Recommended Procedures for Measuring Underwater Radiated Noise Emissions of Ships, for Quiet Ship Certification

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Version 2.0

Acknowledgements:

The procedures presented in this guidance were developed through a series of workshops attended by representatives from the following Classification Societies: American Bureau of Shipping, Bureau Veritas, China Classification Society, DNV, Korean Register, Lloyd’s Register, Registro Italiano Navale. Also in attendance were members of the International Association of Classification Societies and the International Organisation for Standardization (ISO). The expertise and contributions of these representatives and members were instrumental for defining practical, consistent, and technically-sound methods for measuring and reporting underwater radiated noise from ships, suitable for assessing quiet notations.

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Author Affiliations:

JASCO Applied Sciences

David E. Hannay
Michael A. Ainslie
Alexander O. MacGillivray
S. Bruce Martin

2305-4464 Markham Street
Victoria, B.C.
Canada, V8Z 7X8

Vancouver Fraser Port Authority

Krista B. Trounce
Justin Eickmeier

999 Canada Place
Vancouver, B.C.
Canada V6C 7X8

Transport Canada

Veronique Nolet

Innovation Centre
330 Sparks St, Place de Ville,
Tower C, Ottawa, Ontario
Canada, K1A 0N5

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1. Introduction

1.1. Background and Purpose

This document recommends formal methods that can be adopted directly or used by ship classification societies to increase alignment of their quiet vessel certification/notation approaches. Classification societies presently use various methods for measuring vessel underwater radiated noise (URN). In many cases, their noise metrics and compliance thresholds differ, in some cases substantially. The use of disparate approaches and metrics complicates comparison between the different certifications/notations, and users have had difficulty understanding which certifications are most appropriate for a given requirement. This technical memorandum proposes a consistent base measurement approach and recommends a common metric upon which to assess vessel noise emissions. The goal is to encourage societies to adopt approaches that facilitate comparisons, where practical, between each other's certification procedures (which does not necessarily entail using identical methods, nor adopting the same underwater radiated noise (URN) limits for compliance).

The methods presented here include procedures for measuring URN using hydrophones, and procedures for processing the acquired digital acoustic data to obtain metrics that can be evaluated against conformance threshold criteria. While specific thresholds are not identified here, the percentile distributions of measurements from the Vancouver Fraser Port Authority's ECHO Program database have been provided as a reference for possible use by classification societies when determining their own criteria.

The recommendations provided here were developed through a collaborative process involving several classification societies and experts in the field of ship underwater noise measurement. The participant organizations included American Bureau of Shipping (ABS), Bureau Veritas (BV), China Classification Society (CCS), DNV, the International Association of Classification Societies (IACS), the International Organisation for Standardization (ISO), JASCO Applied Sciences, Korean Register (KR), Lloyd's Register (LR), Registro Italiano Navale (RINA), Transport Canada and Vancouver Fraser Port Authority (VFPA).

The process of developing the recommendations was led by VFPA with support from Transport Canada. It involved holding three workshops, in October 2020, November 2021, and October 2022. Prior to each workshop, several options for each of the various procedures were identified through discussions with project participants. The options were documented in technical memoranda that were distributed prior to each workshop, and they were discussed at the workshops. The recommended methods presented here represent the outcome of this iterated process.

1.2. A Note on URN Metrics

The two most used metrics for characterizing ship underwater radiated noise (URN) at present are radiated noise level (RNL; ISO 17208-1) and source level (SL; ISO 17208-2). The metric presently defined as RNL is easiest to calculate, and in deep water its spectra are strongly correlated to sound pressure level (SPL) spectra near the vessel. There is presently no ISO standard method for measuring RNL in shallow water for depths less than the greater of 100 m or one ship length. In shallower water, RNL measured with the procedures of ISO 17208-1 becomes affected by seabed reflected sound energy, making it less representative of vessel noise emissions. SL in theory can be calculated in shallow water, but at low frequencies it is less well correlated than RNL with the SPL experienced nearby in the ocean. SL also depends on a source depth parameter that must be considered when comparing vessels.

The recommendation is to use a modified definition of RNL that is based on the relationship between SL (L_S) and RNL (L_{RN}) defined in formula A.3 of ISO 17208-2 for deep water, reproduced here as equation 1:

$$L_S = L_{\mathrm{RN}} + \Delta L \quad \text{(Deep water)}, \tag{1}$$

where ΔL is a correction that accounts for surface reflection effects near the vessel, but not for seabed reflections. This expression is intended for use at calculating L_S from a measurement of L_{RN} according to ISO 17208-1. We rearrange equation 1 to express an equivalent RNL, L'_{RN}, in terms of L_S, but where L_S can be measured in deep or shallow water.

$$L'_{\mathrm{RN}} = L_S - \Delta L \quad \text{(Deep or shallow water)} \tag{2}$$

This equivalent RNL is referred to by Ainslie et al (2021) as “adjusted source level” and it is equivalent to dipole source level (DSL) (Ainslie 2010, de Jong et al. 2010, Robinson et al. 2011) except that, instead of being evaluated at normal incidence, it is calculated for an average of three specified propagation angles (15°, 30° and 45°). In shallow or deep water, the equivalent RNL can be derived from SL using a form of equation 2. This guidance also recommends an approach for calculating SL using a formulaic approach based on ship and hydrophone geometry, water depth, absorption coefficient, and the seabed reflection critical angle (MacGillivray et al., 2023).

