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International harmonization of procedures for measuring and analyzing of vessel underwater radiated noise

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ABSTRACT

The habitat of the endangered southern resident killer whale (SRKW) overlaps major international shipping lanes near the Port of Vancouver, British Columbia. Shipping is a dominant source of underwater noise, which can hinder SRKW key life functions. To reduce environmental pressure on the SRKWs, Vancouver Fraser Port Authority offers incentives for quieter ships. However, the absence of a widely accepted underwater radiated noise (URN) measurement procedure hinders the determination of relative quietness. We review URN measurement procedures, summarizing results to date from two Canadian-led projects aimed at improving harmonization of shallow-water URN measurement procedures: One supports the International Organization for Standardization (ISO) in the development of a URN measurement standard; the other supports the alignment of URN measurement procedures developed by ship classification societies. Weaknesses in conventional shallow-water URN metrics are identified, and two alternative metrics proposed. Optimal shallow-water measurement geometry is identified.

1. Introduction

Marine mammals and other aquatic organisms use underwater sound for critical life functions such as navigating, communicating, and foraging, and therefore rely on their hearing for survival. Underwater noise can adversely affect marine fauna through behavioral disturbance, stress, acoustic masking, and physical impairment. Marine shipping is a dominant source of anthropogenic noise throughout the world's oceans. The sound from ships contributes to the underwater soundscape, and sound from ships can adversely affect marine fauna (Erbe et al., 2019), whether via behavioral disturbance (e.g., in porpoises (Dyndo et al., 2015, Wiśniewska et al., 2018) or in fishes (Nedelec et al., 2017)); physiological effects (Rolland et al., 2012; Nedelec et al., 2017); or acoustic masking (Erbe et al., 2019). The present work focuses on developing accurate and repeatable methods for measuring underwater radiated noise from ships, suitable for use by organizations providing quiet vessel certifications. The end goal is to support reduction of ship noise in the ocean to lessen its negative effects on marine wildlife.

The southern resident killer whale (SRKW) provides a case study in the effects of noise on marine life. The SRKW are an endangered population of just 74 individuals (Centre for Whale Research, 2021), with designated critical habit that overlaps international shipping traffic lanes in the Salish Sea that serve the ports of Vancouver and Seattle (DFO, 2018). Acoustic masking and disturbance caused by noise from vessel traffic has the potential to negatively affect the key life functions of SRKW, such as communication, which could lead to population-level consequences and hinder the recovery of this population (Erbe et al., 2012; Williams et al., 2013; Cominelli et al., 2018; Joy et al., 2019). Quieter ships would reduce environmental pressure on the SRKW population. In 2017, the Vancouver Fraser Port Authority (VFPA)

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introduced financial incentives for ships with a quiet ship certification from an international ship classification society. Of ship classifications societies globally, five had notations for underwater radiated noise when the port authority implemented incentives: American Bureau of Shipping (ABS), Bureau Veritas (BV), Det Norske Veritas Germanischer Lloyd (DNV), Lloyd's Register (LR), and Registro Italiano Navale (RINA). However, these classification societies do not follow the same ship sound measurement, analysis, and reporting procedures. Thus, certificates provided by different societies are not directly comparable, hindering determination of relative quietness.

In addition to the classification society measurement procedures, international standards exist for measuring underwater radiated noise (URN) in deep water (ISO 17208-1:2016; ISO 17208-2:2019) but not in shallow water. Deep-water measurements are relatively easy to perform repeatably because only the sound arriving directly from the vessel to a hydrophone and the sound reflecting off the sea surface need to be considered. In shallow water, the sound interacting with the seabed (whose properties are rarely known with precision) must also be considered. Depending on the water depth, sound may reflect one or more times from the seabed before arriving at the measurement points. Facilitating repeatable measurements in shallow water is expected to reduce the cost of obtaining quiet certifications (by reducing sailing time to a measurement location) and hence increase the proportion of the global fleet that is characterized.

Here we describe two projects, initiated respectively by Transport Canada and VFPA, aimed at improving harmonization of URN measurement procedures. The first project, executed by JASCO Applied Sciences, in collaboration with DW-ShipConsult and supported by Transport Canada's Innovation Centre (TC-IC), supports the International Organization for Standardization (ISO) to develop a shallow-water URN measurement standard. We refer to this project as the 'URN Standardization Support' project. The VFPA-led Enhancing Cetacean Habitat and Observation (ECHO) Program, with support from Transport Canada, initiated a second project concerning the alignment of URN measurement and analysis procedures used by ship classification societies for quiet ship certification. The purpose is to support VFPA customers striving to design quieter ships and achieve associated certifications.

Both projects support the development of shallow-water URN measurement procedures with broad consensus that the results are repeatable and comparable regardless of where they were performed. Consistent measurement, analysis, and reporting methodologies between classification societies would also allow vessel owners and builders to compare between class society notations, identifying which is most applicable or achievable for their fleet. Such alignment would also provide confidence to all stakeholders that a measurement and associated certification conducted in one area of the world would be reliable and replicable elsewhere. The focus of this second project, referred to henceforth as the 'Certification Alignment' project, is on supporting the alignment of measurement and analysis procedures of ship classification societies.

The *URN Standardization Support* project will provide guidance on how to standardize data collection and analysis in shallow water (Section 3). The information obtained from that project will also assist in the *Certification Alignment* project (Section 4), which reviews and strives to streamline existing and future quiet ship certification procedures developed by ship classification societies.

The remainder of the article is structured as follows: First an introduction to URN is given in Section 2, followed by descriptions of the two projects in Sections 3 and 4, and a summary in Section 5.

The process towards consensus in the development of URN procedures will require effective communication between appropriate stakeholders. To facilitate this communication, we follow the underwater acoustical terminology standard ISO 18405 (ISO, 2017).

2. Vessel underwater radiated noise

2.1. Sound pressure level, radiated noise level, and source level

There are different ways to characterize and quantify the underwater sound radiated by surface vessels. Underwater sound produced by vessels can interfere with normal life functions of aquatic animals, and this sound is commonly referred to as "underwater radiated noise" (URN). Near a vessel (though still in its far field), the sound field follows an inverse square behavior with distance r from the source, with sound pressure level (SPL, symbol L_p) in a specified frequency band varying according to:

$$L_p(r,\theta,\phi) = K_1(\theta,\phi) - 20log_{10}\frac{r}{1\ \mathrm{m}}\ \mathrm{dB}, \tag{1}$$

where K_1 is independent of r, though its value depends on the elevation angle, θ, i.e., the angle between the sea surface and the line connecting the receiver and the point at the sea surface above the source, and (in general) on the bearing angle ϕ, through the source factor $S(\phi)$. It depends also on the source depth d and frequency f through Lloyd mirror interference (Eq. (2.29) of (Ainslie, 2010), neglecting absorption), and can be written:

$$K_1(\theta,\phi) = 20log_{10}\frac{2\sqrt{S(\phi)}|sin(\pi f\ T(\theta))|}{1\ \mu\mathrm{Pa\ m}}\ \mathrm{dB}, \tag{2}$$

where $T(\theta)$ is the difference in the arrival time between the direct and surface-reflected paths, a function of elevation angle given (for sound speed c) by:

$$T(\theta) = \frac{2dsin\theta}{c}. \tag{3}$$

Eq. (1) does not hold far from a ship, where the range-dependence is no longer inverse-square. In this situation, SPL can be written as a function of the propagation loss (PL, symbol N_{PL}) according to:

$$L_p(r,\theta,\phi) = K_2(\phi) - N_{\mathrm{PL}}(r,\theta,\phi), \tag{4}$$

where K_2 is independent of range and elevation angle, θ. The specified frequency bands usually follow the international standard IEC 61260-1, which requires the use of decidecade bands.[1] The dependence on elevation angle is addressed in international standards by specifying the geometry required for the measurement. Specifically, three receivers are required, placed such that the angle θ is equal to 15, 30, and 45°.

Traditional URN metrics are source level (SL; symbol L_S) and radiated noise level (RNL; symbol L_{RN}). SL is a property of a sound source related to its radiated power. It is the sum of SPL, a property of the radiated sound field at a specified location, and PL (the difference between SL and SPL). Thus, the constant K_2 in Eq. (4) is SL. This quantity can therefore be calculated from SPL and PL using:

$$L_S = L_p + N_{\mathrm{PL}}. \tag{5}$$

SL is typically used for sound mapping, to calculate SPL in the far field of the source. It is a property of the source and thus independent of the propagation conditions. To perform the computation shown in Eq. (5), acoustic propagation models are employed to estimate PL. A detailed knowledge of the propagation conditions and one's choice of nominal source depth affect the calculated PL, making it less suitable for vessel comparisons, especially at low frequency.

