Saturn
Developing Solutions for Underwater Radiated Noise

SATURN has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101006443.

SATURN Internal Deliverable – Subtask 2.2.1
Fundamentals of URN measurement and acoustic field evaluation: a critical evaluation

Author(s): Roberto Yubero de Diego
[Internal Deliverable]

Document Information

Document Details	
Grant Agreement Number	101006443
Project Acronym	SATURN
Work Package	2
Task(s)	2.2.1
Deliverable	-
Title	Fundamentals of URN measurement and acoustic field evaluation: a critical evaluation
Authors	Roberto Yubero de Diego
File name	SATURN - T2.2.1. Review fundamentals of URN measurement and acoustic field evaluation
Delivery date	27/4/2022
Dissemination level	Internal deliverable
Keywords	URN, measurements, propagation loss, standards, regulations, acoustic field calibration

Version	Date	Description	Authors	Reviewed by	Approved by
V0.1	12/11/21		Roberto Yubero	Santiago Álvarez-Buylla Alfonso Jurado	Alfonso Jurado
V0.2	8/2/22		Roberto Yubero	Michael Ainslie Christ de Jong	
V0.3	28/3/22		Roberto Yubero	Michael Ainslie Christ de Jong	
V1.0	1/4/22		Roberto Yubero	Michael Ainslie Christ de Jong	
V1.1	26/4/22	Revision of section 2	Roberto Yubero	Mohammad Ghasemi Vincent Lamaison	

Authors (alphabetical) and Organisation	
Roberto Yubero de Diego	TSI - Técnicas y Servicios de Ingeniería

Acknowledgements/contributions (alphabetical)	
Name	Organisation
Christ de Jong	TNO
Michael Ainslie	JASCO
Santiago Álvarez-Buylla	TSI - Técnicas y Servicios de Ingeniería
Publio Beltrán	TSI - Técnicas y Servicios de Ingeniería

Disclaimer

Table of Contents

List of figures

List of tables

Executive Summary

This report aims to set a background based on the fundamentals of URN for the following subtasks included in T2.2, with special interest for the measurement campaign that will be carried out in "Subtask 2.2.2. Full-scale URN (Underwater Radiated Noise) measurements of vessels in deep and shallow waters".

In the first section of the report, a brief overview of the activities related to underwater noise is provided, introducing the progress reached up to date and the future objectives to be achieved.

In Section 2, a thorough analysis of the different standards and classification societies notations is performed, mainly comparing the following aspects: measurement procedure, instrumentation deployment, post-processing of the measured data, and reporting of the URN results.

Most of the available measurement procedures report vessel URN levels applying a distance correction to the measured sound pressure level (SPL). This metric is commonly named radiated noise level (RNL) and it basically corrects measured noise levels by a simple distance law. When applying a more elaborated distance correction, the reported URN level is generally named source level (SL). In most of the cases, this correction is obtained by using underwater propagation models. Section 3 of this report introduces these models and the main aspects to consider when using them.

In the last section of the report an alternative methodology to obtain the propagation loss from measurements is proposed. This methodology intends to be an intermediate solution for the obtention of PL, by improving the simplistic distance correction method (RNL metric) but without incurring into the complexity and time-consuming use of propagation models (SL metric).

Acronyms

ABS	American Bureau of Shipping
ANSI	American National Standards Institute
ANSI-ASA	American National Standard Institute - Acoustical Society of America
aRNL	adjusted radiated noise level
BV	Bureau Veritas
CPA	closest point of approach
DNV	Det Norske Veritas
DSL	dipole source level (also known as aSL, adjusted source level)
FFT	fast Fourier transform
FT	Fourier transform
ICES	International Council for the Exploration of the Sea
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
KR	Korean Register
LR	Lloyd’s Register
MSL	monopole source level (commonly referred to as SL)
PAS	publicly available specification
PL	propagation loss
rms	root mean square
RNL	radiated noise level
SL	source level
SPL	sound pressure level
URN	underwater radiated noise

1. Background

Environmental protection of the seas has been a key point within the agenda of policies around the globe for many decades, especially in Europe, North America and Australia. These policies have aimed to assess different sources of pollution: oil spills, air pollutants such as CO2 or NOx or plastics for instance. Now the time has come to address noise pollution. Underwater radiated noise – henceforth called URN – is not a new concern. It has been of great interest in specific sectors such as research vessels and naval platforms. However, the environmental impact of URN produced by anthropogenic activities in the marine ecosystem has raised public awareness during the last decade, having administrations set sights on the shipping industry. This increasing interest has triggered the immediate transformation of a so far considered minor issue into a real concern to be solved in the coming future. To achieve quieter seas, regulatory bodies, international standards organizations, classification societies, and other companies from the naval industry are working together to define the way ahead.

What makes it difficult to address the URN issue produced by the shipping industry is mainly the wide variety of species affected (e.g., marine mammals, fishes and invertebrates), the broad diversity of vessel types, the number of different noise sources and the inherent difficulties of underwater acoustics. Focusing on the latter one, the complexity of underwater propagation has a significant influence when characterizing the noise produced by vessels. In deep water, there are still uncertainties to reduce as well as repeatability issues. In shallow water, this task becomes even more complex due to, among others, seabed interaction and surface reflections.

Deep water URN measurements have been widely studied, and measurement and analysis procedures are gathered in consolidated national and international standards (ANSI ASA S12.64, ISO 17208-1). However, these testing procedures are intended for deep water and their use in shallow waters is far from being correct. Bathymetry in many areas around the world – for instance, the North Sea with an approximate depth of 30 m – requires the use of a specific underwater noise measurement standard for shallow waters that is not developed yet. Due to this identified need, ISO is working on the development of the first international standard for measuring underwater radiated noise in shallow waters: ISO 17208-Part 3 (included in SATURN T2.1).

In addition to the above-mentioned standards, most of the classification societies have developed their URN notations. These notations usually differ in the measurement procedure, the post-processing activities and the reporting metrics. This report aims to summarise the main features of every studied rule, gathering their measurement and post-processing procedures. Some of the reporting URN metrics require the use of propagation models for underwater noise, which will be introduced in the scope of the report as well. Finally, an alternative methodology for the obtaining of propagation loss from empirical measurements is proposed.