The equivalent RNL replaces the need for original RNL as defined in ISO 17208-1 because it not only reproduces RNL in deep water, but delivers the same value adjusted for seabed reflection effects in shallow water. A highly valuable or even essential feature of this metric is that its values can be compared directly with deep water measurements of RNL made using ISO 17208-1 and several of the existing class society deep water measurement procedures. Its other important feature is that it is closely related to SL through equation 2. The formulaic calculation of these metrics is discussed in Ainslie et al (2022) and in Sections 10.3 to 10.4 of this report.

2. Terms and Definitions

Acoustical terminology used in this document follows ISO 18405. It is strongly recommended that all terms and definitions be compatible with ISO 18405. The measurement units of parameters discussed in this document follow The International System of Units (SI), except where otherwise stated.

3. Site Selection and Water Depth

It is recommended that a minimum water depth be defined for the measurement site, understanding that measurement uncertainty in shallow water tends to increase with decreasing water depth – primarily caused by the need to account for seabed reflections. Very shallow water can also lead to increased drag, possibly requiring greater thrust to achieve the same speed (Lackenby 1963). Lackenby's formula (see equation 3) suggests a transition depth, above which shallow water drag effects can be neglected. As an example, for a vessel with a 27 m beam and 6 m draught travelling at 10 m/s (~20 kn), the minimum water depth is max(38.2 m, 30 m), which is 38.2 m.

Seabed reflectivity can be important especially in shallower waters, so seabed acoustic properties should be understood when seabed reflections could affect measurements. The correction for seabed reflections is most accurate when the reflectivity is known well. The reflection properties of a thick uniform seabed layer of sand are known well, and that seabed type is optimal.

Recommendations:

- Choose sites with a uniform sediment seabed layer that is as thick as possible so that a critical reflection angle can be ascertained.
- Minimum water depth requirement: $H > 35$ m
- Avoid shallow water drag effects:

  $$H > \max\left(3\sqrt{BT}, 0.3\,V^2\right) \tag{3}$$

  where B and T are respectively the breadth and draught of the vessel in metres, and V is its speed in m/s, giving H in metres.
- Choose a site with a seabed consisting of a thick uniform layer of sand, when possible.

4. Weather

High sea states and high wind conditions can adversely affect vessel noise measurements. Large surface waves can lead to variable depths of noise sources including propellers on vessels, often leading to large variations in URN. Breaking waves can increase ambient noise levels that can reduce signal to noise ratio. A maximum sea state or Beaufort wind force (wind speed) should be specified.

Recommendation:

- Maximum wind speed 9 m/s measured at 10 m height above sea surface, corresponding to Beaufort wind force up to 4, and sea state does not exceed 3.

5. Tides and Current

Strong currents can cause hydrophone displacement and flow noise. High currents can also lead to uncertainty in ship speed through water. Large tidal change can affect water depth, and hydrophone depths for bottom-moored hydrophone geometries.

Recommendation:

- Consider requirements for tides and current. Ensure that tide and current effects on vessel speed through water and water depth can be measured or calculated.

6. Instrumentation

6.1. Acoustic Monitoring Equipment

The acoustic monitoring system consists of hydrophones, preamplifiers, amplifiers, analog filters, and digital acquisition system.

Recommendation:

- Follow ISO 17208-1 for choice of acoustic monitoring equipment.

6.2. Number of Hydrophones

Recommendation:

- Use 1 to 3 hydrophones.

6.3. Pre-calibration (Laboratory)

System calibrations document the frequency-dependent sensitivity of the entire acoustic recording system, including hydrophones, preamplifiers, amplifiers, cables, filters, signal conditioning circuits, and digitizing systems.

Recommendations:

- Follow IEC 60565-1 and IEC 60565-2 for hydrophone calibrations.
- Characterize the absolute voltage sensitivity and frequency response of the system components (other than the hydrophone) for systems that are not integral with the hydrophone (e.g., digital hydrophones).
- Perform a full system calibration check with hydrophone attached using a pistonphone, or insert voltage (supported by some hydrophones), for at least one sound frequency but preferably at multiple frequencies.
- Specify a maximum time between successive calibrations (suggestion: ≤24 months).

6.4. In situ Calibration (Field)

In situ calibrations are useful to ensure the recording system sensitivity has not changed since the most recent laboratory calibration. The in situ calibration is also a useful test to ensure all system components are functioning properly.

Recommendation:

- Carry out in situ pistonphone or insert-voltage calibration at a minimum of one sound frequency to confirm consistency with laboratory calibration, before and after each hydrophone deployment.

7. Measurement Geometry

7.1. Hydrophone Horizontal Distance from Ship Track

The horizontal distance from the hydrophone to the ship track (r_{CPA}) is measured at the time of closest point of approach (CPA).

Recommendations:

- Measurement accuracy of r_{CPA}: ±10%
- Minimum r_{CPA}: max (0.5 L, 100 m) and
- Maximum r_{CPA}: min (8 H, 500 m),

where H is the water depth and L is the ship length.

