lead to increased noise levels ("downslope enhancement") and vice versa for upward slopes.

A recent parameter sensitivity study involving bathymetry is given in [6] for offshore wind on the US Atlantic Coast. It was found ([6] Sect. 7.3 Sensitivity Study) that the combination of local water depth and bathymetry was the environmental parameter with the highest impact on the acoustic propagation. The second most influential environmental parameter was found to be the seabed geoacoustic properties. These findings are in line with those of [7] for a more general study of underwater noise modelling.

2.3 Tide levels

An important feature of shallow water sound propagation is the shallow water low-frequency cutoff phenomenon [8]. It implies that the shallow-water channel supports propagation of frequency components above a certain cutoff frequency. At the same time, frequency components below this cutoff "leak" to the seabed, causing quick attenuation over horizontal propagation range. In a practical sense, the shallow water cutoff phenomenon may be seen as a high-pass filter, attenuating frequencies below cutoff.

According to the Metocean Analysis and Coastal Modelling report [9], there is a significant tidal variation at the site. As a larger vertical water volume generally leads to higher noise levels, it was decided to base this study on a high-water scenario: MHWS (Mean High Water Springs).

Since digital bathymetry data was obtained as LAT (Lowest Astronomical Tide), a correction was made. With reference to Table 1 it was decided to add 5 m to the LAT-based water depths for use in the acoustic modelling.

Description	Datum	Jetty South	Tarbert
Mean High Water Springs	MHWS	4.9 m	5.0 m
Mean High Water Neaps	MHWN	3.8 m	3.8 m
Mean Low Water Neaps	MLWN	1.7 m	1.7 m
Mean Low Water Springs	MLWS	0.6 m	0.5 m

Table 1. Tide levels (referred to Chart Datum, i.e. LAT) from [8]. Tarbert town is located approximately 4 km east of the Shannon LNG site.

2.4 Seabed properties

As mentioned in Section 2.2, the geoacoustic properties of the seabed have a strong influence on underwater acoustic propagation in shallow water [6],[7]. Given the shallowness of the considered part of the Shannon Estuary, significant efforts were assigned to deriving a geoacoustic model.

The basis for the derivation was a comprehensive site ground investigation report [10]. This borehole survey report included location map extracts, borehole co-ordinates, borehole logs, field test results, laboratory test results. The report was examined by VG's geophysicists to estimate compressional wave sound speed c_p [m/s], shear wave sound speed c_s [m/s], and density values [kg/m^3] for individual lithological units identified within boreholes and hence derive likely compressional and shear wave attenuation [dB/wavelength] figures for layer models representative of the area.

Outline of the analysis approach:

- Lab test data noted for:
  - Bulk and Dry Density
  - Moisture content
  - Compressional and shear wave speeds c_p and c_s
  - SPT (N) count
- Shear wave speed c_s estimated from Dry Density values [11]
- Bulk Density estimated from c_p values - Gardner's Equation [12]
- Bulk density estimated from SPT 'N' count [11]
- Compressional wave speed c_p estimated from assorted c_p observations and estimations – Catagna's Equation [13]
- Gross estimate of sand content from BH logs
  - Compared with moisture content values
  - Gross estimate of Bulk Density using Gassman's fluid substitution calculator [14]
- Bulk Density values compared, collated and edited from all sources
- C_p values compared, collated and edited from all sources
- C_s values taken from lab-test data direct measurements or estimated from [8]
- Compressional wave attenuation values α_p estimated from c_p and density [8],[15]
- Shear wave attenuation values estimated from c_s and density [8]

The investigation undertaken by VG's geophysicists lead to the following observations:

- Boreholes split into two main groups: East and West
- The Western group displayed a reasonable correlation between individual boreholes
- Boreholes of the Eastern group are apparently highly heterogeneous within the unconsolidated sections overlying bedrock

On this basis, for the acoustic modelling it was decided to apply the geoacoustic model corresponding to the Western boreholes across all of the estuary. The properties are given in Table 2.

Layer, depth below seafloor	Description	Density	Compressional wave speed	Compressional wave attenuation	Shear wave speed	Shear wave attenuation
		ρ [kg/m^3]	c_p [m/s]	α_p [dB/λ]	c_s [m/s]	α_s [dB/λ]
0-4 m	Sandy, clayey gravel	1900	1500	0.9	230	2
4-12 m	Gravelly clay	2100	2019	0.4	275	1.3
12-14 m	Sandy, clayey gravel	2000	1627	0.8	240	2.5
14-30 m	Bedrock	2700	4600	0.1	2340	0.2

Table 2. Geoacoustic model for Shannon Estuary seabed.

It is noted that the seabed down to 14 m depth has rather low shear wave speed (less than 300 m/s), while the bedrock layer below 14 m has high shear wave speed (above 2300 m/s). For seabeds with low shear wave speeds, the shear properties can usually be ignored in the acoustic model. However, in the opposite case, some conversion from the sound wave, i.e. compressional wave to shear wave will take place. This can be regarded as a loss, since the converted energy is no longer contributing to the sound wave (i.e. compressional wave) in the water.

2.5 Sound speed profile in water

The speed of sound c [m/s] in water depends primarily on temperature, salinity, and depth (i.e. hydrostatic pressure) [17]:

$c = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 + (1.34 - 0.010T)(S - 35) + 0.016D$

Here, T [ºC] is temperature, S [parts per thousand] is salinity, and D [m] is water depth. The temperature generally has greater influence than salinity.

For shallow water regions, the speed of sound may either be nearly constant over depth for a well-mixed water column or show some dependence on depth. Typically, in a warm period, the upper part of the water column is heated up, causing increased sound speed here. Similarly, wind tends to mix the water column, leading to near-constant temperature and sound speed over depth.

For the present study, several profile measurements of temperature and salinity were downloaded from the NODC database [18], [19] for locations near the Shannon LNG site. Data were available for 2003-2011, and representative examples of sound speed profiles are plotted in Figure 4. Here, red profiles correspond to late summer, golden to summer, blue to winter, lilac to autumn. The dashed green profile is the one assumed for the present study based on the considerations below:

The water sound speed profile impacts the sound propagation in mainly two ways:

- Refraction

  The sound tends to bend towards the water depth having lowest sound speed, due to acoustic refraction. As a consequence, profiles with decreasing sound speed for increasing depth are downward refracting. This will generally lead to more sound interaction with the seabed materials, and increased losses over propagation range. On the contrary, upward refracting or (near-)vertical profiles lead to a smaller amount of bottom interaction.

- Coupling to seabed

  When the (compressional) sound speeds of the water and the upper seabed layers are close in range, a relatively large amount of acoustic energy is absorbed into the seabed. Seen from receiver positions in the water, this scenario has relatively strong attenuation over range. On the contrary, when water sound speed and seabed sound speed are very different, more energy is reflected at the seafloor, leading to higher noise levels in the water.

Based on the above discussion and the database sound speed profiles, it was decided to assume a near-constant sound speed profile of approximately 1485 m/s, shown as the dashed green line in Figure 4. This represents a conservative choice, as profiles corresponding to stratified conditions or significantly higher temperatures would lead to lower noise levels

In shallow water, the bathymetry and seabed acoustic properties generally constitute the more influential propagation parameters [6],[20].

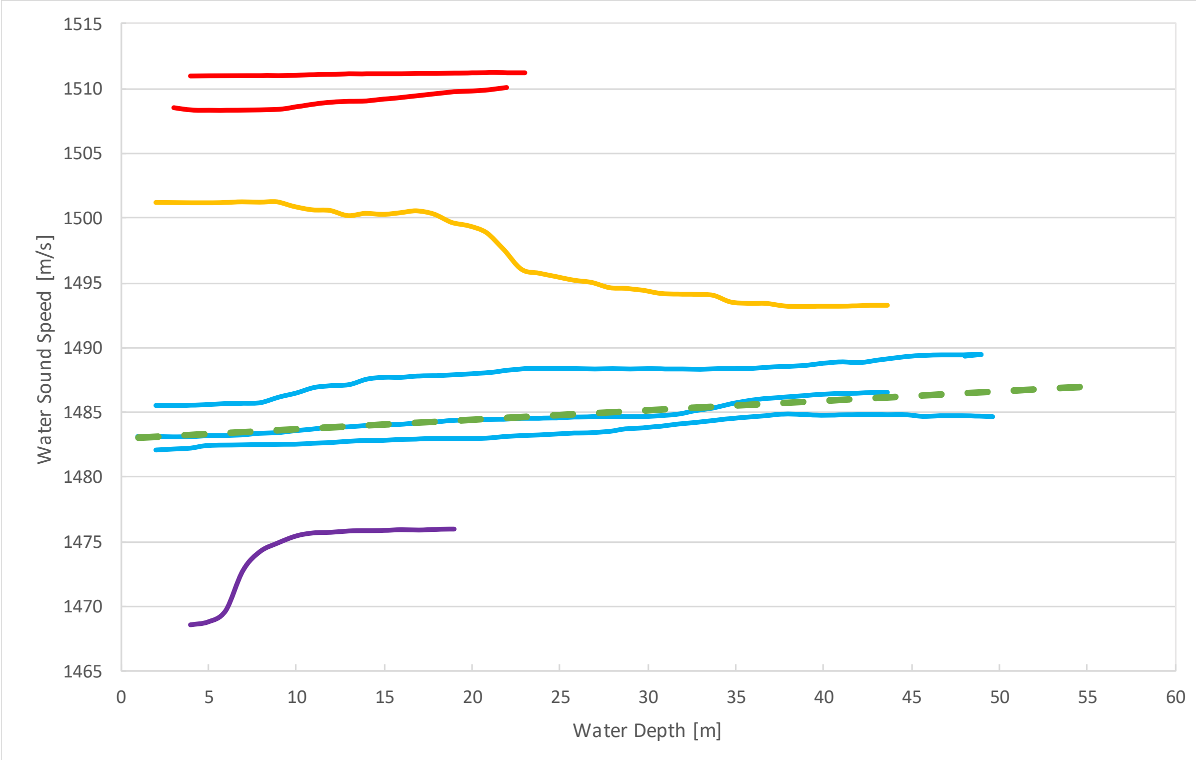

Figure 4. Sound speed profiles in water. Dashed green line is the profile applied for the underwater acoustic modelling. See the text for other colours.

2.6 Sound absorption of sea water

As sound propagates through sea water, it experiences attenuation due to volume absorption of the water. The related losses are proportional to frequency and travelled distance of the sound wave, see the following simplified formula for absorption α_{water} [dB/km] where FkHz is frequency in kHz [8]:

$$\alpha_{water} = 3.3 \cdot 10^{-3} + \frac{0.11FkHz^2}{1 + FkHz^2} + \frac{44FkHz^2}{4100 + FkHz^2} + 3.0 \cdot 10^{-4} \cdot FkHz^2$$

In engineering terms this loss feature only becomes significant above some kHz, and for long ranges.

3 Underwater acoustic metrics and weighting functions

3.1 Level metrics

Multiple level metrics are defined to quantify underwater sound. Generally, dB levels of field quantities F (e.g. pressure, particle displacement...) are defined as [21]:

$$L_F = 20 \log \frac{F}{F_0} \text{ dB}$$

Here, F_0 is the reference value, and "log" is the logarithm to base 10. Similarly, level metrics of power quantities W (e.g. sound exposure) are defined as:

$$L_W = 10 \log \frac{W}{W_0} \text{ dB}$$

Sound pressure level

From this, sound pressure level L_p becomes:

$$L_p = 20\log\frac{p}{p_0}\ \mathrm{dB}$$

For underwater sound pressure, the reference is p_0= 1 µPa.

0-to-peak level

The "0-to-peak" level $L_{p,0\text{-}pk}$ is the single largest deviation of the sound pressure from zero, i.e. max(|p(t)|). Note that this may occur with either a negative or positive value of the sound pressure.

RMS or Leq sound pressure level

Particularly for continuous noise, an energy-based time averaged level is often used. It is the Root Mean Square (RMS) taken over a time interval T=t_2-t_1 [s], and the related level in dB is often referred to as equivalent continuous sound pressure level", or L_{eqT} over time interval T.

Starting from the Mean Square average pressure p_{ms}, [Pa^2] the RMS pressure p_{rms} [Pa] follows as:

$$p_{ms} = \overline{p^2} = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} p^2(t)dt$$

$$p_{rms} = \sqrt{p_{MS}}$$

The RMS sound pressure level in dB is then:

$$L_{p,rms} = 20\log\frac{p_{rms}}{p_0}\ \mathrm{dB}$$

As before, the reference value for underwater sound pressure is p_0=1 µPa.

Sound exposure level

For assessment of piling underwater noise, the sound exposure level (SEL) L_E [1µPa^{2}s] is a common metric. For a single hammer strike event, one starts from the sound exposure E [Pa^{2}s], also called the time-integrated squared sound pressure, which is based on the sound pressure p [Pa] as:

$E = \int_{t_1}^{t_2} p^2(t)\,dt$ in units of Pa^{2}s, based on pulse time duration T=t_2-t_1 [s]. Usually, t_1 and t_2 are taken as the times at which 5% and 95% of the event's sound exposure has been reached.

The dB level for SEL is then:

$$L_E = 10\log\frac{E}{E_0}\ \mathrm{dB}$$

The reference value for underwater sound exposure is $E_0=(p_0)^2T_0$ = 1 µPa^{2}s as T_0=1 s.

SEL considering a single hammer strike event is called a single-strike SEL, or SEL_{ss}.

Cumulative sound exposure level

Sound exposure level based on multiple events is called cumulative sound exposure level, or SEL_{cum}. Cumulative sound exposure level is calculated by summing the sound exposure (linear units) of each event and converting to 1 µPa^{2}s (see e.g.[22]):

$$L_{E,cum} = 10\log\sum_{i=1}^{n} 10^{\frac{L_{E,i}}{10}}\ \mathrm{dB}$$

For a number of n equal events, SEL_{cum} is SEL_{ss}+10Log(n).

It is common to assess the cumulative sound exposure level for a period of 24 hours, $L_{E,24h}$ [23].

Sound intensity and Transmission loss

Sound intensity is the average rate of flow of energy through a unit area normal to the direction of propagation. Considering the magnitude of a propagating plane wave, sound intensity I [W/m^2] is:

$$I = \frac{p_{rms}^2}{\rho_0 c}$$

Here, p_{RMS} is the RMS sound pressure [Pa], ρ_0 is the density [kg/m^3], and c is the sound speed.

The sound transmission loss describes the change in signal strength with range, defined as the ratio in dB between the acoustic intensity I at a field point and the intensity I_{1m} at 1 m:

$$TL = 10\log_{10}\frac{I}{I_{1m}} = 20\log_{10}\frac{p}{p_{1m}}$$

Here, in the last part p [Pa] is the sound pressure at a field point, and p_{1m} is the sound pressure at 1 metre distance from the source.

3.2 Frequency spectra and auditory weighting functions

In addition to single-value metrics as described in Section 3.1, sound is often described in terms of frequency spectra. These describe the sound energy distribution as a function of frequency, the latter having units of "cycle per s", which is [Hz]. Frequency spectra are either constant bandwidth, or constant percentage bandwidth. The most common constant percentage bandwidth spectrum is a 1/3-octave spectrum. Alternatively, analysis may be done in narrowband frequency bands (typically "FFT" type), having constant bandwidth.

For the purpose of assessing impact on differentiated sea mammals, auditory weighting functions were defined by the National Marine Fisheries Service (USA) [23]. These reflect the different hearing properties categorized for 5 specific groups of animals, see weighting curves in Figure 5.

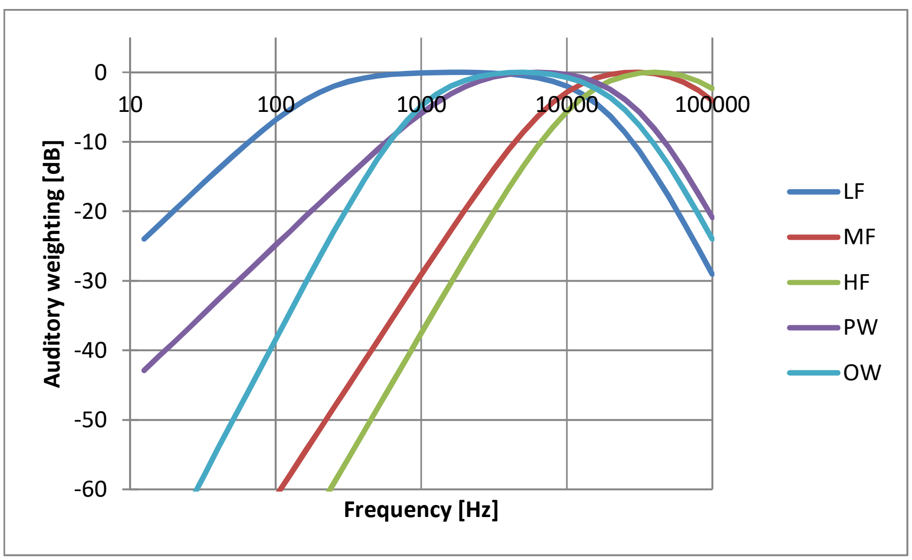

Figure 5. Frequency weighting functions for hearing groups as defined in [23]. See Table 3 for abbreviations.

The hearing groups are listed in Table 3. Of these, the Mid-frequency (MF) cetaceans, High-frequency (HF) cetaceans, and the Phocid pinnipeds (PW) are considered in this study.

Abbreviation	Hearing group	Weighted metric for sound exposure
LF	Low-frequency cetaceans	$L_{E,p,LF}$
MF	Mid-frequency cetaceans	$L_{E,p,MF}$
HF	High-frequency cetaceans	$L_{E,p,HF}$
PW	Phocid pinnipeds (underwater)	$L_{E,p,PW}$

Table 3. Overview of marine mammal hearing groups [23].

The weighting functions presented here are mostly used for relating sound exposure levels to the various hearing groups. Hence, sound exposure levels without applied frequency weighting are referred to as $L_{E,flat}$. Applying the frequency weighting functions to the underlying spectra of $L_{E,flat}$ produce a new set of weighted sound exposure levels as listed in the rightmost column of Table 3. Similarly, unweighted levels of RMS sound pressure $L_{p,rsm,flat}$ can be combined with the weighting functions to account for the hearing abilities of the corresponding hearing group.

4 Measurements of ambient underwater noise

The ambient underwater noise level in the area was investigated by spot check measurements. Due to the imposed travel restrictions of the COVID-19 pandemic, VG was prohibited from carrying out the measurements. The ambient underwater noise measurements were therefore performed by external company Aquafact Environmental Consultants (www.aquafact.ie) using VG's hydrophone logger equipment (Table 4) deployed from a small boat. Measurements were taken on 21st and 26th of May 2020, and the GPS track plotted in Figure 7 indicates the location. Subsequently, the recorded time series were extracted from the logger equipment and analysed by VG.

The ambient noise mainly originates from natural sounds, such as waves noise and noise from animals and from ship traffic in the area. Both grey seals and dolphins were spotted during the measurements. The ship traffic mainly includes the ferry crossing from Killimer to Tarbert, but also noise from distant cargo ships was present during the measurements. Several small speed boats and jet skis also passed at some distance during the measurements. On the 26th four ships were on anchor at Scattery Island. Engine noise was audible in the recordings during night-time with low noise levels, possibly originating from nearby generators.

The measurements on 21st May 2020 were conducted in the period from 07:00AM – 13:00PM. In the beginning of this period the weather was sunny with wind F2 SW, and the sea state calm with very small wavelets. The predicted tide was HW – 5:45 4.6m, LW – 11:43 0.8m. The wind increased to F3-4 SE with start of caps on waves, and the hydrophone was retrieved at 13:00PM due to weather and sea state.

The measurements on 26st May 2020 were conducted in the period from 19:00PM – 00:45AM. In the beginning of this period the weather was overcast with wind F2 W, and the sea state calm with very small wavelets. The predicted tide was HW – 20:48 4.4m, LW – 02:52 0.8m. The wind decreased during the measurements to <F1 with calm sea state.

Instrument	Make	Type	Serial no.
Logger	RTSys	SYLence	SYL205
Hydrophone	HTI	96-min	785052
Hydrophone calibrator	Brüel & Kjær	4223	817757

Table 4. Equipment used for ambient underwater noise measurements

Figure 6. Picture of buoy with submerged hydrophone from the ambient noise measurements. (photo taken by Aquafact).

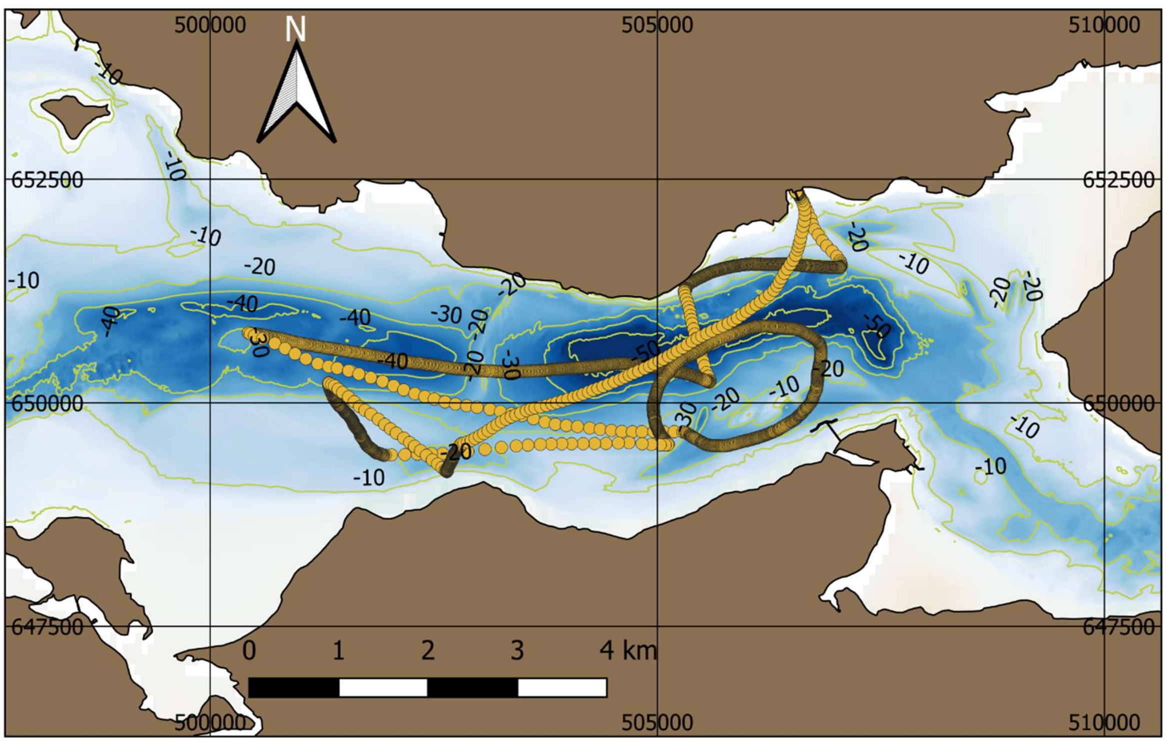

Figure 7. GPS track of ambient noise measurements. For source of bathymetry data, see Section 2.1. Land polygons ©OpenStreetMap contributors [1].

The measurements were performed as “drifting measurements” with the logger and the hydrophone submerged from a floating buoy. The hydrophone was deployed at a depth of 10-15 m corresponding to approx. half the water depth in the area. The signals were recorded with a sampling rate of 96000 Hz.

The recordings were analysed in terms of various statistical exceedance levels Lx (i.e. L90 means the level that is exceeded in 90% of the measurement time). The analysis was carried out for both the unweighted signal and the MF weighted signals (MF refers to the Mid-frequency (MF) cetaceans, as defined in [23]).

Further, frequency analysis was performed for a set of selected periods in both 1/3-octave bands and in narrow band frequency resolution (FFT). The results are shown in the below tables and figures.