Definitions of RNL and URN are also needed, but neither is defined by ISO 18405. According to ISO 17208-1, the constant K_1 in Eq. (1) is RNL. This quantity can therefore be calculated from SPL and r using:

[1] A decidecade (1 ddec) is one tenth of a decade (1/10 dec). A decidecade is referred to by IEC 61260-1:2014 as a "one-third octave", presumably because 1/10 dec is approximately equal to 1/3 oct.

$$L_{\mathrm{RN}} = L_p + 20log_{10}\frac{r}{1\ \mathrm{m}}\ \mathrm{dB}. \quad (6)$$

RNL is more straightforward to calculate than SL because it does not require the determination of PL. RNL is directly related to SPL near a vessel, making it useful for characterizing differences between vessels or changes over time for a single vessel, assuming the measurements are carried out the same way. Its value does depend on elevation angle, and this point is addressed in standards by specifying the geometry. In shallow water, RNL also depends on propagation conditions. RNL is unsuitable for sound mapping because (unlike SL) in shallow water it is not related to the far-field SPL in a simple way.

There exist international standards for measuring SL and RNL in deep water (see Section 2.2), but none presently for use in shallow water. To address the complications of shallow water propagation, the concepts of adjusted source level (aSL) and adjusted radiated noise level (aRNL) are proposed (see Section 4.2). The aSL is the source level of a dipole (Ainslie et al., 2021b), evaluated at a grazing angle of 30°. In deep water with no absorption, aSL and RNL are equal (see Section 4.2.3).

2.2. National and international standards

The first standard in underwater acoustics known to the authors was ANSI/ASA s12.64-2009, developed by ASA Working Group S12/WG 47, Underwater Noise Measurement of Ships, (Bahtiarian, 2009; Blaeser and Struck, 2019). ANSI S12.64 (Table 1) describes a procedure to measure RNL in deep water (>150 m). At that time, there was no widely accepted terminology and the quantity RNL was referred to as “source level” or “affected source level”. The ANSI standard served as a basis for the first international standard for measuring RNL (ISO 17208-1), later supplemented by a post-processing procedure for calculating SL (ISO 17208-2), following modern definitions of these two terms (ISO 17208-1:2016; ISO 18405:2017). ISO 17208-1 and -2 were developed by ISO/TC 43/SC 3/WG 1 (ISO Technical Committee 43, Sub-committee 3, Working Group 1, henceforth abbreviated WG1), and both are applicable in deep water. WG1 met in September–October 2021 to discuss initial steps for developing ISO 17208-3, intended as a URN measurement standard for shallow water (Table 1).

2.3. Quiet ship certification procedures

URN measurement methods are described in the quiet ship certification procedures of the five ship classification societies that had quiet notations at the time of project inception:

- American Bureau of Shipping (ABS, 2018),
- Bureau Veritas (BV, 2014),
- Det Norske Veritas Germanischer Lloyd (DNV GL, 2019),
- Lloyd's Register (LR, 2018), and
- Registro Italiano Navale (RINA, 2016).

The output of a URN measurement is referred to as the URN level (symbol L_{URN}). In general, the five procedures result in five different L_{URN} values (although in deep water, the American Bureau of Shipping and Registro Italiano Navale procedures are nearly identical). All five quiet ship certification procedures use either SL (Lloyd's Register), RNL (Registro Italiano Navale), or a modification of one of these (American Bureau of Shipping, Bureau Veritas, and Det Norske Veritas - Germanischer Lloyd), as summarized in Table 2.

3. Project 1: URN standardization support

3.1. Approach

The *URN Standardization Support* project (Ainslie et al., 2021b) will assist WG1 in developing standard 17208-3 by providing measurements of vessel URN in shallow water. Development of ISO 17208-3 has been impeded by a lack of data to demonstrate combinations of sensors and analysis methods that can yield repeatable measurements of vessel underwater sound levels in shallow water. The shallow-water levels should be consistent with those known to be accurate in deep water when measured following ISO Standards 17208-1 for radiated noise levels and 17208-2 for source levels.

Table 1
National and international standards for underwater radiated noise (URN) measurement and analysis. TBC means to-be-confirmed as the standard develops.

Standard	URN metric	Frequency band	Notes
ANSI S12.64-2009	RNL	Unspecified	Refers to RNL as “source level”
ISO 17208-1:2016	RNL	1/3 oct or 1/10 dec	First international URN measurement standard
ISO 17208-2:2019	SL	1/10 dec	First international SL measurement standard
ISO 17208-3:XXXX	SL (TBC)	1/10 dec (TBC)	At the time of writing, a Committee Draft (ISO/CD 17208-3) is in preparation

Table 2
Quiet ship certification procedures. The L_{URN} reference values for ABS (2018), LR (2018), RINA (2016) is 1 μPa m. Reference values for BV (2014) and DNV GL (2019) are stated in the table.

Originator (year)	Underwater radiated noise level (L_{URN})	Notes
ABS (2018)	L_{RN}	ABS (2018) is based on RNL. It permits application of an optional “bottom effect correction” if the receiver is near the seabed. With this modification, the expression for URN would become: $L_{\mathrm{URN}} = L_{\mathrm{RN}} - 5$ dB
BV (2014)	$L_{\mathrm{S}} - 20log_{10}\frac{\Delta f^{0.5}}{1\ \mathrm{Hz}^{0.5}}$ dB	BV (2014) is based on SL. Subtracting the bandwidth term from the source level results in the source spectral density level (Ainslie et al., 2020), resulting in a reference value of 1 μPa m Hz$^{-0.5}$. Calculating SL requires a prediction of PL; BV (2014) provides advice on the choice of propagation model.
DNV GL (2019)	$L_{\mathrm{RN}} - 20log_{10}\frac{r^{0.1}}{1\ \mathrm{m}^{0.1}}$ dB	DNV GL (2019) is based on RNL. The difference between L_{RN} and L_{URN} is equal to $(X-20)log_{10}\frac{r}{1\ \mathrm{m}}$ dB, with $X = 18$. Subtracting the range-dependent modification and applying the division rule (Ainslie et al., 2021a) results in a reference value of 1 μPa m$^{0.9}$. DNV GL (2019) requires application of a “pressure reflection correction” if the receiver is near the seabed. With this modification, the expression for URN would become $L_{\mathrm{URN}} = L_{\mathrm{RN}} - 20log_{10}\frac{r^{0.1}}{1\ \mathrm{m}^{0.1}}$ dB − 5 dB
LR (2018)	L_{S}	LR (2018) results in SL. In deep water, LR (2018) follows ISO 17208-2 for SL (Table 1).
RINA (2016)	L_{RN}	RINA (2016) follows ISO 17208-1 for RNL (Table 1). This procedure is applicable in deep water.

The project has two phases: 1) developing a shallow-water source level measurement plan informed by extensive acoustic propagation modeling to investigate the issues associated with the measurements; and 2) executing the experiments and analyzing the collected data to address the knowledge gaps.

3.2. Progress to date

To investigate the issues that complicate vessel URN measurements in shallow water, extensive acoustic propagation modeling experiments were performed in Phase 1. The experiments compared the suitability of different hydrophone geometries and analysis methods.

The analysis simulated the steps of measuring source level. In accordance with ISO 17208, the process evaluating URN is measuring the sound field at some range and depth, and then accounting for the effects of propagation effects. In 17208-1, the propagation is accounted for following Eq. (6). In 17208-2, the effect of sound reflecting off the sea surface is also included in the computation, resulting in SL (Eq. (5)). The method described in 17208-2 is applicable to SL in deep water, and an alternative is sought for shallow water, which could involve the use of numerical acoustic propagation models (Simard et al., 2016; Jansen and de Jong, 2017; MacGillivray et al., 2019).

In the numerical experiments, the sound field was estimated using JASCO's Marine Operations Noise Model (MONM) implementation of the parabolic equation model (Collins, 1993) at decidecade and centidecade intervals.[2] The sound field from a hypothetical vessel was modeled for sand and mud seabeds, assuming uniform sound speed in water (Ainslie et al., 2021b), and for a 50 m water depth. The sound from vessels is the sum of the sound arriving directly from the vessel as well as the sound reflected off the surface. This creates regions of constructive and destructive interference in the first few hundred meters, most clearly seen in the mud-bottom case at 3.16 kHz (Fig. 1). The sound also reflects from the seabed, resulting in many more regions of interference, especially for sand. The properties of the interference fringes depend on the depth of the sound source (primarily propeller cavitation) as well as the seabed properties. These parameters are often difficult to obtain precisely, which leads to uncertainty in the propagation loss and hence in the source level.