7.2. Hydrophone Depths (Vertical Propagation Angles)

In deep water, defined here as $H \geq \min(r_{\mathrm{CPA}})$, the recommendation is to use the ISO 17208-1 vertical measurement angles of 15°, 30°, and 45° at CPA when using three hydrophones. The two steeper angles: 30° and 45°, are recommended when using two hydrophones, and selection of an angle between 30° and 45° is recommended for a single hydrophone in deep water. Because the SL and equivalent RNL metrics can account for hydrophone geometry differences, this guidance provides the flexibility to use different r_{CPA} and depths for different hydrophones for the same measurement. Hydrophones can be placed at any depth, including on or near the seabed.

In shallow water, defined by $H < \min(r_{\mathrm{CPA}})$ it is not possible to sample the steepest (45°) vertical angle at the minimum CPA distance, so a modified vertical angle approach is defined. The closest hydrophone will be deployed on or near the seabed at a CPA distance of minimum r_{CPA} that, due to limited depth, samples a vertical angle less than 45°. This smaller angle (θ_1) is used to set the vertical sampling angles θ_2 and θ_3 for the other hydrophones, if used.

Recommendations:

For Deep Water: $H \geq \min(r_{\mathrm{CPA}})$

- Vertical Propagation Angle for one hydrophone: $30° \leq \theta_1 \leq 45°$
- Vertical Propagation Angle for two hydrophones: $\theta_1 = 45°$, $\theta_2 = 30°$
- Vertical Propagation Angles for three hydrophones: $\theta_1 = 45°$, $\theta_2 = 30°$, $\theta_3 = 15°$

For Shallow Water: $H < \min(r_{\mathrm{CPA}})$

- Hydrophone depths: all hydrophones will be deployed on or near the seabed, at depth $h <\approx \mathrm{H}$.
- One hydrophone: set r_{CPA1} as small as possible but $\geq \min(r_{\mathrm{CPA}})$. Calculate $\theta_1 = \arctan(h/r_{\mathrm{CPA1}})$.
- Two hydrophones: set first hydrophone at r_{CPA1} as above and set $\theta_2 = \theta_1/2$ and $r_{\mathrm{CPA2}} = h/\tan(\theta_2)$, where θ_1 is as for a single hydrophone.
- Three hydrophones: set first hydrophone at r_{CPA1} as above. Calculate $\theta_2 = 2\theta_1/3$ and $\theta_3 = \theta_1/3$, and set $r_{\mathrm{CPA2}} = h/\tan(\theta_2)$ and $r_{\mathrm{CPA3}} = \min(\frac{h}{\tan(\theta_3)}, \max(r_{\mathrm{CPA}}))$, where θ_1 is as for a single hydrophone.

Note: when $\frac{h}{\tan(\theta_1/3)} > \max(r_{\text{CPA}})$, then $\theta_3 = \arctan\,(h/\max\,(r_{\text{CPA}})$, leading to $\theta_3 < \theta_1/3$. This occurs only for h < 39 m and arises from the horizontal distance requirement $\max(r_{\text{CPA}}) \le 8H$.

7.3. Hydrophone Geometry Diagrams

Deep Water Geometries: $H \ge \min(r_{\text{CPA}})$:

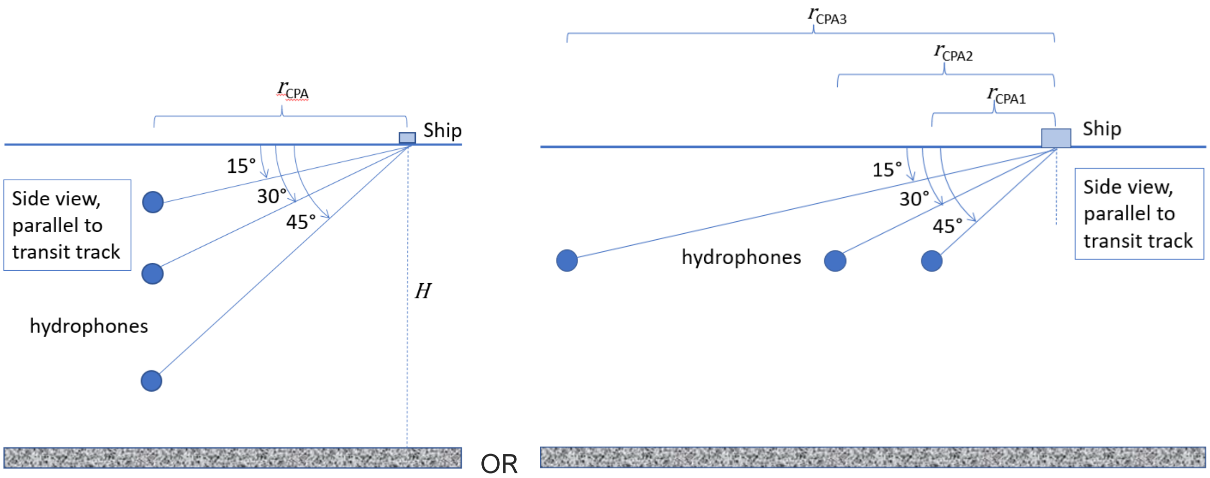

Figure 1. Two possible geometries for deep water environments. Hydrophones can be placed at different depths and/or different closest point of approach (CPA) distances, subject to meeting the vertical angle sampling requirements: 15°, 30°, and 45°. Hydrophone deployment depths in the water column and on or near the seabed are supported.