2. URN standards and classification societies' notations

2.1. Introduction

The first underwater sound standard was published in 2009; ANSI ASA S12.64. This standard aimed to contribute to the reduction of the impact caused by noise in marine mammals. Its contribution was to define a methodology to measure underwater radiated noise for surface vessels in deep water. It was published by the American Society of Acoustics, covering a national application that was not extended until 2016, when the first international standard for underwater sound measurement was published; ISO 17208-1. These two standards are quite similar, as ISO 17208-1 is based on Grade B of ANSI ASA S12.64, with slight modifications (as nomenclature or specific terms definitions) having an international validity. For this reason, ISO 17208-1 is considered the reference standard in the scope of this report.

ISO 17208-1 details instrumentation requirements, test setup and execution, and the later post-processing tasks required to report vessel URN levels. This standard is applicable just for deep water and does not provide any limit curve. Since 2010, classification societies started to publish their own notations, based on ANSI ASA S12.64 or in ISO 17208-1 standard to a greater or lesser extent. Unlike ANSI ASA S12.64 or ISO 17208-1, notations usually provide limit curves (generally specific for a particular ship type), with the aim of comparing measurement results, and reporting if the tested vessel meets their classification requirements.

Although there is not any international standard covering URN measurements in shallow water, some classification societies have developed their own methods to cover this scope. However, provided details, mainly in the testing procedures are, in the authors' opinion, imprecise. International Standard Organisation (ISO) realised the need of covering shallow water application and it is currently working on its development. It is planned to have the first international standard covering URN measurements in shallow waters probably by 2024; ISO 17208-3. Its development will use performed measurements in on-going research international projects, one of which is the SATURN project.

Standards and classification societies' notations studied in this report are listed below, providing a summary of everyone. In the following subsections, their details are breakdown according to their measurement procedures and post-processing activities, summarising their main features in table format. This reporting structure tries to comprise the great amount of information provided in this report, intending to ease the understanding of the notations' differences.

ANSI ASA S12.64: *Quantities and Procedures for Description and Measurement of Underwater Sound from Ships – Part 1: General Requirements (2009)*. First published standard for underwater noise measurements. It provides a standardised measurement method for ship underwater radiated noise in deep water. It provides three testing procedures according to test setup; Grade A, B, and C.

- **Det Norske Veritas (DNV)**: *Measurement procedure for noise emission. DNVGL-CG-0313 (First issue: 2010).* It mainly follows ISO 17208-1 measurement procedure for deep water, including slight modifications in post-processing. DNV additionally provides limit curves for different vessel types in a later document (*DNVGL-RU-SHIP Pt.6 Ch.24. (First issue: 2010)*). This notation also covers shallow waters.

- **International Organization for Standardization (ISO)**: *Underwater Acoustics – Quantities and procedures for description and measurement of underwater sound from ships*. It is composed of two parts, with a third one (for shallow water) currently ongoing:

    - ISO 17208–1. *Requirements for precision measurements in deep waters used for comparison purposes (First issue: 2012).* Based on ANSI ASA S12.64 – Grade B, it is the first international standard for measuring underwater noise in deep water.

    - ISO 17208–2. *Determination of source levels from deep water measurements (First issue: 2019)*. It is the first international standard for measuring Source Level (SL). It follows the same measurement procedure as ISO 17208–1 and proposes a methodology to compute SL from URN levels obtained according to ISO 17208–1 post-processing methodology. This conversion is specific for deep water measurements with a specific hydrophone geometry. This standard is not included in the summary tables of this report (Section 2.2 and Section 2.3) as it just extends ISO17208–1 post-processing scope.

- **Bureau Veritas (BV)**: *Underwater Radiated Noise (URN). Rule Note NR 614 DT R02 E (First issue: 2014).* Notation that proposes a methodology to obtain URN levels both in deep and shallow waters. The measurement and post-processing procedure notably differ from those gathered in ISO 17208-1.

- **China Classification Society (CCS):** *Guidelines for underwater radiated noise of ships (First issue: 2016).* It follows a different approach compared with the rest of the notations. Instead of splitting the tests in deep and shallow water, test conditions are dependent on the number of hydrophones used and the vessel type.

- **Registro Italiano Navale (RINA)**: *Rules for the Classification of Ships Part F. Chapter 13 - Other Additional Class Notations. Section 25 - Dolphin Quiet Ship and Dolphin Transit Ship (First issue: 2017).* It covers deep and shallow waters with important details overlooked or ambiguously defined.

- **American Bureau of Shipping (ABS)**: *Guide for the classification notation: Underwater Noise (First issue: 2018).* This notation combines features from both ISO 17208-1 and BV notation. Its scope covers deep and shallow waters.

- **Lloyd's Register (LR)**: *ShipRight. Additional Design and Construction Procedure for the Determination of a Vessel's Underwater Radiated Noise (First issue: 2018).* It mainly follows ISO 17208-1 measurement procedure and proposes the use of MSL (Monopole Source Level) following ISO 17208-2 methodology. It covers deep and shallow waters.

- **Korean Register (KR)**: *Guidance for Underwater Radiated Noise. GC-37-E (First issue: 2021).* This notation combines features from both ISO 17208-1 and BV notation. Its scope covers deep and shallow waters.

Below, Figure 1 shows the timeline of the above-mentioned URN procedures developed by regulatory bodies and classification societies. This figure is inspired in one from the report released by EMSA (Cruz, et al., 2021):

Figure 1: Timeline of URN measurement procedures. National standards (green), international standards (blue) and classification societies' notations (purple). Just first issues of the documents are gathered. Consulted documents for this report are available in Table 3.

2.2. Measurement procedures

This subsection addresses the test preparation and test execution for URN measurements, both for deep and shallow water. First, instrumentation details and test preparation are introduced, and the specific details per standard or notation are provided in table format. Then, test execution is addressed, covering aspects as vessel distance to hydrophones, water depth, or vessel speed, gathering those details in table format as well.

It is important to mention that just Grade C from ANSI ASA S12.64 is covered in this study. Although this standard provides two additional measurement procedures (Grade A and Grade B), with their particular instrumentation deployment and post-processing activities. Grade C is currently the most popular procedure of the ANSI standard, mainly due to its use in an ongoing and important research project called the ECHO Program (project based on measurements of opportunity to study vessels noise in an area of Canada populated with killer whales, that showed anomalies in their behaviour).