Parameter	DAY 21 May 2020 07:00-13:10	EVENING-NIGHT 26 May 2020 19:00-00:45	NIGHT 27 May 2020 00:12-00:45	ALL 21+26 May 2020 (-)
L99	95.5	91.4	91.4	92.3
L95	101.8	93.9	92.0	95.5
L90	104.8	95.7	92.4	99.9
L50	117.3	112.5	95.2	116.4
L10	121.1	125.4	102.3	124.5
L5	124.0	126.9	104.3	126.1
L1	129.4	131.0	109.1	130.3

Table 5. Statistical data of underwater noise levels (Exceedance Levels, in dB re 1 µPa, 10 Hz high-pass filter, based on 5 sec. $L_{p,rms}$ levels, unweighted levels)

Parameter	DAY 21 May 2020 07:00-13:10	EVENING-NIGHT 26 May 2020 19:00-00:45	NIGHT 27 May 2020 00:12-00:45	ALL 21+26 May 2020 (-)
L99	86.2	86.1	86.6	86.1
L95	86.5	86.2	86.7	86.3
L90	86.7	86.3	86.9	86.5
L50	88.2	88.9	88.8	88.4
L10	98.2	105.4	95.5	104.4
L5	102.8	105.9	97.3	105.6
L1	109.0	106.9	98.5	108.0

Table 6. Statistical data of underwater noise levels (Exceedance Levels, in dB re 1 µPa, 10 Hz high-pass filter, based on 5 sec. $L_{p,rms}$ levels, MF-weighted levels)

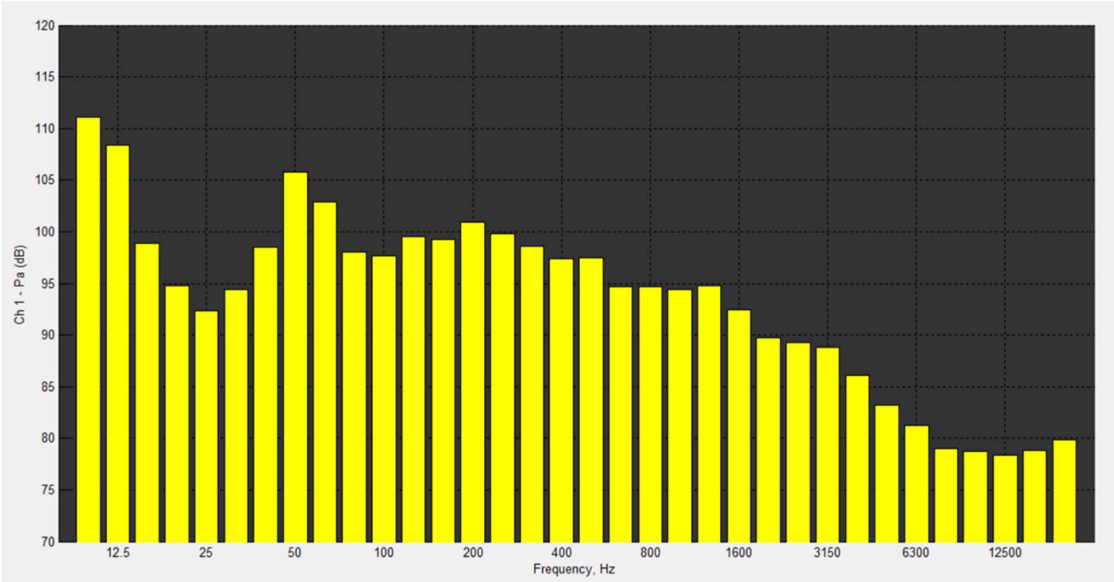

Figure 8. Typical 1/3 octave frequency band spectrum, DAY- Ferry 200 m away crossing from Killimer to Tarbert ($L_{p,rms}$, unweighted dB re 1 µPa).

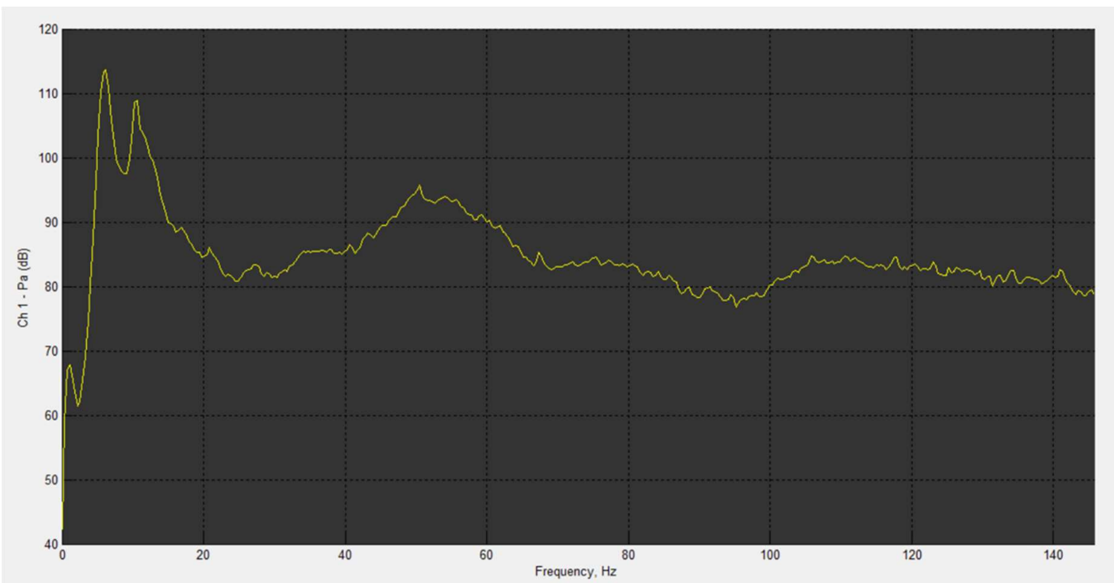

Figure 9. Typical narrowband frequency band spectrum, DAY - Ferry 200 m away crossing from Killimer to Tarbert ($L_{p,rms}$, un-weighted dB re 1 µPa, Hanning window, 10 Hz HP filter)

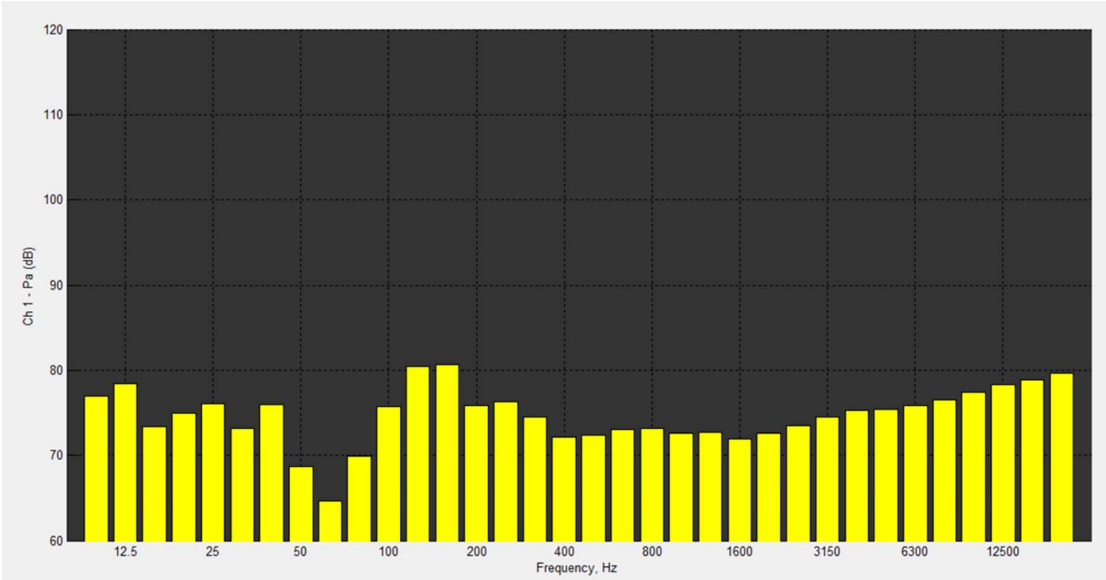

Figure 10. Typical 1/3 octave frequency band spectrum, NIGHT – No audible ships ($L_{p,rms}$, unweighted dB re 1 µPa)

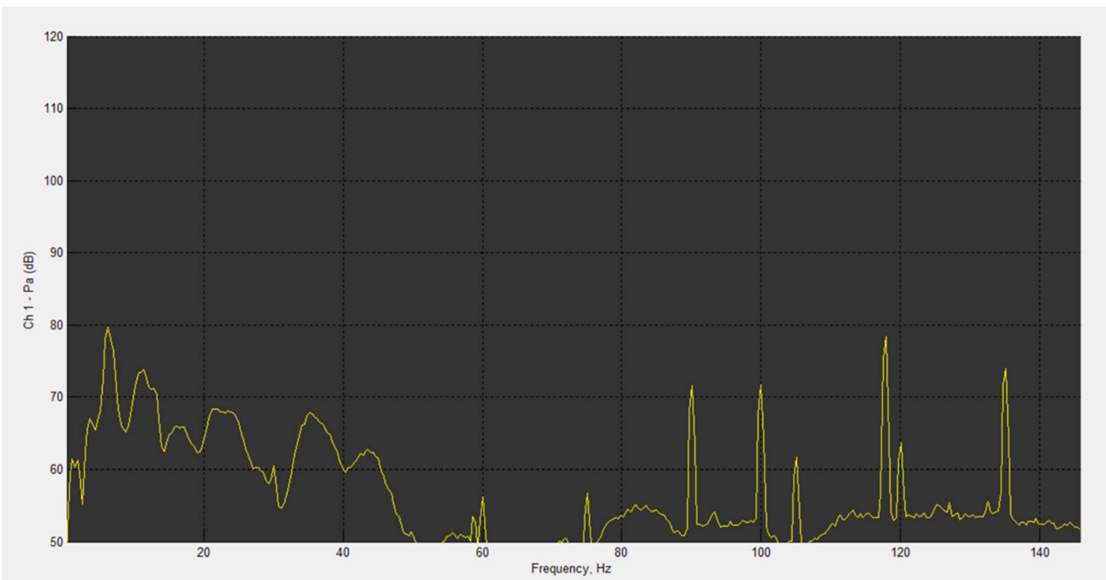

Figure 11. Typical narrowband frequency band spectrum, NIGHT - Distant engine audible in recording - possibly generator – peaks seen in spectrum ($L_{p,rms}$, un-weighted dB re 1 µPa, Hanning window, 10 Hz HP filter)

4.1 Underwater noise from nearby vessel

An event of the Killimer-Tarbert ferry crossing the estuary at approximately 200 m from the measurement location was registered. The estimated sailing speed of the ferry was 5 knots. The corresponding noise spectra are shown in Figure 8 and Figure 9. The broadband $L_{p,rms}$ level was 120 dB re 1 µPa (unweighted), and 88 dB re 1 µPa with MF weighting.

5 Acoustic modelling approach

5.1 Survey mapping approach

The modelling study was carried out following VG's Survey mapping methodology. This involves an "n x 2D" approach, i.e. calculating sound propagation in a number of two-dimensional (depth vs. range) transects by means of a point source (i.e. monopole) based long-range models out to a maximum range away from the source. As illustrated in Figure 12 and Figure 13, 15 such azimuthal transects were modelled for each of the two source positions A and B. Due to the irregular geometry of the estuary, these transects have lengths varying from a few hundreds of meters to 19 km. Similarly, the bathymetry profile varies greatly between the transects.

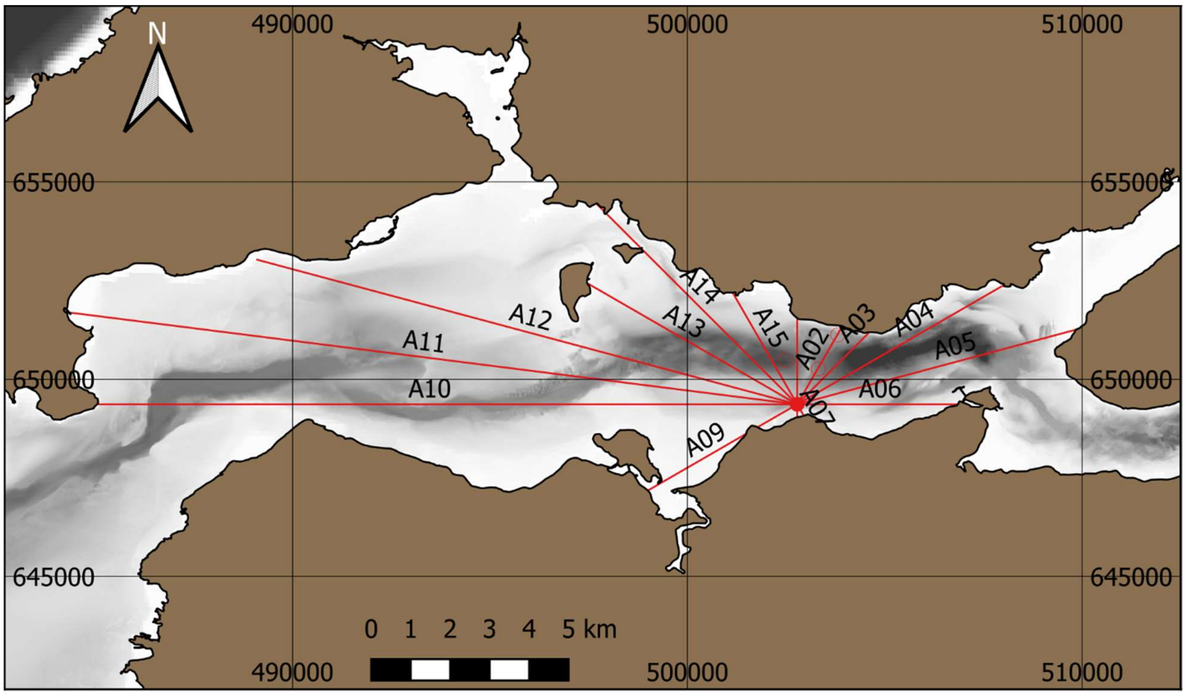

Figure 12. Transects A01-15 emanating from source position A.

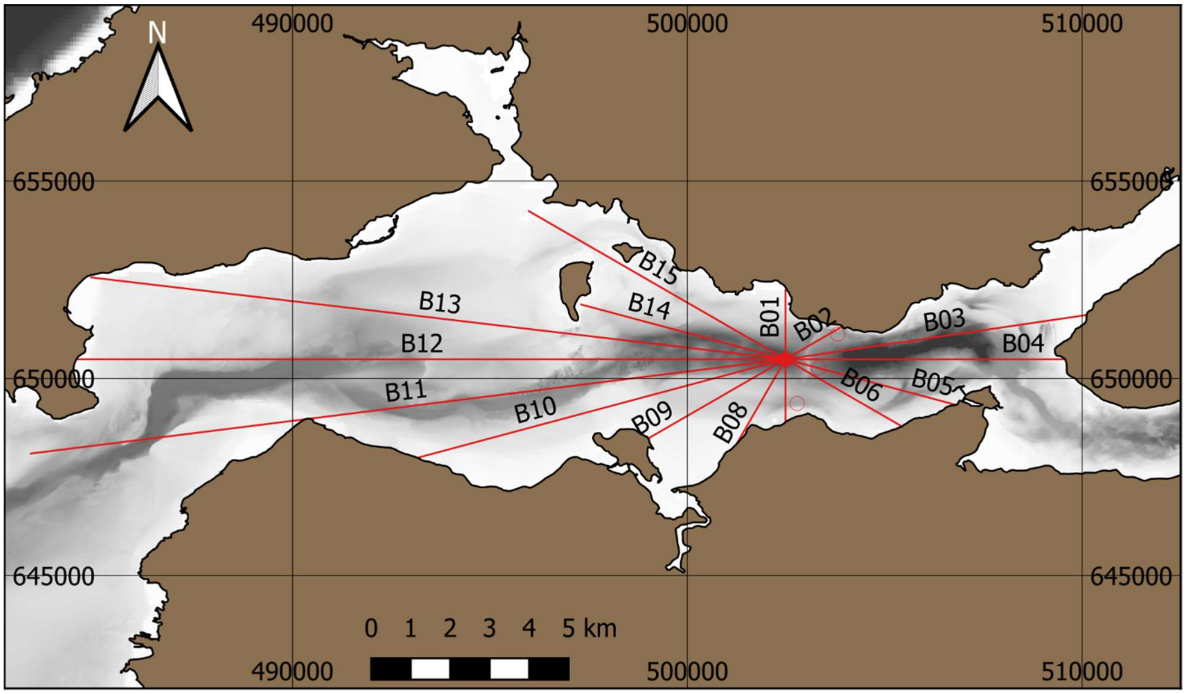

Figure 13. Transects B01-15 emanating from source position B.

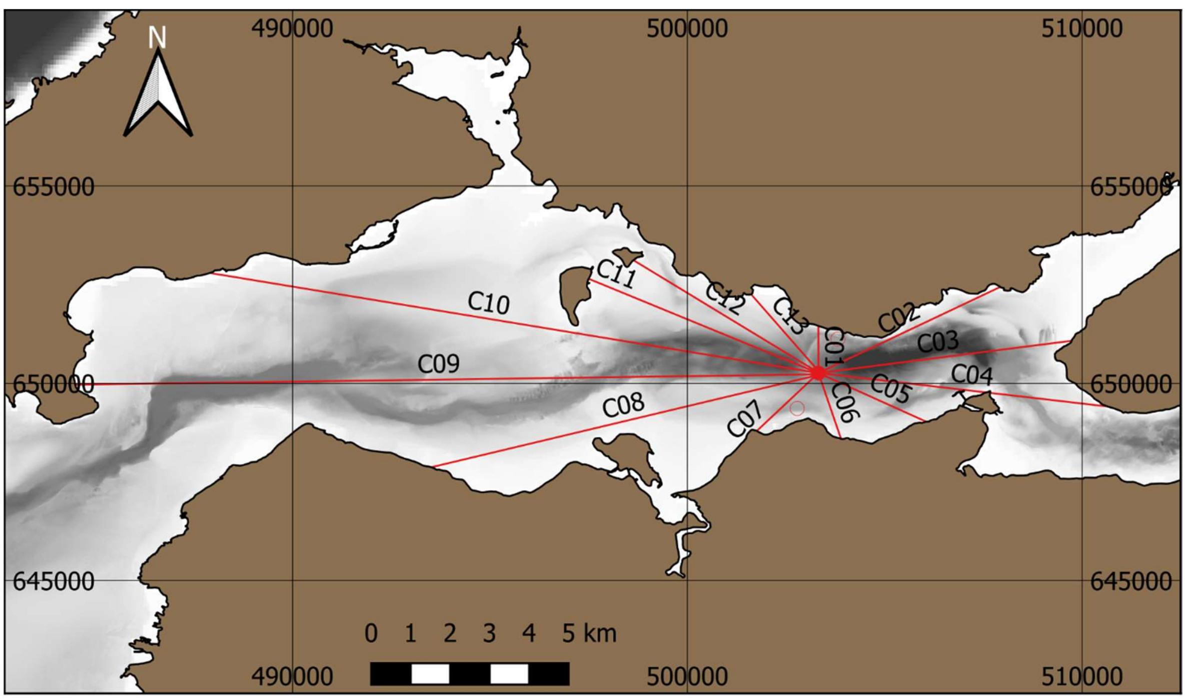

Figure 14 Transects C01-13 emanating from source position C.

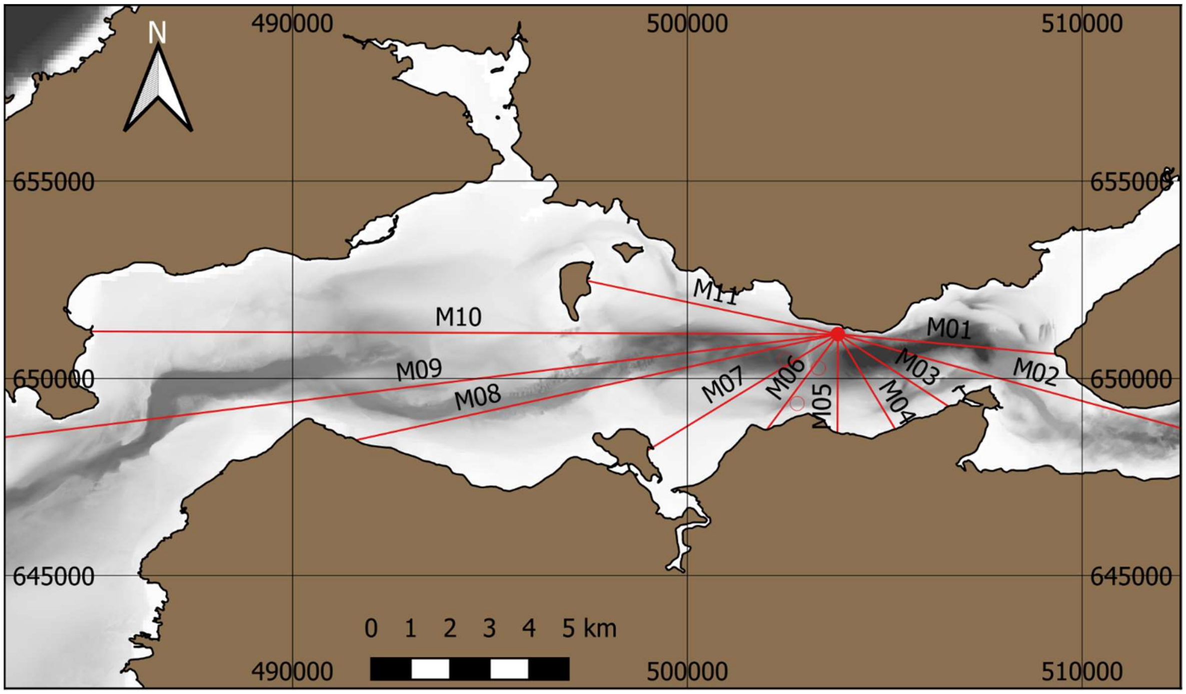

Figure 15 Transects M01-M11 emanating from source position M.

5.2 Model components

5.2.1 Background for sound propagation model

Any numerical model is an approximated representation of the actual physics. Following [24] any physical or mathematical model has inherent limitation in applicability, leading to a “domain of applicability” of that model.

Fundamentally, acoustic models are based on the Wave Equation for pressure:

$$\nabla^2 p - \frac{1}{c^2}\frac{\delta^2 p}{\delta t^2} = 0$$

Here, ∇^2 is the Laplacian operator, p is the acoustic pressure, c is the sound speed, and t is the time. The wave equation can only be solved analytically for simple cases. It is therefore often simplified according to various assumptions, leading to the Helmholtz equation, which is the basis for many underwater acoustic models [8], [20]. For the present study, the **Parabolic Equation** (PE) type of model is used for the frequency range up to 1600 Hz. This assumes a single point source and acts on the Helmholtz formulation of the Wave Equation. The Helmholtz Equation derives from the Wave Equation by assuming that properties are constant over time, leading to a frequency domain representation. For even higher frequencies, a **Beam Tracing** (BT) type of model is used. A brief introduction to these and other common underwater noise model types is found in [20].

Parabolic Equation (PE) parts from the Helmholtz equation by assuming that only out-going wave propagation is considered [20]. Then, the solution is found from range-wise step-by-step marching away from the sound source. The PE variant applied in the present study is a split-step Padé expansion type for approved numerical accuracy, developed by Collins, which allows for range-dependent properties such as bathymetry. The model was extensively benchmarked [26].The actual code is **RAMGeo**, as implemented by CMST in the Matlab based AcTUP suite [16]. In VG implementation, the calculation core is unchanged from RAMGeo while memory use and file logistics have been optimised for speed.

In 2017 the US regulatory entity Bureau of Ocean energy Management (BOEM) held a workshop on best practices for offshore wind and marine protected species [27]. One topic was the suitability of various types of underwater noise modelling. Specifically, the PE model type was found to perform well in the verification study.

