SHIP SOURCE LEVEL MEASUREMENT IN SHALLOW WATER USING AN ENHANCED SEABED CRITICAL ANGLE METHOD

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1. INTRODUCTION

Distant ships are a dominant source of ambient underwater sound at low frequency (50–100 Hz),[1, 2] while nearby ships can cause disturbance at frequencies of multiple kilohertz.[3] Measurement of a ship's source level (SL) is needed for soundscape prediction, for quiet ship certification and for validation of prediction models. An international measurement standard exists for the determination of SL using deep water measurements (ISO 17208-2[4]). A draft international standard (DIS) for measuring SL in shallow water, currently under development (ISO/DIS 17208-3[5]), needs an SL formula that is both accurate and straightforward to implement.

The seabed critical angle (SCA) method provides a simple formula for the propagation factor F, as introduced by MacGillivray et al.[6] The SCA method is specified by ISO/DIS 17208-3[5] for converting measurements of sound pressure level in shallow water to ship (or vessel) SL by adding propagation loss (PL) given by

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

The semi-coherent formula (SCF) refers to a semi-coherent image sum method for calculating F using a semi-coherent sum over images.[7] The SCA and SCF methods are compared in DIS 17208-3.[5] SCA underestimates PL by 1–2 dB at frequencies above about 1 kHz.

Our present purpose is to describe a formula to improve SCA. In principle, one could use the full SCF, as specified by Ainslie and Wood,[7] but SCF can be simplified, if desired, by approximating the discrete sum over multipaths by an integral. In the following, a formula is presented, referred to as "SCA+". The SCA+ method is specified in Section 2, followed by its verification and validation in Sections 3 and 4. Conclusions are drawn in Section 5. Underwater acoustical terminology follows ISO 18405:2017.[8]

2. ENHANCED SEABED CRITICAL ANGLE FORMULA (SCA+)

Inputs to the SCA+ method are sound speed in water (c_{w}) and sediment (c_{b}), density of water (ρ_{w}) and sediment (ρ_{b}), water depth (H), source depth (d_s) and hydrophone depth (d_{h}), decidecade band centre frequency (f_{c}), and horizontal closest point of approach (CPA) distance (d_{CPA}). The proposed SCA+ formula is:

$$F = F_0 + \min(\Delta F_{\mathrm{LF}}, \Delta F_{\mathrm{HF}})\,, \tag{2}$$

where F_0 is the contribution from direct and surface-reflected paths, and ΔF is the sum over all other paths, the form of which depends on frequency as indicated by the subscripts LF (low frequency) and HF (high frequency). The quantities F_0, ΔF_{LF}, and ΔF_{HF} are given by Equations 3 to 5.

F_0 is the contribution from the direct and surface-reflected paths with either zero or one bottom reflection (i.e., D, S, B, and SB, not BS; Figure 1):

$$F_0 = \frac{\gamma_-}{s_-^2} + R\frac{\gamma_+}{s_+^2}, \tag{3}$$

and

$$\Delta F_{\mathrm{LF}} = \frac{16\xi\,\pi^2}{3}\frac{(f_{\mathrm{c}}\,d_{\mathrm{s}}/c_{\mathrm{w}})^2}{d_{\mathrm{CPA}}H}\left({\psi_{\mathrm{c}}}^2\sin\psi_{\mathrm{c}} - \theta_{\mathrm{min}}^2\sin\theta_{\mathrm{min}}\right), \tag{4}$$

where $\xi = (1 + f_{\mathrm{hi}}/f_{\mathrm{lo}} + f_{\mathrm{lo}}/f_{\mathrm{hi}})/3 \approx 1.0177$, the upper and lower band edge frequencies are $f_{\mathrm{hi}} = 10^{0.05}f_{\mathrm{c}}$ and $f_{\mathrm{lo}} = 10^{-0.05}f_{\mathrm{c}}$, respectively, and

$$\Delta F_{\mathrm{HF}} = \frac{2}{d_{\mathrm{CPA}}H}(\psi_{\mathrm{c}} - \theta_{\mathrm{min}})\,. \tag{5}$$

where the critical angle ψ_{c} is given by acos($c_{\mathrm{w}}/c_{\mathrm{b}}$). In Equation 3, the slant range is $s_\pm = d_{\mathrm{CPA}}\sec\theta_\pm$.