Two main types of URN measurements can be distinguished: opportunistic and dedicated. Opportunistic measurements are made when vessels pass a monitoring station, in order, for example, to estimate the shipping URN levels in the vicinity, or analyse temporal (daily, annual) trends. Therefore, the data recorded will represent noise levels for typical local marine traffic, with numerous vessel types and operating conditions included. Data processing and analysis then require additional information, primarily automatic identification system (AIS) data, to determine individual vessel source levels and categorise or aggregate their sound level spectra. The ECHO program is a good example of these sorts of measurements. On the other hand, dedicated measurements concern noise trials of a specific vessel. These may be performed following standards, classification societies' notations, or other recommended procedures, and their main purpose is to determine the total (spectral) source level of a particular vessel. Procedures gathered in this report correspond to dedicated measurements and, although all of them are optional, this may change in the coming years.

2.2.1. Instrumentation setup

This subsection covers the described details in the studied standards and notations regarding the instrumentation setup. These details comprise aspects as number of hydrophones and their properties, their deployment in the test site, their accuracy, or their calibration requirements (in-situ calibration to be performed during the test period and periodic calibration; mandatory to consider the system suitable for its use). Some of the studied notations require the use of underwater propagation models to precisely compute vessel URN levels. To properly characterise the test site, it is necessary to obtain the propagation speed of the water column, generally extracted from the CTD (Conductivity, Temperature and Depth). This equipment measures the mentioned magnitudes, using them to obtain the sound propagation speed for the test site at different water depths. Table 1 summarises the details of the mentioned requirements for each of the studied notations.

	ANSI ASA S12.64 (Grade C[1])	ISO 17208-1	DNV	BV	CCS	RINA	ABS	LR	KR
Nº Hydrophones	1	3	1 or 3	3	1 or 3	3	3	3	3
Directionality	Omni-directional	Omni-directional	Deep water: as ISO 17208-1 Shallow water: Not specified	Omni-directional	Omni-directional	Omni-directional	Omni-directional	As ISO 17208-1	Omni-directional
Hydrophone deployment: Deep water	Floating line or bottom mounted. Angles from the sea surface at CPA distance: 20º ±5º	Floating line or bottom mounted. Angles from the sea surface at CPA distance: 15º, 30º and 45º.	As ISO 17208-1	Floating line or bottom mounted. Upper hydrophone > 40 m from the sea surface. Distance between hydrophones > 30 m	Conditioned by the selected number of hydrophones. The notation does not split the hydrophone deployment according to water depth but according to the number of hydrophones installed	As ISO 17208-1	As ISO 17208-1	As ISO 17208-1	Floating line or bottom mounted. Upper hydrophone > 40 m from the sea surface. Distance between hydrophones > 30 m
Hydrophone deployment: Shallow water	-	-	1 hydrophone (bottom mounted). Up to 0.2 m above the seabed	Bottom mounted. Hydrophones separated 15 - 20 m, the lower 3-5 m from the seabed and the upper > 15 m from the sea surface.		-	Bottom Mounted	Lower hydrophone 5 m above seabed, upper hydrophone H/10 from sea surface and middle hydrophone at H/2	Floating line or bottom mounted. Hydrophones separated ≥ 20 m, ≥ 5 m from the seabed and the upper ≥ 15 m from the sea surface
Hydrophone sensitivity accuracy	Not specified	± 2 dB	Deep water: as ISO 17208-1 Shallow water: Not specified	± 2.5 dB	± 3 dB	± 1 dB	± 3 dB	As ISO 17208-1	± 2 dB
Hydrophone calibration	Every 12 months (in accordance with IEC 60565)	Every 12 months (in accordance with IEC 60565)	Deep water: as ISO 17208-1 Shallow water: in accordance with manufacturer	Every 2 years	"Within the validity period"	Every 12 months (in accordance with IEC 60565)	Every 12 months (in accordance with IEC 60565 or ANSI S1.20)	As ISO 17208-1	Every 12 months (in accordance with IEC 60565)
Hydrophone in situ calibration	Required (daily during test campaign)	Required (daily during test campaign)	Deep water: as ISO 17208-1 Shallow water: before and after each "measurement survey"	Required (before and after the test)	Not specified	Required (daily during test campaign)	Required (daily during test campaign)	As ISO 17208-1	Required (before the test)
Hydrophone drift angle	≤ 5º: No actions >5º: Update Slant Range[3]	≤ 5º : No actions >5º : Update Slant Range[3]	Deep water: as ISO 17208-1 Shallow water: not specified	Measured to ensure Distance Accuracy	Not specified	≤ 5º : No actions >5º : Update Slant Range[3]	Not specified	As ISO 17208-1	≤ 5º : No actions >5º : Update Slant Range[3]
CTD	Not specified	Not specified	Deep water: as ISO 17208-1 Shallow water: not specified	Just for MSL Celerity profile to be measured every 2 m before and "after the trials"	Suggested	Not specified	Just for MSL	As ISO 17208-1	Not specified

Table 1: Instrumentation setup – Details per standard or notation

Slant Range: Distance from the acoustic centre of the ship under test to each hydrophone.

2.2.2. Test procedure

Description of the test procedure is the wider part of the rules, having the greater number of details to be considered. This part of the notations describes aspects as the test site (deep or shallow water), the distance between measurement location and vessel under test, the measurement time, the number of runs per boat side, the data window length, or the vessel speed. To properly understand the contents of the summary tables, it is necessary to previously define some concepts related to the measurements. The following definitions are gathered from ISO 17208-1:

- Acoustic centre (referred to as ship reference point): is the point on the ship where all the sources are assumed to be located. The longitudinal coordinate is required to properly monitor the distance between vessel and hydrophones. The acoustic centre depth (vertical coordinate) is just required for standards using SL (Source Level) to report URN levels.

- Background noise: "*noise from all sources (biotic and abiotic) other than the ship measured, including self-noise*". It could influence measured noise levels and therefore its measurement and evaluation are mandatory.

- CPA (Closest Point of Approach): "*point where the horizontal distance (during a test run) from the ship reference point of the ship under test to the hydrophone(s) is the smallest*".