Since this analysis relied on a modified version of the RAM model, its accuracy was checked by comparing with OASES (Schmidt and Tango, 1986; OASESVersion 3.1, n.d.), which obtains the exact solution to the wave equation using the wave-number intergration approach. Differences (Fig. 2) are after decidecade band processing, simulated here by a proportional range average (Harrison and Harrison, 1995). Errors are small at 31.6 Hz, except in the first 20 m. At 3.16 kHz, they are more variable but with no bias except in the first 20 m, where MONM overestimates PL.

The choice of centidecade bands and center frequencies is explained next, considering the equation:

$$f_{c,x} = 10^{x/10}\cdot(1\ \text{kHz}). \tag{7}$$

Standard decidecade band center frequencies (Ainslie et al., 2018) are obtained with integer $x = N$, i.e.,:

$$f_{c,N} = 10^{N/10}\cdot(1\ \text{kHz}), \tag{8}$$

with lower and upper decidecade edge frequencies:

$$f_{-,N} = 10^{-1/20} f_{c,N} \tag{9}$$

and

$$f_{+,N} = 10^{+1/20} f_{c,N}. \tag{10}$$

[2] A centidecade is one hundredth of a decade, e.g., 100 logarithmically spaced frequencies between 8.91 and 89.1 Hz. see Eqs. (11) to (13).

Each decidecade band can be subdivided into ten centidecade bands, with center frequencies given by $x = (2M + 1)/20$ for integer M, such that:

$$f_{c,M} = 10^{(2M+1)/20}\cdot(1\ \text{kHz}), \tag{11}$$

with lower and upper centidecade edge frequencies:

$$f_{-,M} = 10^{-1/200} f_{c,M} \tag{12}$$

and

$$f_{+,M} = 10^{+1/200} f_{c,M}. \tag{13}$$

To estimate SL, we need to measure or predict PL. Predicting PL is straightforward in deep water. For a given source depth, the effect of the sea surface reflections is known (Ainslie, 2010, ISO 2019) so the source depth can be estimated from the ship draft (Gray and Greeley, 1980, ISO 2019). Several models are available to model shallow water propagation (Jensen et al., 2011), with wavenumber integration (Schmidt 2004) or parabolic equation (PE) methods (Collins, 1993) being particularly suitable for frequencies below 1 kHz, and ray-tracing methods being suitable at higher frequencies (Porter and Liu, 1994). Successful use of these models requires precise information about the seabed that is often unavailable.

Typically, vessel source levels are computed in decidecade bands. For the propagation modeling investigations, we replicated the measurement and modeling process by computing the approximate sound fields calculated at decidecade center frequencies and subtracting these fields from the more precise fields (representing a measurement) computed from centidecades. Next, we consider a comparison, showing the error in estimated PL incurred by approximating the broadband PL in a decidecade band by the narrowband PL evaluated at the decidecade center frequency. The simulated measurement of RNL and SL comprises the following steps (Ainslie et al., 2021b):

Step 1: Calculate PL at centidecade center frequencies between 9.02 Hz ($x = -20.45$, corresponding to $M = -205$ in Eq. (11)) and 111 kHz ($x = +20.45$, $M = +204$), illustrated by Fig. 1 (at 31.6 Hz and 3.16 kHz);
Step 2: Estimate signal SPL in centidecade bands using Eq. (32) of Ainslie et al. (2021b), by subtracting PL at the center frequency from the Wales-Heitmeyer source level (Wales and Heitmeyer, 2002) (abbreviated SLo), illustrated by Fig. 3;
Step 3: Estimate noise SPL in centidecade bands corresponding to Wenz sea state 4;
Step 4: Estimate signal-plus-noise SPL in centidecade bands by adding contributions from signal and noise;
Step 5: Estimate signal-plus-noise SPL in decidecade bands between 10 Hz ($N = -20$) and 100 kHz ($N = +20$) by adding contributions from ten successive centidecade bands; and
Step 6: Estimate SL and RNL as described below, using Eqs. (42) and (37), respectively, from (Ainslie et al., 2021b).

SL is estimated using Eq. (5) and compared with SLo by plotting the difference between them (Fig. 4) at 31.6 Hz ($N = -15$, upper panels) and 3.16 kHz ($N = +5$, lower panels), for a mud seabed (left panels) and sand seabed (right panels). White indicates good agreement (SL = SLo), blue means SL is overestimated (SL > SLo), and red means SL is underestimated (SL < SLo). At the lower frequency (31.6 Hz), the difference between SL and SLo is approximately zero for both sand and mud sediments. At 3.16 kHz, the difference varies spatially, suggesting the desirability of spatially averaging the results. Similarly, the purpose of measuring the received level in ISO 17208-1 and -2 is to average over the peaks and nulls of the surface-reflected interference pattern.

RNL is estimated using Eq. (6) and compared with the known value of adjusted source level (abbreviated aSLo) by plotting the difference between them (Fig. 5) at 31.6 Hz (upper panels) and 3.16 kHz (lower

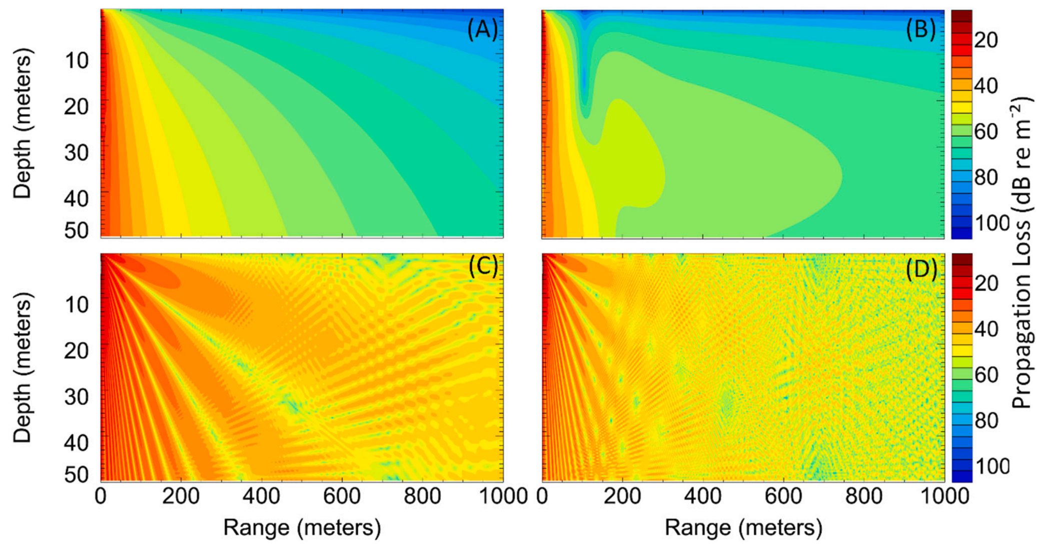

Fig. 1. PL re 1 m, in decibels for mud (left: A&C) and sand (right: B&D) seabeds at 31.6 Hz (upper: A&B) and 3.16 kHz (lower: C&D) as a function of range (m) and depth (m). Results are for a source depth of 3.4 m. The frequencies are center frequencies of decidecade bands corresponding to $x = -15$ and $x = 5$ in Eq. (8).