The frequency range 2kHz to 160 kHz is addressed using a Beam Tracing model, which uses a high-frequency approximation to solve the Wave Equation. In a simpler form, bundles of geometric rays are emitted from the point source and traced as they propagate through the acoustic environment. Rather than such infinitely narrow rays, the more sophisticated BT approach assigns a Gaussian profile to the these, forming “beams”. This BT used in this study is **Bellhop**, as implemented by CMST’s AcTUP suite [16].

Volume absorption is included in the calculations according to section 2.6.

5.2.2 Additional, derived metrics

The main output of the Survey mapping method is either the unweighted (“flat”), single-strike sound exposure level $L_{E,p,ss}$ for impulsive sources such as pile driving or blasting, or the RMS sound pressure level $L_{p,rms}$ for continuous noise such as ship noise. From these, several additional metrics were derived:

- 24h cumulative sound exposure level, with frequency weightings
- Zero-to-peak sound pressure level
- Root-Mean-Square (RMS) sound pressure level (for piling and blasting)

The approach behind each of these derived metrics is discussed in the sections below.

5.2.2.1 Cumulative sound exposure level, with frequency weightings

Piling noise

For a N hammer strike events of equal acoustic energy (e.g. same single-strike Sound Exposure Level), the cumulative Sound Exposure Level is calculated as $L_{E,p,24h} = L_{E,p,single-strike} + 10\log_{10} N$, with N being the number of strikes within the 24 hours period [22].

Continuous noise

For vessel noise, the cumulative Sound Exposure Level is calculated from the RMS (which is the same as the Leq) sound pressure level with a correction for the time duration of the activity:

$$L_{E,p,24h} = L_{p,RMS} + 10\log_{10}\frac{T}{T_0}$$

Here, T_0 is 1 s.

5.2.2.2 Hearing group specific, cumulative sound exposure level

In accordance with [23], the 24-hour cumulative sound exposure level was calculated for the MF hearing group. This was done by applying the corresponding frequency weighting to the centre frequency of each 1/3-octave band of the flat-weighted, cumulative sound exposure level, and calculating the overall value.

5.2.2.3 Zero-to-peak sound pressure level

For pile driving, the zero-to-peak sound pressure level was derived from the single-strike Sound Exposure Level based on the following semi-empirical formula [28]:

$$L_{p,0pk} \approx 1.12 \cdot L_{p,E} + 7.3\ \mathrm{dB}$$

Here, the original peak-to-peak expression from [28] was subtracted 5 dB for conversion to zero-to-peak.

5.2.2.4 RMS sound pressure level

For continuous noise sources, such as ships, the RMS (Root Mean Square) sound pressure $L_{p,rms}$ is directly calculated by the model.

For impact pile driving, the RMS sound pressure may be estimated from the single-strike, sound exposure level by accounting for the pulse duration, T_p [s]:

$$L_{p,rms} \approx L_{p,E} - \Delta_{Tp}$$

$$\Delta_{Tp} = 10 \log_{10} \frac{T_p}{T_0}$$

Here, T_0 =1 s. For this study, the following semi-empirical expression was used [28]

$$L_{p,rms} \approx 1.23 L_{p,E} - 23.9 \text{ dB}$$

5.2.3 Extension of frequency range

The hearing ability of marine mammals generally spans an enormous frequency range. As an example, the -frequency (MF) cetacean weighting correspond to effective hearing up to 160 kHz [23], with the highest sensitivity approximately between 25 kHz and 70 kHz (see MF curve in Figure 5). However, the frequency range of noise source of this study typically peaks already at 80-300 Hz, with main energy within the first kHz. For higher frequencies, the generally spectrum falls off steadily.

Source data are typically not available for the for the full frequency spectrum up to 160 kHz. Real-world measured noise spectra tend to reduce steadily in level for frequencies above 1-2 kHz. On that background, it seems fair and conservative to assign a steady high-frequency slope to the noise spectra.

Where data were missing at higher frequencies it was decided to extrapolate the noise spectra by a constant slope according to Table 7:

Noise source	High-frequency slope, dB per 1/3-octave band
Impact piling	-2.8
Socket drilling	-1.9
Vibratory driving	-4.0
Rock blasting	-3.0
Carier offloading and sailing, tugboats,crew boat, cargo ships	-1.4
FSRU and crane barge	-2.0
Jack-up rig	-1.0

Table 7. Overview of assumed slope constants for high-frequency extrapolation of source spectra.

It is noted that several additional phenomena with frequency dependent losses become significant in the kHz range, with losses increasing with frequency, e.g. sea surface absorption (interaction with air bubbles from waves and vessels). Such losses add to the bottom loss, causing even higher losses than for say 0-1 kHz range.

5.3 Application of underwater acoustic propagation models

The point source based models RAMGeo and Bellhop introduced in Section 5.2.1 were run for all transects. Each transect was implemented as a 2D axisymmetric slice, including variations in bathymetry along the transect (see Figure 16 as an example), and with the seabed layer properties (density and compression wave properties) of Table 2. As discussed in Section 2.4 this is a fluid-type representation of the seabed, which is assumed to be slightly conservative.

The RAMGeo model was run for centre frequencies of the 1/3-octave bands from 50 Hz to 1600 Hz for pile driving with a frequency range extending down to 20 Hz for the ship sources. The Bellhop model was run for centre frequencies of the 1/1-octave bands from 2 kHz to 160 kHz. Examples of the calculated transmission loss slices are given in Figure 16 and Figure 17. It is seen how the sound field for lower frequencies is characterised by modal interference patterns, and a significant amount of acoustic penetration of the seabed. The spatial resolution was approximately 0.5 m. It is seen how the sound field for lower frequencies is characterised by modal interference patterns, and a significant amount of acoustic penetration of the seabed.

Separate sets of TL transects were calculated for source positions A, B, C, and M (see Figure 2), as well as for sources corresponding to different depth locations.

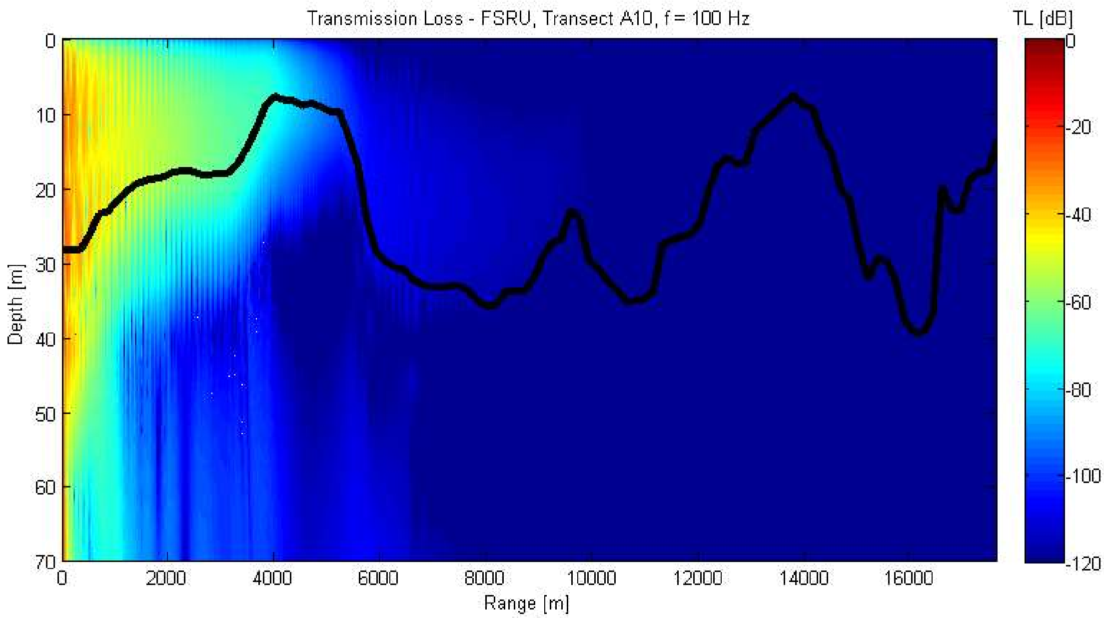

Figure 16. Transmission loss along transect A10 at 100 Hz. Black line indicates seafloor.

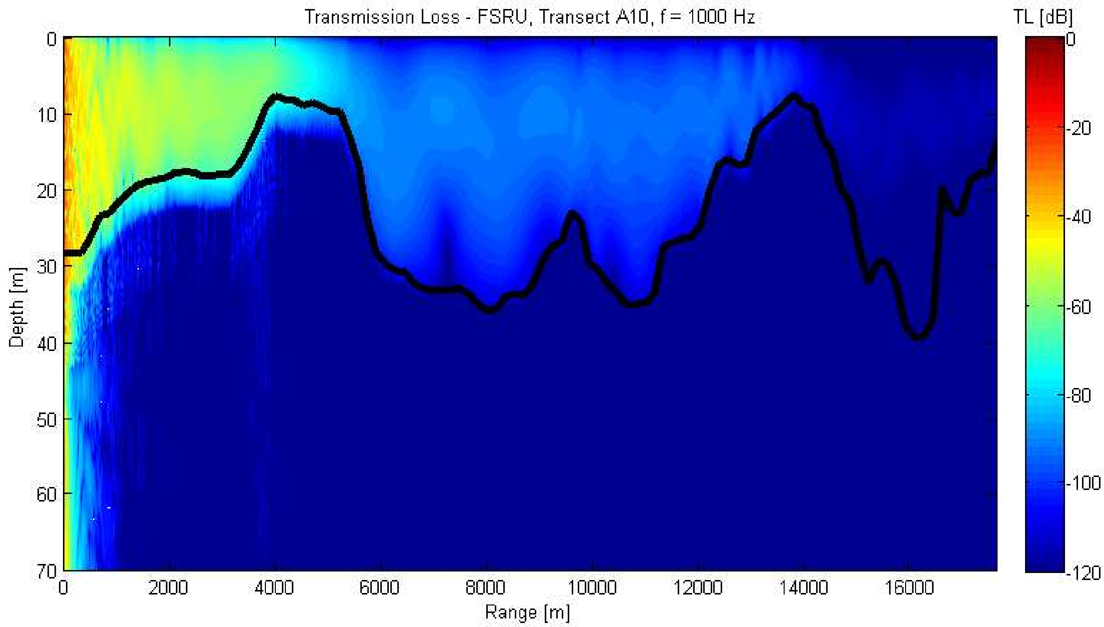

Figure 17. Transmission loss along transect A10 at 1 kHz. Black line indicates seafloor.

5.3.1 Method for evaluating acoustic criteria

The source spectra of Section 6.2 were combined with the transmission loss calculated by RAMGeo and Bellhop. Subsequently, the detailed grids of results were condensed to curves showing Max-over-Depth as illustrated in Figure 18. In this figure each curve represents the Max-over-Depth RMS sound pressure across the water column for a given transect, A1-A15. For the simplest scenarios with only a single source position, it is possible to compare this type of predicted range-dependent metric to the relevant acoustic criteria of Section 5.4 to find the corresponding Distance-to-Threshold. This is the distance from the source to the point after which the source falls below the assessment criteria level. In Figure 18, the red horizontal line represents a criteria threshold of $L_{p,rms}$=120 dB. It follows graphically that the plotted transects exceed this level for ranges within approximately 2000 m, which is then taken as the Distance-to-Threshold.

Due to the often-significant variation between directions caused by differences in bathymetry, the Distance-to-Threshold values of multiple directions are furthermore combined into an Area-to-Threshold for the same criteria.

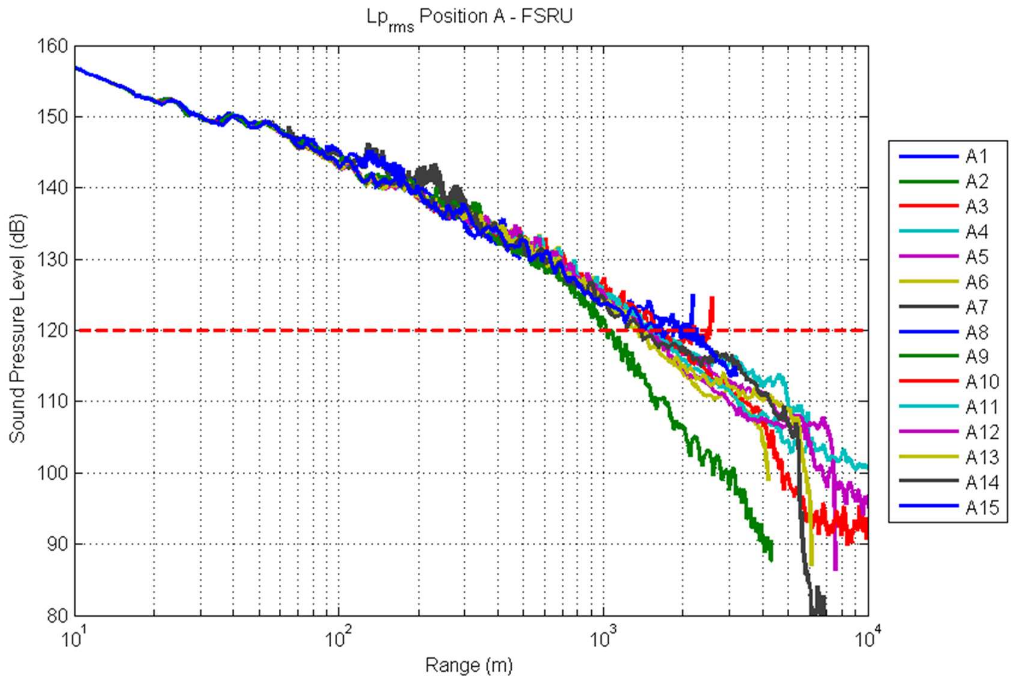

Figure 18. Max-over-depth of flat-weighted RMS sound pressure level $L_{p,rms}$ for FSRU.

Since the present study involves scenarios with multiple simultaneous source positions, an alternative method was applied for assessing Distance- and Area-to-Threshold. In the case of multiple source positions, the concept of transects becomes problematic, since it is not evident where their common origin should be located. The following approach was implemented:

- From the noise map of the whole area covered, contours are calculated, showing the areas where the evaluated acoustic metric exceeds a given threshold, as shown by the two green areas in the figure. These could represent local threshold contours of two sources, or they could be local "hot-spots" of the sound field.
- The Area-to-Threshold is calculated by directly summing the areas covered by these contours, i.e. the two green regions in the figure.
- Distance-to-Threshold is evaluated along 8 principal directions (North, North East, East, South East, South, South West, West, North West) as follows:
    - The geometric centroid is found of the convex hull enclosing all the contours. This convex hull is the blue line in Figure 19.
    - The Distance-to-Threshold is found in each direction by casting a ray from the centroid and finding the furthest distance at which the tangent to this ray intersects with the blue envelope line. This is illustrated by the red lines in the figure for selected directions. As examples, for directions N, E, and SW the corresponding distance end-points are indicated with blue ovals. The resulting Distance-to-Threshold for N, E, and SW are shown with black arrows.

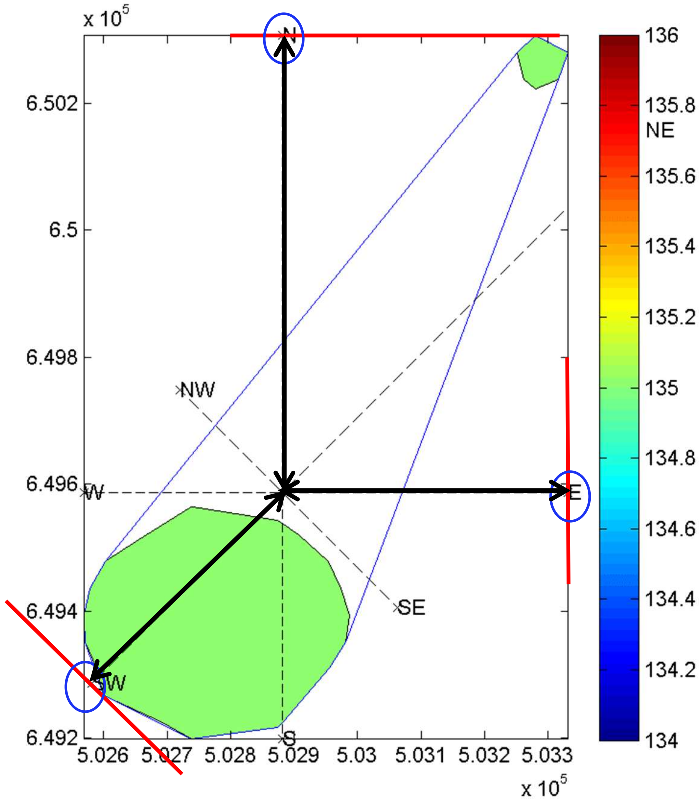

Figure 19. Example for calculation of Distance-to-Threshold for complex multiple source scenarios, shown with an example threshold of 135 dB.

5.4 Acoustic criteria for impact assessment

The Shannon Estuary is home to a colony of bottlenose dolphins, which are characterised as Mid-frequency cetaceans in [23]. For detailed evaluation of the project's acoustic impact on these specific animals, VG's sub-contractor LGL prepared a set of acoustic criteria. These are described in the following. This report presents the findings in terms of Distance-to-Threshold, and Area to Threshold. The results are subsequently undergoing detailed assessment by LGL, as will be presented in LGL's separate assessment report.

5.4.1 PTS/"Level A" criteria

Hearing group	Metric	Threshold value, non-impulsive noise	Threshold value, impulsive noise
Mid-frequency cetaceans (MF)	$L_{p,0\text{-}pk}$	-	230 dB
	$L_{E,p,MF,24h}$	198 dB	185 dB
High-frequency cetaceans (HF)	$L_{p,0\text{-}pk}$	-	202 dB
	$L_{E,p,HF,24h}$	173 dB	155 dB
Phocid Pinnipeds (PW)	$L_{p,0\text{-}pk}$	-	218 dB
	$L_{E,p,PW,24h}$	201 dB	185 dB

Table 8. Level A harassment thresholds for marine mammals according to the National Marine Fisheries Service 2018 guideline [23], for the relevant hearing groups. Units of $L_{p,0\text{-}pk}$ are dB re 1µPa. Units of $L_{E,p,xx,24h}$ are dB re 1µPa^{2}s.

5.4.2 TTS criteria for marine mammals

Hearing group	Metric	Threshold value, non-impulsive noise	Threshold value, impulsive noise
Mid-frequency cetaceans (MF)	$L_{p,0\text{-}pk}$	-	224 dB
	$L_{E,p,MF,24h}$	178 dB	170 dB
High-frequency cetaceans (HF)	$L_{p,0\text{-}pk}$	-	196 dB
	$L_{E,p,HF,24h}$	153 dB	140 dB
Phocid Pinnipeds (PW)	$L_{p,0\text{-}pk}$	-	212 dB
	$L_{E,p,PW,24h}$	181 dB	170 dB

Table 9. TTS thresholds for marine mammals as provided by LGL (based on the National Marine Fisheries Service 2018 guideline [23]), for the relevant hearing groups. Units of $L_{p,0\text{-}pk}$ are dB re 1µPa. Units of $L_{E,p,xx,24h}$ are dB re 1µPa^{2}s.

5.4.3 Behavioural criteria for marine mammals

For impulsive noise, a multiple tiered step function of threshold is investigated, for $L_{p,rms}$ with auditory frequency weighting. Hence, thresholds in steps of 10 dB from 120 to 180 dB are investigated for **impulsive** noise.

Similarly, for **non-impulsive** noise, thresholds of $L_{p,rms}$ in steps of 5 dB from 120 to 180 dB are investigated.

Besides the multi-tier steps, the following specific criteria apply:

Hearing group	Metric	Threshold value, non-impulsive noise
Mid-frequency cetaceans (MF)	$L_{p,rms,MF}$	160 dB
High-frequency cetaceans (HF)	$L_{p,rms,HF}$	160 dB
Phocid Pinnipeds (PW)	$L_{p,rms,PW}$	160 dB

**Table 10. Behavioural thresholds for marine mammals ("Level B") [29].
Units of $L_{p,rms}$ are dB re 1 µPa.**

5.4.4 Acoustic criteria for fish species

Type of animal	Metric	Threshold value		
		Mortality and potential mortality	Recoverable injury	Temporary Threshold Shift (TTS)
Fish: no swim bladder	$L_{p,0\text{-}pk}$	213 dB	213 dB	-
	$L_{E,p,flat,24h}$	219 dB	216 dB	186 dB
Fish: swim bladder not involved in hearing	$L_{p,0\text{-}pk}$	207 dB	207 dB	-
	$L_{E,p,flat,24h}$	210 dB	203 dB	186 dB
Fish: swim bladder involved in hearing	$L_{p,0\text{-}pk}$	207 dB	207 dB	-
	$L_{E,p,flat,24h}$	207 dB	203 dB	186 dB

Table 11. Thresholds corresponding to mortality, injury, or temporary threshold shift for fish [30]. Units of $L_{p,0\text{-}pk}$ are dB re 1 µPa. Units of $L_{E,p,flat,24h}$ are dB re 1 µPa^{2}s. The cumulative SEL criteria refers to the duration of the piling operation, which has the same value as the $L_{E,p,flat,24h}$ stated in the table.

Type of animal	Metric	Threshold value,
Fish	$L_{p,rms,flat}$	150 dB

Table 12. Thresholds corresponding to behavioural response for fish [31]. Units of $L_{p,rms}$ are dB re 1 μPa.

6 Construction Phase

6.1 Scenario overview

The following scenarios were modelled:

C1 Impact pile driving

C2 Vibratory pile driving, including support vessels

C3 Drilling for socket piles, including support vessels

C4 Rock blasting on land

For all scenarios C1-C4 it is assumed that only one of the respective installation events takes place within a 24-hour window. For the modelling, in all scenarios C1-C4 the noise sources are assumed to be located at position A of Figure 2.

The included support vessels in C2 and C3 are:

- One jack-up rig (100% operation time)
- One crane barge (100% operation time)
- One tugboat (20% sailing, 80% idling)
- One crew boat (10% operation time).

Support vessels are not included in the C1 scenario for impact pile driving, as the criteria values are stated differently for impulsive sources (impact pile driving) and continuous sources (support vessels). Mixing the acoustic metrics across the two types of sources will therefore not allow any meaningful comparison with criteria thresholds. The results for scenarios C1 are therefore intended for comparison with the criteria specifically for impulsive sources.

6.2 Noise source assumptions

6.2.1 Impact pile driving

Installation by impact pile driving involves a large hydraulic hammer impacting the pile head, causing impulsive (i.e. transient) noise.

The driven pile was assumed to be of steel material with outer diameter 1.067 m. The coarse hammer protocol in Table 13 and the subsequent details were provided by SISK for purpose of the acoustic modelling. An example of a representative hammer for the impact driving is an IHC Hydrohammer S-150 hydraulic hammer of nominal energy 150 kJ.

Energy level	Metric	No. of strikes
30%	45 kJ	30
70%	105 kJ	2376
100%	150 kJ	234
		Total 2640 strikes

Table 13. Coarse hammer protocol

Driving of one pile was assumed to take approximately 1 hour at an average blow rate of 44 strikes per minute. It was assumed that only one pile was installed per 24 hours.

Based on VG's in-house measurement experience as well as literature, the source spectrum of Figure 20 was applied, corresponding to a broadband level of 208 dB (single-strike SEL). The spectral shape is mainly based on measurements relating to a 0.7 m diameter pile installed at water depth 13 m in coarse sand overlaying a hard calcarenite bottom [28]. Frequencies above 8 kHz were extrapolated assuming a constant slope.