- COMEX (commence exercise): "*start test range location*". At this location, vessel operating conditions shall be fixed and kept stable up to the FINEX distance.

- FINEX (finish exercise): "*end test range location*". From this location, vessel operating conditions are not fixed, and the test run is considered finished.

- DWL (Data Window Length): "*distance between the start data location and end data location*". The recorded data within this window is the data to be used for the post-processing and reporting of the URN levels.

Some other interesting definition, not gathered in ISO 17208-1, but typically mentioned in the studied notations is:

- COMEX-FINEX distance: overall distance along which the vessel is under test. Within this path, the vessel shall maintain uniform operating conditions, which means that it should have reached the test speed before arriving at the COMEX, keeping it until FINEX and maintaining the rudder as steady as possible.

The following tables summarise the main features for the studied notations according to their testing procedures.

		ANSI ASA S12.64 (Grade C[1])	ISO 17208-1	DNV	BV	CSS	RINA	ABS	LR	KR
Scope		Deep water	Deep water	Deep & shallow water	Deep & shallow water	Not specified	Deep water	Deep & shallow water	Deep & shallow water	Deep & shallow water
Water depth	Deep water	H ≥ max (75 m, 1L)	H ≥ max (150 m, 1.5L)	H > 150 m	H ≥ max (200 m, 2L)	Not specified	H > 150 m / H > 200m (see comments)	H ≥ max (150 m, 1.5L)	As ISO 17208-1	H > 150 m
	Shallow water	-	-	max(30 m, 3T) ≤ H ≤ 150m	max (60 m, 0.3v^2) ≤ H < 200 m	Not specified	-	max (60 m, 0.3v^2) ≤ H < 150 m	max (60 m, 0.3*v^2) ≤ H ≤ min (150 m, 1.5L)	60 m ≤ H ≤ 150 m
CPA distance		max (100 m, L)	max (100 m, L)	100 m ≤ CPA ≤ 200 m	max (200 m, L) It could be lowered if background noise issue	Conditioned by ship type and installed equipment	CPA > 100m	max (100 m, L)	As ISO 17208-1	max (200 m, L)
Distance accuracy measurement		≤ 5% of the CPA	≤ 10% of CPA	Deep water: as ISO 17208-1 Shallow water: ± 5 m	± 10 m	± 5m (for distances) ± 2m (for hydrophones position)	5% CPA	≤ 10% of CPA	As ISO 17208-1	10 m
CPA distance tolerance		± 10%	-10% to 25%	Deep water: as ISO 17208-1 Shallow water: Not specified	± 10 m	Not specified	± 10%	Not specified	As ISO 17208-1	Not specified
Data Window Length (DWL)		2d_{CPA} * tan(30º)	2d_{CPA} * tan(30º)	Deep water: as ISO 17208-1 Shallow water: depending on ship speed (L if v ≤ 5 Kn, 2L otherwise)	max(100m, L)	Conditioned by ship type and installed equipment	1.5L	2d_{CPA} * tan(30º)	As ISO 17208-1	400 m
COMEX-FINEX distance		4*DWL	4*DWL	Deep water: as ISO 17208-1 Shallow water: Not specified	1600 m	Not specified	4*DWL	4*DWL	As ISO 17208-1	> 1600 m
Acquisition bandwidth[2]		10 Hz - 50 kHz	10 Hz - 50 kHz	Deep water: as ISO 17208-1 Shallow water: 10 Hz - 100 kHz	10 Hz - 50 kHz fs ≥ 2.56 * 50KHz	10 Hz - 100 kHz	10 Hz - 50 kHz	10 Hz - 100 kHz	10 Hz - 20 kHz	10 Hz - 50 kHz

Table 2: Test procedure – Detail per standard or notation (1/2)

D = Distance from measurement point to source, H = Water Depth, L = Vessel Length, T = Vessel Draught, v = Vessel Speed (not always in Kn)
[1] The maximum value usually defines the highest centre frequency (for 1/3 octave bands). This means that the acquisition bandwidth shall be increased up to the initial frequency for the next 1/3 octave band.