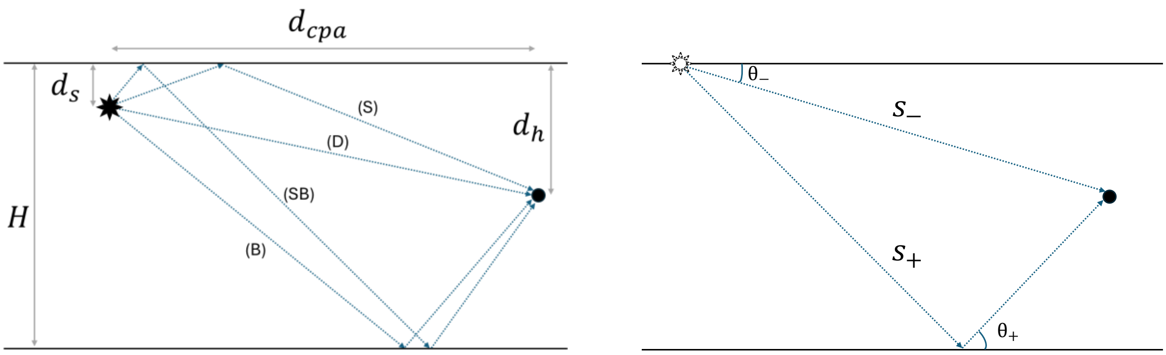

Figure 1. Left: Ray geometry for the contributions from direct and surface reflected paths. (S) is the source-surface-hydrophone path, (D) is the direct path, (B) is the source-bottom-hydrophone path, and (SB) is the source-surface-bottom-hydrophone path. Right: Paths included in the F_0 computation, $s\_$ is a simplification that accounts for paths (D) and (S), while s+ accounts for paths (B) and (SB). The dipole source assumed in this simplification is placed on the surface.

The seabed reflection coefficient R is approximated using:

$$R = \begin{cases} 1 & \theta_+ < \psi_{\mathrm{c}} \\ \left(\dfrac{\rho_{\mathrm{b}}c_{\mathrm{b}} - \rho_{\mathrm{w}}c_{\mathrm{w}}}{\rho_{\mathrm{b}}c_{\mathrm{b}} + \rho_{\mathrm{w}}c_{\mathrm{w}}}\right)^2 & \theta_+ > \psi_{\mathrm{c}} \end{cases}, \tag{6}$$

and the ray angle relative to the surface from source to hydrophone is:

$$\theta_\pm = \mathrm{atan}\frac{H \pm (H - d_{\mathrm{h}})}{d_{\mathrm{CPA}}}\,. \tag{7}$$

The frequency band averaged dipole interference term is:

$$\gamma_\pm = 2 - 2\frac{\sin\phi_{\mathrm{hi},\pm} - \sin\phi_{\mathrm{lo},\pm}}{\phi_{\mathrm{hi},\pm} - \phi_{\mathrm{lo},\pm}}, \quad (8)$$

where $\phi_{\mathrm{hi},\pm} = 2\pi f_{\mathrm{hi}} T_\pm$ and $\phi_{\mathrm{lo},\pm} = 2\pi f_{\mathrm{lo}} T_\pm$, and the delay time is:

$$T_\pm = \frac{2d_\mathrm{s}\sin\theta_\pm}{c_\mathrm{w}}. \quad (9)$$

In Equations 4 and 5, the minimum ray angle is:

$$\theta_{\min} = \min\left(\psi_\mathrm{c}, \mathrm{atan}\frac{2H}{d_{\mathrm{CPA}}}\right). \quad (10)$$