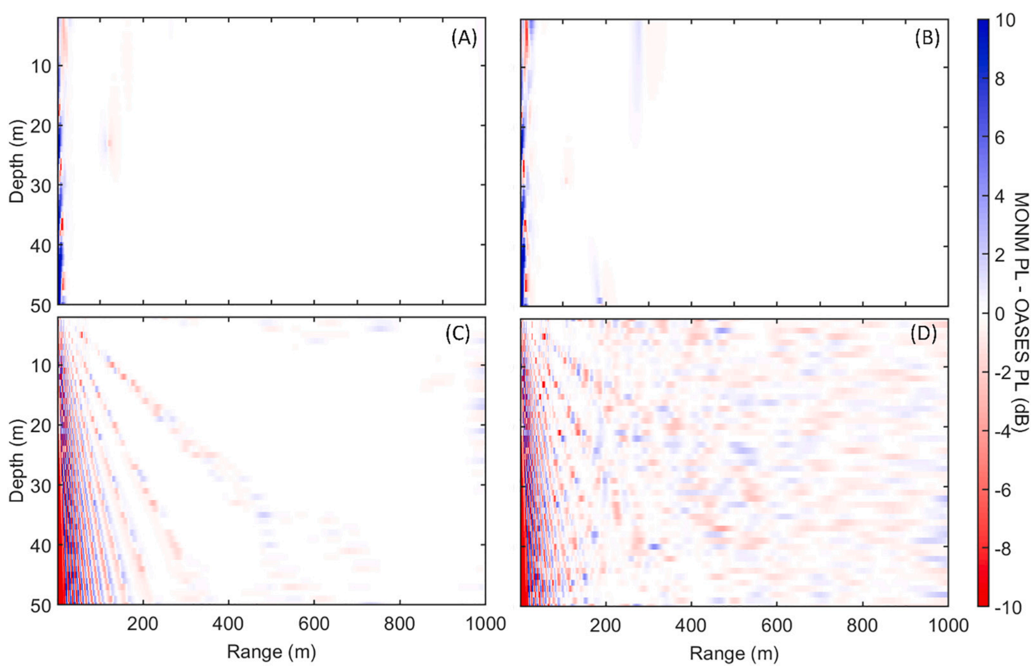

Fig. 2. Difference between PL, in decibels, calculated by OASES and MONM for mud (left: A&C) and sand (right: B&D) seabeds at 31.6 Hz (upper: A&B) and 3.16 kHz (lower: C&D) as a function of range (m) and depth (m). Results are for a 3.4 m source depth.

panels), for a mud seabed (left panels) and sand seabed (panels). Blue means RNL overestimates the value of aSL. Errors are lowest near the seabed and at ranges less than 200 m.

The results of the modeling study (Ainslie et al., 2021b) indicate that:

- A suitable location for single hydrophone measurements is at the seabed, as close as possible to the vessel track (Figs. 4 and 5) while remaining in the source's acoustic far field (see ISO (2016)). Fig. 5 suggests that, for a measurement of RNL, the horizontal distance to closest point of approach (CPA) should not exceed approximately four times the water depth. Some frequency averaging (e.g., by means of an incoherent ray sum) is likely needed at higher frequencies (2 kHz and above) to remove interference (Fig. 4).
- Making measurements at multiple receiver depths facilitates averaging across peaks and nulls in the interference patterns, reducing variability in the source level estimates. The recommended location for such arrays is 3–7 water depths from the vessel (i.e., 150–350 m in Fig. 4).
- In shallow water, where a vertical array of hydrophones is impractical (<70 m), a horizontal array of hydrophones can be employed to average over the peaks and nulls of the interference patterns to obtain source level.

For all measurement locations and at lower frequencies (300 Hz and below), a coherent method to estimate the propagation loss is needed to account for the Lloyd mirror interference patterns from the surface and seabed (Ainslie et al., 2021b).

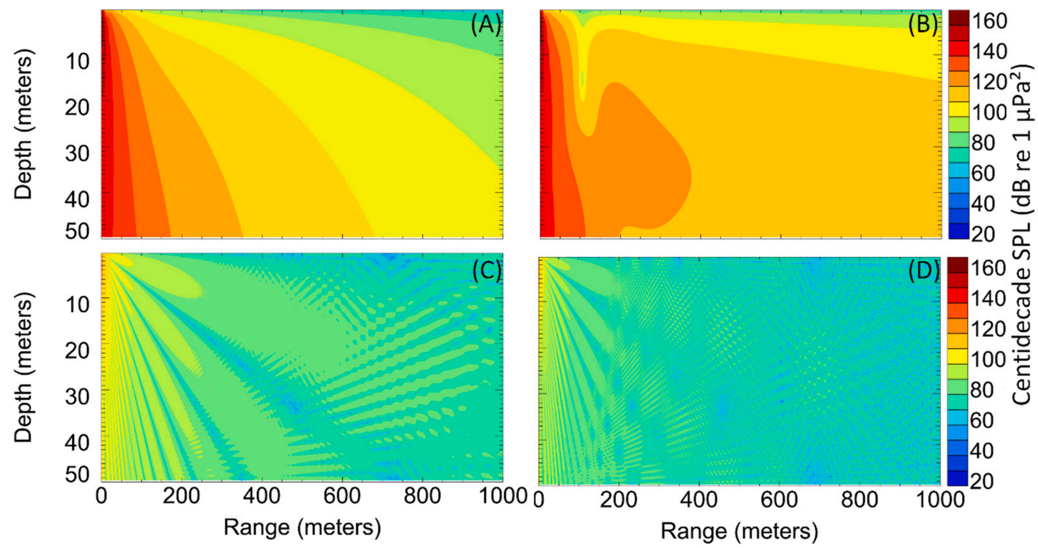

Fig. 3. Centidecade SPL (step 2), re 1 μPa, in decibels, for mud (left: A&C) and sand right: (B&D) seabeds at 31.6 Hz (upper: A&B) and 3.16 kHz (lower: C&D) as a function of range (m) and depth (m). Results are for a 3.4 m source depth.

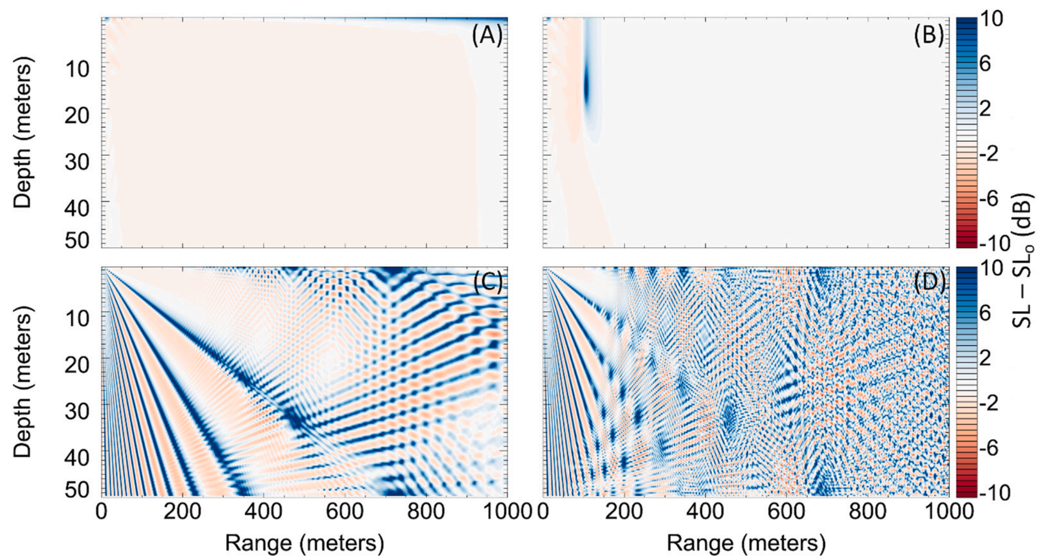

Fig. 4. Decidecade SL (step 6) – SLo, in decibels, for mud (left: A&C) and sand (right: B&D) seabeds at 31.6 Hz (upper: A&B) and 3.16 kHz (lower: C&D) as a function of range (m) and depth (m). Results are for a 3.4 m source depth.

In August 2020, the measurement water depths and sensor geometries were considered in consultation with WG1. Fig. 6 shows the recommended measurement geometries. Three measurement locations are represented: A) deep water that replicates the ISO 17208-1 geometry; B) a horizontal array to evaluate performance in very shallow waters; and C) vertical arrays at two distances as well as a three-element horizontal array to evaluate geometries at 70 m water depth. Water depths greater than 65 m were identified as desirable because the lowest frequencies associated with vessel noise (10 Hz) are able to propagate in this water depth (Ainslie et al., 2021b).

3.3. Measurements and future work

A large set of real-world measurements from multiple hydrophone locations, analyzed using a spectrum of simple to complex methods, will provide the data needed to advance the development of ISO 17208-3. The analysis methods to be investigated will be the use of full acoustic propagation modeling (Eq. (5)), as well as methods based on the adjusted source level (Eq. (21)) and adjusted radiated noise level (Eq. (24)). By comparing the source level estimates from the different methods, at the 30 and 70 m water depths, to the reference source levels estimated at the 180 m water depth, the *URN Standardization Support* project will provide guidance on the suitability of different measurement geometries and analysis approaches.