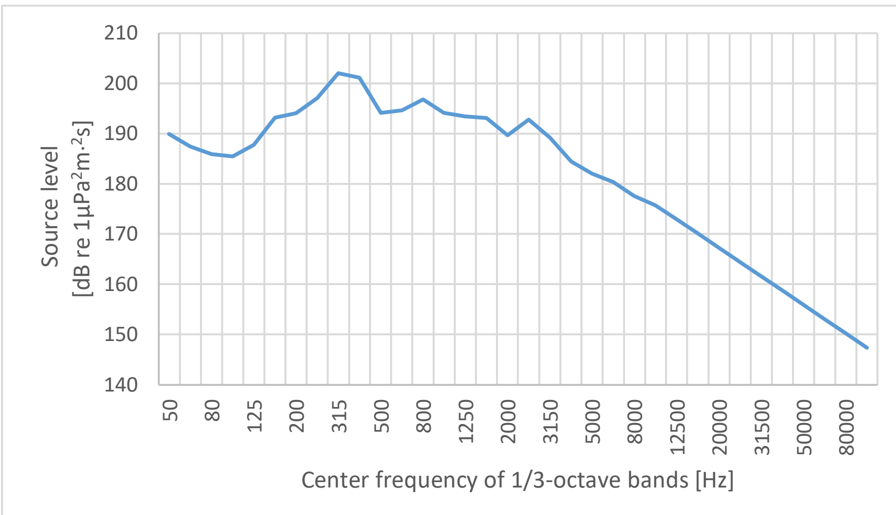

Figure 20. Source level 1/3-octave spectrum for pile driving, stated as $L_{S,E}$.

The piling noise source was assumed to be located at Position A (see Figure 2). The assumed monopole source level $L_{S,E}$ for impact pile driving was 208 dB re 1 µPa²m²s, and the assigned source depth was 20 m below the sea surface.

6.2.2 Vibratory pile driving

In a vibratory hammer, or vibro-hammer, the driving unit consists of contra-rotating eccentric masses in a housing attached to the pile head. As opposed to the impact technique of Section 6.2.1, vibratory (or vibro-) driving causes continuous noise.

The driven pile was assumed to be of steel material with outer diameter 1.067 m. According to information by SISK, a representative vibratory hammer is the ICE 815C Vibro Hammer, which has an eccentric moment of 46 kgm and max. centrifugal force 1250 kN. The vibro hammer's maximum rotational speed 1570 RPM, which corresponds to a fundamental frequency component of 26 Hz.

For the installation of one pile, approximate 20 minutes of vibro-driving is required according to SISK. It is assumed that only one vibro-driving event takes place per 24 hours.

For the acoustic modelling, VG's in-house measurement experience combined with literature cases led to an estimated monopole source level L_S of 182 dB re 1 µPa·m when accounting for the current pile size and hammer force. The source was assigned a source depth of 20 m at Position A. The shape of the assumed spectrum shown in Figure 21 was based mainly on [32] in combination with various other sources. Frequencies above 2500 Hz were extrapolated assuming a constant slope.

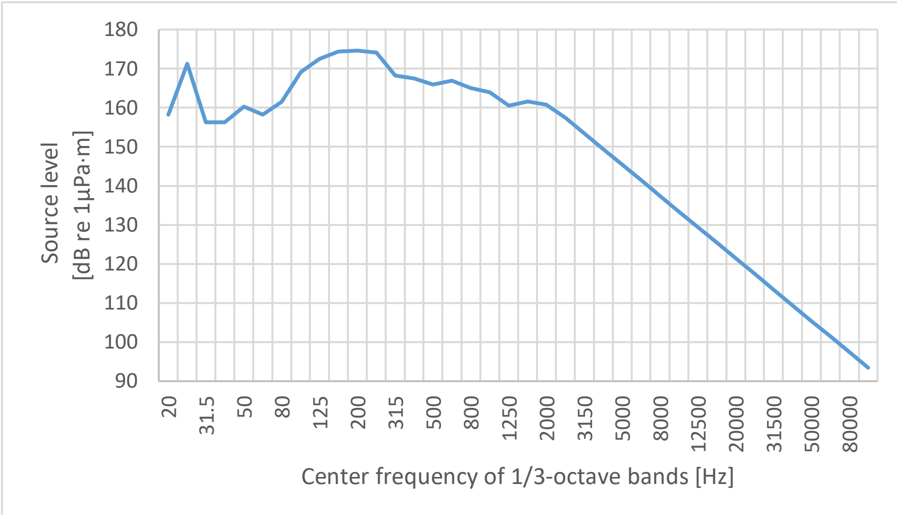

Figure 21. Source level 1/3-octave spectrum for vibro-driving, L_s dB re 1 µPa·m.

6.2.3 Socket pile drilling

This pile installation technique emits continuous type noise during operation. According to information provided by SISK, a representative drill machinery is the LD408 pile top drill rig. This has drilling diameter range 1.3 to 2.0 m, maximum power swivel torque 81 kNm, and variable drill speed 0-38 RPM.

For the installation of one pile, approximately 25 hours of drilling is required according to SISK. For the modelling it is assumed that the drilling event takes full 24 hours.

Measurements from a small-diameter socket drill were reported in [33]. These were converted to 1/3-oct spectra and scaled to a larger drill in [34]. For the present study, the noise source data of the latter is used after slight re-scaling to the Shannon pile diameter of 1.067 m.

For socket drilling, the assumed monopole source level L_S was 168 dB re 1 µPa·m, and the assigned source depth was 20 m at Position A. The corresponding 1/3-octave band spectrum is shown in Figure 22.

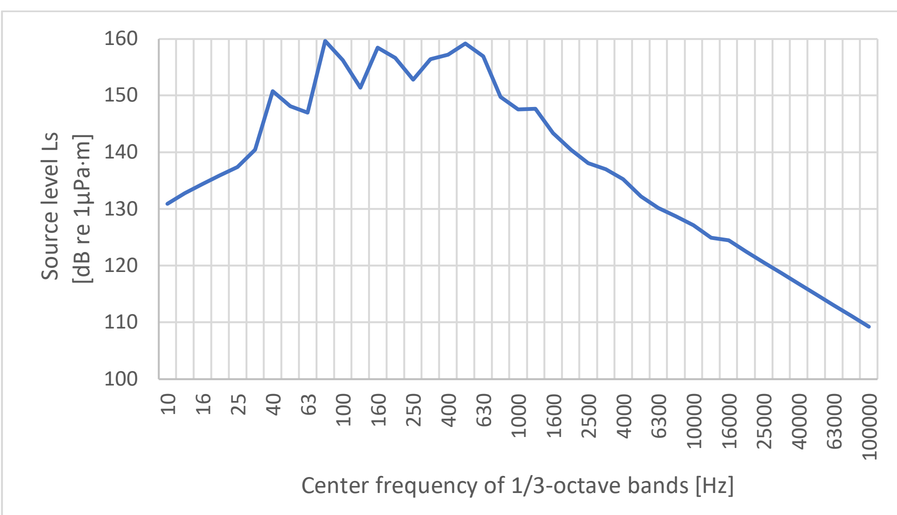

Figure 22. Source level 1/3-octave spectrum for socket drilling, L_s dB re 1 µPa·m.

6.2.4 Blasting

For the on-shore LNG terminal, a certain amount of rock blasting is envisioned. The blast holes will be distributed inside the sandstone area indicated by dark brown in Figure 23. It is noted that this area is approximately 70 m or further in-land from the coastline.

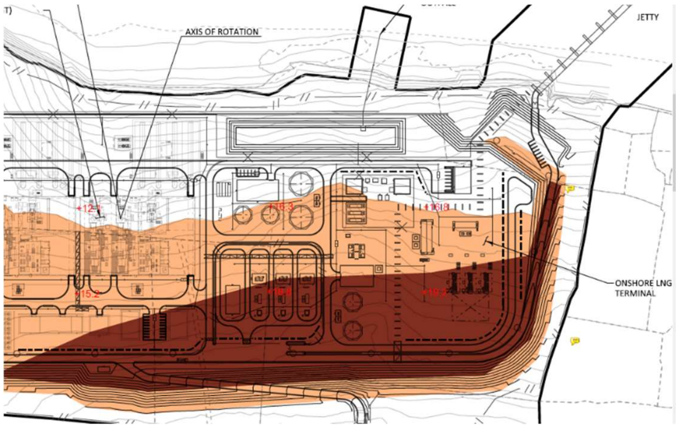

Figure 23. Overview of on-land blasting area (dark brown polygon).

The rock material is sandstone, and the following information was provided by SISK:

Blasting charge is assumed to be Sureblend 100. It is informed that this emulsion has a density of 1.2 g/cm^2, and that 1.35 kg of the Sureblend is equivalent to 1 kg of TNT.

Taking a maximum hole depth of 10 m, a conservative estimate of maximum of 90 kg (TNT equivalent) is required per hole.

For the acoustic modelling, one blasting event per 24 hours is assumed.

As a practical and conservative assessment of a blasting event source level, the following approach was applied:

1. Based on the TNT equivalent weight, a semi-empirical expression from [35] was used to estimate the Peak sound pressure level for an in-water blasting charge.

2. The report [36] makes reference to measurement work by the same organization indicating that the peak sound pressure is reduced to approximately 5% when the same blasting charge is embedded e.g. in a borehole. On that background, the in-water $L_{p,pk}$ from step 1 was reduced by 26 dB, i.e. 20Log(5%) and the corresponding Sound Exposure Level was estimated from $L_{p,pk}$ using a semi-empirical expression from [35]. This provides a source level for an embedded charge, in terms of broadband SEL $L_{S,E}$.

3. To account for the propagation distance between the nearest blasting location and the water, a spectral attenuation was used to shape the measured far-field spectrum reported in [37] (extrapolated at a constant slope above 2 kHz). The attenuation assumed propagation through a sandstone layer with generic geoacoustic properties. For this simplified assessment only compressional wave properties were considered, having attenuation α_p=0.10 dB/λ [15]. Assuming 70 m of propagation, the resulting source level spectrum is shown in Figure 24. The monopole source level is 206 dB re 1 μPa^{2}m^{2}s.

For the acoustic modelling, the blasting source is assumed to be located at Position A at source depth 20 m. As an approximation, the semi-empirical relations between L_E, $L_{p,pk}$ and $L_{p,rms}$ for piling (Sect. 5.2.2.3 and 5.2.2.4) were applied for blasting.

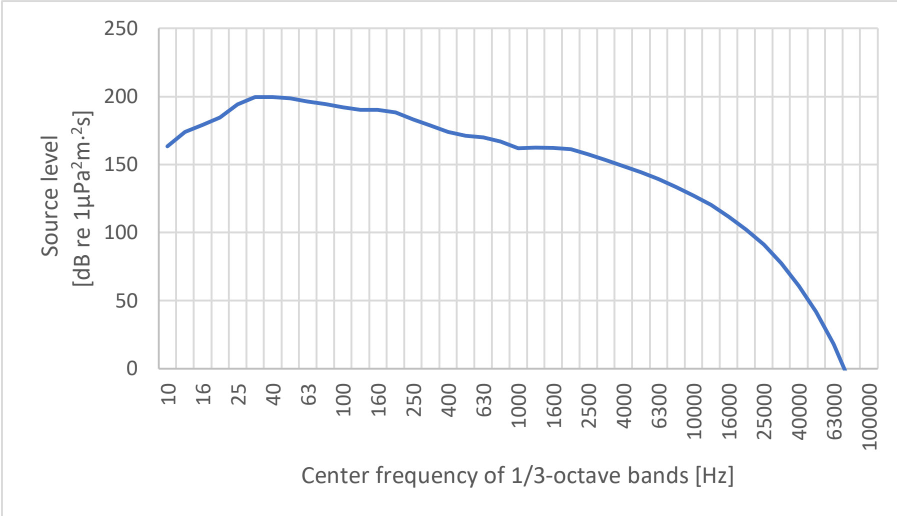

Figure 24. Source level 1/3-octave spectrum for blasting event, stated as $L_{S,E}$.

6.2.5 Support vessels

The source levels for the vessels used in the prediction were assessed based on literature data and VG's in-house data from measurements on similar vessels. The corresponding spectra assumed for this study are stated in Figure 25. The values are given as monopole source levels L_s in dB re 1 µPa·m.

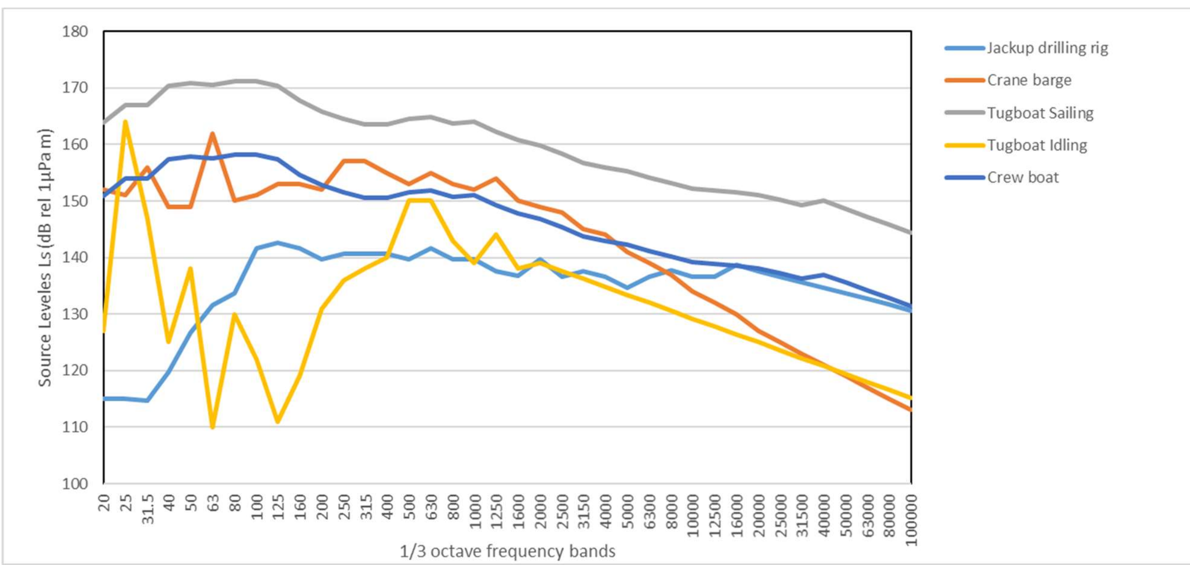

Figure 25. Underwater source levels for support vessels used in the predictions (L_s dB re 1 µPa·m).

For the drilling rig, the source level is based on measurements by Vysus on a large jack-up drilling rig. The source level has been corrected by subtracting the drilling contribution, leading to a source level only including the jack-up rig. The rig has been assumed in operation 100% of the time. The crane barge source level has been taken from JIP report [44]. This gives a source level of 168 dB and the spectral shape has been assumed to be similar to a pipe layer vessel. The barge has been assumed in operation 100% of the time. The source level of the sailing tugboat has been taken from the Port of Vancouver ECHO1 database [40]. The tug is stated to be sailing 20% of the effective time, and the remaining time (80%) is on idle. The crew boat source level is also taken from the JIP report [44]. This gives a source level of 168 dB and the spectral shape has been assumed to be similar to the sailing tugboat. The crew boat has been assumed to be in operation in 10% of the effective time. The sources have been collected into one combined source strength with correction for the respective operation times. The source depth for the support vessels is assigned as 3.5 m.

6.3 Results – Construction Phase

In the following, all noise results represent the maximum observation across all depth positions at the same range, or “Max-over-depth”.

Selected contour maps of the sound fields are shown in Figure 26 to Figure 29. Note that these represent interpolated results based on the detailed transects and are included for visual overview mainly. Tables of distance-to-threshold and area-to-threshold are provided in Appendices C to F. These were derived directly from the detailed transect results.

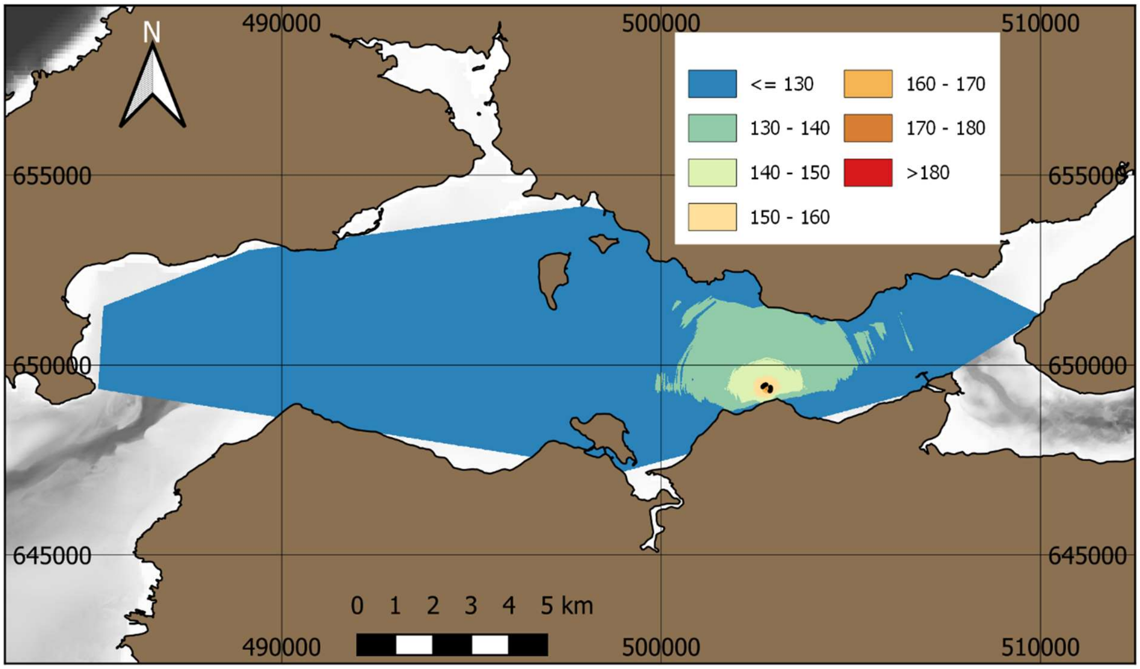

Figure 26. Scenario C1) Construction Impact Pile driving. Contour map of $L_{p,rms}$ (MF-weighted, “Max-over-depth”). Values in dB re 1 µPa. Behavioural criteria of 160 dB is indicated by dashed line.

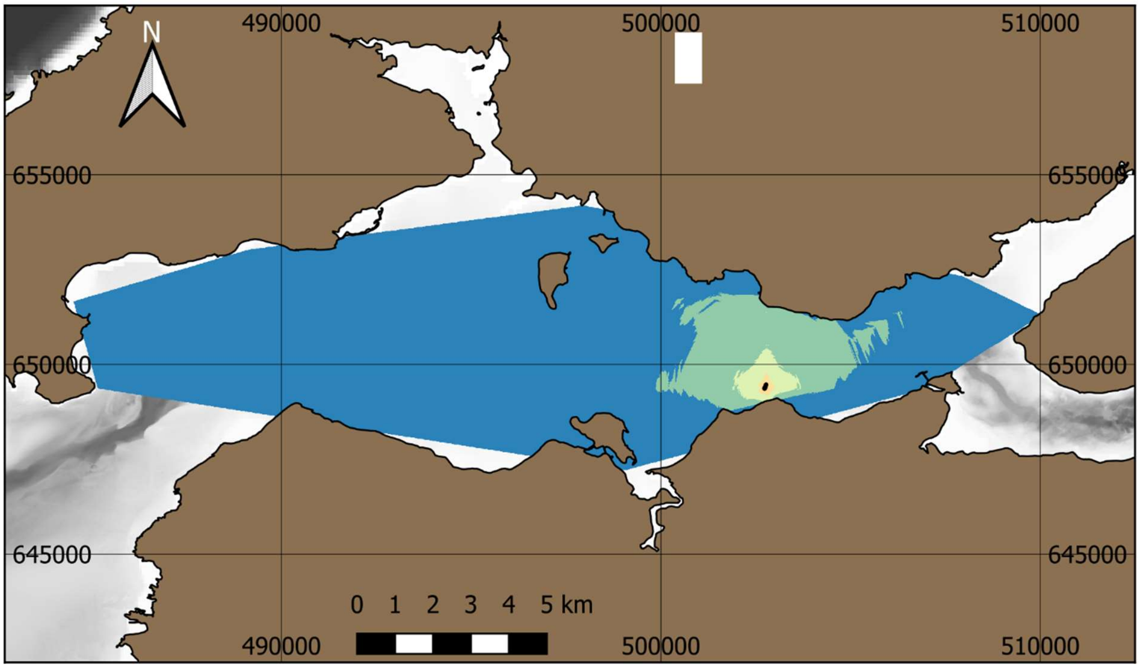

Figure 27. Scenario C2) Construction Vibratory driving incl. supporting vessels. Contour map of $L_{p,rms}$ (MF-weighted, “Max-over-depth”). Values in dB re 1 µPa. Behavioural criteria of 120 dB is indicated by dashed line.

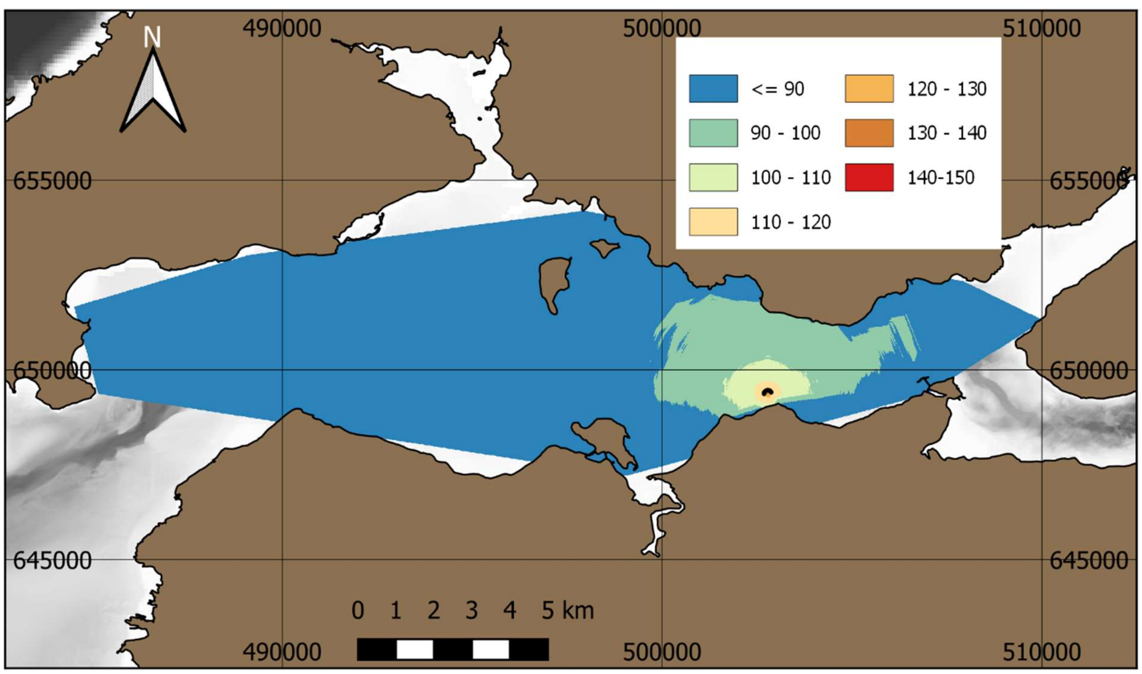

Figure 28. Scenario C3) Construction Socket pile drilling. Contour map of $L_{p,rms}$ (MF-weighted, “Max-over-depth”). Values in dB re 1 µPa. Behavioural criteria of 120 dB is indicated by dashed line.