Shallow Water Geometries: $H < \min(r_{\text{CPA}})$:

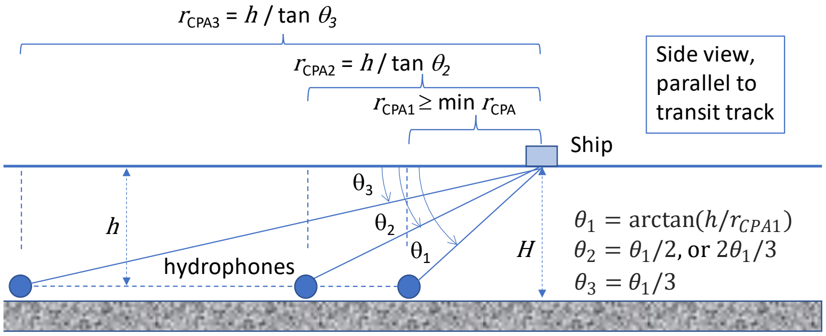

Figure 2. Geometry diagram for shallow water environments. Hydrophones are deployed on or near the seabed at depth h. The first hydrophone position, at closest point of approach (CPA) distance $r_{\text{CPA1}} \ge \min(r_{\text{CPA}})$, is used to calculate θ_1, and this angle is used to calculate θ_2 and θ_3.

7.4. Number of Transits

Averaging of measurements made on multiple transits improves accuracy and can be useful for averaging directional effects such as when ships radiate noise preferentially to one side.

Recommendations:

- Minimum number of transits*:* 2.
- Aspects*:* Half of the passes should be port and half starboard relative to the hydrophones.

8. Ship Transit Speed and Draught

Recommendations:

- Prescribe a range of speed and draught for certification. This range would be representative of operational conditions, and specific to each ship category.
- Consider the chosen vessel speed(s) when setting limits, perhaps using speed scaling of previous measurements if those were made at different speeds. The ECHO program has provided a spreadsheet with formulas to scale the category-dependent percentiles of measurements from their ship noise database that can be used for this purpose. The spreadsheet is named “ECHO RNL Scaled quantiles (all measurements to August 2022).xlsx”.

9. Initial Processing

9.1. Frequency Bands

Most quiet ship certification procedures presently require the use of frequency bands referred to by IEC 61260 as “one-third octave” bands. These IEC 61260 frequency bands have a bandwidth of precisely one tenth of a decade (i.e., one decidecade[1]). This guidance recommends a minimum decidecade frequency band with centre frequency 10 Hz. In shallow water, the measurement of low frequency source levels might be affected by interference from sounds reflected from the sea surface and seabed. Depending on the water depth there might be a need to increase this minimum frequency. A study designed to compare shallow water SL measurements in decidecade frequency bands with the same vessels measured in deep water, showed reasonable agreement for measurement depths as shallow as 31.7 m at frequency bands to 10 Hz (MacGillivray et al., 2022). For that reason, a water depth-dependent frequency limit is not suggested here, but further investigation of this potential effect should be undertaken.

Recommendations:

- Frequency Bands: Use decidecade bands, following IEC 61260-1:2014 for the frequency specification and ISO 18405 (2017) for terminology.
- Lowest frequency band*:* 10 Hz, but possibly increased for shallow water measurements.
- Highest frequency band: 50 kHz.

9.2. Data Window Period (DWP)

The data window represents the section of the ship’s sail track that is used for the URN measurement. The data window period (DWP) represents the corresponding time period of the recorded sound data that is used for the calculations of SPL, from which the URN measurements are derived. The DWP depends on ship speed and on r_{CPA}, so will differ between hydrophones when different r_{CPA} distances are used.

Recommendation:

- Use the DWP specified in ISO 17208-1, which sets the start and end times to the times the vessel’s acoustic centre passes locations on its track that are ±30° from a horizontal line passing through the ship CPA position on its track to directly over the hydrophone, as shown in Figure 3. The duration of the DWP will be smaller for faster moving vessels, and it will increase with increasing CPA.
- One approach for identifying the time of acoustic centre CPA is to select the time of the minimum Lloyd mirror “bathtub” frequency modulation pattern in the spectrogram (graph of sound intensity versus frequency and time) over the ship transit. The DWP start and end times are then determined from the CPA time using the vessel speed and CPA distance. This approach becomes less useful in situations where a clear minimum of the modulation pattern cannot be identified.

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[1] A decade frequency band has a ratio of upper to lower band limit frequencies equal to 10. A decidecade is one tenth of a decade and is approximately one third of an octave. For this reason, a decidecade is sometimes referred to as a “one-third octave”. See Ainslie et al. (2022).