Measurements were conducted from May to July 2021 using the recorder configuration shown in Fig. 6. The experimental location was along the Swartz Bay – Tsawwassen route (Fig. 7). Between 611 and 883 ferry CPAs were recorded at ranges of less than 1 km at each of the recorders, yielding a total of over 9000 individual source level estimates. Two different types of ferries, a single-ended twin propeller vessel and double-ended single propeller vessel, were recorded. The cruising speed of both classes of ferry as they passed the recording locations was 19 knots (9.8 m/s). The actual speeds and distances depended on current, schedules, and the presence of small vessel traffic or marine mammals on the ferry route. All hydrophones and recorders were calibrated before deployment and on retrieval. The large number of measurements will

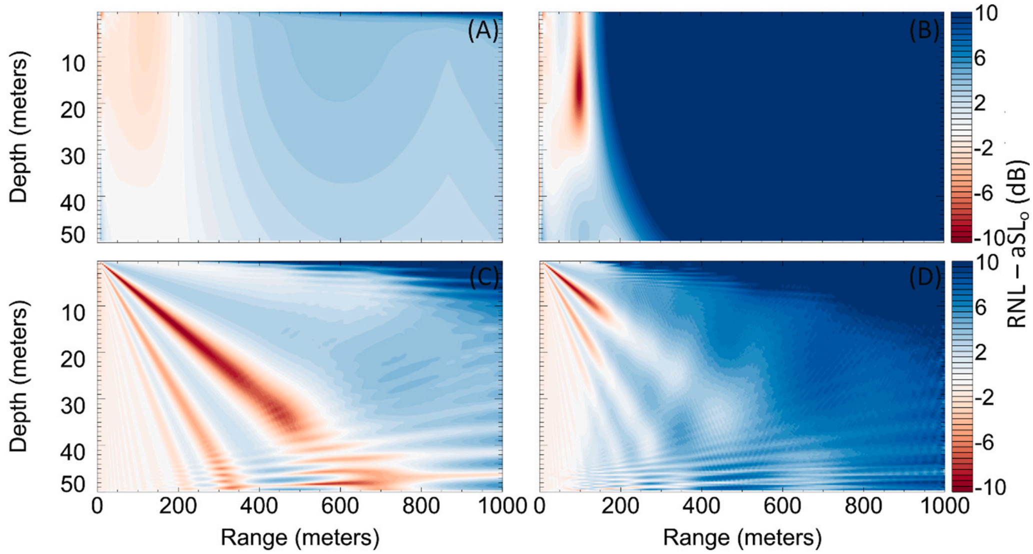

Fig. 5. Decidecade RNL (step 6) – aSLo, in decibels, for mud (left: A&C) and sand (right: B&D) seabeds at 31.6 Hz (upper: A&B) and 3.16 kHz (lower: C&D) as a function of range (m) and depth (m). Results are for a 3.4 m source depth.

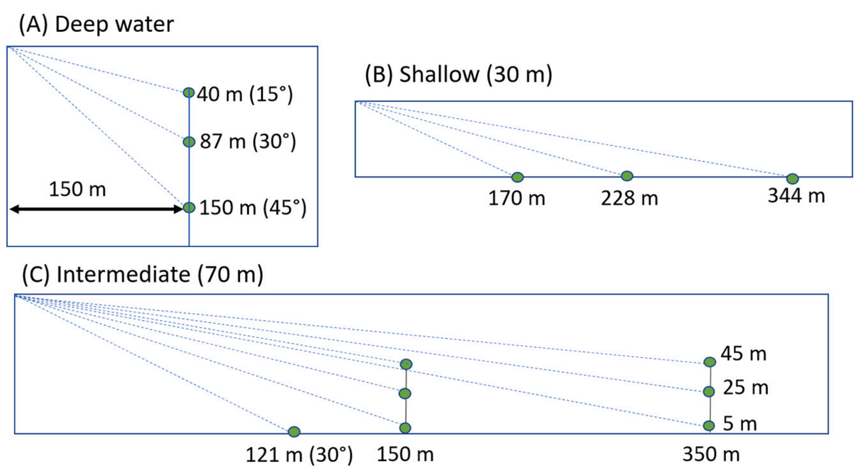

Fig. 6. Measurement geometries for the *URN Standardization Support* field trials as agreed with WG1 members. Green dots represent the hydrophone locations. The vertical arrays of hydrophones are shown with their heights above the seabed.

facilitate analysis of the repeatability of the vessel source levels and their dependence on depth and the analysis method employed.

Collecting non-acoustic data was essential to help analyze the acoustic data. The ferry operator provided data on the operation conditions of the vessels. Conductivity-temperature-depth (CTD) profiles of the water column were performed in May, June, and July to characterize the acoustic propagation conditions. Automated Identification System (AIS) tracks for all vessel traffic were purchased from Marine Traffic to help us understand when other vessels may have contaminated the ferry recordings.

Perhaps the most important determinant of acoustic propagation at the short ranges and shallow water conditions considered are the seabed geoacoustic conditions. To measure the geoacoustic properties, a controlled sound source was deployed (source level re 1 μPa m of 170 dB, frequency 600–1200 Hz, duty cycle 20%) and was recorded with receivers near the seabed and at 1 m from the source. An analysis of the propagation loss was performed to estimate the effect of sediment acoustic properties on sound propagation using Bayesian inversion techniques (Dosso et al., 2014). An inversion of the sediment properties using the sounds of the ferries was also performed. The source level of the ferries will be estimated using a priori estimates of the sediment properties, as well as using the properties determined by the inversions. This analysis will provide insight into the effects on the source level estimates from mismatch between the estimated and actual geoacoustic properties.

4. Project 2: certification alignment

4.1. Background and objectives

The ECHO Program led by VFPA is a research and management program that seeks better to understand and minimize the cumulative effects on at-risk whales of shipping, particularly the effects of ship-generated underwater noise. Since 2015, the ECHO Program and the Government of Canada have been engaging with stakeholders on the issue of vessel-generated underwater noise, and the measurement of vessel source levels at underwater listening stations on the approach to the Port of Vancouver.

With the ability to measure ship source levels, and the implementation of financial incentives for quiet ship notations by VFPA, regional operators and port customers began investigating the potential to obtain quiet vessel notations. The *Certification Alignment* project aims

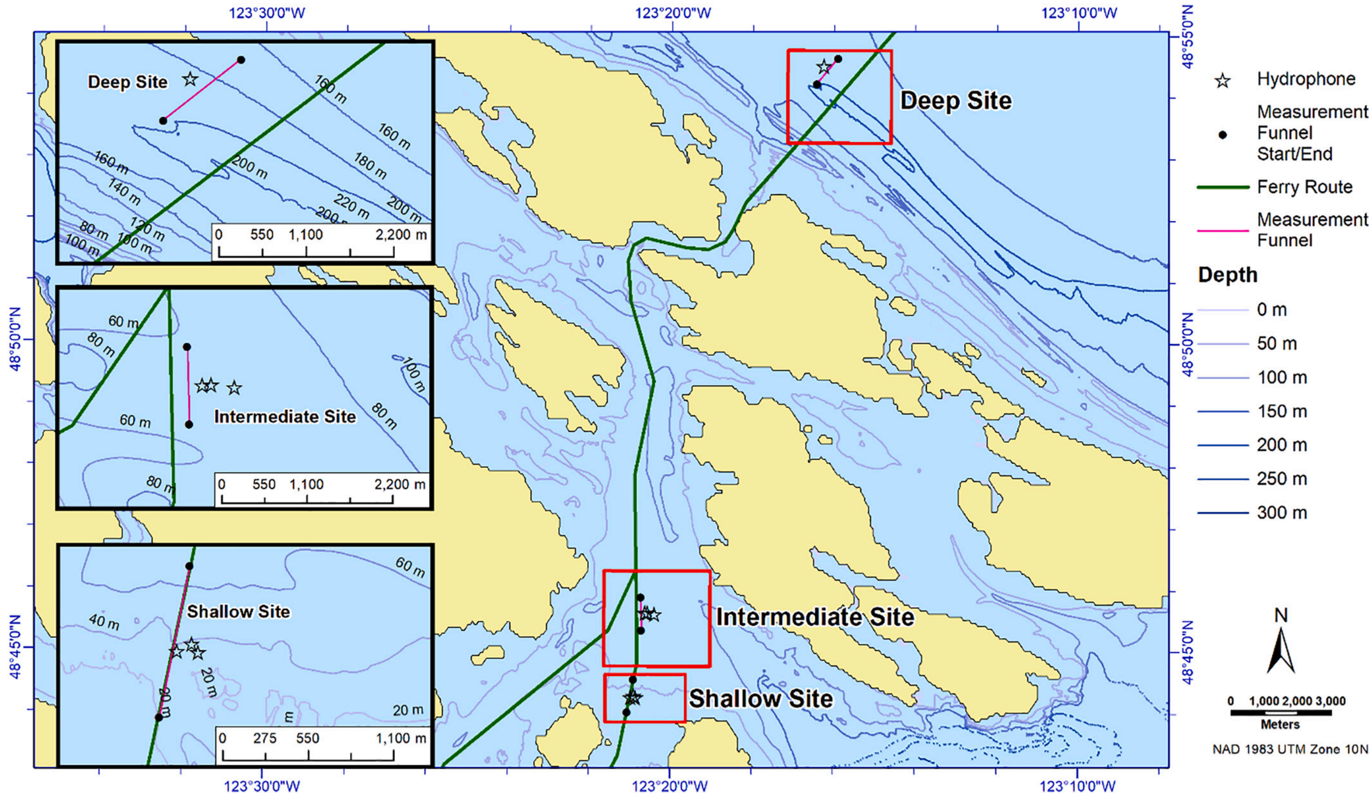

Fig. 7. Locations for the May to July 2021 field measurements. The green line shows the route for the Swartz Bay – Tsawwassen (Victoria – Vancouver) route. The stars indicate the recorder locations.

to improve the alignment of measurement and analysis procedures and reporting metrics between the various class societies, to provide customers with more clarity about how quiet ship notations are obtained, and to allow for comparisons between them.