The SCA+ method adds the following enhancements to the SCA method[6]:

- It includes the minimum ray angle in the calculation of the contribution of multiply reflected ray paths (ΔF). Ignoring this minimum angle was a main source of bias in the SCA method.
- It includes an analytical averaging within each decidecade frequency band.
- It includes a contribution from the first seabed reflection for grazing angles greater than the seabed critical angle, with an approximation based on the power reflection coefficient for normal incidence.
- It uses the horizontal range d_{CPA} in the equations for ΔF, whereas the SCA method uses the slant range to the hydrophone.

3. VERIFICATION

In this section, the SCA+ method is compared with SCA on synthetic scenarios.

3.1. Inputs for verification (synthetic scenarios)

Two numerical test cases were selected for comparing the propagation loss calculations from the SCA and SCA+ methods with results from the OASES wavenumber-integration model[9] and Matlab™ implementations of a coherent image source model. See Oppeneer et al.[10] for a brief description of these models. The results are also compared with the semi-coherent image model proposed by Ainslie and Wood.[7] The two test cases represent different measurement geometries that are considered in ISO/DIS 17208-3.[5] One is for measurements at a CPA distance that is shorter than the water depth, and the other is for measurements at a larger CPA distance of four times the water depth. The results shown are for the deepest hydrophone and for an environment with a coarse sand and a fine silt sediment. The sediment properties are taken from Table 4.18 in Ainslie[11]. Table 1 gives an overview of the parameters for the two test cases.

3.2. Verification results

Figures 2 and 3 show propagation loss versus frequency for the selected test cases as calculated by the different models. These propagation loss curves represent the propagation factor averaged within each decidecade band, where the average is determined either analytically (in the SCF and SCA+ models) or from calculation results for 11 logarithmically distributed frequencies per band. The right-hand graph of Figure 2 is the only case for which $\theta_{\min}$ is less than the seabed critical angle, ψ_c, and therefore the only case for which the ΔF terms in Equation 2 are non-zero.

Table 1. Numerical test cases used to compare SCA+ and SCA methods with more elaborate propagation loss models. The sediment reflection coefficient is the value at normal incidence. The sound speed and density of seawater are 1490 m/s and 1027 kg/m^3, respectively. The term $\mathrm{atan}(2H/d_{\mathrm{CPA}})$ is used in Equation 10 for the minimum integration angle, θ_{min}.

Test case	**A**	**B**	**Sediment properties**		
Water depth H	100 m	50 m	type	coarse sand	fine silt
CPA-distance d_{CPA}	80 m	200 m	Median grain size	0.5 ϕ	6.5 ϕ
d_{CPA}/H	0.8	4	Sound speed ratio c_b/c_w	1.2503	1.0239
$\mathrm{atan}(2H/d_{\mathrm{CPA}})$	68°	27°	Critical angle (ψ_c)	37°	12°
Hyd. depth d_{h}	80 m	49 m	Density ratio ρ_b/ρ_w	2.231	1.513
Angle θ_{0-}	45°	14°	Attenuation coefficient $\beta_b\lambda_b$	0.87 dB	0.17 dB
Angle θ_{0+}	56°	14°	Reflection coefficient R	0.22	0.05