	ANSI ASA S12.64 (Grade C[1])	ISO 17208-1	DNV-	BV	CSS	RINA	ABS	LR	KR
Runs per distance	4 runs at CPA (At least 1 Port & 1 Starboard)	4 runs at CPA (2 Port & 2 Starboard)	Deep water: as ISO 17208-1 Shallow water: 1 Port & 1 Starboard at CPA	6 runs[2]. 1 Port & 1 Starboard at CPA. 1 Port & 1 Starboard at min(1.5*CPA, 400m. 1 Port & 1 Starboard at min(2*CPA, 500m)	Conditioned by ship type and installed equipment	4 runs at CPA (2 Port & 2 Starboard)	4 runs at CPA (2 Port & 2 Starboard)	As ISO 17208-1	4 runs at CPA (2 Port & 2 Starboard)
Vessel speed	v ≤ 50 Kn	v ≤ 50 Kn	Depending on vessel type (details in DNV-RU-SHIP-Pt6 Ch7)	To be determined according to contract specifications or at NCR	Depending on installed equipment and vessel size	Not specified	Depending on vessel type.	Shall be agreed with the client	≥ 85 % MCR (of the main engine in normal operation)
Acoustic centre	Halfway between the engine room and the propeller	1/4 L forward of the stern at sea surface	Deep water: as ISO 17208-1 Shallow water: as ISO 17208-1	Halfway between propeller and main engines at 2/3 of the vessel draught from waterline	Halfway between propeller and main engines at 2/3 of the vessel draught from waterline	Not specified	Halfway between propeller and engine room, at sea surface (assumed)	As ISO 17208-1	As ISO 17208-1
Background noise measurement	30 seconds Before and after test period or after significant weather or traffic changes. Vessel at least 2km away from hydrophone in a quiet operation condition.	≥ 30 seconds Before and after test period or after significant weather or traffic changes. Vessel at least 2km away from hydrophone in a quiet operation condition.	Deep water: as ISO 17208-1 Shallow water: Not specified	2 minutes Before and after the test. Vessel at least 2 miles away from hydrophones.	≥ 2 minutes Before and after test period	≥ 30 seconds Before and after test period. Vessel at least 2km / 3km away from hydrophones (see comments)	≥ 1 minute Before and after each run. Vessel at least 2km away from hydrophone while all vessel engines and generators are in idle conditions.	As ISO 17208-1	1 minute Before and after each run. Vessel at least 2 km away from hydrophones.
Seabed	Not specified	Not specified	Deep water: as ISO 17208-1 Shallow water: sloping seabed preferred but not mandatory.	Shallow water: as flat as possible. Bottom features could be extracted from database.	As flat as possible	Not specified	As flat as possible	As ISO 17208-1	Shallow: as flat as possible
Weather	Wind ≤ 20 Kn (Recommended)	Wind ≤ 20 Kn (Recommended)	Deep water: as ISO 17208-1 Shallow water: Sea State ≤ 3 & Beaufort ≤ 4	Depending on hydrophone positions: Floating line: Beaufort ≤ 2. Bottom mounted: Beaufort ≤ 3. No Rain Allowed	Sea State ≤ 3 & Beaufort ≤ 4	Sea State ≤ 3 & Wind ≤ 10 Kn	Sea State ≤ 3 & Beaufort ≤ 4	Sea State ≤ 2 (SS3 may be acceptable) & Beaufort ≤ 4 Rain to be avoided, but accepted	Sea State ≤ 3 & Beaufort ≤ 4
Consulted document	ANSI/ASA S12.64-2009/Part 1 (Rev.2019)	ISO 17208-1:2016(E)	DNVGL-CG-0313 (2019) DNVGL-RU-SHIP Pt.6 Ch.7. (2020)	NR 614 DT R02 E (2018)	GUIDELINES FOR UNDERWATER RADIATED NOISE OF SHIPS. CHINA CLASSIFICATION SOCIETY. GUIDANCE NOTES GD 28-2018	RINA Rules 2021. Pt F, Ch 13, Sec 25	ABS GUIDE FOR THE CLASSIFICATION NOTATION UNDERWATER NOISE. 2018	Additional Design and Construction Procedure for the Determination of a Vessel's Underwater Radiated Noise (2018)	GC-37-E (2021)

Table 3: Test procedure – Detail per standard or notation (2/2)

D = Distance from measurement point to source, H = Water Depth, L = Vessel Length, T = Vessel Draught, v = Vessel Speed (not always in Kn), NCR = Normal Continuous Rate
[2] If vessel weight is above 10000GT, number of runs can be reduced to 2 runs at CPA distance. For these vessels, the measurement uncertainty should be risen by +1.5 dB.

2.3. Post-processing

Post-processing activities are focused on the obtention of URN levels produced by the vessel, according to a certain test setup and its corresponding test procedure. Those levels are obtained from the sound pressure level (SPL) measured at the hydrophone locations and corrected to a reference distance of 1 m from the tested vessel. Every notation defines aspects as the processing bandwidth, the required background noise corrections, the distance adjustment, or the reporting units (always expressed as decibels but with different reference units). URN levels are typically reported in the spectral domain, providing noise levels in frequency bands (one-third octaves or decidecades; commonly used interchangeably as their difference is a 0.08%). Some notations suggest reporting URN levels not only in frequency bands but also in narrowband. However, although this information is highly valuable, its use is not widely extended.

Once measurement data are acquired, and raw data are considered valid, it is necessary to process them to obtain their spectral representation. To do so, two approaches can be followed: (i) to compute the Fourier transform (Bloomfield [1976]) over the measured time signals, obtaining the spectral representation of the signals in narrowband and then aggregating the noise levels per frequency band or (ii) to filter the measured time signals with a bank of overlapping filters to directly obtain the spectral representation in band levels (ANSI, 2004). Option (i) provides narrowband and band representations, while option (ii) just provides band levels, being impossible to extract narrowband information as the process is not reversible. As narrowband representation provides a lot more details of the nature of a sound and allows to later represent those levels in frequency bands, procedure (i) is considered the most suitable choice. Therefore, its details are explained below as it will be used to process the results of URN tests within the scope of the SATURN project.

Studied notations do not provide plenty of details about the spectral processing performed and therefore users shall assume important aspects that may cause differences in the reported URN levels. When using the Fourier transform (FT) - or its computational optimisation; the FFT (fast Fourier transform, (Bloomfield P. , 2000) - the following details shall be provided: frequency resolution, percentage of overlapping, window type, and averaging strategy to merge processed windows. A typical processing definition for stationary measurements is to use 1 Hz frequency resolution, 50% overlap, Hann window, and energy average between processed windows, using a certain amplitude scaling (rms or peak-hold) according to the application requirements. Industries as aerospace use international standards that provide such processing details (e.g., MIL-STD-810; for shock and vibrations (United States Department of Defense, 2014)).

After the conversion of the measured levels to the frequency domain (represented as frequency band values; whether as decidecades or one-third octaves) it is necessary to apply some corrections over these values. The corrections cover background noise, hydrophone sensitivity, measurement chain influence, and distance. Although all notations cover these aspects, there is not a standard procedure or harmonized methodology. What it is common, is the definition of the minimum noise level differences that should exist between measured vessel noise and measured background noise. If those minimum differences are not met (those values depend on class notation or standard), it is required to correct, or even discard, the measurement. It is important to mention that every run and hydrophone is processed separately up to the final averaging phase, performed at the end of the post-processing stage.

If background noise correction is not required or if it can be performed successfully, sensitivity and measurement corrections are performed and then, distance correction is carried out. Distance correction propagates backwards (from hydrophone to vessel) measured noise levels to represent ship noise calculated with a reference distance of 1 m. The following equation explains the correction process.

$$L_{\mathrm{URN}}\,(r,h,b) = L''_{p}\,(r,h,b) + \Delta L_{\mathrm{URN}}\,(r,h,b) \tag{1}$$

$L_{\mathrm{URN}}\,(r,h,b)$: Level of underwater radiated noise for a certain run, hydrophone, and frequency band;
$L''_{p}\,(r,h,b)$: sound pressure level after background noise, sensitivity and measurement chain corrections for a certain run, hydrophone and frequency band;
$\Delta L_{\mathrm{URN}}\,(r,h,b)$: Correction factor for a certain frequency band to convert the sound pressure level to underwater radiated noise level. It could be a simple distance correction (from analytical formulae) or propagation loss values.