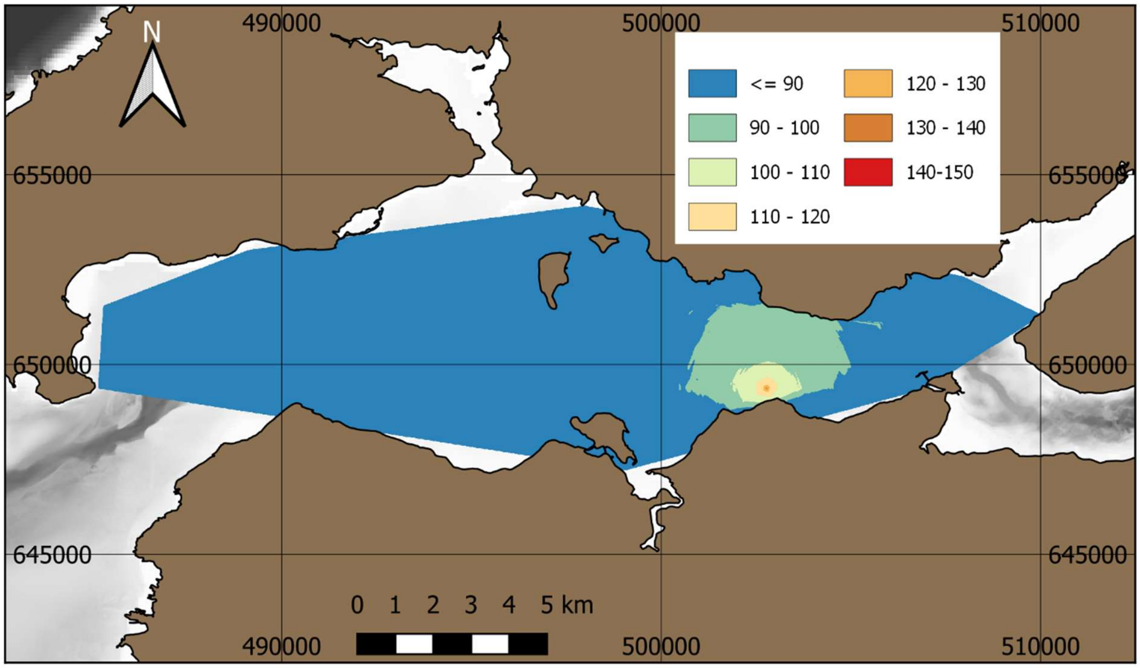

Figure 29. Scenario C4) Blasting. Contour map of $L_{p,rms}$ (MF-weighted, “Max-over-depth”). Values in dB re 1 µPa. Entire sound field is below the behavioural criteria of 160 dB.

7 Operational Phase

7.1 Scenario overview

The following scenarios were modelled in the operational scenario, with reference to the locations of Figure 2:

A **FSRU alone**. This is assumed to be a single, continuous noise source, located at position A.

B **FSRU together with an offloading LNG carrier**, including 1 tug in idling mode close to the carrier. This scenario covers 24 hours. All sources are located at position A. The scenario includes the following activities with corresponding time durations:

- FSRU operating continuously
- LNG carrier and tug involved in offloading for 23 hours and 45 minutes
- Carrier and 4 sailing/engaged tugs transiting for 15 minutes

D **FSRU together with approaching LNG carrier**, including 4 sailing/engaged tugs close to the carrier. All sources are assumed to be continuous during the transit time from Position B to A (see Figure 2). FSRU source located at position A, carrier and tugs located at position B. This scenario only addresses the 15 minutes during which the approach activity takes place.

E **FSRU together with berthing LNG carrier, including 4 engaged tugs, a general cargo ship sailing in the middle of the Estuary, and ship moored at Moneypoint**. FSRU, LNG Carrier and Tugs are located at Position A, the general cargo ship at Position C, and the moored ship at position M. This scenario is an expansion of the Offloading scenario and covers 24 hours. It includes the following activities with corresponding time durations:

- FSRU operating continuously
- LNG carrier and tug berthed for 23 hours and 45 minutes
- Carrier and 4 sailing/engaged tugs transiting for 15 minutes

- Cargo ship sailing in estuary for 15 minutes
- Moored ship at Moneypoint, operating continuously

Further as described in Appendix B, Scenario A with the FSRU was modelled for two additional conditions that include onboard noise abatement measures.

7.2 Noise source assumptions

7.2.1 FSRU, LNG carrier, tugs, and cargo ships

The source levels for the vessels used in the prediction are assessed based on literature data and VG's in-house data for measurements on similar vessels. The spectra assumed for this study are stated in Figure 30. The values are given as monopole source levels L_s in dB re 1 μPa·m. The source depth for the vessels is assigned as 0.7 times the draught of that vessel.

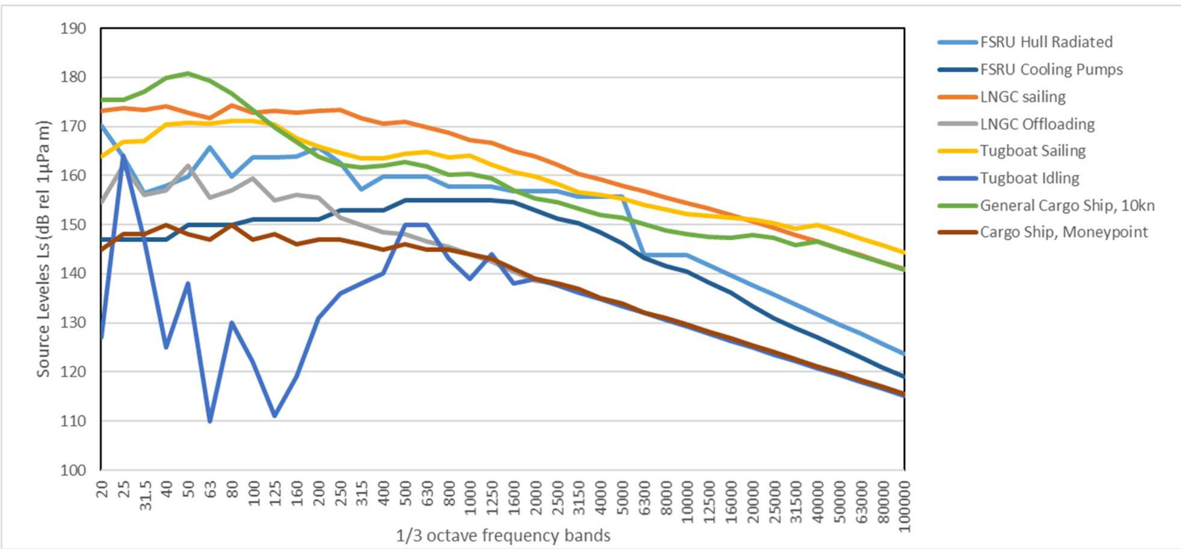

Figure 30. Underwater source levels for ships used in the predictions (L_s dB re. 1 μPa·m).

The basis of the evaluations is the use of an FSRU size 180.000 m³ with an estimated length of ~300 m, draught of 12.9 m, operating diesel generators located low in the hull, and various pumps and compressors running for the regassification process. Sea water cooling intake/outlets are located approx. 3.5 m below the surface at a flow rate of 22.000 m³/hr plus additional 3500 m³/hr for engine and aux. equipment cooling. The diesel generators are assumed to be fitted with standard vibration isolators on both engines and generators. Operation of potential propulsion or thrusters is excluded from the evaluation / assumed not in operation.

The underwater noise from the FSRU will consist of hull radiated noise, and noise from sea chest outlets and inlets for the onboard cooling water systems - no propulsion system is in operation. As no literature information on underwater source data for FSRUs could be located, several initiatives were made to provide as accurate data as possible for the underwater noise from the FSRU. These included the following:

- An underwater noise measurement campaign was conducted on the Golar Freeze FSRU, located in the Old Harbour in Jamaica. This was found to be a practical opportunity for obtaining actual measured data from an FSRU, considering potential interfering noise from other ships etc. The measurements are documented in Appendix A of this report.
- To further investigate the underwater noise emission from the FSRU, a detailed model and prediction was carried out using Statistical Energy Analysis methodology of the Golar Igloo FSRU. The study and results are shown in the Appendix B of this report.

The two initiatives gave results within the range of expectations for the source data. However, the frequency content of the two investigations gave different results, as the equipment and operation conditions were not fully comparable. The predicted noise levels on the Golar Igloo was higher at higher frequencies than the measured levels on the Golar Freeze. As a conservative approach, it was decided to use the highest level in each 1/3 octave band from the two studies and combine these into a source level, which was used for the hull radiated noise from the FSRU.

The noise emission from the onboard sea water cooling pumps has been estimated based on information in the paper Robinson et al. 2012 Measurement of underwater noise from arising from marine aggregate operations [39], including an estimated 3 dB reduction for sea chest attenuation.

The approaching LNG carrier sailing condition is assumed to be at low speed (~5 knots) with main propulsion engaged and with assistance of 4 tugs. During the docked conditions for offloading the LNG carrier is assumed to have auxiliary generators in low to mid-load condition and no propulsion system engaged. The main source in this condition is expected to be the cargo pumps and the onboard generators. The draught of the LNG carrier is assumed to be 11.6 m.

The tugs are assumed to be operating in two conditions: Sailing while assisting the LNG carrier, and idling close to the jetty. The draught of each tug is assumed to be 6.1 m. The data for the tugs are taken form the Port of Vancouver ECHO1 data base, using the 50% average level for tugs [40].

The size of the general cargo ship sailing in the estuary is based on Shannon Foynes Port Authority Risk assessment [41]. The ship is assumed to be 40.000 DWT sailing at approx. 10 knots, and with a draught of 10.9 m. The source data are also taken from the Port of Vancouver ECHO1 data base [40]. The ship moored at Moneypoint is assumed to be 150.000 DWT, berthed (0 knots) with only one auxiliary generator running (low load), draught assumed to be 16.9 m, and source data taken from [42] .

In Figure 31 the broadband source levels are shown for a comparison of the relative importance of the individual sources, revealing that sailing vessels (general cargo vessels, LNG carrier, and tugs) are expected to have the highest overall levels.

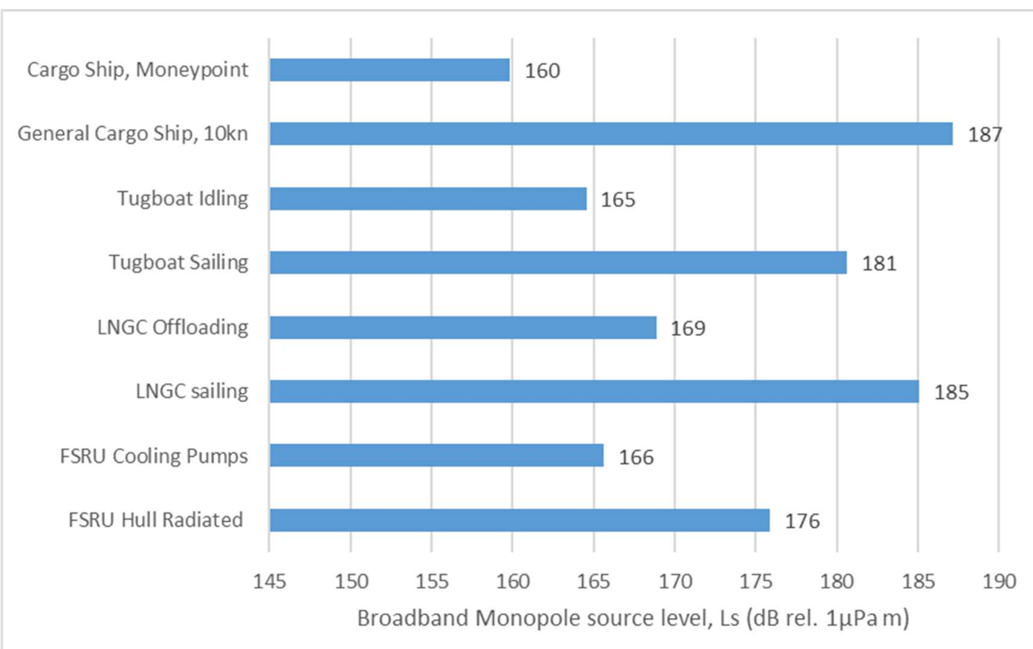

Figure 31. Broadband underwater source levels for ships used in the predictions (L_s dB re 1 µPa·m)

7.3 Results – Operation Phase

In the following, all noise results represent the maximum observation across all depth positions at the same range, or “Max-over-depth”.

Tables of distance-to-threshold and area-to-threshold are provided in Appendices A to E.

Selected contour maps of the sound fields are shown in Figure 32 to Figure 35. Note that these represent interpolated results based on the detailed transects and are mainly included for visual overview. The distances and areas of Appendices G to J were derived directly from the detailed transect results.

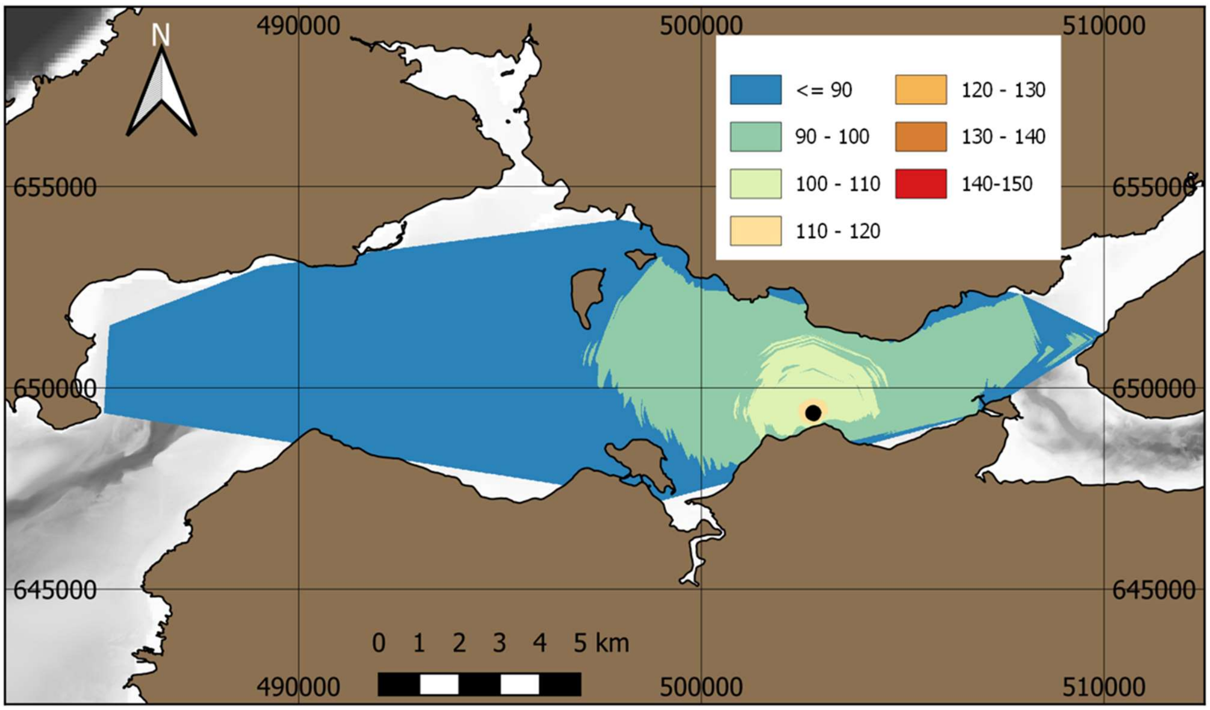

Figure 32. Scenario A) FSRU with onboard seawater pumps. Contour map of $L_{p,rms}$ (MF-weighted, “Max-over-depth”). Values in dB re 1µPa. Behavioural criteria of 120 dB is indicated by dashed line.

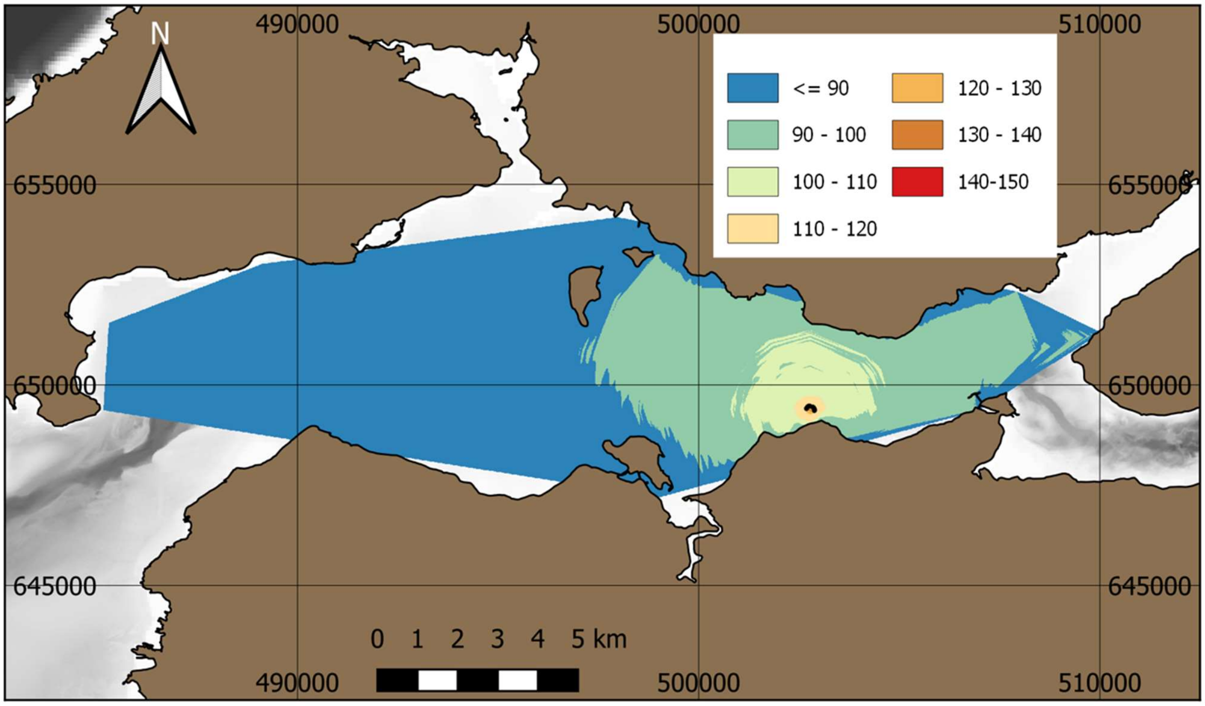

Figure 33. Scenario B) FSRU together with an offloading LNG carrier, including 1 tug in idling mode. Contour map of $L_{p,rms}$ (MF-weighted, "Max-over-depth"). Values in dB re 1 μPa. Behavioural criteria of 120 dB is indicated by dashed line.

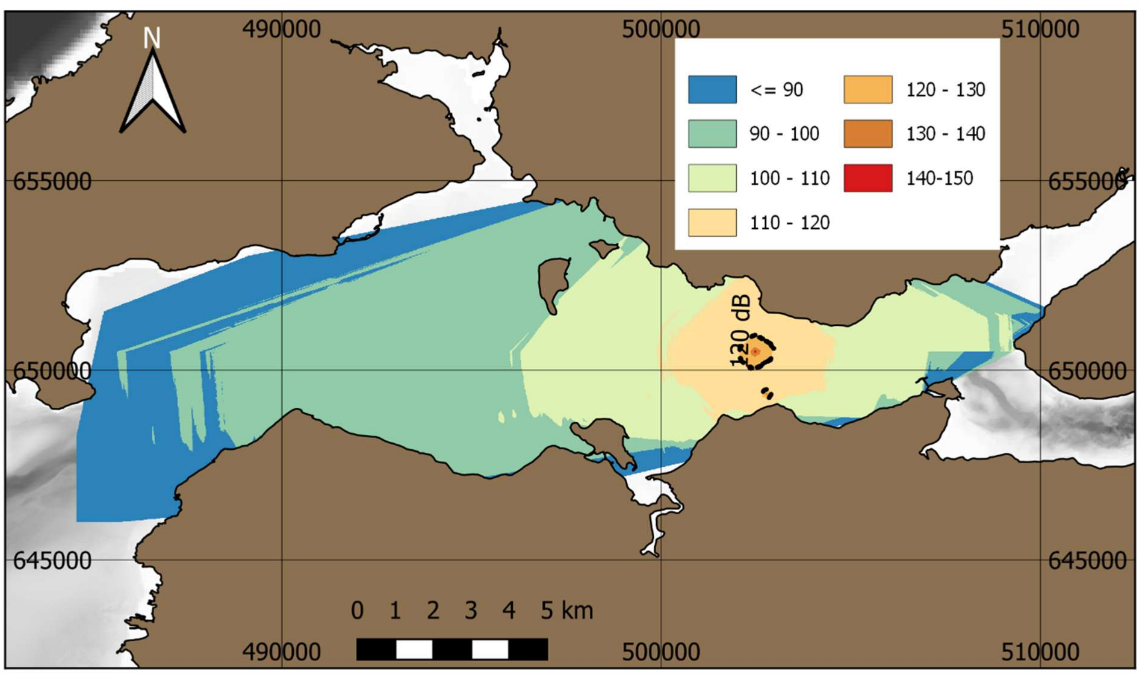

Figure 34. Scenario D) FSRU together with approaching LNG carrier, including 4 sailing tugs. Contour map of $L_{p,rms}$ (MF-weighted, "Max-over-depth"). Values in dB re 1 μPa. Behavioural criteria of 120 dB is indicated by dashed line.

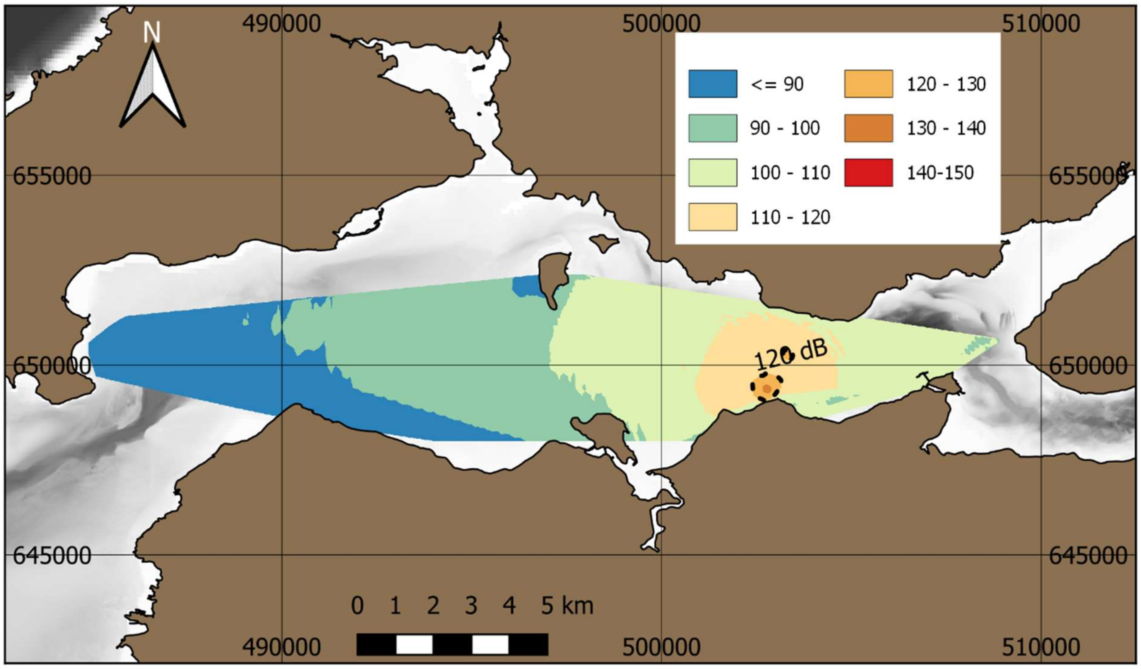

Figure 35. Scenario E) FSRU together with berthing LNG carrier, including 4 idling /engaged tugs, a general cargo ship sailing in the middle of the Estuary, and ship moored at Moneypoint. Contour map of $L_{p,rms}$ (MF-weighted, "Max-over-depth"). Values in dB re 1 μPa. Behavioural criteria of 120 dB is indicated by dashed line.

8 Final Comments

Section 4 describes the existing ambient noise at the site as 88 dB using MF-weighting, based on the statistical Median (L50) of all measurements. Assuming MF-weighting, Table 14 shows a rough comparison with the predicted $L_{p,rms}$ for the modelled scenarios. It follows that the various scenarios produce noise levels exceeding the ambient noise at all multiple km ranges.