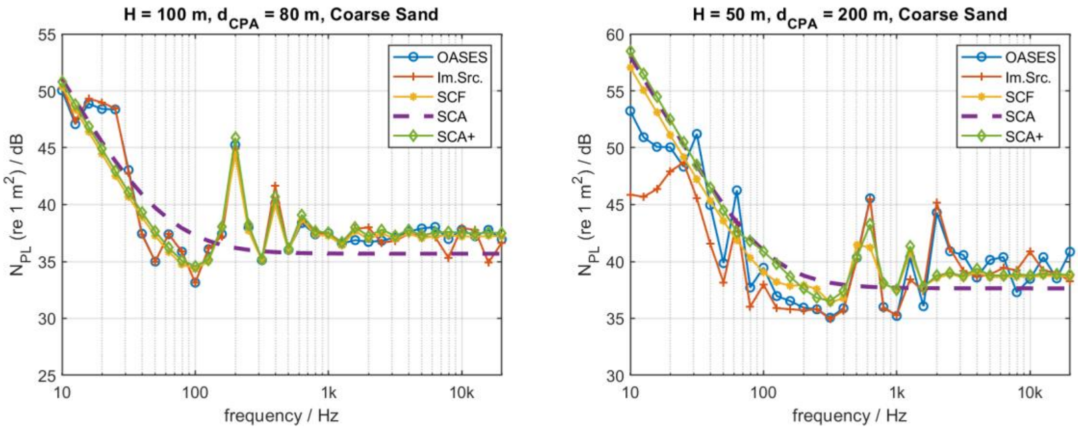

Figure 2. Calculated propagation loss versus frequency for (left) test case A and (right) test case B and a coarse sand sediment, comparing results from the wavenumber integration (OASES), coherent image source (Im.Src.), semi-coherent image source (SCF) models with the SCA and SCA+ methods.

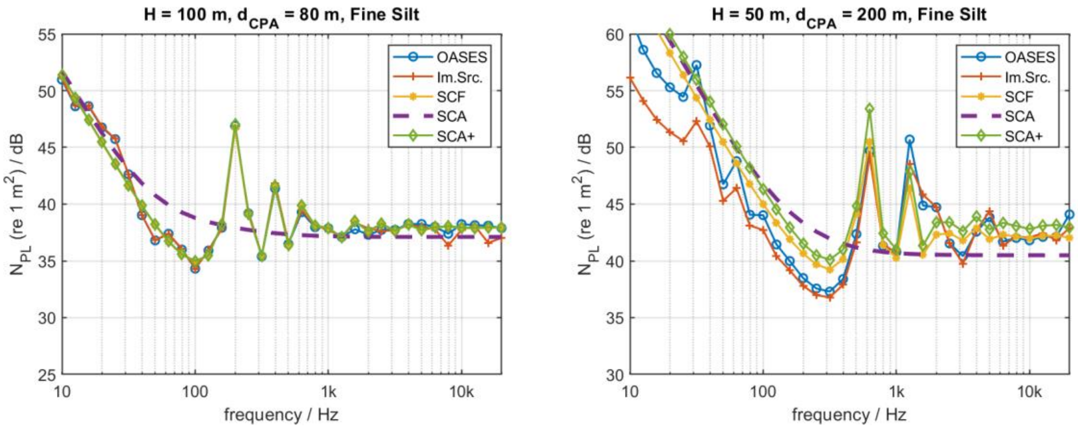

Figure 3. Calculated propagation loss versus frequency for (left) test case A and (right) test case B and a fine silt sediment, comparing results from the wavenumber integration (OASES), coherent image source (Im.Src.), semi-coherent image source (SCF) models with the SCA and SCA+ methods.

These results confirm that SCA underestimates PL by 1–2 dB at frequencies above about 1 kHz, as already indicated in DIS 17208-3. SCA does also not predict the peaks and valleys at mid frequencies (about 200 and 400 Hz for case A and about 600 and 1200 Hz for case B) that are associated with the first reflection at the sea surface. The height of these peaks corresponds with the depth of the nulls in the propagation factor. The peaks are lower for the coarse sand than for the fine silt sediment, because of the stronger contribution from seabed reflections at these frequencies. For case A all model results, except SCA, agree very well above 100 Hz. Below 100 Hz, the models that include the coherent sum of the bottom reflected rays (OASES and Im.Src.) deviate from the models that approximate this by an incoherent sum (SCF and SCA+). This approximation could also explain the differences between these two groups of models at higher frequencies for case B, but this was not further investigated.