Correction factor (from equation (*1*)) can be obtained through different procedures:

a) applying previously developed analytical corrections (assuming spherical propagation and considering that attenuation is just caused by spreading over distance),
b) empirically (according to test performance),
c) using propagation models (considering aspects as source depth, seabed, surface, sound speed, etc).

Methodology (a) is the most widely used. Methodology (b) implies difficulties due to the complexity of performing such tests, adding the disadvantage that these tests are not clearly defined neither in the notations nor in the international standards. Option (c), despite its intrinsically associated uncertainties as a numerical model, allows a better characterisation than just assuming attenuation caused by distance (option (a)) avoiding the difficulties mentioned when performing PL tests (option (b)). However, the use of models requires considerable previous expertise (further details are provided in Section 3). The last two options (option (b) and option (c)) are based in the use of propagation loss (PL) as the correction factor. PL consider aspects as noise attenuation due to the distance, sound reflexions caused by seabed and surface, seabed geometry or sound speed propagation.

Every mentioned approach directly conditions the reporting metric used to represent vessel URN levels. Methodology (a) is used for determining RNL (or its modified versions), while methodologies (b) and (c) are more suited for SL. The details of the metrics used to report URN levels are as follows:

- RNL (Radiated Noise Level): metric based on analytical corrections. It considers a scaling proportional to the distance, applying a fixed factor of 20, associated to spherical spreading. For the RNL metric, the propagation loss is defined according to equation (2), where the resulting Radiated Noise Level is represented in equation (3).

$$\Delta L_{\mathrm{URN}} = 20 \log_{10}\left(\frac{d}{1\mathrm{m}}\right) \mathrm{dB} \tag{2}$$

$$L_{\mathrm{RN}}(r,h,b) = L''_p(r,h,b) + 20 \log_{10}\left(\frac{d}{1\mathrm{m}}\right) \mathrm{dB} \tag{3}$$

ΔL_{URN} : Correction factor to convert sound pressure level to underwater radiated noise level. In this case this is a distance correction (from analytical formulae);
d: distance between hydrophone and vessel under test;
$L_{\mathrm{RN}}(r,h,b)$: Radiated noise level for a certain run, hydrophone, and frequency band, at 1 m from the vessel;
$L''_p(r,h,b)$: sound pressure level after background noise, sensitivity and measurement chain corrections for a certain run, hydrophone and frequency band.

- The use of other multiplying factors results in another reporting metric: the $\mathrm{RNL}_{\mathrm{Modified}}$ (Ainslie, et al., 2022).
- $\mathrm{RNL}_{\mathrm{Modified}}$ (Modified Radiated Noise Level): this metric is based on corrections provided by some classification societies. They set their own multiplying factor (typically 18 or 19) based on their own propagation hypothesis, however, the origin of and motivation for these values are unspecified in their notations. The resulting URN levels using this approach are usually lower than those obtained when computing RNL, reporting the same vessel as less noisy when using RNL_{Modified}. However, their reference values are different and comparing RNL_{Modified} with RNL is not correct (further details provided in section 2.4).

$$\Delta L_{\mathrm{URN}} = X \log_{10}\left(\frac{d}{1\mathrm{m}}\right) \mathrm{dB} \tag{4}$$

$$L_{\mathrm{RN,Modifed}}(r,h,b) = L''_p(r,h,b) + X \log_{10}\left(\frac{d}{1\mathrm{m}}\right) \mathrm{dB} \tag{5}$$

ΔL_{URN} : Correction factor to convert sound pressure level to underwater radiated noise level. In this case this is a distance correction (from analytical formulae);
d: distance between hydrophone and vessel under test;
X: a multiplying factor which varies according to notation. Typical values are 18 or 19;
$L_{\mathrm{RNModifed}}(r,h,b)$: Radiated noise level modified for a certain run, hydrophone and frequency band, at 1m from the vessel;
$L''_p(r,h,b)$: sound pressure level after background noise, sensitivity and measurement chain corrections for a certain run, hydrophone and frequency band.

- MSL (Source Level): for this reporting metric, propagation loss is obtained whether from experimental measurements or using propagation models. When using propagation models, MSL considers source depth, sound speed, surface reflections, and seabed influence. However, the use of propagation models requires a solid technical understanding. Further details on the use of propagation models are available in section 3. Regarding measurements, MSL can be obtained according to ISO 17208-2, where its computation is based on applying the surface reflection correction to the RNL measured and computed according to ISO 17208-1 (see equation (7)). If the hydrophone deployment deviates from ISO 17208-1, ISO 17208-2 additionally provides an alternative correction to properly obtain MSL from RNL (equations (B.3) and (B.4) from that document).

$$\Delta L_{\mathrm{URN}}\,(b) = N_{\mathrm{PL}}(b) \tag{6}$$

$$L_s(r,h,b) = L_{\mathrm{RN}}(r,h,b,1m) + N_{\mathrm{PL}}(b) \tag{7}$$

$\Delta L_{\mathrm{URN}}\,(b)$: Correction factor to convert sound pressure level to source level. In this case this is the propagation loss;
$N_{\mathrm{PL}}(b)$: Propagation loss per frequency band;
$L_s(r,h,b)$: Source level for a certain run, hydrophone and frequency band, at 1m from the vessel;
$L_{\mathrm{RN}}(r,h,b)$: Radiated noise level for a certain run, hydrophone and frequency band, at 1m from the vessel.

Some other metrics have been proposed in the last few years, trying to improve the precision of the mentioned URN metrics; those are the DSL (dipole source level; (de Jong, et al., 2010)) and the aRNL (radiated noise level adjusted; (Ainslie, et al., 2022)). DSL metric considers not only the point source but also its surface-reflected image and combines them as a whole underwater source. An advantage is that DSL is robust to the choice of nominal source depth, making it suitable as a URN metric for ship certification. On the other hand, aRNL tries to cover the current limitations of the RNL metric (specific for deep water and for low frequencies), extending its approach to shallow water and higher frequencies (Ainslie, et al., 2022). These two metrics are not widely used yet, but this could happen in the coming years. A detailed explanation and a thorough comparison of the mentioned metrics (RNL, MSL, aRNL and DSL) was already performed (Ainslie, et al., 2022).