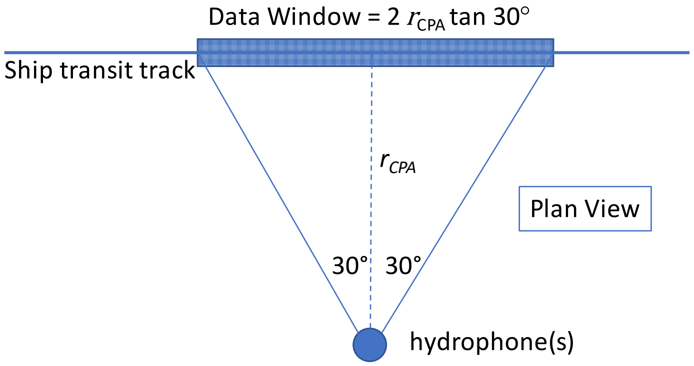

Figure 3. Diagram of Data Window used to select the Data Window Period (DWP), representing the time period of the acoustic recording that is analyzed. The DWP is the time period during which the ship's acoustic centre lies within the Data Window.

9.3. SPL Calculation Time Windows

The SPL calculation time windows (SPL windows) are the time periods over which calculations of SPL are made. ISO 17208-1 specifies that the entire DWP be processed as a single time window and that the CPA distance be used for geometric corrections to calculate URN. It is noted that the horizontal ship distance at both ends of the ISO 17208-1 Data Window are 15.5 % larger than r_{CPA}, thus propagation loss when the ship is near the ends of the Data Window would be approximately 1.2 dB less than when the ship is at the centre, assuming spherical spreading propagation loss. Further differences in SPL will occur because the vertical propagation angle changes within the DWP, and because absorption loss differences occur at higher frequencies through the DWP.

It is recommended to calculate SPL in smaller time windows than the DWP, to account for the changing geometry over the time of the DWP. The geometric corrections for calculating URN should be applied separately to each SPL window and the resulting URN estimates from all SPL windows are later averaged to obtain the final reported URN. Only a small number of SPL windows will be necessary (typically five or fewer).

Recommendations:

- Define the DWP for each hydrophone according to ISO 17208-1. For vertical arrays the DWP will be the same for all hydrophones in the array. DWP is dependent on r_{CPA}, so will differ between hydrophones for configurations that do not use vertical arrays.
- Divide the entire time of the DWP into multiple time windows, within which SPL will be calculated. These time windows are referred to as SPL windows and each has a corresponding horizontal and slant distance from the hydrophone as shown in Figure 4.
- The choice of the number of SPL windows should be made so that the error in propagation loss (N_{PL}) caused by using the ship-hydrophone geometry at CPA rather than the geometry corresponding to the ship position during each time window, does not exceed 0.5 dB.
- The minimum duration of the SPL windows should consider the effect on frequency-domain filter characteristics.
- When time domain windowing functions (e.g., Hann window) are applied with Fourier analysis (see Section 10.1) then the SPL windows can be overlapped.

- The received SPL values for all SPL windows are calculated in all decidecade frequency bands and stored for later processing to calculate URN.
- The horizontal distance from acoustic centre to the hydrophone for each SPL window (r_i) is stored for later calculations of URN (see Figure 4).

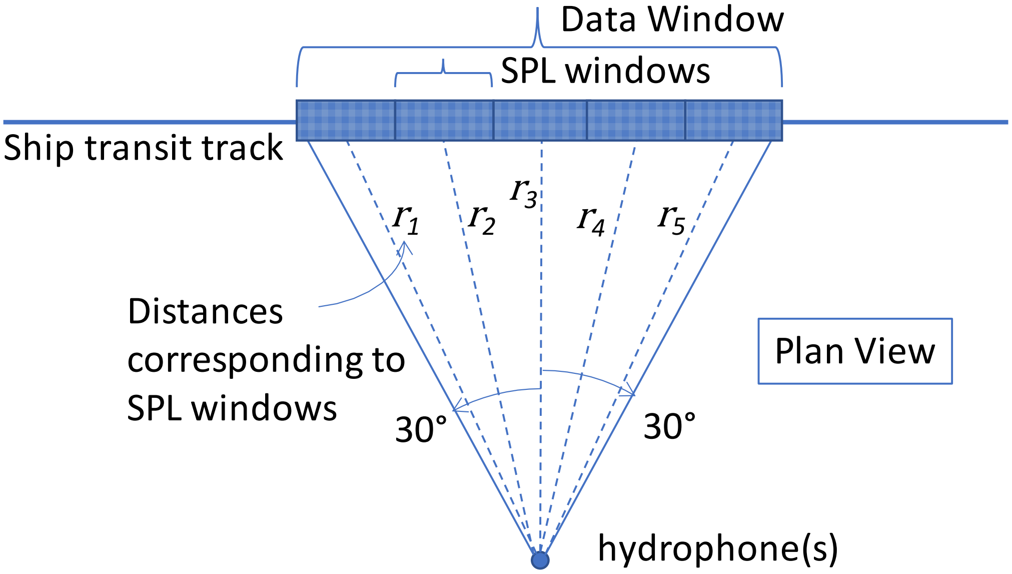

Figure 4. Diagram showing the Data Window and the fractional spatial zones that correspond with several SPL windows. The SPL windows are the time periods corresponding with the ship's acoustic centre being located in these sections of the Data Window. This example shows 5 SPL windows but a different number of windows may be used. The values r_1 to r_5 shown here are the horizontal distances from the hydrophone to the ship's acoustic centre at the central times of the SPL windows.