4. VALIDATION

In this section, the SCA+ method is compared with SCA on two sets of measurements, one from the MMP2 project[6] and one from SATURN.[12]

4.1. MMP2

The purpose of the MMP2 experiment was to test whether it was possible to obtain reproducible vessel SL estimates in shallow water comparable to ISO-compliant measurements in deep water.[6] The measurement campaign involved repeated measurements of opportunity for three test vessels in water depths of 31, 66, and 184 m over a period of three months. Measurements were obtained using five fixed hydrophone arrays deployed at three test sites along the vessel route. SL measurements at the two shallow test sites were compared to reference measurements obtained at the deep test site. Comparisons are presented here for two shallow water array geometries: a vertical line array (VLA) deployed at the intermediate depth site and a horizontal line array (HLA) deployed at the shallow site (Table 2).

Table 2. Array geometries used to compare SCA and SCA+ methods based on the MMP2 measurements. The seabed critical angle varied with frequency according to the inverted seabed geoacoustic properties, as shown in MacGillivray et al.[6], Fig. 7.

Site	Array	PL method	H/ m	$d_{h,i}$/ m	ψ_c/ deg	$d_{CPA,i}$/ m	ρ_b/ρ_w
Deep (reference)	VLA	ISO 17208-2[4]	184	78, 125, 178	4–56	210	1.3
Intermediate	VLA	SCA, SCA+	66	59, 39, 19	17–42	150	1.8
Shallow	HLA	SCA, SCA+	31, 38, 38	31, 37, 37	3–40	170, 210, 310	1.6

Average source levels for a 167 m length vessel were computed from an ensemble of ten passes on each array for a narrow range of transit speeds (±0.25 m/s) and CPA distances (±20 m) to ensure repeatable underwater radiated noise (URN) conditions.[6] Both single-channel and array-averaged source levels were computed from the array measurements. Comparisons with deep water reference source levels on the intermediate-depth VLA (Figure 4) and shallow HLA (Figure 5) showed that the SCA+ method improved upon the systematic underestimation by the SCA method above 200 Hz, particularly at the intermediate site where the seabed was more reflective. However, the SCA+ method overestimated the SL at frequencies between 300 and 4000 Hz, corresponding to coherent nulls in the PL spectrum. The influence of these nulls may be more pronounced if fewer than 10 vessel passes are included in the SL average (see next section). Both methods compared favourably with the deep water reference source levels at frequencies below 200 Hz.

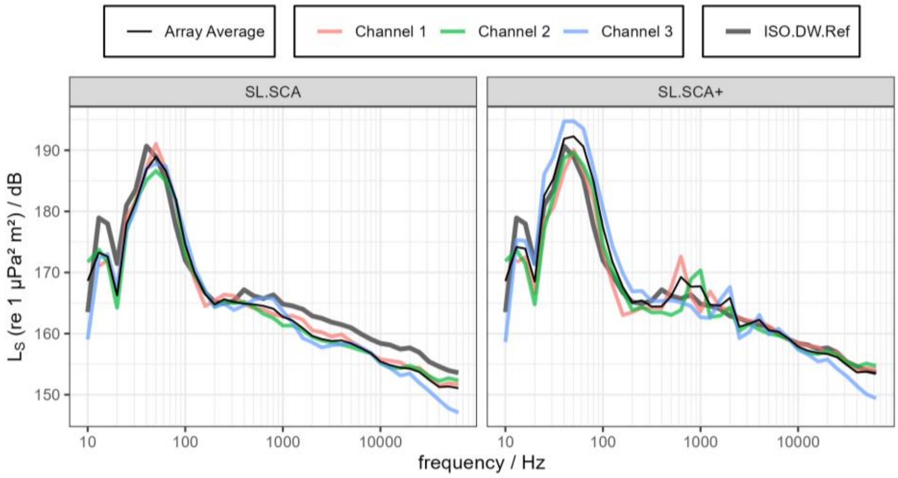

Figure 4. Single-channel (coloured lines) and array-averaged source levels (thin black line) measured during the MMP2 experiment on a vertical line array in 66 m water depth, compared to reference source levels measured in deep water using the ISO 17208-2[4] formula. Left: Source levels calculated using the SCA formula. Right: Source levels calculated using the SCA+ formula.