Once measured noise levels are corrected (background noise, hydrophone sensitivity, measurement chain and distance correction), those results must be averaged. This averaging comprises the information gathered by the different runs, hydrophones, processing windows, and vessel sides. This procedure is aimed to reduce measurements scatter, but differs between notations. Results obtained after this step are used for the final reporting of vessel URN levels. Table 4 gathers the details for the studied documents.

Saturn
Developing Solutions for Underwater Radiated Noise

		ANSI ASA S12.64 (Grade C[1])	ISO 17208-1	DNV	BV	CCS	RINA	ABS	LR	KR
Measurement metric	Deep water	RNL	RNL	$RNL_{MODIFIED}$	MSL / RNL / $RNL_{MODIFIED}$	RNL / $RNL_{MODIFIED}$	RNL	MSL / RNL	MSL[4]	RNL
	Shallow water	-	-				-		MSL	RNL / $RNL_{MODIFIED}$
Reporting unit		dB	dB	dB	dB	dB	dB	dB	dB	dB
Reference value		1µPa . m	1µPa . m	1µPa . $m^{0.9}$	1µPa . m / √Hz 1µPa . $m^{0.95}$ / √Hz	1µPa . m 1µPa . $m^{0.9}$	1µPa . m	1µPa . m	1µPa . m	1µPa . m 1µPa . $m^{0.95}$
Processing bandwidth		50Hz - 10 KHz	10 Hz - 20 kHz or 50 kHz	Deep water: as ISO 17208-1 Shallow water: 10 Hz - 100 kHz	10 Hz -50 kHz	10 Hz - 50 kHz or 100 kHz	10 Hz - 40 kHz	10 Hz - 50 kHz or 100 kHz	10 Hz - 20 kHz	10 Hz - 50 kHz
Frequency representation		One-Third Octave Band	One-Third Octave Band	One-Third Octave Band	One-Third Octave Band	One-Third Octave Band	One-Third Octave Band	One-Third Octave Band	One-Third Octave Band	One-Third Octave Band
Acceptance criteria		No	No	Yes (5 curves; one per operation type)	Yes (2 curves)	Yes (3 curves. Scope not clearly explained)	Yes (2 curves)	Yes (5 curves)	Yes (3 curves)	Yes (2 curves)
Data window number		1	1	1	19 - 45° to 45° each 5°	1	1	1	As ISO 17208-1	10 Evenly Distributed
Background noise correction		No correction: If SPL_{S+N} - SPL_N > 10 dB Correction: If 3 dB ≤ SPL_{S+N} -SPL_N ≤10 dB Non-valid: If SPL_{S+N} - SPL_N < 3 dB	No correction: If SPL_{S+N} - SPL_N > 10 dB Correction: If 3 dB ≤ SPL_{S+N} -SPL_N ≤10 dB Non-valid: If SPL_{S+N} - SPL_N < 3 dB	Deep water: as ISO 17208-1 Shallow water: No correction: If SPL_{S+N} - SPL_N > 10 dB See notation: If SPL_{S+N} - SPL_N ≤10 dB	No correction: If SPL_{S+N} - SPL_N > 10 dB Correction: If 3 dB ≤ SPL_{S+N} - SPL_N ≤ 10 dB Non-valid: If SPL_{S+N} - SPL_N < 3 dB	No correction: If SPL_{S+N} - SPL_N > 10 dB Correction: If 3 < dB SPL_{S+N} -SPL_N ≤10 dB Non-valid: If SPL_{S+N} - SPL_N ≤ 3 dB	No correction: If SPL_{S+N} - SPL_N > 10 dB Correction: If 3 dB ≤ SPL_{S+N} -SPL_N ≤10 dB Non-valid: If SPL_{S+N} - SPL_N < 3 dB	No correction: If SPL_{S+N} - SPL_N > 10 dB Correction: If 3 dB ≤ SPL_{S+N} - SPL_N ≤ 10 dB Non-valid: If SPL_{S+N} - SPL_N < 3 dB	As ISO 17208-1	No correction: If SPL_{S+N} - SPL_N > 10 dB Correction: If 3 dB ≤ SPL_{S+N} - SPL_N ≤ 10 dB Non-valid: If SPL_{S+N} - SPL_N < 3 dB
Seabed reflection correction		No correction	No correction	Deep water: as ISO 17208-1 Shallow water: 5 dB reduction	No correction applied: for RNL or $RNL_{MODIFIED}$ MSL: considered in propagation model	5 dB reduction	Not specified	If lower hydrophone is < 0.2 m from the seabed: 5 dB reduction	As ISO 17208-1	Not specified
Distance adjustment	Deep water	RNL: 20log10(D)	RNL: 20log10(D)	$RNL_{MODIFIED}$: 18log10(D)	MSL: Propagation model or RNL: If H ≥ 100m: 20log10(D) $RNL_{MODIFIED}$: If H < 100m: 19log10(D)	RNL: If H > 100m: 20log10(D) $RNL_{MODIFIED}$: If H ≤ 100m: 18log10(D)	RNL: 20log10(D)	MSL: Propagation model or RNL: 20log10(D)	MSL[4]: 20log10(D) + $PL_{ISO17208-2,A9}$	RNL: If H ≥ 100: 20log10(D)
	Shallow water	-	-				-		MSL: Propagation model	RNL: If H ≥ 100: 20log10(D) $RNL_{MODIFIED}$: If H < 100: 19log10(D)
Global uncertainty		Provided values for guidance but exact values not specified.	1/3 Octave Bands 10 - 100 Hz: 5dB 1/3 Octave Bands 125 - 16000 Hz: 3 dB 1/3 Octave Bands ≥ 20 kHz: 4dB	Deep water: as ISO 17208-1 Shallow water: not specified	MSL: Deep: ±3,5 dB Shallow: ±4,0 dB RNL / $RNL_{MODIFIED}$: Deep: ±4,0 dB Shallow: ±4,5 dB	No specified	Not specified	Not specified	As ISO 17208-1	Not specified

Table 4: Post-processing - Details per standard or notation

[4] MSL obtained from RNL according to ISO 17208-2 procedure.