Similarly, 4.1 describes the noise from a passing ferry. Applying a coarse conversion, this corresponds to approximately $L_{p,rms}$ = 108 dB (using MF-weighting) at a distance of 10 m from the ferry. The right-most column in Table 14 shows the distance within which the predicted noise exceeds that of 10 m from the ferry.

Scenario	Range within which the prediction exceeds...	
	Ambient noise	Noise from ferry
C1 – Impact pile driving	All ranges, i.e multiple km	15 km
C2 – Vibratory driving	9.8 km	1.0 km
C3 – Socket pile drilling	9.8 km	1.1 km
C4 - Blasting	7.4 km	0.8 km
A - FSRU as the only noise source	15 km	1.2 km
B - FSRU together with an offloading LNG carrier	15 km	1.2 km

D - FSRU together with approaching LNG carrier	All ranges, i.e multiple km	6.2 km
E - FSRU together with berthing LNG carrier, 4 tugs engaged, cargo ship sailing in estuary, berthed ship at Moneypoint	All ranges, i.e multiple km	6.5 km

Table 14. Predicted noise compared to ambient noise (Median, L50), and noise from ferry. Based on MF-weighted $L_{p,rms}$.

For scenarios corresponding to C1 impact pile driving, D approaching LNG carrier, and E multiple vessels, the noise exceeds that of the ferry for more than 6 km away from the source. However, for the scenarios A and B with the FSRU as only noise source or FSRU with offloading carrier, respectively, the noise only exceeds that of the ferry for approximately 1.2 km distance from the source. Similarly, for C2 vibro-driving, C3 drilling, and C4 blasting, the same distance is at 0.8-1.2 km.

It is noted that the above comparisons are based on physical, acoustic metrics. In cases of excessive noise, the degree of audibility or potential animal response strongly depend on the respective hearing abilities.

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Appendix A. Measurement of Underwater noise source level for Golar Freeze FSRU

Vysus Group (VG) has undertaken measurements of the underwater noise emission from the Floating Storage and Regasification Unit (FSRU) Golar Freeze located at Old Harbour (Jamaica). The measurements were carried out on 19th March 2021 in the period 07:00AM – 08:15AM local time. Due to Covid19 restrictions, it was not possible for Vysus technicians to perform the measurements. The measurements were therefore caried out by New Fortress Energy crew on site following a detailed description from VG. The measurements were performed using equipment from VG's lab.

Description of FSRU

The FSRU was located at Old Harbour in Jamaica at the offshore mooring point, see Figure 36. Local water depth at the offshore mooring point is approx. 15 m.

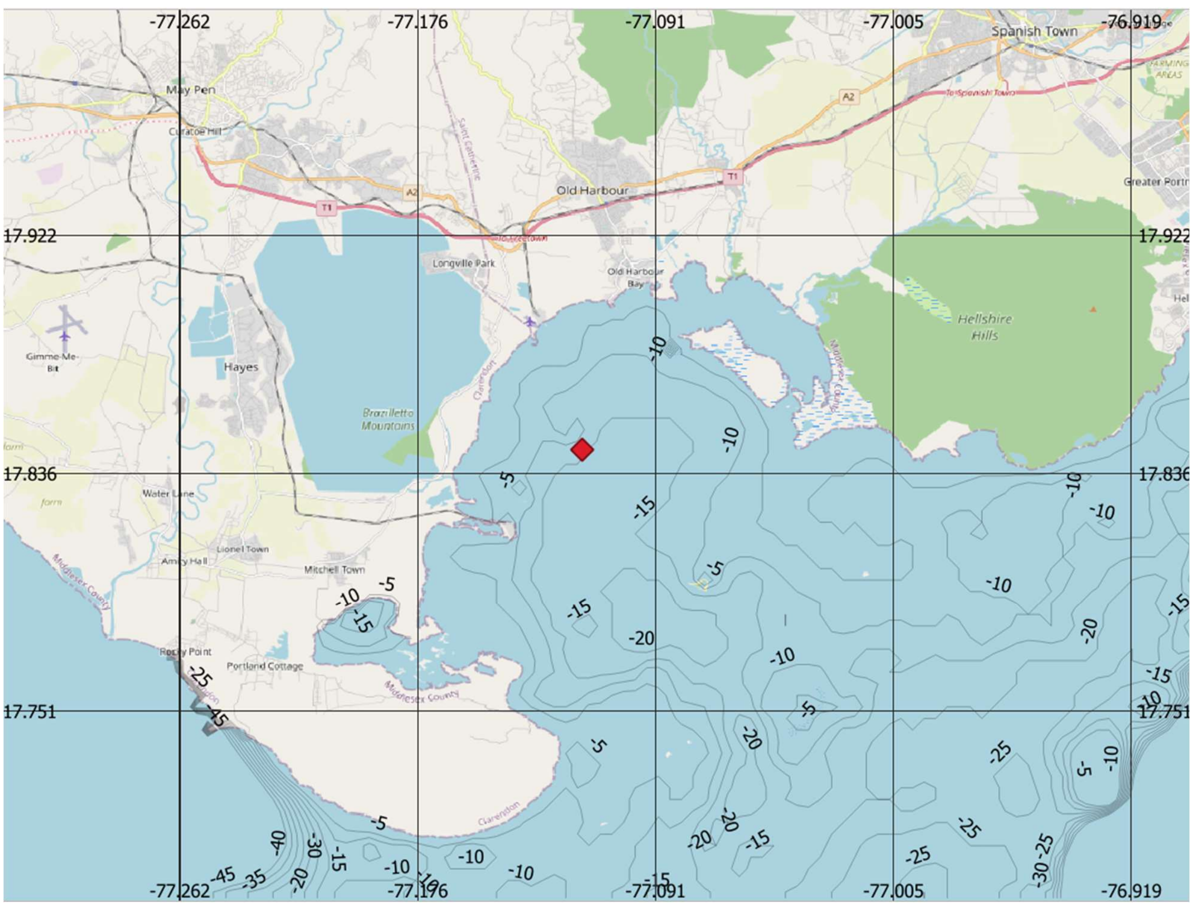

Figure 36. Location of Golar Freeze FSRU (red diamond).

© OpenStreetMap contributors, https://www.openstreetmap.org/copyright, Depth data from GEBCO Compilation Group (2020) GEBCO 2020 Grid (doi:10.5285/a29c5465-b138-234d-e053-6c86abc040b9).

The FSRU main particulars and operating conditions given in the following tables:

Feature	Value
Length over all	287.55 m
Breath moulded	43.4 m
Draught	11.9 m
Cargo Capacity	125,862 m3 (100% -160°C)

Table 15. Main particulars of FSRU.

Feature	Property
Gas export	48.624 MMSCFD
Cargo volume	62,212 m^3
Cargo volume send out at time of testing	2,558.2 m^3
Turbo generator #1	2040KW/1798 RPM
Turbo generator #2	2078KW/1800 RPM
Booster pumps	Two running
MSO compressor	One running
Diesel generators	None running

Table 16. Operating conditions during the measurements.

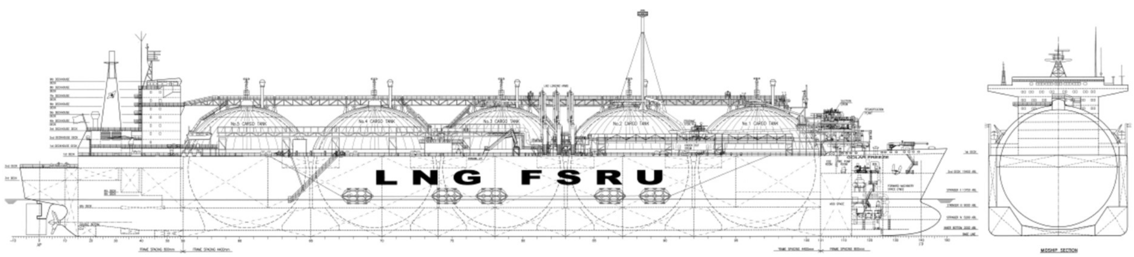

Figure 37. Side view and section of the Golar Freeze FSRU.

<u>Measurements</u>

The measurements were carried out using a 4-channel SoundTrap 4300 underwater logger unit connected with two HTI 96-min hydrophones. The hydrophones were deployed at 6 and 10 m depth. The hydrophones were located on a drifting submerged line with a floating buoy and an elastic release to supress wave motions. Time signals were recorded with a sampling rate of 96 kHz and later analysed by Vysus Group's noise specialists in Denmark.

The underwater noise was measured in 6 points (P1 – P6) around the FSRU in distances varying from 712 m to 211 m to the geometrical centre of the FSRU. The distance to the vessel was determined by registering the GPS position at the start and end of each measurement together with the fixed position of the FSRU, corrected to the geometrical centre of the vessel.

The ambient noise was measured in a position in the centre of the bay at approximately 1.5 km from the FSRU.

During the measurements the air temperature was 25 °C, wind ≈3 m/s (N), air pressure 1017 mBar, and current in NE direction. The wave height was assessed as < 0.5 m - Sea state 2.

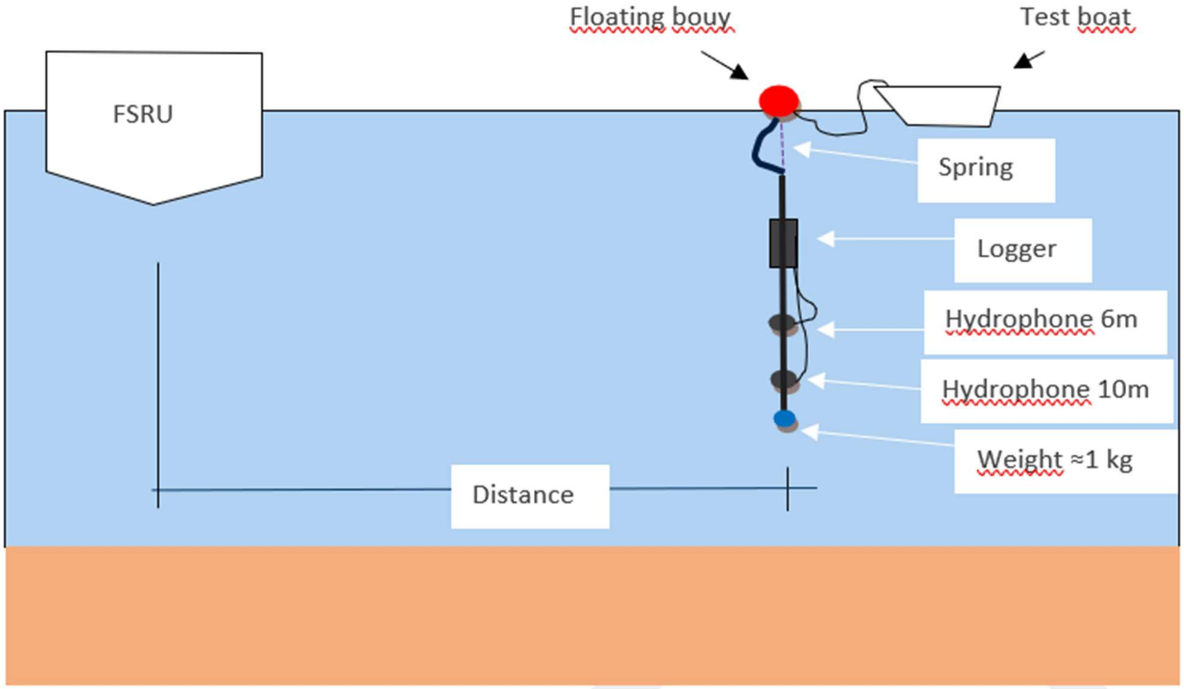

Figure 38. Sketch of measurement setup.

Figure 39. Measurement equipment on deck of test boat.

Figure 40. Golar Freeze FSRU seen from position P3.

Figure 41. Golar Freeze FSRU seen from position P6.

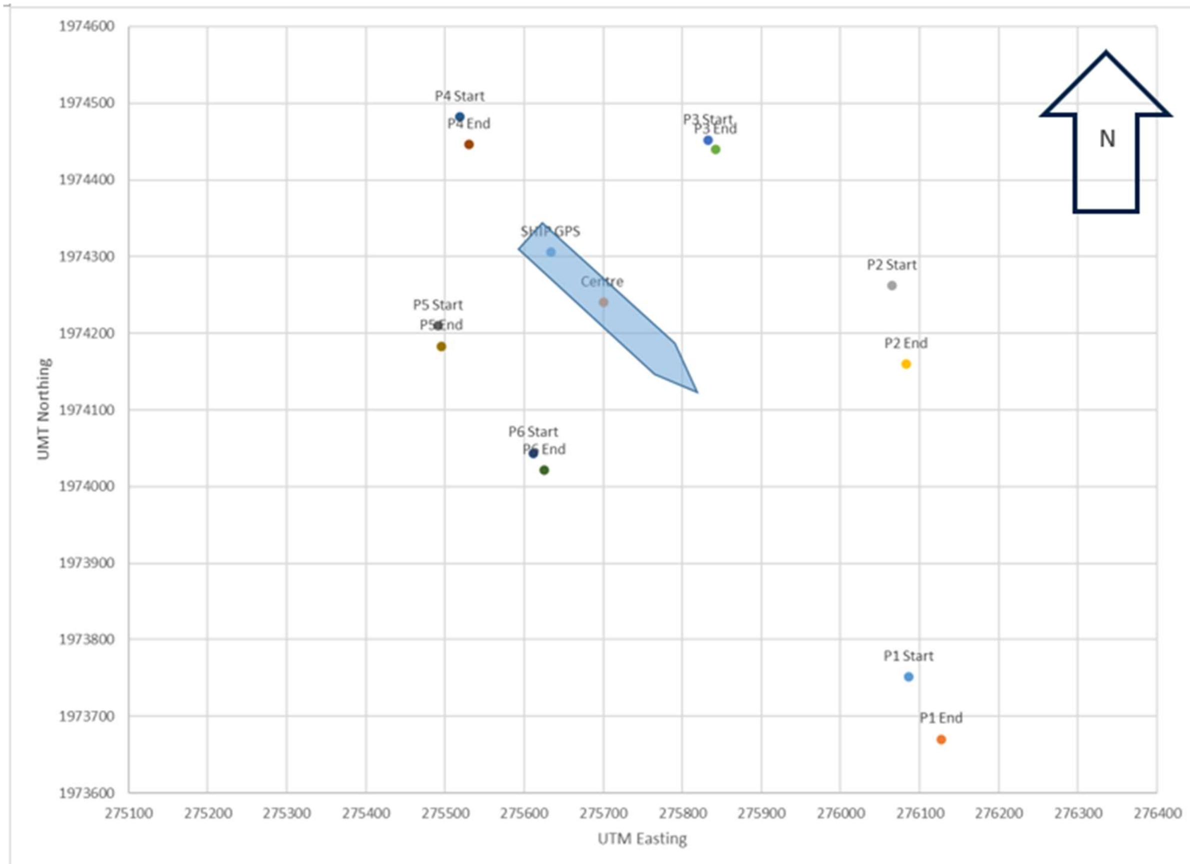

Figure 42. Location of measurement points relative to Golar Freeze FSRU.

Conversion to source level

The shallow water of only 15 m on the test site is affecting the measured underwater noise levels significantly. It is therefore necessary to perform a calculation of the expected transmission loss in the water to correct to an equivalent source level level for the vessel. The calculation of the transmission loss (TL) between the ship's geometrical centre and the individual positions has been made using the RAMGeo Parabolic Equation propagation code of the ActUP suite. The calculations were performed at each 1/3-octave band centre frequency from 20-10.000 Hz in vertical steps of 0.25 m and horizontal steps of 0.5 m. The source level (SL, equivalent monopole source level) was subsequently determined for each measurement position as the measured underwater noise levels (Lp,rms in dB re. 1µPa) plus the calculated transmission loss: SL= Lp+TL.

The sound pressure level was analysed over a period of approximately 2 minutes deemed to represent the most stable period in the measurements, excluding periods evaluated to be affected by the deployment, currents and surface waves. To compensate for the drifting hydrophones the calculated transmission losses were horizontally averaged over a distance corresponding to the start and end positions in each position, and a vertical average of ±0.5 m of the nominal depths of 6 m and 10 m. The source levels computed in each position were averaged on energy basis to get the final source level for the FSRU.

The input data assumed in the calculation of the transmission loss are given below in Table 17 and Table 18:

Depth below surface [m]	Temperature [°C]	Salinity [ppt]	Sound Speed [m/s]
0	27	36	1540.1
15	25	33.2	1532.7

Table 17. End points of linear sound speed profile.

Layer Description	Layer, position below seafloor		Compressional wave speed	Density	Compressional wave Attenuation	Shear wave speed	Shear wave Attenuation
	z-top [m]	z-bottom [m]	c_p [m/s]	ρ [kg/m3]	α_p [dB/λ]	c_s [m/s]	α_s [dB/λ]
Silty sand	0	3	1600	1800	0.70	-	-
Clayey silt	3	7	1500	1940	0.20	-	-
Silty clay	7	60	1550	1800	0.20	-	-
Limestone	60	200	5350	2700	0.10	2400	0.2

Table 18. Geoacoustic model for Old Harbour seabed.

Results

The determined source levels are given in the below Figure. The measured levels were assessed as being affected by ambient noise for frequencies above 3150 Hz. Further, the shallow water cut-off frequency was determined as approximately 70 Hz, caused by the shallow water depth of only 15 m.

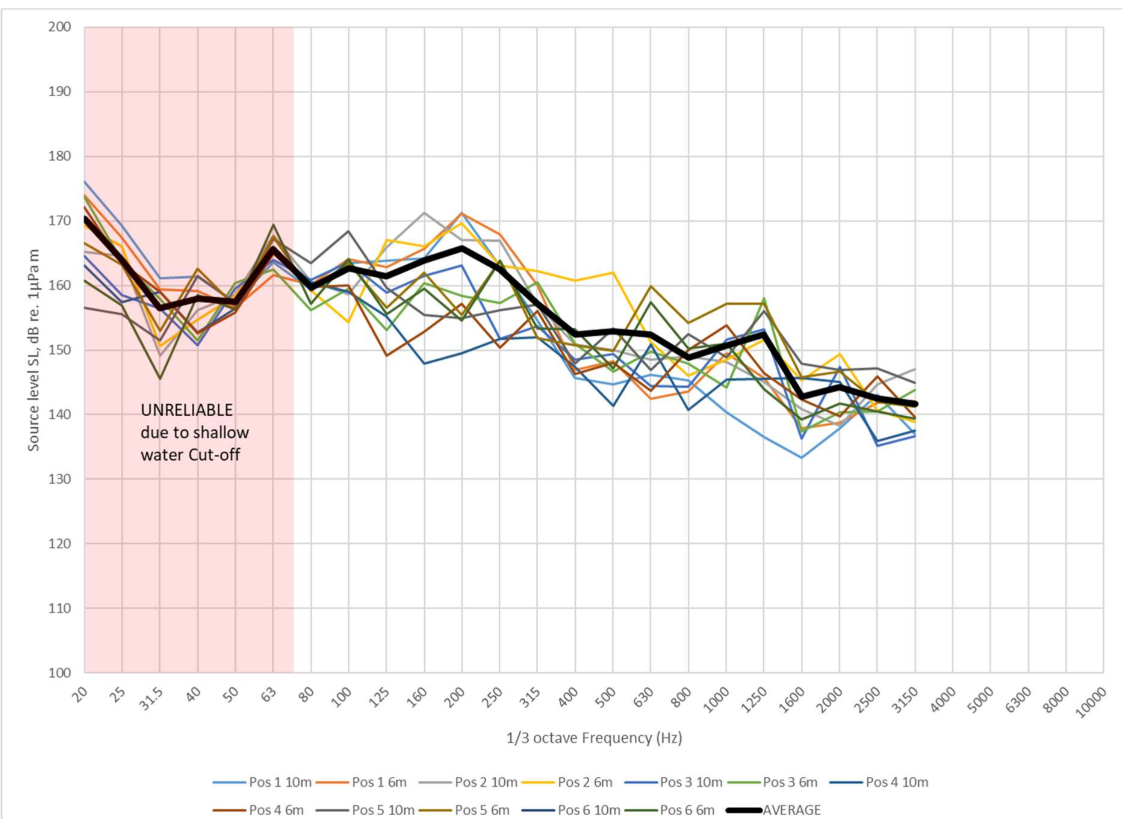

Figure 43. Measured underwater source level spectra - Golar Freeze FSRU.

The results show quite some variance in the different directions measured. This could be due to directivity of the vessel, but it could also be due to uncertainties in the measurements and the calculation of the transmission loss in. It should also be noticed that the measurements were carried out by non-specialist crew due to Covid-19 restrictions. However, the results are deemed to be a reasonable indication of the true source level of the FSRU.

Appendix B. SEA modelling of underwater noise source level for FSRU Golar Igloo

The following describes the results of detailed predictions of the underwater noise from the FSRU Golar Igloo. The calculations are done by Statistical Energy Analysis (SEA) using the commercial software VAOne. The objective of the calculations is to evaluate the underwater noise source strength of the FSRU. It should be noted that the Golar Igloo is only an example of a potential FSRU which could be located at the Shannon Technology and Energy Park – other FSRUs could be used too.

A 3D calculation model of the Golar Igloo FSRU has been constructed, including the main geometries of shell plates, bulkheads, stiffeners etc. The model incudes material data for the steel structure including, density, loss factors and young's modulus. The various located sources are then added to the model with both a structure-borne and airborne source strength. The source strengths are vendor data were available – other source data are taken from previous measurements on similar equipment.

Description

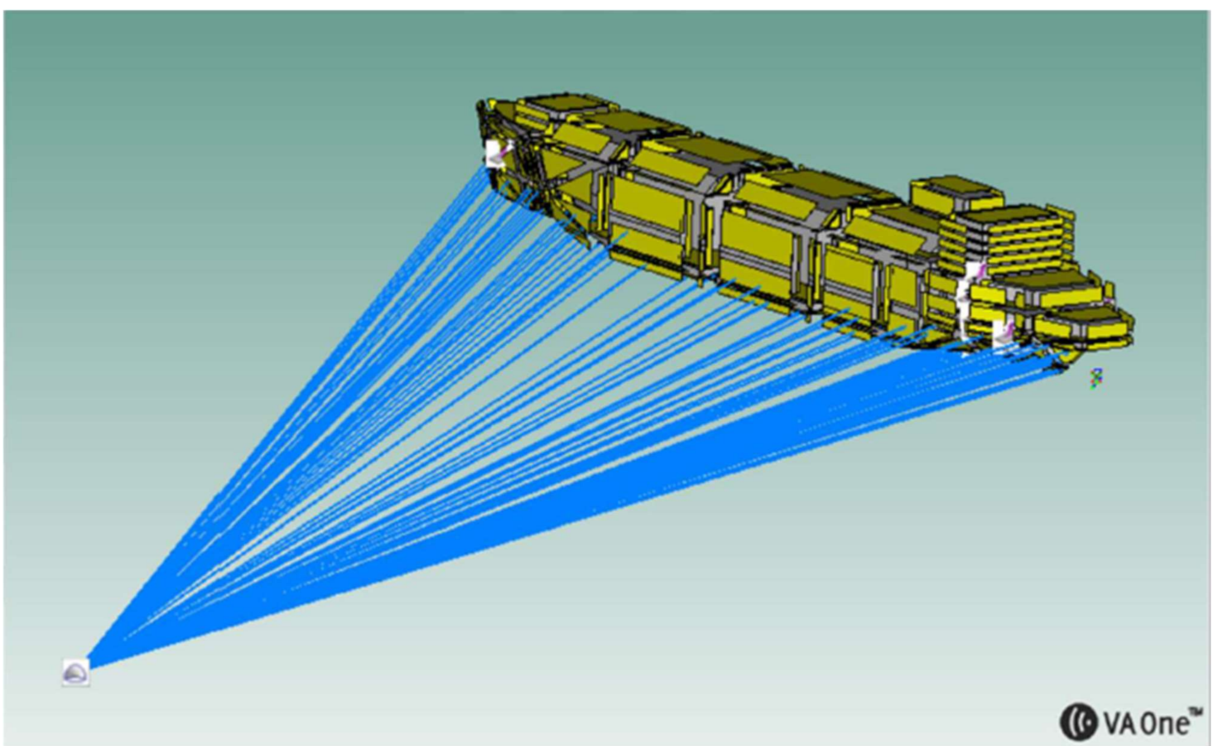

Figure 44. Picture of VAOne model of the Golar Igloo (exploded view).