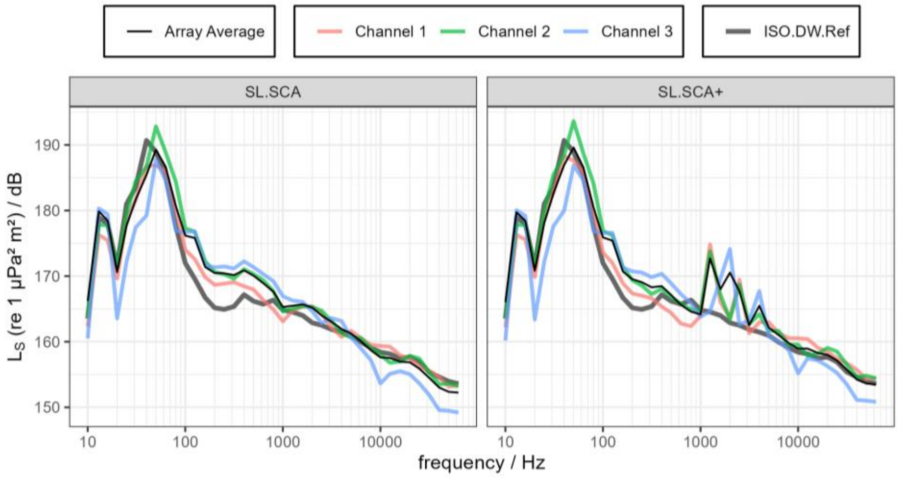

Figure 5. Single-channel (coloured lines) and array-averaged source levels (thin black line) measured during the MMP2 experiment on a horizontal line array in 31 m water depth, compared to reference source levels in deep water using the ISO 17208-2[4] formula. Left: Source levels calculated using the SCA formula. Right: Source levels calculated using the SCA+ formula.

4.2. SATURN

In the scope of the SATURN project, an eleven-day test campaign was carried out to characterize the URN for a 50 m length research vessel under different procedures. ISO 17208-1[13] and ISO/DIS 17208-3[5] standards were tested (deep and shallow water methods, respectively) to use results from Part 1 as the reference to explore the accuracy of Part 3. Both procedures were executed using three hydrophones and a CTD to measure the sound speed in the water column to derive SL. ISO 17208-1 measurements were repeated five times during two different days and then processed as described by ISO 17208-2[4] to report vessel signatures as source levels. Table 3 lists the cases used to evaluate the accuracy of ISO 17208-3[5] results based on the SCA and SCA+ PL methods.

Plots from Figure 6 compare SLs from the cases listed in Table 3. The reference curve is the median of five signatures measured according to ISO 17208-1. The left plot shows a general consistency in the results obtained using the SCA method, with a ~2 dB underestimation from mid frequencies. This comparison motivated the development of the SCA+ method, previously described in Section 2. Results are reported from 125 Hz as these measurements experienced background noise influence at lower frequencies.[12] Additionally, single-channel and array-averaged source levels for Case I (site depth of 80 m) are shown in Figure 7.

Table 3. Cases used to compare SCA versus SCA+ methods (SATURN project measurements). The parameters used to compute PL and derive SL per case are listed in columns 4 to 10.