As part of the *Certification Alignment* project led by VFPA and supported by Transport Canada, JASCO prepared an unpublished memorandum comparing the five notations available at the time and suggesting possible ways to improve alignment. A series of three annual stakeholder workshops was planned, with the first conducted in October 2020, to refine the alignment document based on stakeholder feedback and emerging science. The intended outcomes are recommended amendments to existing quiet ship notations to reflect the consensus from the three workshops.

4.2. Evaluation of URN metrics

Some quiet ship certification procedures use URN based on Eq. (6), resulting in URN equal to or closely related to RNL, while others are based on Eq. (5), resulting in URN equal to or closely related to SL. In deep water and for a source depth of 4 m, SL differs from RNL (and PL differs from $20\log_{10}R$ dB) by an amount:

$$\Delta L \equiv L_{\mathrm{RN}} - L_{\mathrm{S}}, \tag{14}$$

which is between −15 dB and +5 dB in the frequency range considered by ISO 17208-2 (10 Hz to 50 kHz) (Fig. 8).

The level difference (in deep water) is:

$$\Delta L = 20log_{10}\sqrt{\overline{\gamma}}\mathrm{dB}, \tag{15}$$

where $\overline{\gamma}$ is the dipole to monopole source factor ratio averaged over the three angles specified by ISO 17208-1, i.e.,

$$\overline{\gamma} = \frac{\gamma(0.5\,\pi/6) + \gamma(1.0\,\pi/6) + \gamma(1.5\,\pi/6)}{3}, \tag{16}$$

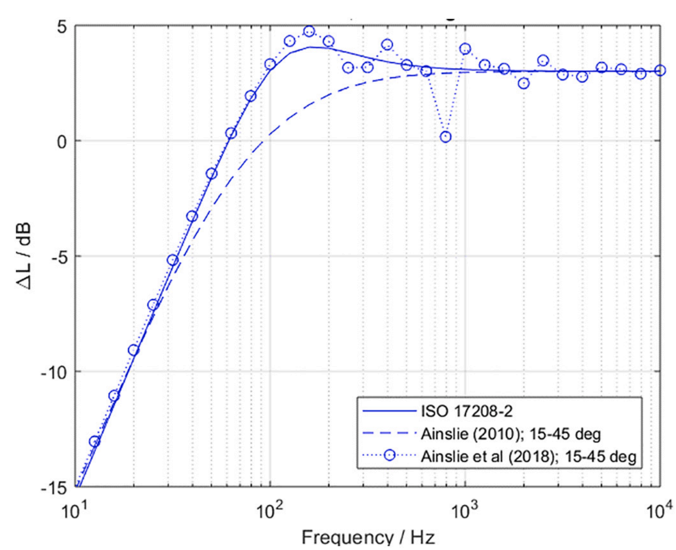

Fig. 8. Difference between RNL and SL at band center frequencies. Also equal to the difference between $20\log_{10}R$ dB and PL. Source depth $d = 4$ m; grazing angle $\theta = 30°$.

and $\gamma(\theta)$ is the ratio of dipole to monopole source factor for angle θ. Three different approaches for $\overline{\gamma}$ are shown in Fig. 8. One (shown as symbols in the graph) uses Eq. (16) with the following expression for $\gamma(\theta)$:

$$\gamma(\theta) = 2 - \frac{sin(2\pi Tf_2) - sin(2\pi Tf_1)}{\pi T\ (f_2 - f_1)}, \tag{17}$$

obtained by averaging from f_1 to f_2 (the lower and upper limits of each decidecade frequency band, respectively), where $T = T(\theta)$ is the function of angle given by Eq. (3).

Another (dashed line in Fig. 8) uses Eq. (16) with the approximation suggested by Ainslie (2010, see p. 419):

$$\gamma(\theta) \approx \left(2^{-1} + (2kd\sin\theta)^{-2}\right)^{-1} \tag{18}$$

where k is the wavenumber, given by:

$$k = \frac{2\pi f}{c}. \tag{19}$$

The third (solid line in Fig. 8) is the approximation adopted by ISO 17208-2:

$$\overline{\gamma} \approx \frac{14(kd)^2 + 2(kd)^4}{14 + 2(kd)^2 + (kd)^4}. \tag{20}$$

The three angles used in Eq. (16) are 15, 30, and 45°, chosen for consistency with ISO 17208.

4.2.1. Source level, radiated noise level, and adjustments

The following subsections consider the choice of metric to represent vessel URN for quiet ship certification purposes. Conventional metrics are SL and RNL. The natural choice in deep water is RNL, while SL is potentially advantageous in shallow water because it accounts for the propagation conditions, albeit at the expense of increased complexity. However, the conversion from SPL to URN depends on the choice of nominal source depth during propagation modeling, making it difficult to compare two URN measurements if different source depths are used.[3]

No such dependence on source depth exists for RNL. However, if applied unmodified in shallow water, RNL is less useful than in deep water because inverse-square spreading no longer applies. In the following subsections, in addition to SL and RNL, we consider adjustments to both, namely aSL, which is robust to the choice of nominal source depth and aRNL, robust to propagation conditions.

All four metrics, SL, RNL, aSL, and aRNL, have the same reference value, which may be written either as 1 μPa m or 1 $\mu\text{Pa}^2\,\text{m}^2$; there is no difference in meaning between these two reference values. A reference value of 1 μPa m is used throughout this paper. Other URN metrics, however, do not necessarily have this reference value (Table 2).

4.2.2. Source Level (SL)

ISO 17208-2 and LR (2018) use the SL metric unmodified, whereas a bandwidth-adjusted form of SL is used by BV (2014). For SL, the choice of nominal source depth is important. BV (2014) specifies a source depth of 2/3 the vessel draught, compared with 7/10 vessel draught specified by ISO 17208-2. Wales and Heitmeyer (2002) propose a Gaussian distribution over depth. An alternative might be to choose a fixed source depth for a given ship type, irrespective of draught. This choice would make SL more suitable for quiet ship certification because it would remove the inherent variability of SL associated with changes in nominal source depth. However, the arbitrary choice of nominal source depth makes the SL value less suitable for accurate predictions of the sound field.

4.2.3. Adjusted Source Level (aSL)

An alternative to the usual (monopole) source level is the dipole source level[4] (DSL) used by de Jong et al. (2010) and Robinson et al. (2011) for reporting the URN of dredgers. The benefit of using DSL is that it is robust to the choice of nominal source depth, making it a suitable URN metric for ship certification. DSL is a function of angle. In the remainder of this report, when evaluated at a grazing angle of 30°, the DSL is referred to as aSL.

The aSL (symbol L'_S) is calculated from SL (L_S):

$$L'_S = L_S + 20\log_{10}\sqrt{\overline{\gamma}}\,\text{dB}, \tag{21}$$

where $\overline{\gamma}$ is calculated using Eq. (20). Substituting Eq. (15) in Eq. (14) and rearranging for RNL reveals that aSL and RNL are equal in deep water.[5]

4.2.4. Radiated Noise Level (RNL)

ANSI S12.64, ISO (17208-1:2016), and RINA (2016) all use the RNL metric unmodified. DNV GL (2019) modifies RNL by replacing $20\log_{10}\frac{r}{1\text{ m}}$ in Eq. (6) with $X\log_{10}\frac{r}{1\text{ m}}$ (see Table 2). The American Bureau of Shipping uses a modified form of RNL, obtained by (optionally) subtracting 5 dB from RNL if the receiver is near the seabed (Table 2).