10. Calculating Equivalent Radiated Noise Level

The recommended URN metric is equivalent RNL (L'_{RN}) derived from source level (L_{S}). The calculations are based on decidecade band SPL measurements (L_{p}) calculated using the approach discussed in Section 10.1 for all SPL windows of all hydrophones and ship transits. Corrections for background noise are applied to the L_{p} measurements as discussed in Section 10.2. L_{S} estimates are calculated from the noise corrected L_{p} for each non-rejected SPL window, using the approach discussed in Section 10.3. These source level estimates are averaged to obtain average L_{S}. The reported L'_{RN} is obtained by applying the surface interference correction factor to L_{S} as shown in equations 13 and 14.

Reporting of source level and source depth is not required under this guidance but it is encouraged since source level is already calculated as an interim step of the calculation of equivalent RNL. Source level is not recommended for ship noise comparisons but it has other important uses, including being the required input of many predictive acoustic models.

10.1. Calculate SPL

Sound pressure level (SPL or L_{p}) represents the decibel level of the rms sound pressure measured at the positions of hydrophones in decidecade (1/10 decade) frequency bands. SPL calculations can be performed either in the time or frequency domains. Time domain calculations require initial decidecade pass-band filtering of the broadband signal prior to calculating the rms sound pressures. L_{p} (in dB) is calculated in this approach as 20 times the base-ten logarithm of the rms sound pressure divided by 1 μPa in each decidecade frequency band. Frequency domain calculations can be performed by first calculating the power spectral density function, as the magnitude squared Fourier transform of the broadband time domain pressure, with appropriate normalization. It is important to apply time domain windowing with a smooth windowing function (e.g., Hann window) before calculating the Fourier transforms, to avoid spectral leakage through side lobes. Decidecade band levels are obtained by integrating the power spectral density function in the frequency domain through the respective bandwidths of each decidecade band. The application of Parseval's theorem, to compare the sum of all decidecade band SPL with the broadband SPL calculated in the time domain, is often helpful to confirm the correct Fourier transform normalization. When applying the frequency domain approach described here, it is recommended to overlap the SPL windows so that all time series data contribute approximately equally to the average spectrum. A common overlap value is 50 %. Frequency dependent hydrophone and recording system sensitivities must be accounted for through adjustments added to the spectra or decidecade band levels.

10.2. Correct for Ambient Noise

ISO 17208-1 applies a correction to account for ambient noise in measurements when signal-plus-noise level to noise level difference (SNLD) is between 3 and 10 dB. When SNLD is less than 3 dB the data are discarded, and when above 10 dB the correction is not applied. It is recommended to follow this general approach but to continue the correction for SNLD > 10 dB, as the resulting noise contribution is still ~0.5 dB when SNLD = 10 dB. SNLD < 3 dB should generally lead to rejected band measurements as it does in ISO 17208-1, but the final bullet of the recommendations immediately below should be considered for that decision. The noise correction should be applied to the L_p of each SPL window. It is recommended that all measurements be rejected on transits for which more than half of the SPL windows are rejected based on SNLD < 3 dB. This is to avoid excessive biasing of the measurement by only accepting times of higher ship noise emissions. However, the final bullet point below should be considered for that decision too.

Recommendations:

- Use the approach of ISO 17208-1 to calculate ambient noise levels
- Reject time windows having L_p with SNLD < 3 dB
- Basic approach is to correct L_p with 3 dB < SNLD < 10 dB
- Preferred approach is to correct all data with SNLD > 3 dB, so do not stop applying the correction at SNLD = 10 dB.
- Use the approach of ISO 17208-1 for applying the correction to L_p for ambient noise.
- If more than half of the time windows of a transit are rejected, then reject all time windows for that transit.
- Important Note: the rejection of a measurement due to the ambient noise criterion may be caused by low ship noise emissions in the corresponding frequency band. When an entire transit rejection occurs, noise-corrected L_p should still be calculated and used as the upper limit of the ship's noise in that band. The SL and equivalent RNL calculations can still occur, but those should be flagged as noise-affected upper limits. The resulting equivalent RNL values may still be less than the notation criteria, and in that case this approach will allow rejected transit data to be used for notation purposes.

10.3. Calculate Source Level for Each SPL window

The calculation of SL is an intermediate step that is required to calculate the primary reported metric: equivalent RNL. Calculating SL (L_S) relies on estimating propagation loss (N_{PL}), and two methods for calculating N_{PL} are proposed.

Recommended approach:

The following equations should be applied for each non-rejected time step within the DWP.

The equation for source level is:

$$L_\mathrm{S} = L_\mathrm{p} + N_\mathrm{PL} \,, \tag{4}$$

where N_PL is the propagation loss corresponding to the geometry of the ship's acoustic centre relative to the hydrophone for the SPL window. Two approaches for calculating N_PL are supported:

1. Use an acoustic model, or
2. Use the Seabed Critical Angle (SCA) method (MacGillivray et al., 2023).

This guidance does not provide recommendations for acoustic models suitable for the first option. The SCA method approach is described below.