The model has been created using the information from the steel drawings for the vessel on steel thicknesses of deck plates and other steel structures. The steel thickness in the outer shell above the propeller is around 40 mm. The shell below water is 18-19.5 mm and the main part of the hull above water is 14.5 mm. The main decks in the aft part of the hull, incl. engine rooms are 15 mm. Bulkheads have a general steel thickness of 11 mm.

The steel structure has been calculated with a frequency independent loss factor of 1%, which is found to be representative based on measurements in ship structures. Each enclosed room is modelled as an acoustic cavity with and airborne absorption coefficient as stated in the below Table 19.

Parameter	31.5	63	125	250	500	1000	2000	4000	8000
Mech. Loss factor (%)	1%	1%	1%	1%	1%	1%	1%	1%	1%
Absorption coeff. (-)	0.005	0.008	0.01	0.05	0.10	0.10	0.10	0.10	0.10

Table 19. Structural mechanical loss factor in steel and air absorption coefficients used in model.

The calculations are carried out using the statistical energy analysis methodology with the software VAOne ver. 2014. This method considers each steel plate, beam of acoustic cavity as a subsystem and an energy storage, and the method tracks the energy flow between the different subsystems. The energy flow between the subsystems are determined by coupling loss factors calculated according to the SEA theory. Steel plates are coupled together as well as acoustic cavities are coupled to the steel plates in the model. For the steel plates both bending, shear and longitudinal waves fields are considered as each wave type is calculated as a separate subsystem. The calculations can therefore also handle the coupling between different wave types in different connected plates, e.g. coupling between longitudinal ways in one plate to bending was in a coupled plate. The sound radiation efficiencies are theoretically calculated in the software, based on the steel properties, stiffening elements, and acoustic medium (air/seawater).

The calculations are carried out in 1/1-ocatve bands from 31.5 to 8000 Hz. The Statistical Energy Analysis method has a fundamental assumption of a sufficient modal density in each subsystem. The modal density will decrease with frequency, which means there is a lower frequency where the results gets unreliable. The lower frequency limit is determined to be around 100 Hz, and results below this frequency should be considered as a guideline only.

The outer shell part below the waterline is loaded with water on one side. The underwater noise level is calculated using an energy sink at a distance of 300 m from the FSRU centre line and 80m below the surface, corresponding to approx. 15° angle to the water surface. Previous calculations have shown that the calculation results in other depts gives the same results and therefore only one point is used in the calculations. Reflections from the sea surface are not included in the calculation model and the calculated sound pressure level in the energy sink point is therefore the unaffected underwater sound pressure level. Hence, the monopole underwater source level (SL) can be determined by only correcting for the distance from the energy sink point to the determined acoustical centre of the vessel, which is the vessel centreline at a depth of 0.7 times the draught of 11.9 m.

Table 20 shows an overview of the sources included in the model. The table show the number of sources assumed to be running in each of the two calculated scenarios; With gensets running, and with gensets stopped and using shore power. It is in general assumed that one piece of each type equipment will be on standby, e.g. only 3 out of the 4 generator sets are assumed in operation.

The calculations include both airborne and structure-borne source contributions from the identified sources. The used airborne source levels are given in Table 21. The airborne levels are introduced in the model directly as sound power sources. The structure-borne sources are introduced into the model by equivalent power sources giving the levels indicated in Table 22. The sources are based on a combination of vendor data and Vysus measurements on similar equipment on previous projects. The generators are assumed to be equipped with standard vibration isolators.

Location on Deck	Room	Equipment - Source level	Generators running	Generators Stopped
Floor	Aux. room	Ballast Pumps – A	2	2
		Main CSW Pumps – A	2	2
		Aux boiler Sea water pumps – B	2	2
		MDO Transfer Pump – B	1	1
		CSW pumps for Cargo Mach. – A	1	1
		Sewage grey water Dist. Pump – B	1	1
		Clean water discharge pump – B	1	1
4th Deck	Engine rooms	Main Generator Engine -C	3	
		Main GE Chiller units – D	2	
	Purifyrer room PS	Main GE HFO Circ. Pumps – B	2	
		Main GE HFO supply Pumps - B	2	
		Main GE purifier pumps – B	2	
	Purifyrer room SB	Main GE HFO Circ. Pumps – B	2	
		Main GE HFO Supply Pumps – B	2	
		Main GE purifier pumps – B	2	
3rd Deck		Sewage treatment unit – B	1	1
		Aux. boiler water Circ. Pumps – B	4	4
		Fresh Water Unit – B	1	1
2nd Deck		Hydraulic Power Unit – E	1	1
Tank Top	FWD Pump Room	Large Pumps – A	2	2

Table 20. Number of equipment assumed to be running in the two calculations scenarios (with Gensets running, and with Gensets stopped, with equipment running on shore power).

Equipment	31.5	63	125	250	500	1000	2000	4000	8000	Tot
A Large Pump	50	65	82	91	94	94	92	86	75	99
B Small Pump	50	65	85	89	88	90	88	83	69	96
C Main Generator	66	81	99	109	118	119	118	114	105	124
D Chiller	50	65	85	89	88	90	88	83	69	96
E HPU	54	68	82	93	89	86	89	79	65	96

Table 21. Airborne source levels used, per source (LwA, A-weighted sound power level in 1/1-octave bands, in dB rel. 1pW).

Equipment	31.5	63	125	250	500	1000	2000	4000	8000
A Large Pump	112	113	111	95	93	89	83	83	76
B Small Pump	101	106	103	90	91	88	86	73	65
C Main Generator	120	114	116	104	104	90	81	70	69
D Chiller	91	102	96	96	90	90	91	90	79
E HPU	105	113	112	111	107	90	90	87	75

Table 22. Structure-borne source levels used, per source (Lv, velocity levels in 1/1-octave bands in dB rel. 10^{-9} m/s).

Results

The results of the calculations are shown in the below Figure.

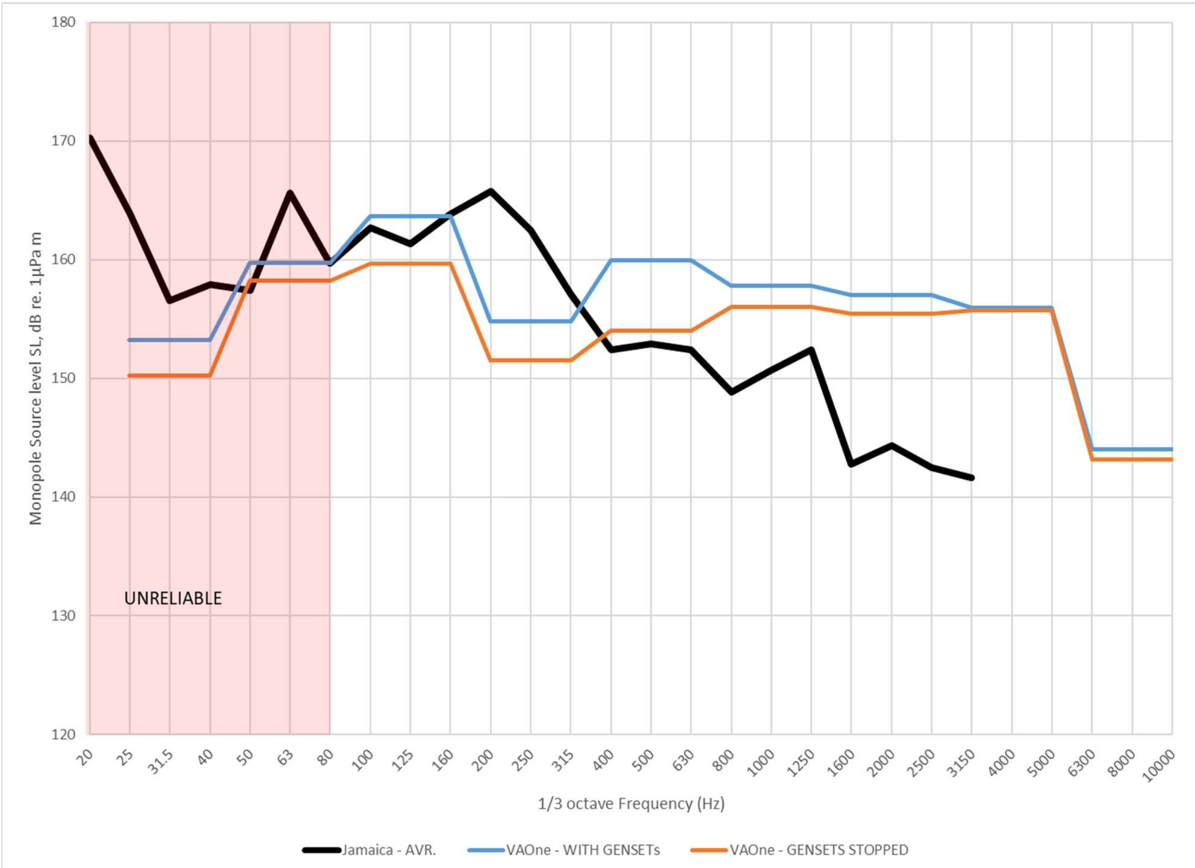

Figure 45. Predicted underwater source level for the hull-radiated noise from FSRU Golar Igloo, compared to the measurements on the Golar Freeze FSRU measured in Jamaica.

Figure 45 shows the predicted underwater source level for the FSRU for the scenarios with and without the gensets in operation. The estimated source level used in the previous predictions together with the source level measured on the Golar Freeze in Jamaica are shown for comparison. For reference the sound pressure level inside the engine room with two diesel generators running is predicted by the model as 111 dB(A), which is very realistic compared to measurements in other generator rooms.

Looking at the results it appears the calculated source levels for the Golar Igloo are above the measured source strength at high frequencies and a below at lower frequencies. It should be noted that the Golar Freeze did not have diesel generators operating during the measurements, as the power on Golar Freeze was provided by two steam turbines, so the calculated and measured source levels are not directly comparable.

From the detailed results it appears the underwater noise is dominated by the structure-borne sources compared to the airborne sources. Especially the diesel generators and the large pumps, such as ballast pumps and seawater cooling pumps have a significant contribution to the source levels.

Appendix C. CONSTRUCTION SCENARIO C1 – Impact Pile driving Results

Distance-to-Threshold, impulsive, SELcum

Transect	PW weighted		MF weighted		HF-Weighted	
	TTS	PTS	TTS	PTS	TTS	PTS
Criteria (dB)	170	185	170	185	140	155
N	1464	393	430	90	2013	1337
NE	3692	505	585	82	5713	2731
E	4010	590	786	91	7640	3163
SE	2443	465	634	71	5103	2153
S	1775	427	444	83	2439	1506
SW	3096	500	539	73	4288	2539
W	3267	516	636	94	5398	2602
NW	2852	452	541	84	3909	1987
Area, m2	15527129	644681	808257	19962	31919440	8565018

Distance-to-Threshold, impulsive, 0-peak, flat

Transect	Mid-frequency cetaceans (MF)		High-frequency cetaceans (HF)		High-frequency cetaceans	
	TTS	PTS	TTS	PTS	TTS	PTS
Criteria (dB)	224	230	196	202	212	218
N	-	-	227	128	32	-
NE	-	-	246	138	33	-
E	-	-	261	140	38	-
SE	-	-	231	125	43	-
S	-	-	246	147	48	-
SW	-	-	257	114	43	-
W	-	-	288	119	39	-
NW	-	-	252	131	34	-
Area, m2	-	-	183563	48881	4238	-

Distance-to-Threshold (m), RMS Flat-Weighted

Criteria / Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	2702	2629	2486	2370	2128	2023	1593	1522	1321	1240	663	476	308
NE	8097	7575	6025	5388	5092	4948	4134	3596	2791	1716	806	549	367
E	11085	10304	8125	7240	6836	6635	4614	3853	2949	1680	1021	669	384
SE	7654	7030	5471	4868	4596	4437	2984	2304	1861	1487	831	502	332
S	2927	2733	2616	2519	2415	2227	2098	1853	1702	1526	657	485	335
SW	8077	7744	6154	5083	4336	3686	3463	2967	2373	1910	868	595	345
W	11789	11228	8363	6528	5794	4826	4447	3151	2287	1725	1039	627	374
NW	8594	8135	5679	4311	4354	4057	3850	3029	2273	1290	786	538	348
Area (m2)	65594356	55722103	47898145	42961055	38134838	32001422	23375830	16676217	10400842	4461838	1823398	844884	357795

Distance-to-Threshold (m), RMS MF-Weighted

Criteria / Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	1900	1679	1377	943	572	412	289	183	103	60	31	-	-
NE	4960	4295	2979	1417	849	581	336	188	99	61	31	-	-
E	6618	5901	3853	1924	1073	780	366	200	131	75	36	-	-
SE	4409	4079	2685	1837	904	635	293	181	126	69	41	-	-
S	2214	2087	1662	1584	656	446	310	215	138	77	43	-	-
SW	3731	3407	2797	2076	889	518	346	231	119	70	42	-	-
W	4922	3940	2828	1754	1002	598	374	221	108	77	37	-	-
NW	3932	3476	2521	1173	778	511	329	186	83	63	32	-	-
Area (m2)	26053612	16816979	10553816	4081897	1637963	765300	294879	115344	37865	12981	3730	-	-

Distance-to-Threshold (m), RMS HF-Weighted

Criteria / Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	1752	1381	1047	555	421	285	203	110	60	31	-	-	-
NE	4091	2857	1453	773	522	296	203	110	60	30	-	-	-
E	4756	3303	1785	976	683	349	201	133	74	36	-	-	-
SE	3406	2320	1746	843	546	278	172	119	69	41	-	-	-
S	1966	1589	1471	670	418	303	186	125	76	43	-	-	-
SW	3154	2599	1977	926	537	357	207	111	69	42	-	-	-
W	3663	2613	1745	1056	650	357	209	107	77	37	-	-	-
NW	3298	2372	1239	811	527	321	183	89	63	32	-	-	-
Area (m2)	15353121	9670425	3453322	1530618	711774	285436	110438	37320	12792	3656	-	-	-

Distance-to-Threshold (m), RMS PW-Weighted

Criteria / Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	2458	2465	2245	1992	1700	1435	1264	701	490	367	240	157	85
NE	8172	6595	5432	5130	4560	3682	1836	982	634	387	255	139	76
E	11126	8867	7262	6852	5932	4004	1952	1186	937	434	273	144	96
SE	7571	5947	4847	4560	4029	2399	1677	1016	750	362	240	129	86
S	2702	2564	2449	2312	2108	1759	1478	728	544	375	238	161	99
SW	7322	6365	4988	4115	3378	3069	2148	1093	664	430	240	149	92
W	10706	8869	6434	5681	4256	3170	2072	1274	722	447	227	157	97
NW	7819	6216	4295	4294	3801	2820	1718	909	686	387	217	151	81
Area (m2)	51851436	43411276	38083225	32594664	23686276	14965221	7872275	2453186	1102119	452879	172071	64873	23327

Distance-to-Threshold, Impulsive, 0-peak flat weighting, fish species

Transect	No swim bladder		Swim bladder not involved in hearing		Swim bladder involved in hearing	
	Recoverable injury	Mortality and potential mortality	Recoverable injury	Mortality and potential mortality	Recoverable injury	Mortality and potential mortality
Criteria (dB)	213		207		207	
N	28		66		66	
NE	28		62		62	
E	30		81		81	
SE	36		74		74	
S	42		85		85	
SW	36		75		75	
W	30		81		81	
NW	29		65		65	
Area, m2	2946		15756		15756	

Distance-to-Threshold, Impulsive, SELcum flat weighting, fish species

Transect	TTS	No swim bladder		Swim bladder not involved in hearing		Swim bladder involved in hearing	
		Recoverable injury	Mortality and potential mortality	Recoverable injury	Mortality and potential mortality	Recoverable injury	Mortality and potential mortality
Criteria (dB)	186	216	219	203	210	203	207
N	-	-	-	-	-	-	-
NE	-	-	-	-	-	-	-
E	-	-	-	-	-	-	-
SE	-	-	-	-	-	-	-
S	-	-	-	-	-	-	-
SW	-	-	-	-	-	-	-
W	-	-	-	-	-	-	-
NW	-	-	-	-	-	-	-
Area, m2	-	-	-	-	-	-	-

Appendix D. CONSTRUCTION SCENARIO C2 – Vibratory driving Results

Distance-to-Threshold, Non-impulsive, SELcum

Transect	PW weighted		MF weighted		HF-Weighted	
	TTS	PTS	TTS	PTS	TTS	PTS
Criteria (dB)	181	201	178	198	153	173
N	-	-	-	-	-	-
NE	-	-	-	-	-	-
E	-	-	-	-	-	-
SE	-	-	-	-	-	-
S	-	-	-	-	-	-
SW	-	-	-	-	-	-
W	-	-	-	-	-	-
NW	-	-	-	-	-	-
Area, m2	-	-	-	-	-	-

Distance-to-Threshold, Non-impulsive, SELcum flat weighting, fish species

Transect	TTS	No swim bladder		Swim bladder not involved in hearing		Swim bladder involved in hearing	
		Recoverable injury	Mortality and potential mortality	Recoverable injury	Mortality and potential mortality	Recoverable injury	Mortality and potential mortality
Criteria (dB)	186	216	219	203	210	203	207
N	-	-	-	-	-	-	-
NE	-	-	-	-	-	-	-
E	-	-	-	-	-	-	-
SE	-	-	-	-	-	-	-
S	-	-	-	-	-	-	-
SW	-	-	-	-	-	-	-
W	-	-	-	-	-	-	-
NW	-	-	-	-	-	-	-
Area, m2	-	-	-	-	-	-	-

Distance-to-Threshold (m), RMS Flat-Weighted

Criteria Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	1732	1563	1295	620	398	199	96	-	-	-	-	-	-
NE	3445	2721	1768	716	462	228	102	-	-	-	-	-	-
E	3624	2755	1640	875	449	215	99	-	-	-	-	-	-
SE	2272	1883	1500	707	388	230	117	-	-	-	-	-	-
S	1966	1732	1605	607	395	213	98	-	-	-	-	-	-
SW	2983	2317	1818	738	392	195	112	-	-	-	-	-	-
W	3151	2294	1588	800	437	204	118	-	-	-	-	-	-
NW	3142	2080	1284	663	417	220	113	-	-	-	-	-	-
Area (m2)	18095932	11058753	4114585	1423649	512365	129372	32670	-	-	-	-	-	-

Distance-to-Threshold (m), RMS PW-Weighted

Criteria Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	529	322	174	75	-	-	-	-	-	-	-	-	-
NE	608	346	178	86	-	-	-	-	-	-	-	-	-
E	737	359	189	94	-	-	-	-	-	-	-	-	-
SE	606	297	180	81	-	-	-	-	-	-	-	-	-
S	523	313	170	79	-	-	-	-	-	-	-	-	-
SW	623	350	176	98	-	-	-	-	-	-	-	-	-
W	662	366	187	117	-	-	-	-	-	-	-	-	-
NW	534	344	170	95	-	-	-	-	-	-	-	-	-
Area (m2)	1014792	333785	97471	23043	-	-	-	-	-	-	-	-	-

Distance-to-Threshold (m), RMS MF-Weighted

Criteria Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	1	-	-	-	-	-	-	-	-	-	-	-	-
NE	1	-	-	-	-	-	-	-	-	-	-	-	-
E	1	-	-	-	-	-	-	-	-	-	-	-	-
SE	2	-	-	-	-	-	-	-	-	-	-	-	-
S	2	-	-	-	-	-	-	-	-	-	-	-	-
SW	2	-	-	-	-	-	-	-	-	-	-	-	-
W	1	-	-	-	-	-	-	-	-	-	-	-	-
NW	1	-	-	-	-	-	-	-	-	-	-	-	-
Area (m2)	2	-	-	-	-	-	-	-	-	-	-	-	-

Distance-to-Threshold (m), RMS HF-Weighted

Criteria Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	-	-	-	-	-	-	-	-	-	-	-	-	-
NE	-	-	-	-	-	-	-	-	-	-	-	-	-
E	-	-	-	-	-	-	-	-	-	-	-	-	-
SE	-	-	-	-	-	-	-	-	-	-	-	-	-
S	-	-	-	-	-	-	-	-	-	-	-	-	-
SW	-	-	-	-	-	-	-	-	-	-	-	-	-
W	-	-	-	-	-	-	-	-	-	-	-	-	-
NW	-	-	-	-	-	-	-	-	-	-	-	-	-
Area (m2)	-	-	-	-	-	-	-	-	-	-	-	-	-

Appendix E. CONSTRUCTION SCENARIO C3 – Socket Pile Drilling Results

Distance-to-Threshold, Non-impulsive, SELcum

Transect	PW weighted		MF weighted		HF-Weighted	
	TTS	PTS	TTS	PTS	TTS	PTS
Criteria (dB)	181	201	178	198	153	173
N	33	-	-	-	248	-
NE	24	-	-	-	176	-
E	24	-	-	-	77	-
SE	33	-	-	-	213	-
S	43	-	-	-	280	-
SW	33	-	-	-	214	-
W	25	-	-	-	80	-
NW	24	-	-	-	175	-
Area, m2	2058	-	-	-	43784	-

Distance-to-Threshold, Non-impulsive, SELcum flat weighting, fish species

Transect	TTS	No swim bladder		Swim bladder not involved in hearing		Swim bladder involved in hearing	
		Recoverable injury	Mortality and potential mortality	Recoverable injury	Mortality and potential mortality	Recoverable injury	Mortality and potential mortality
Criteria (dB)	186	216	219	203	210	203	207
N	180	-	-	-	-	-	-
NE	129	-	-	-	-	-	-
E	104	-	-	-	-	-	-
SE	149	-	-	-	-	-	-
S	202	-	-	-	-	-	-
SW	154	-	-	-	-	-	-
W	110	-	-	-	-	-	-
NW	125	-	-	-	-	-	-
Area, m2	42791	-	-	-	-	-	-

Distance-to-Threshold (m), RMS Flat-Weighted

Criteria Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	1471	1615	480	242	85	39	-	-	-	-	-	-	-
NE	1207	1185	348	179	62	28	-	-	-	-	-	-	-
E	951	517	245	126	73	28	-	-	-	-	-	-	-
SE	1334	843	389	191	98	27	-	-	-	-	-	-	-
S	1467	1073	432	246	109	34	-	-	-	-	-	-	-
SW	1449	978	363	185	101	27	-	-	-	-	-	-	-
W	962	496	260	123	78	30	-	-	-	-	-	-	-
NW	1258	1175	331	163	59	27	-	-	-	-	-	-	-
Area (m2)	2932827	838789	238322	65671	16627	2379	-	-	-	-	-	-	-

Distance-to-Threshold (m), RMS PW-Weighted

Criteria Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	228	109	51	-	-	-	-	-	-	-	-	-	-
NE	169	78	37	-	-	-	-	-	-	-	-	-	-
E	129	79	38	-	-	-	-	-	-	-	-	-	-
SE	194	103	46	-	-	-	-	-	-	-	-	-	-
S	236	126	57	-	-	-	-	-	-	-	-	-	-
SW	195	103	46	-	-	-	-	-	-	-	-	-	-
W	117	81	39	-	-	-	-	-	-	-	-	-	-
NW	154	76	36	-	-	-	-	-	-	-	-	-	-
Area (m2)	67643	21773	4863	-	-	-	-	-	-	-	-	-	-