4.2.5. Adjusted Radiated Noise Level (aRNL)

For the same vessel under identical operational conditions (with the same source level), the RNL depends in principle on water depth H, absorption coefficient α, measurement angle θ_1, and (in shallow water) on bottom type. ISO 17208 was developed with these limitations in mind by fixing the measurement angle and limiting its use to deep water (thus avoiding bottom reflections) and low frequency (to avoid seawater absorption, which unadjusted RNL does not account for).

We seek to extend the RNL approach to shallow water and higher frequency by explicitly including adjustments to compensate for the dependence on water depth and absorption coefficient. The measurement geometry is also converted to an equivalent measurement at the ISO 17208 geometry (30° from horizontal, the average of the angles specified by ISO 17208-1). We first define aRNL as:

$$L'_{\text{RN}} \equiv L_p(r,\theta_1) + 20\log_{10}\frac{\sqrt{2\,\overline{\gamma}/F(r,\theta_1)}}{1\text{ m}}\ \text{dB}, \tag{22}$$

where $F(r,\theta_1)$ is the propagation factor. Adding the direct path and surface reflection and an absorption term to Eq. (9.35) or (9.42) from Ainslie (2010), for the cylindrical spreading region:

$$F(r,\theta_1) = \left(\frac{2\gamma(\theta_1)}{r^2} + \frac{2\psi}{rH}\right)10^{-\frac{\alpha r}{10\text{ dB}}}, \tag{23}$$

where ψ is the critical angle of the seabed, and r is the slant range between source and receiver.

The resulting adjusted radiated noise level (aRNL) is obtained by substituting Eq. (23) in Eq. (22)

$$L'_{\text{RN}} = L_{\text{RN}}(r\theta_1) + \Delta L_S + \Delta L_H(r\theta_1) + \Delta L_\alpha(r), \tag{24}$$

where

$$\Delta L_S = 20\log_{10}\sqrt{\overline{\gamma}}\text{dB}, \tag{25}$$

$$\Delta L_\alpha = \alpha r, \tag{26}$$

and

[3] An example is a report (Gassmann et al., 2017), cited by [CISMaRT] Canadian Network For Innovative Shipbuilding, Marine Research And Training, and Transport Canada (2019) as demonstrating a 6–8 dB reduction in URN. While the 2017 report demonstrated a 6–8 dB reduction in source level, after compensating for the change in nominal source depth this amounted to a smaller (0–2 dB) reduction in RNL. In the frequency range of these measurements, a vessel's RNL provides a more direct measure of SPL near the vessel than does SL.

[4] The dipole source level is a property of a point source near the sea surface. It is the source level of the dipole formed by the point source and its image in the sea surface. The concept implies an assumed surface reflection coefficient equal to −1.

[5] They are not equal in shallow water, nor when absorption is not negligible.

$$\Delta L_H(r,\theta_1) = -20log_{10}\sqrt{\left(\gamma(\theta_1)+\frac{\psi r}{H}\right)}\ \text{dB}. \tag{27}$$

4.2.6. Comparisons between SL, RNL, aSL, and aRNL for four transits of the same tanker

The ECHO Program, in partnership with Transport Canada, Ocean Networks Canada, and JASCO, installed an underwater listening station in the Strait of Georgia, on the approach to the Port of Vancouver, in 2015. This station allowed for the collection and analysis of source levels for passing commercial vessels. The data collected from this station between 2015 and 2018, as well as data collected during a temporary deployment in Haro Strait in 2017, constitute the ECHO 1 database of vessel source levels, which is analyzed for both SL and RNL. Fig. 9 shows the four metrics for a tanker traveling at 7.2 m/s (see Table 3): RNL and aRNL (blue) and SL and aSL (red), using measurements from the ECHO 1 database. The RNL and aRNL spectra are converted to a nominal measurement angle of 30° using Eq. (25), with Eq. (18) for $\gamma(\theta)$. Eq. (25) was chosen because it is robust to the interference pattern associated with the measurement geometry, but it could underestimate the magnitude of the correction at some frequencies. The main takeaway from Fig. 9 is that aSL is close to RNL at low frequency, while aRNL is close to SL at high frequency. The reproducibility for multiple transits of the same ship for nominally the same conditions is investigated next.

Fig. 10 shows the same four metrics as Fig. 9 for four transits of the same tanker (see Table 3), at four different speeds and distances. Two of the four (the two right-hand graphs) are close to 6 m/s and 336 m, and these two have very similar spectra. The top left graph is for a lower speed (4 m/s), exhibiting strong tonals at 300 Hz and harmonics. Despite the large differences in these spectra, the aSL and aRNL spectra are similar in shape to each other in all four, although differences in magnitude are visible, especially around 500 Hz. There is a need to determine the optimum measurement distance, which can be achieved by measuring the signature at multiple ranges for the same transit. There is also a need to test the method in shallow water, for geometries involving a CPA of multiple water depths. Both needs are addressed by the measurements described in Section 3.3. See also Figs. 6 and 7.

4.3. Stakeholder engagement

To advance the objectives of the *Certification Alignment* project, participants in the 2020 workshop included representatives from the

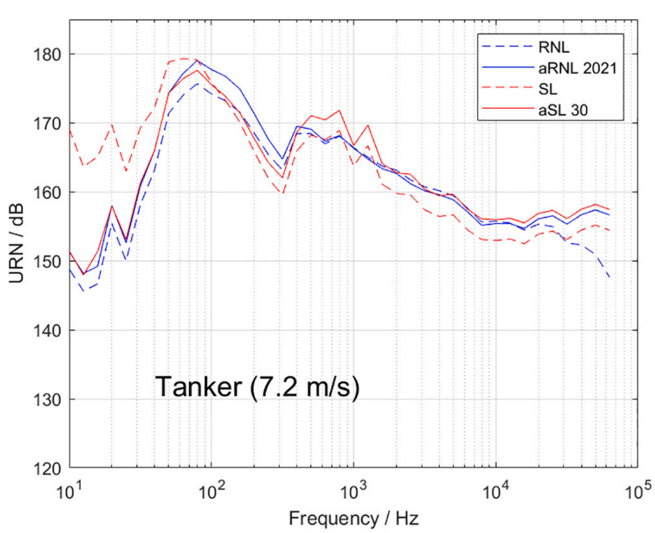

Fig. 9. SL and RNL spectra for a tanker transit at speed through water 7.2 m/s (14.1 kn). SL depends on nominal source depth at low frequency, while RNL depends on absorption at high frequency. By contrast, aSL and aRNL are adjusted for these effects. See Table 3.

Table 3
Measurement geometry and assumptions for four transits of the same tanker at the Strait of Georgia underwater listening station. Water depth = 172 m; sound speed ratio = 1.011.

Source depth d/m	Horizontal range r/m	Grazing angle θ_1 /°	Speed through water/ (m/s)
3.85	361.4	25.5	4.0
3.85	334.9	27.2	5.8
3.90	338.1	27.0	6.0
3.10	426.7	22.0	7.2

five ship classification societies providing quiet ship certifications at project inception, the International Association of Classification Societies, and individual experts from WG1.

The desired outcomes of the 2020 workshop were to:

- Achieve improved alignment on measurement conditions,
- Discuss URN metrics (source level or radiated noise level),
- Consider the feasibility of category-specific thresholds for commercial ship certification,
- Identify knowledge or research gaps required to advance the project, and
- Achieve general agreement to continue the process.

Before the first workshop, the differences between the five available quiet ship certification procedures were summarized in an unpublished memorandum distributed to workshop participants, which also proposed options for increasing their alignment. To a large extent, observed differences between quiet ship certification procedures arise from the use of different metrics of URN without formally distinguishing between them. This observation leads naturally to the following two opportunities for increased alignment:

- Distinguish clearly between the different metrics, and
- Adopt common metrics, where appropriate.

Discussing increased alignment requires new terminology, not yet defined by ISO 18405. In addition to RNL, the concept of aSL, the source level of a point source and its surface-reflected image combined, is needed. Also needed is a modified form of RNL, accounting for propagation conditions in shallow water, referred to here as aRNL.

Workshop participants discussed aspects of the existing notations, including terminology, metrics and criteria, and the need for future work. The following sections summarize the findings from the workshop discussions.

4.3.1. Terminology and preparation prior to measurement

Use of concise and unambiguous terminology facilitates effective communication. There was unanimous agreement among the participants to follow ISO 18405:2017, the international standard for underwater acoustical terminology.