Propagation Loss $N_\mathrm{PL}$can be expressed in terms of the propagation factor F (ISO 18405):

$$N_\mathrm{PL} = 10 \log_{10} \frac{F^{-1}}{r_0^2} \mathrm{dB} \,, \tag{5}$$

where r_0 is defined as 1 m. In the SCA method, the propagation factor F is:

$$F = \frac{\sigma_1 + \frac{\psi r}{H} \sigma_\psi}{r^2} 10^{\frac{-\alpha r}{10}}, \tag{6}$$

where H is the water depth, α is the absorption coefficient in dB/m, r is the slant range from the ship's acoustic centre to the hydrophone at the time step of L_p, and:

$$\sigma_1 = \left(\frac{1}{2} + \frac{1}{4k^2 d^2 \sin^2 \theta}\right)^{-1}, \tag{7}$$

$$\sigma_\psi = \left(\frac{1}{2} + \frac{3}{4k^2 d^2 \sin^2 \psi}\right)^{-1}, \tag{8}$$

where θ is the vertical propagation angle (depression angle) measured relative to horizontal for the SPL window time step corresponding to L_p, and d is the source depth. The wavenumber k is given by:

$$k = \frac{2\,\pi f}{c} \,, \tag{9}$$

where f is the band centre frequency in hertz and c is the water sound speed near the surface in metres per second. This guidance recommends d be chosen as 0.7 of the ship draught, to be consistent with ISO 17208-2.

Equation (6) for the propagation factor, combined with Equations (7) and (8) is compatible with Clause 7.1 of the draft international standard ISO/DIS 17208-3, balloted in 2023. The absorption term αr is negligible for the geometry and frequency range of the DIS, but is included here because larger CPA distances and higher frequencies are considered in this Guidance.

The parameter ψ in the SCA method is the seabed critical angle in radians, defined for a sea bottom with sound speed c_b such that $\sin^2\psi = 1 - c_\mathrm{w}^2/c_\mathrm{b}^2$. The sound speed ratio $c_\mathrm{b}/c_\mathrm{w}$ is strongly correlated to the sediment type (Hamilton & Bachman 1985) and can be related to grain size using tables from (Ainslie 2010) as shown in Table 1.

Table 1. Sine of seabed critical angle (ψ) for different sediment types, based on Ainslie (2010), Table 4.18.

Sediment description	Representative grain size / ϕ	Sound speed ratio	sin(ψ)
Very coarse sand	-0.5	1.307	0.64
Coarse sand	0.5	1.250	0.60
Medium sand	1.5	1.198	0.55
Fine sand	2.5	1.152	0.50
Very fine sand	3.5	1.112	0.44
Coarse silt	4.5	1.077	0.37
Medium silt	5.5	1.048	0.30
Fine silt	6.5	1.024	0.21
Very fine silt	7.5	1.005	0.10

The calculations of N_PL are made using either the acoustic model method or the SCA method described above, for all non-rejected SPL windows. The N_PL values are added to L_p for the corresponding SPL windows as per equation 4 to calculate values for L_S.

In equation 6, α is the attenuation coefficient in dB/m, which can be estimated using equation 2.2 of Ainslie (2010):

$$\alpha = 0.0485\frac{F^2}{76.5^2 + F^2}\,, \tag{10}$$

where F is the frequency in kHz. Equation 10 is applicable for a temperature of 10 °C and practical salinity of 35.

10.4. Calculate Average Source Level

The calculations of SL estimates in all SPL windows are performed using the methods described in Sections 10.1 to 10.3. The SL (L_S) values for each transit are calculated as the power average of the estimates of L_S from all non-rejected SPL windows of all hydrophones for that transit. To be consistent with ISO 17208-1, the final estimates of L_S are calculated as the decibel average of SL estimates of all transits.

Recommended approach:

- For each transit, where transit number is indicated by index I, calculate L_{S_i} from the power average of the SL estimates for all non-rejected SPL window time steps of that transit on all hydrophones:

$$L_{\mathrm{S}_i} = 10\ \log_{10}\left(\frac{1}{n_h}\sum_{j=1}^{n_h}\left[\frac{1}{n_\mathrm{win}(i,j)}\sum_{k=1}^{n_\mathrm{win}(i,j)} 10^{\frac{L_{\mathrm{S}i,j,k}}{10\ \mathrm{dB}}}\right]\right)\ \mathrm{dB} \tag{11}$$

where n_h is the number of hydrophones, $n_\mathrm{win}(i,j)$ is the number of non-rejected SPL window measurements during transit i on hydrophone j, and k is the SPL window time step index.

- Calculate the average L_{S} values as the decibel average of L_{S_i} over all transits:

$$L_{\mathrm{S}} = \frac{1}{n_{tr}} \sum_{i=1}^{n_{tr}} L_{\mathrm{S}_i} \tag{12}$$

  where n_{tr} is the number of transits. Equations 11 and 12 are applied separately for all decidecade frequency bands.

10.5. Calculate Equivalent RNL

The equivalent RNL (L'_{RN}) is calculated from L_{S} of equation 12, using the SL to deep-water RNL conversion factor from ISO 17208-2, as shown in equations 13 and14.

Recommended approach:

Calculate the equivalent RNL:

$$L'_{\mathrm{RN}} = L_S + 20 \log_{10} \sqrt{\bar{\sigma}}\, \mathrm{dB}\,, \tag{13}$$

The right term of equation 11 includes the surface interference factor $\bar{\sigma}$, used in ISO 17208-2 that is based on an average of three vertical propagation angles: of 15°, 30°, and 45°, and it is calculated as:

$$\bar{\sigma} \approx \frac{14(kd)^2 + 2(kd)^4}{14 + 2(kd)^2 + (kd)^4}\,, \tag{14}$$

where d is the source depth in metres and k is defined in equation 9. The recommended value of d is 0.7 of the ship draught, to be consistent with ISO 17208-2. The depth d should be the same value used in the SL calculations of equations 7 and 8.