Case	**Measuring method**	**PL method**	**H / m**	$d_{h,i}$ / m	$d_{\mathrm{CPA},i}$ / m	**c_w / m s^{-1}**	d_s / m	**c_b / m s^{-1}**	**ρ_b/ρ_w**
Ref.	ISO17208-1	ISO17208-2[4]	200	27, 58, 100	100	1527	3.9	-	-
I	ISO17208-3	SCA	80	13, 29, 50	50	1530	3.9	1750	-
II	ISO17208-3	SCA	50	20, 27.5, 35	50	1534	3.9	1750	-
III	ISO17208-3	SCA+	80	13, 29, 50	50	1530	3.9	1750	1.9
IV	ISO17208-3	SCA+	50	20, 27.5, 35	50	1534	3.9	1750	1.9

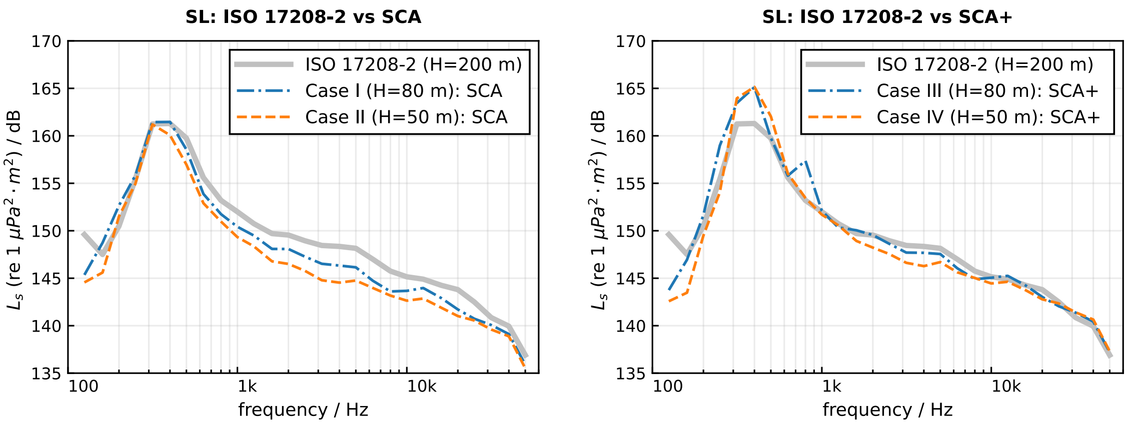

Figure 6: Source levels measured during the SATURN trials in deep (solid lines) and shallow (dashed lines) water following ISO 17208 procedures (Parts 1 and 3, respectively). Dashed lines for the left plot are obtained using the SCA formula to compute the PL, while the right plot used the SCA+.

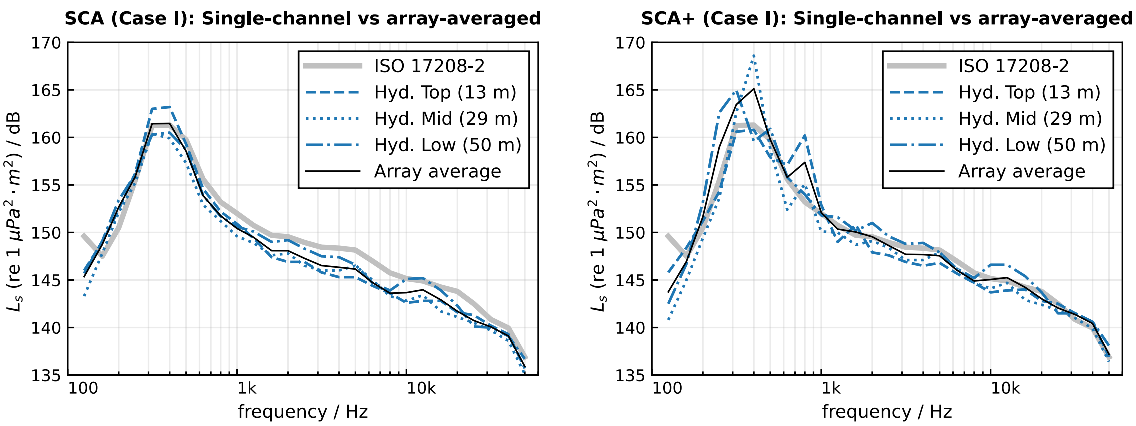

Figure 7. Single-channel (dashed lines) and array-averaged source levels (thin black line) measured during the SATURN trials compared to source levels in deep water (thick grey line). Left: Source levels calculated using the SCA formula. Right: Source levels calculated using the SCA+ formula.