Additional proposals were made to increase alignment of the preparation aspects of quiet ship certification procedures. General agreement was reached on measurement parameters such as equipment calibration, CPA, and number of hydrophones required for certification. It was also agreed that limiting environmental conditions, such as sea state and wave height, during certification measurement would be appropriate.

4.3.2. Metrics and criteria

Four of five quiet ship certification procedures express URN in terms of total sound pressure level (SPL) in a decidecade band, while one divides the power by bandwidth to obtain spectral density level (SDL). Adopting SPL in all quiet ship certification procedures, to align with ISO 17208, which also uses SPL, was suggested as most appropriate.

Discussion of the appropriate minimum and maximum frequency

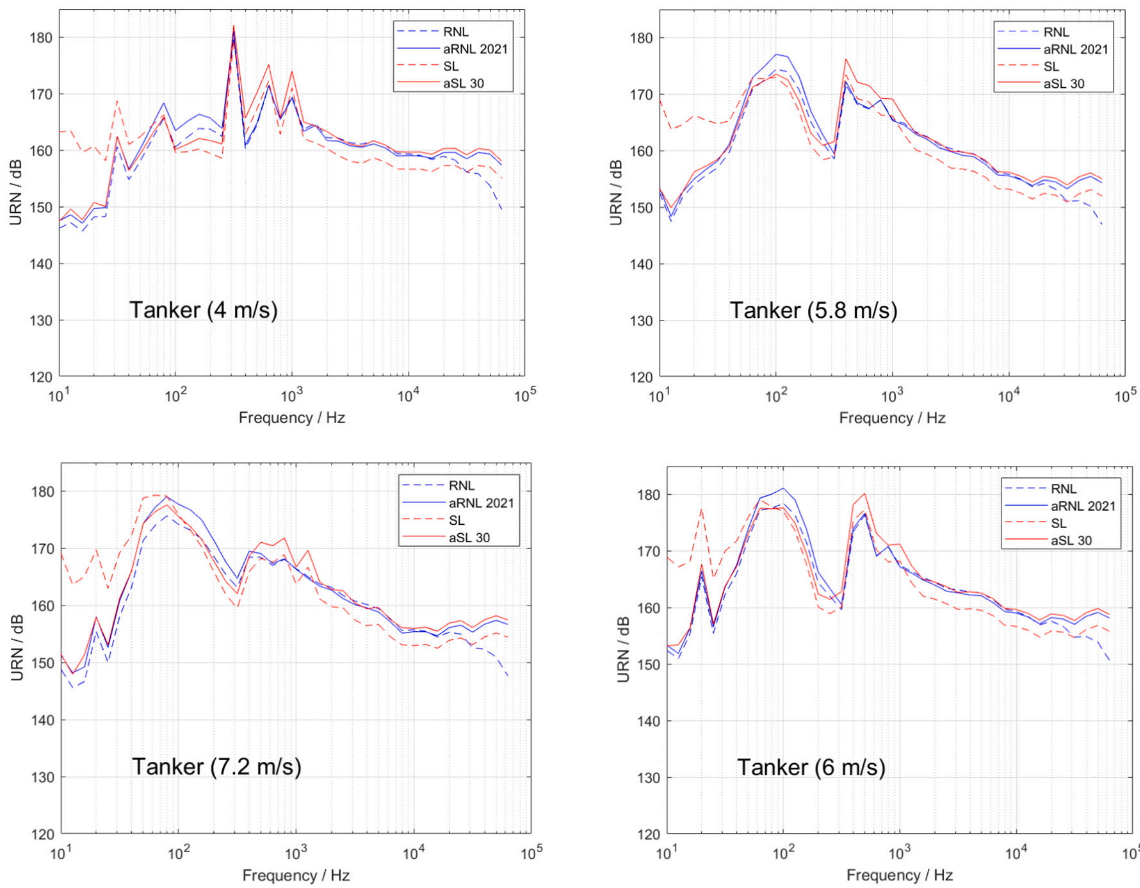

Fig. 10. aSL and aRNL spectra for four transits of the same tanker; in order of increasing speed through water, clockwise from top left: 4.0, 5.8, 6.0, and 7.2 m/s. The bottom left panel is reproduced from Fig. 9.

ranges for measurement and certification yielded a recognition of the challenges in accurate measurement of very low (below 10 Hz) or high (above 50 kHz) frequencies, indicating the notations should set bounds on the frequency range for measurement and reporting.

The stakeholders indicated that the decidecade band level notation limits need not be the same for all classification societies, and that minor exceedances should be allowed in a small number of band levels when seeking certification.

Three of the five ship classification societies use RNL, whereas the others use SL. There are benefits and drawbacks to both metrics. To achieve greater consistency, the concepts of adjusted source level (aSL) and adjusted radiated noise level (aRNL) were introduced. No clear consensus emerged for these adjusted metrics. Discussions highlighted that selection of a common metric should consider the complexity and challenges in obtaining the appropriate data to support the adjusted metrics, and whether the resulting values provide sufficient benefit to merit the additional complexity.

It was also noted that the selected metric should provide the same ship measurement result for the same ship wherever it is measured. Repeatability, consistency, and the quantification of the uncertainty in the measurement are key considerations for class societies, shipyards, and owners.

4.3.3. Future work

Auditory frequency weighting functions have been developed for marine mammals (Southall et al., 2007; Finneran, 2015; Southall et al., 2019). Southall et al. (2019) provided the most recent update of these weighting functions, which were developed for situations where there is a concern for noise-induced temporary hearing threshold shift (TTS). The effects of most concern arising from shipping noise, however, are masking and behavioral changes. If suitable weighting functions were available for these effects, the weighting functions could be used to evaluate a weighted broadband rating. While the auditory sensitivity of each individual or species dictates the limits of what might cause behavioral response, there are many aspects contributing to the elicitation of behavioral reactions, such as behavioral context (Ellison et al., 2012; Neo et al., 2018), noise type, impulsiveness, and kurtosis (Martin et al., 2020; Müller et al., 2020).

In principle, these weighting functions can be used to place more or less weight on different parts of the frequency spectrum, depending on whether a particular hearing group is more or less susceptible to noise at a given frequency. The workshop participants indicated that frequency weighted levels, with a corresponding scalar limit, may be considered for potential inclusion in quiet vessel certification at a later date.

Participants in the *Certification Alignment* workshop supported the project concept and agreed to continue the process, noting additional research is needed to select a common metric. The *URN Standardization Support* project is expected to provide such results. Since the project began, several classification societies have updated their notations, and two other classification societies, China Classification Society and Korean Register, issued underwater noise notations (China Classification Society, 2018; Korean Register, 2021). The project will continue to progress, integrating new research and new class society notations that may be issued, with a goal of alignment and project completion in 2023.

5. Summary

We reviewed underwater radiated noise (URN) measurement procedures published by international standards bodies and ship classification societies, explaining the difference between source level (SL) and radiated noise level (RNL) in this context. We described two Canadian projects whose aim is to increase international harmonization of these measurement procedures, by supporting the International Organization for Standardization (ISO) and the international ship classification societies, respectively.

Support for developing the ISO standard involved a modeling study designed to identify combinations of hydrophone depth and closest point of approach distance in shallow water that are optimized for determining vessel SL. The results of the modeling study indicated the following:

- A good place for single hydrophone measurements is at the seabed, as near as possible to the vessel track consistent with staying in the source's acoustic far field. Some frequency averaging is likely needed at 3 kHz and above to remove interference.
- Making measurements at multiple receiver depths permits one to average across peaks and nulls in the interference patterns, reducing variability in the source level estimates. The recommended location for such arrays is 3–7 water depths from the vessel.
- In shallow water, where a vertical array of hydrophones can result in a collision risk (<70 m), a horizontal array of hydrophones can be employed to average over the peaks and nulls of the interference patterns (see Fig. 4).
- At 300 Hz and below, adjustments are needed to account for coherent propagation for the 50 m water depth considered.

Some quiet ship certification procedures are based on RNL, and others on SL. The value of SL depends on the choice of nominal source depth; this weakness is addressed by introducing an adjusted source level (aSL), which is robust to the choice of nominal source depth. The value of RNL depends on propagation conditions; an adjusted radiated noise level (aRNL) is introduced that is robust to shallow-water propagation conditions.

The projects described herein will continue over the next few years, striving to support international alignment of methodologies for measuring URN, with a goal to better understand and reduce vessel-generated underwater noise for the benefit aquatic species.

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CRediT authorship contribution statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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