10.6. Measurement Uncertainty

The procedures and geometries recommended in this guidance were included in the methods of a study designed to test several shallow water measurement approaches (MacGillivray et al. 2022, MacGillivray et al., 2023). That study examined the differences between SL measurements in deep (184.2 m) water, using a 3-element vertical hydrophone array and conforming approximately with ISO 17208-1, with measurements of the same vessels operating in intermediate depth (65.7-65.9 m), and shallow water (31.3-37.3 m). It also examined differences in source levels calculated using several propagation loss approaches, including a full-wave acoustic propagation model and the Seabed Critical Angle (SCA) method. MacGillivray et al.'s findings on repeatability and reproducibility are relevant to understanding uncertainty of measurements made using the procedures recommended in this guidance, and they are summarized below.

The MacGillivray et al (2022) study found broadband SL measurements of multiple transits of the same ship, using the SCA method in shallow water, to have a standard deviation of 1.5 dB and that is their reported repeatability. They reported broadband reproducibility (relative to deep water measurements) in intermediate and shallow water as ±2.5 dB, but this was found to be frequency dependent. MacGillivray et al (2023) provided supplementary materials tables that list reproducibility in three wider frequency bands obtained by summing several decidecade bands with centre frequencies from: 10-80 Hz, 100-800 Hz, and ≥1000 Hz for both the intermediate depth and shallow environments. Those results are summarized in Table 2 for the acoustic model and SCA methods.

Table 2. Means of absolute residuals, in decibels, of SL measurements using single element and 3-element horizontal arrays in intermediate and shallow water relative to measurements on a 3-element vertical array in deep water. Results are shown for SL calculated with an acoustic model and with the SCA method. These results are from MacGillivray et al. (2023) supplementary materials.

Decidecade Band Centre Frequency Range	**Acoustic Model Mean Residual (dB)**		**SCA Method Mean Residual (dB)**	
	Single Element	3-Element Array	Single Element	3-Element Array
Intermediate Depth (65.7-65.9 m)				
10-80 Hz	7.38	6.74	4.0	3.59
100-1000 Hz	3.91	2.93	2.23	1.59
≥ 1000 Hz	1.58	0.97	2.58	2.1
Shallow Depth (31.3-37.3 m)				
10-80 Hz	10.83	8.75	2.9	2.01
100-1000 Hz	6.27	5.28	4.12	4.28
≥ 1000 Hz	1.52	1.36	1.31	0.83

These results indicate that the SCA method performed better than the acoustic model below 1 kHz. The 3-element horizontal arrays had lower absolute residuals than the single element geometries, on average by 0.46 dB.

Literature Cited

[ISO] International Organization for Standardization. 2017. *ISO 18405:2017. Underwater acoustics – Terminology*. Geneva. https://www.iso.org/obp/ui/en/#!iso:std:62406:en.

Ainslie, M.A. 2010. *Principles of Sonar Performance Modeling*. Praxis Books. Springer, Berlin. https://doi.org/10.1007/978-3-540-87662-5.

Ainslie, M.A., M.B. Halvorsen, and S.P. Robinson. 2022. A Terminology Standard for Underwater Acoustics and the Benefits of International Standardization. *IEEE Journal of Oceanic Engineering* 47(1): 179-200. https://doi.org/10.1109/JOE.2021.3085947.

de Jong, C.A.F., M.A. Ainslie, J. Dreschler, E. Jansen, E. Heemskerk, and W. Groen. 2010. *Underwater noise of Trailing Suction Hopper Dredgers at Maasvlakte 2: Analysis of source levels and background noise*. Document TNO-DV 2010 C335. TNO.

Lackenby, H. 1963. The effect of shallow water on ship speed. *Shipbuilder and Marine Engineer* 70: 446-450.

MacGillivray, A.O., S.B. Martin, M.A. Ainslie, J.N. Dolman, Z. Li, G.A. Warner, C.B. Lawrence, F. Pace, M. Schuster, et al. 2022. *Towards a Standard for Vessel URN Measurement in Shallow Water: Final Report on Transport Canada Innovation Centre Project MMP2*. Document 02427, Version 2.0. Techincal report by JASCO Applied Sciences.

MacGillivray, A.O., S.B. Martin, M.A. Ainslie, J.N. Dolman, Z. Li, G.A. Warner. 2023. Measuring vessel underwater radiated noise in shallow water. J. Acoust. Soc. Am. 153 (3), 1506, March 2023; doi: 10.1121/10.0017433

Robinson, S.P., P.D. Theobald, G. Hayman, L.-S. Wang, P.A. Lepper, V.F. Humphrey, and S. Mumford. 2011. *Measurement of Underwater Noise Arising from Marine Aggregate Dredging Operations: Final Report*. Document 09/P108. Marine Environment Protection Fund (MEPF). https://webarchive.nationalarchives.gov.uk/20140305134555/http://cefas.defra.gov.uk/alsf/projects/direct-and-indirect-effects/09p108.aspx.