5. CONCLUSIONS

Application of SCA is compared with enhanced SCA (SCA+). SCA+ is shown to have advantages and disadvantages compared with SCA. The main benefit of using SCA+ is the elimination of a 1–2 dB underestimation of source level at high frequency when using SCA. SCA+ agrees better with OASES than SCA at intermediate frequencies. However, SCA+ is found to be less robust than SCA at low frequency.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

[1] G. M. Wenz, "Acoustic Ambient Noise in the Ocean: Spectra and Sources," J. Acoust. Soc. Am. **34**, 1936–1956 (1962).

[2] R. J. Urick, *Principles of Underwater Sound*, 3rd edition., Volume. McGraw-Hill, New York, London. 423 pp (1983).

[3] C. R. Findlay, L. Rojano-Doñate, J. Tougaard, M. P. Johnson, and P. T. Madsen, "Small reductions in cargo vessel speed substantially reduce noise impacts to marine mammals," Sci. Adv. **9**, eadf2987 (2023).

[4] [ISO] International Organization for Standardization, "ISO 17208-2:2019. Underwater acoustics — Quantities and procedures for description and measurement of underwater sound from ships — Part 2: Determination of source levels from deep water measurements," https://www.iso.org/standard/62409.html (2019).

[5] [ISO] International Organization for Standardization, "ISO/DIS 17208-3. Underwater acoustics — Quantities and procedures for description and measurement of underwater sound from ships — Part 3: Requirements for measurements in shallow water," https://www.iso.org/obp/ui/en/#iso:std:iso:17208:-3:dis:ed-1:v1:en (2019).

[6] A. O. MacGillivray, S. B. Martin, M. A. Ainslie, J. N. Dolman, Z. Li, and G. A. Warner, "Measuring vessel underwater radiated noise in shallow water," J. Acoust. Soc. Am. **153**, 1506–1524 (2023).

[7] M. A. Ainslie and M. A. Wood, "Semi-coherent image method to estimate propagation loss in shallow water for measuring surface vessel source level," Proceedings of Meetings on Acoustics **47**, (2022).

[8] [ISO] International Organization for Standardization, "ISO 18405:2017. Underwater acoustics — Terminology," Geneva, https://www.iso.org/obp/ui/en/#!iso:std:62406:en (2017).

[9] H. Schmidt and F. B. Jensen, "A full wave solution for propagation in multilayered viscoelastic media with application to Gaussian beam reflection at fluid–solid interfaces," J. Acoust. Soc. Am. **77**, 813–825 (1985).

[10] V. O. Oppeneer, C. A. F. de Jong, B. Binnerts, M. A. Wood, and M. A. Ainslie, "Modelling sound particle motion in shallow water," J. Acoust. Soc. Am. **154**, 4004–4015 (2023).

[11] M. A. Ainslie, *Principles of Sonar Performance Modeling*. Praxis Books, Volume. Springer, Berlin (2010).

[12] R. Yubero de Diego, M. Ghasemi, and Ø. Solheim Pettersen, "Deliverable D2.1: Final Report on Vessel URN Measurements." Version 1.0. Technical report for Saturn (2023).

[13] [ISO] International Organization for Standardization, "ISO 17208-1:2016. Underwater acoustics — Quantities and procedures for description and measurement of underwater sound from ships – Part 1: Requirements for precision measurements in deep water used for comparison purposes," https://www.iso.org/obp/ui/en/#iso:std:iso:17208:-1:ed-1:v1:en (2016).