Distance-to-Threshold (m), RMS MF-Weighted

Criteria Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	-	-	-	-	-	-	-	-	-	-	-	-	-
NE	-	-	-	-	-	-	-	-	-	-	-	-	-
E	-	-	-	-	-	-	-	-	-	-	-	-	-
SE	-	-	-	-	-	-	-	-	-	-	-	-	-
S	-	-	-	-	-	-	-	-	-	-	-	-	-
SW	-	-	-	-	-	-	-	-	-	-	-	-	-
W	-	-	-	-	-	-	-	-	-	-	-	-	-
NW	-	-	-	-	-	-	-	-	-	-	-	-	-
Area (m2)	-	-	-	-	-	-	-	-	-	-	-	-	-

Distance-to-Threshold (m), RMS HF-Weighted

Criteria Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	-	-	-	-	-	-	-	-	-	-	-	-	-
NE	-	-	-	-	-	-	-	-	-	-	-	-	-
E	-	-	-	-	-	-	-	-	-	-	-	-	-
SE	-	-	-	-	-	-	-	-	-	-	-	-	-
S	-	-	-	-	-	-	-	-	-	-	-	-	-
SW	-	-	-	-	-	-	-	-	-	-	-	-	-
W	-	-	-	-	-	-	-	-	-	-	-	-	-
NW	-	-	-	-	-	-	-	-	-	-	-	-	-
Area (m2)	-	-	-	-	-	-	-	-	-	-	-	-	-

Appendix F. CONSTRUCTION SCENARIO C4 – Blasting Results

Distance-to-Threshold, Non-impulsive, SELcum

Transect	PW weighted		MF weighted		HF-Weighted	
	TTS	PTS	TTS	PTS	TTS	PTS
Criteria (dB)	170	185	170	185	140	155
N	-	-	-	-	-	-
NE	-	-	-	-	-	-
E	-	-	-	-	-	-
SE	-	-	-	-	-	-
S	-	-	-	-	-	-
SW	-	-	-	-	-	-
W	-	-	-	-	-	-
NW	-	-	-	-	-	-
Area, m2	-	-	-	-	-	-

Distance-to-Threshold, impulsive, 0-peak, flat

Transect	Mid-frequency cetaceans (MF)		High-frequency cetaceans (HF)		High-frequency cetaceans	
	TTS	PTS	TTS	PTS	TTS	PTS
Criteria (dB)	224	230	196	202	212	218
N	-	-	272	86	8	-
NE	-	-	217	79	6	-
E	-	-	221	92	7	-
SE	-	-	280	78	8	-
S	-	-	276	104	8	-
SW	-	-	233	78	9	-
W	-	-	262	97	8	-
NW	-	-	292	86	6	-
Area, m2	-	-	175058	20811	124	-

Distance-to-Threshold (m), RMS Flat-Weighted

Criteria / Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	3005	2889	2634	2539	2386	2103	1659	1697	1515	1304	1835	533	412
NE	6072	5809	5598	5370	5096	4204	4378	3729	3151	2226	1245	621	406
E	8325	7813	7582	7266	6828	5491	4869	4120	3420	2296	1213	790	466
SE	5775	5315	5199	4922	4668	3716	3470	2916	2107	1747	1081	616	386
S	3194	2953	2916	2770	2652	2470	2424	2039	1860	1735	898	554	388
SW	5348	5071	4884	4589	4144	4549	3865	3024	2635	2194	1107	714	386
W	6870	6506	6088	5843	5632	5981	4597	3643	2552	1981	1188	735	408
NW	4730	4806	4595	4494	4444	4779	3959	3201	2529	1659	1369	649	444
Area (m2)	57011154	53327312	49576497	45795612	41954211	35788196	27149493	19736285	13103047	6996218	2329581	1109353	434450

Distance-to-Threshold (m), RMS MF-Weighted

Criteria / Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	87	43	23	-	-	-	-	-	-	-	-	-	-
NE	80	49	21	-	-	-	-	-	-	-	-	-	-
E	102	58	16	-	-	-	-	-	-	-	-	-	-
SE	86	56	26	-	-	-	-	-	-	-	-	-	-
S	99	58	31	-	-	-	-	-	-	-	-	-	-
SW	90	59	27	-	-	-	-	-	-	-	-	-	-
W	101	59	17	-	-	-	-	-	-	-	-	-	-
NW	84	49	21	-	-	-	-	-	-	-	-	-	-
Area (m2)	24361	7846	1401	-	-	-	-	-	-	-	-	-	-

Distance-to-Threshold (m), RMS HF-Weighted

Criteria / Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	29	-	-	-	-	-	-	-	-	-	-	-	-
NE	29	-	-	-	-	-	-	-	-	-	-	-	-
E	29	-	-	-	-	-	-	-	-	-	-	-	-
SE	36	-	-	-	-	-	-	-	-	-	-	-	-
S	39	-	-	-	-	-	-	-	-	-	-	-	-
SW	37	-	-	-	-	-	-	-	-	-	-	-	-
W	30	-	-	-	-	-	-	-	-	-	-	-	-
NW	29	-	-	-	-	-	-	-	-	-	-	-	-
Area (m2)	2976	-	-	-	-	-	-	-	-	-	-	-	-

Distance-to-Threshold (m), RMS PW-Weighted

Criteria / Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	1742	1565	1367	818	543	411	224	118	56	27	-	-	-
NE	3783	3210	2288	950	607	422	212	112	58	26	-	-	-
E	4116	3450	2299	1284	829	439	222	130	75	34	-	-	-
SE	2775	2101	1719	1077	705	431	272	130	69	39	-	-	-
S	1954	1803	1644	813	650	433	269	152	74	39	-	-	-
SW	3012	2609	2166	1074	811	454	251	113	72	40	-	-	-
W	3589	2568	2035	1263	785	448	249	117	79	36	-	-	-
NW	3155	2630	1763	913	638	426	234	103	62	27	-	-	-
Area (m2)	19884774	13521517	7773359	2670459	1321794	551528	170608	42993	12165	2986	-	-	-

Distance-to-Threshold, Impulsive, 0-peak flat weighting, fish species

Transect	No swim bladder		Swim bladder not involved in hearing		Swim bladder involved in hearing	
	Recoverable injury	Mortality and potential mortality	Recoverable injury	Mortality and potential mortality	Recoverable injury	Mortality and potential mortality
Criteria (dB)	213		207		207	
N	-		32		32	
NE	-		-		34	
E	-		-		50	
SE	-		-		51	
S	-		-		47	
SW	-		-		52	
W	-		-		52	
NW	-		-		36	
Area, m2	-		-		5017	

Appendix G. OPERATION SCENARIO A – FSRU

Distance-to-Threshold, Non-impulsive, SELcum

Transect	PW weigthed		MF weighted		HF-Weighted	
	TTS	PTS	TTS	PTS	TTS	PTS
Criteria (dB)	181	201	178	198	153	173
N	-	-	-	-	36	-
NE	-	-	-	-	39	-
E	-	-	-	-	47	-
SE	-	-	-	-	49	-
S	-	-	-	-	49	-
SW	-	-	-	-	50	-
W	-	-	-	-	48	-
NW	-	-	-	-	39	-
Area, m2	-	-	-	-	5430	-

Distance-to-Threshold, Non-impulsive, SELcum flat weighting, fish species

Transect	TTS	No swim bladder		Swim bladder not involved in hearing		Swim bladder involved in hearing	
		Recoverable injury	Mortality and potential mortality	Recoverable injury	Mortality and potential mortality	Recoverable injury	Mortality and potential mortality
Criteria (dB)	186	216	219	203	210	203	207
N	-	-	-	-	-	-	-
NE	-	-	-	-	-	-	-
E	-	-	-	-	-	-	-
SE	-	-	-	-	-	-	-
S	-	-	-	-	-	-	-
SW	-	-	-	-	-	-	-
W	-	-	-	-	-	-	-
NW	-	-	-	-	-	-	-
Area, m2	-	-	-	-	-	-	-

Distance-to-Threshold (m), RMS Flat-Weighted

Criteria Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	1160	751	515	314	189	91	33	-	-	-	-	-	-
NE	1939	840	584	334	185	80	31	-	-	-	-	-	-
E	2033	1021	675	356	159	87	31	-	-	-	-	-	-
SE	1724	832	545	340	208	76	37	-	-	-	-	-	-
S	1836	733	547	309	184	97	48	-	-	-	-	-	-
SW	2081	913	568	338	179	75	37	-	-	-	-	-	-
W	1747	1084	646	377	173	88	31	-	-	-	-	-	-
NW	1403	848	571	349	200	81	31	-	-	-	-	-	-
Area (m2)	6127265	2070326	967474	332684	96311	20927	3578	-	-	-	-	-	-

Distance-to-Threshold (m), RMS PW-Weighted

Criteria Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	387	223	121	62	30	-	-	-	-	-	-	-	-
NE	504	243	137	64	30	-	-	-	-	-	-	-	-
E	521	270	142	82	40	-	-	-	-	-	-	-	-
SE	401	226	125	74	43	-	-	-	-	-	-	-	-
S	409	240	130	79	43	-	-	-	-	-	-	-	-
SW	471	250	123	74	44	-	-	-	-	-	-	-	-
W	549	240	130	82	40	-	-	-	-	-	-	-	-
NW	471	238	117	66	31	-	-	-	-	-	-	-	-
Area (m2)	584691	169989	48520	14801	3844	-	-	-	-	-	-	-	-

Distance-to-Threshold (m), RMS MF-Weighted

Criteria Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	98	57	22	-	-	-	-	-	-	-	-	-	-
NE	91	61	20	-	-	-	-	-	-	-	-	-	-
E	112	64	22	-	-	-	-	-	-	-	-	-	-
SE	95	53	30	-	-	-	-	-	-	-	-	-	-
S	111	49	33	-	-	-	-	-	-	-	-	-	-
SW	104	54	31	-	-	-	-	-	-	-	-	-	-
W	110	66	23	-	-	-	-	-	-	-	-	-	-
NW	94	62	20	-	-	-	-	-	-	-	-	-	-
Area (m2)	30790	8994	1664	-	-	-	-	-	-	-	-	-	-

Distance-to-Threshold (m), RMS HF-Weighted

Criteria Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	58	29	-	-	-	-	-	-	-	-	-	-	-
NE	61	30	-	-	-	-	-	-	-	-	-	-	-
E	76	34	-	-	-	-	-	-	-	-	-	-	-
SE	70	40	-	-	-	-	-	-	-	-	-	-	-
S	72	41	-	-	-	-	-	-	-	-	-	-	-
SW	70	40	-	-	-	-	-	-	-	-	-	-	-
W	76	35	-	-	-	-	-	-	-	-	-	-	-
NW	61	30	-	-	-	-	-	-	-	-	-	-	-
Area (m2)	12609	3344	-	-	-	-	-	-	-	-	-	-	-

Appendix H. OPERATION SCENARIO B - FSRU with offloading LNG carrier

Distance-to-Threshold, Non-impulsive, SELcum

Transect	PW weigthed		MF weighted		HF-Weighted	
	TTS	PTS	TTS	PTS	TTS	PTS
Criteria (dB)	181	201	178	198	153	173
N	100	-	29	-	392	35
NE	100	-	29	-	495	39
E	115	-	35	-	564	46
SE	100	-	40	-	399	49
S	115	-	41	-	417	49
SW	111	-	40	-	434	50
W	116	-	35	-	509	47
NW	100	-	30	-	440	39
Area, m2	34069	-	3334	-	570321	5361

Distance-to-Threshold, Non-impulsive, SELcum flat weighting, fish species

Transect	TTS	No swim bladder		Swim bladder not involved in hearing		Swim bladder involved in hearing	
		Recoverable injury	Mortality and potential mortality	Recoverable injury	Mortality and potential mortality	Recoverable injury	Mortality and potential mortality
Criteria (dB)	186	216	219	203	210	203	207
N	290	2	-	-	-	-	-
NE	295	1	-	-	-	-	-
E	314	0	-	-	-	-	-
SE	334	1	-	-	-	-	-
S	311	1	-	-	-	-	-
SW	357	1	-	-	-	-	-
W	338	0	-	-	-	-	-
NW	316	1	-	-	-	-	-
Area, m2	293155	1	-	-	-	-	-

Distance-to-Threshold (m), RMS Flat-Weighted

Criteria Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	1366	1608	544	395	192	103	39	-	-	-	-	-	-
NE	2227	1709	639	410	203	92	36	-	-	-	-	-	-
E	2247	1055	762	379	187	96	40	-	-	-	-	-	-
SE	1625	1111	655	343	232	108	44	-	-	-	-	-	-
S	1734	1161	646	393	224	132	57	-	-	-	-	-	-
SW	2136	1312	684	377	217	102	44	-	-	-	-	-	-
W	1949	1231	684	472	194	97	39	-	-	-	-	-	-
NW	1691	1209	577	426	215	96	36	-	-	-	-	-	-
Area (m2)	7614427	2447536	1153412	441100	124522	29307	5153	-	-	-	-	-	-

Distance-to-Threshold (m), RMS PW-Weighted

Criteria Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	378	238	126	63	31	-	-	-	-	-	-	-	-
NE	498	237	130	65	31	-	-	-	-	-	-	-	-
E	530	257	127	83	41	-	-	-	-	-	-	-	-
SE	419	214	112	75	44	-	-	-	-	-	-	-	-
S	431	239	130	80	44	-	-	-	-	-	-	-	-
SW	489	263	135	75	45	-	-	-	-	-	-	-	-
W	554	267	151	83	41	-	-	-	-	-	-	-	-
NW	464	257	135	67	33	-	-	-	-	-	-	-	-
Area (m2)	601081	176067	50230	15314	4043	-	-	-	-	-	-	-	-

Distance-to-Threshold (m), RMS MF-Weighted

Criteria Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	99	58	23	-	-	-	-	-	-	-	-	-	-
NE	92	61	21	-	-	-	-	-	-	-	-	-	-
E	113	65	23	-	-	-	-	-	-	-	-	-	-
SE	96	54	31	-	-	-	-	-	-	-	-	-	-
S	112	50	34	-	-	-	-	-	-	-	-	-	-
SW	105	55	31	-	-	-	-	-	-	-	-	-	-
W	111	67	24	-	-	-	-	-	-	-	-	-	-
NW	95	63	21	-	-	-	-	-	-	-	-	-	-
Area (m2)	31466	9219	1778	-	-	-	-	-	-	-	-	-	-

Distance-to-Threshold (m), RMS HF-Weighted

Criteria Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	59	30	-	-	-	-	-	-	-	-	-	-	-
NE	62	31	-	-	-	-	-	-	-	-	-	-	-
E	77	35	-	-	-	-	-	-	-	-	-	-	-
SE	71	40	-	-	-	-	-	-	-	-	-	-	-
S	74	42	-	-	-	-	-	-	-	-	-	-	-
SW	71	41	-	-	-	-	-	-	-	-	-	-	-
W	77	36	-	-	-	-	-	-	-	-	-	-	-
NW	62	31	-	-	-	-	-	-	-	-	-	-	-
Area (m2)	13000	3513	-	-	-	-	-	-	-	-	-	-	-

Appendix I. OPERATION SCENARIO D – FSRU with approaching LNG carrier

Distance-to-Threshold, Non-impulsive, SELcum

Transect	PW weigthed		MF weighted		HF-Weighted	
	TTS	PTS	TTS	PTS	TTS	PTS
Criteria (dB)	181	201	178	198	153	173
N	-	-	-	-	217	-
NE	-	-	-	-	216	-
E	-	-	-	-	223	-
SE	-	-	-	-	208	-
S	-	-	-	-	213	-
SW	-	-	-	-	208	-
W	-	-	-	-	220	-
NW	-	-	-	-	187	-
Area, m2	-	-	-	-	135022	-

Distance-to-Threshold, Non-impulsive, SELcum flat weighting, fish species

Transect	TTS	No swim bladder		Swim bladder not involved in hearing		Swim bladder involved in hearing	
		Recoverable injury	Mortality and potential mortality	Recoverable injury	Mortality and potential mortality	Recoverable injury	Mortality and potential mortality
Criteria (dB)	186	216	219	203	210	203	207
N	104	-	-	-	-	-	-
NE	94	-	-	-	-	-	-
E	115	-	-	-	-	-	-
SE	85	-	-	-	-	-	-
S	103	-	-	-	-	-	-
SW	106	-	-	-	-	-	-
W	120	-	-	-	-	-	-
NW	123	-	-	-	-	-	-
Area, m2	30713	-	-	-	-	-	-

Distance-to-Threshold (m), RMS Flat-Weighted

Criteria Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	2897	1940	1461	1355	1056	755	271	115	55	-	-	-	-
NE	4038	2510	1852	1163	925	587	241	117	36	-	-	-	-
E	5384	3653	2175	1131	755	468	256	143	55	-	-	-	-
SE	3841	3049	1808	1307	1097	897	248	106	45	-	-	-	-
S	2382	2137	1825	1343	1139	986	273	123	57	-	-	-	-
SW	5186	2894	2212	1205	722	554	310	130	43	-	-	-	-
W	5955	3142	2362	1390	900	553	282	144	35	-	-	-	-
NW	4027	2515	1817	1255	898	682	252	145	42	-	-	-	-
Area (m2)	34052129	18146714	8965558	4274785	1949453	767905	207605	44434	5147	-	-	-	-

Distance-to-Threshold (m), RMS PW-Weighted

Criteria Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	2004	1258	715	462	127	41	8	-	-	-	-	-	-
NE	2172	1114	569	343	110	42	6	-	-	-	-	-	-
E	2797	1230	423	232	116	75	12	-	-	-	-	-	-
SE	2631	1613	908	818	107	71	10	-	-	-	-	-	-
S	1903	1417	990	939	118	70	10	-	-	-	-	-	-
SW	2686	1245	605	539	128	65	9	-	-	-	-	-	-
W	2387	1308	555	309	154	66	10	-	-	-	-	-	-
NW	1822	885	648	405	131	38	6	-	-	-	-	-	-
Area (m2)	12646663	3402926	690433	175543	44588	8797	193	-	-	-	-	-	-

Distance-to-Threshold (m), RMS MF-Weighted

Criteria Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	669	258	120	65	17	-	-	-	-	-	-	-	-
NE	569	212	106	65	11	-	-	-	-	-	-	-	-
E	401	215	124	82	21	-	-	-	-	-	-	-	-
SE	906	203	128	66	20	-	-	-	-	-	-	-	-
S	983	232	136	64	20	-	-	-	-	-	-	-	-
SW	578	263	143	58	17	-	-	-	-	-	-	-	-
W	496	268	151	71	18	-	-	-	-	-	-	-	-
NW	582	228	118	59	12	-	-	-	-	-	-	-	-
Area (m2)	601362	162767	48419	11825	710	-	-	-	-	-	-	-	-

Distance-to-Threshold (m), RMS HF-Weighted

Criteria Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	490	169	85	36	2	-	-	-	-	-	-	-	-
NE	397	166	88	34	1	-	-	-	-	-	-	-	-
E	294	194	118	63	3	-	-	-	-	-	-	-	-
SE	860	189	117	62	2	-	-	-	-	-	-	-	-
S	988	195	116	64	2	-	-	-	-	-	-	-	-
SW	560	181	108	55	2	-	-	-	-	-	-	-	-
W	355	182	107	53	2	-	-	-	-	-	-	-	-
NW	413	151	79	33	2	-	-	-	-	-	-	-	-
Area (m2)	300460	95795	29681	6499	11	-	-	-	-	-	-	-	-

Appendix J. OPERATION SCENARIO E – FSRU with offloading LNG carrier, 4 tugs engaged, general cargo ship in the estuary, berthed ship at Moneypoint

Distance-to-Threshold, Non-impulsive, SELcum

Transect	PW weigthed		MF weighted		HF-Weighted	
	TTS	PTS	TTS	PTS	TTS	PTS
Criteria (dB)	181	210	178	198	153	173
N	100	-	29	-	392	35
NE	100	-	29	-	495	39
E	115	-	35	-	564	46
SE	100	-	40	-	399	49
S	115	-	41	-	417	49
SW	111	-	40	-	434	50
W	116	-	35	-	509	47
NW	100	-	30	-	440	39
Area, m2	34069	-	3334	-	570321	5361

Distance-to-Threshold, Non-impulsive, SELcum flat weighting, fish species

Transect	TTS	No swim bladder		Swim bladder not involved in hearing		Swim bladder involved in hearing	
		Recoverable injury	Mortality and potential mortality	Recoverable injury	Mortality and potential mortality	Recoverable injury	Mortality and potential mortality
Criteria (dB)	186	216	219	203	210	203	207
N	290	-	-	2	-	-	-
NE	295	-	-	1	-	-	-
E	314	-	-	0	-	-	-
SE	334	-	-	1	-	-	-
S	311	-	-	1	-	-	-
SW	357	-	-	1	-	-	-
W	338	-	-	0	-	-	-
NW	316	-	-	1	-	-	-
Area, m2	293155	-	-	1	-	-	-

Distance-to-Threshold (m), RMS Flat-Weighted

Criteria Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	1708	1628	1340	1341	1061	1136	631	506	439	-	-	-	-
NE	4719	3356	2570	1970	992	1280	652	570	484	-	-	-	-
E	6260	4443	3277	2082	1134	682	450	360	291	-	-	-	-
SE	4175	3016	2395	1588	1261	488	345	233	173	-	-	-	-
S	2153	1985	1651	1405	1539	925	716	588	544	-	-	-	-
SW	3863	3046	2278	1759	1751	1055	798	647	603	-	-	-	-
W	5840	4715	3116	2027	1256	757	547	404	318	-	-	-	-
NW	4551	3809	2912	1765	1015	569	405	236	148	-	-	-	-
Area (m2)	27473607	18768378	12197431	7244537	3481064	1244175	301462	60156	8917	-	-	-	-

Distance-to-Threshold (m), RMS PW-Weighted

Criteria Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	1302	1388	1375	719	87	26	-	-	-	-	-	-	-
NE	1507	1653	1576	808	92	24	-	-	-	-	-	-	-
E	1869	965	855	449	103	29	-	-	-	-	-	-	-
SE	1773	781	419	256	85	37	-	-	-	-	-	-	-
S	1328	800	652	387	99	41	-	-	-	-	-	-	-
SW	1922	1118	760	425	120	33	-	-	-	-	-	-	-
W	1869	1103	614	313	134	22	-	-	-	-	-	-	-
NW	1469	690	375	228	108	22	-	-	-	-	-	-	-
Area (m2)	5974153	1487891	435492	118418	30592	2211	-	-	-	-	-	-	-

Distance-to-Threshold (m), RMS MF-Weighted

Criteria Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	762	727	113	38	-	-	-	-	-	-	-	-	-
NE	939	820	120	45	-	-	-	-	-	-	-	-	-
E	637	470	123	52	-	-	-	-	-	-	-	-	-
SE	414	264	95	55	-	-	-	-	-	-	-	-	-
S	542	405	105	59	-	-	-	-	-	-	-	-	-
SW	814	436	124	49	-	-	-	-	-	-	-	-	-
W	900	336	147	43	-	-	-	-	-	-	-	-	-
NW	491	240	127	36	-	-	-	-	-	-	-	-	-
Area (m2)	439904	141686	41173	6110	-	-	-	-	-	-	-	-	-

Distance-to-Threshold (m), RMS HF-Weighted

Criteria Transect	120	125	130	135	140	145	150	155	160	165	170	175	180
N	722	705	80	26	-	-	-	-	-	-	-	-	-
NE	802	778	82	24	-	-	-	-	-	-	-	-	-
E	483	422	95	27	-	-	-	-	-	-	-	-	-
SE	306	235	78	36	-	-	-	-	-	-	-	-	-
S	506	379	97	40	-	-	-	-	-	-	-	-	-
SW	575	426	111	31	-	-	-	-	-	-	-	-	-
W	465	305	123	20	-	-	-	-	-	-	-	-	-
NW	282	238	97	22	-	-	-	-	-	-	-	-	-
Area (m2)	260169	88342	25717	2049	-	-	-	-	-	-	-	-	-