2.4. URN results comparison

It is important to remark that comparing URN results from different notations is usually incorrect. To start with, different testing procedures and post-processing activities end up in different URN levels for the same tested vessel. These differences seem to be more obvious and could be studied and even corrected to allow such comparisons.

On the other hand, there is another extended misleading practice; the idea of considering that the different URN metrics are comparable. All the notations report URN levels in decibels, but many of them employ different reference units. This assumption makes their direct comparison erroneous. Additionally, even if the reference units are equal, SL and the various forms of RNL specified by the classification societies are different quantities that cannot be directly compared. Table 5 summarises the main features to consider before performing any comparison. Only the notations that belong to the same reporting metric (first column) and use the same reference unit (last column) could be properly compared. If these two premises are not met, performing the comparison would lead to erroneous conclusions.

<table>
<tr><th>Reporting Metric</th><th>Notation</th><th>Depth</th><th>Reporting Unit</th><th>Reference Value</th></tr>
<tr><td rowspan="6">RNL</td><td>ANSI ASA S12.64</td><td>> 75m</td><td rowspan="6">dB</td><td rowspan="6">1μPa . m</td></tr>
<tr><td>ISO 17208-1</td><td>> 150m</td></tr>
<tr><td>CCS</td><td>> 100m</td></tr>
<tr><td>RINA</td><td>> 150m</td></tr>
<tr><td>ABS</td><td>> 150m</td></tr>
<tr><td>KR</td><td>> 100m</td></tr>
<tr><td rowspan="6">$RNL_{MODIFIED}$</td><td rowspan="2">DNV</td><td>> 150m</td><td rowspan="6">dB</td><td rowspan="3">1μPa . $m^{0.9}$</td></tr>
<tr><td>>30m</td></tr>
<tr><td>CCS</td><td>< 100m</td></tr>
<tr><td>KR</td><td>< 100m</td><td>1μPa . $m^{0.95}$</td></tr>
<tr><td rowspan="2">BV</td><td>> 100m</td><td>1μPa . m / √Hz</td></tr>
<tr><td>< 100m</td><td>1μPa . $m^{0.95}$ / √Hz</td></tr>
<tr><td rowspan="2">MSL</td><td>ISO 17208-2</td><td>> 150m</td><td rowspan="2">dB</td><td rowspan="2">1μPa . m</td></tr>
<tr><td>LR</td><td>> 150m</td></tr>
</table>

Table 5: Reporting metrics per URN notation and their corresponding reference unit values.

Some of the studied notations propose different formulae for the URN levels reporting, ending up in esoteric reference units. In some cases, the resulting reference units are not well reported in the corresponding documents, making it unfeasible to realise that the comparison of some metrics is erroneous. Table 6 gathers the procedures followed to compute the different URN reporting metrics (per notation) and therefore, the origin of the resulting reference units showed in Table 5.

Reporting Metric	Notation	Comment	Calculation	Resulting Reference Value
SPL	All	Just to report sound level at hydrohpone's position	$\mathrm{SPL} = 20\log_{10}(\frac{p}{p_0})$	1µPa
RNL	ANSI ASA S12.64	> 75m	$\mathrm{RNL} = \mathrm{SPL} + 20\log_{10}(\frac{r}{r_0}) = 20\log_{10}(\frac{p}{p_0} * \frac{r}{r_0})$	1µPa . m
	ISO 17208-1	> 150m		
	CCS	> 100m		
	RINA	> 150m		
	ABS	> 150m		
	KR	> 100m		
$\mathrm{RNL}_{\mathrm{MODIFIED}}$	DNV	> 30m	$\mathrm{RNL}_{\mathrm{MODIFIED}} = \mathrm{SPL} + 18\log_{10}\left(\frac{r}{r_0}\right) = \mathrm{SPL} + \frac{20}{20}18\log_{10}(\frac{r}{r_0}) = \mathrm{SPL} + 20\log_{10}(\frac{r}{r_0})^{18/20} = 20\log_{10}(\frac{p}{p_0} * \left(\frac{r}{r_0}\right)^{0,9})$	$1\mu\mathrm{Pa}\,.\,\mathrm{m}^{0.9}$
	CCS	< 100m		
	KR	< 100m	$\mathrm{RNL}_{\mathrm{MODIFIED}} = \mathrm{SPL} + 19\log_{10}\left(\frac{r}{r_0}\right) = \mathrm{SPL} + \frac{20}{20}19\log_{10}(\frac{r}{r_0}) = \mathrm{SPL} + 20\log_{10}(\frac{r}{r_0})^{19/20} = 20\log_{10}(\frac{p}{p_0} * \left(\frac{r}{r_0}\right)^{0,95})$	$1\mu\mathrm{Pa}\,.\,\mathrm{m}^{0.95}$
	BV	> 100m	$\mathrm{RNL} = \mathrm{SPL} + 20\log_{10}(\frac{r}{r_0}) - 10\log_{10}\left(\frac{\Delta f}{f_0}\right) = \mathrm{SPL} + 20\log_{10}(\frac{r}{r_0}) - \frac{20}{20}10\log_{10}\left(\frac{\Delta f}{f_0}\right) = \mathrm{SPL} + 20\log_{10}(\frac{r}{r_0}) - 20\log_{10}\left(\frac{\Delta f}{f_0}\right)^{10/20} = 20\log_{10}(\frac{p}{p_0} * \frac{r}{r_0} * \left(\frac{f_0}{\Delta f}\right)^{0,5})$	1µPa . m / √Hz
		< 100m	$\mathrm{RNL}_{\mathrm{MODIFIED}} = \mathrm{SPL} + 19\log_{10}\left(\frac{r}{r_0}\right) - 10\log_{10}\left(\frac{\Delta f}{f_0}\right) = \mathrm{SPL} + \frac{20}{20}19\log_{10}(\frac{r}{r_0}) - \frac{20}{20}10\log_{10}\left(\frac{\Delta f}{f_0}\right) = \mathrm{SPL} + 20\log_{10}(\frac{r}{r_0})^{19/20} - 20\log_{10}\left(\frac{\Delta f}{f_0}\right)^{10/20} = 20\log_{10}(\frac{p}{p_0} * \left(\frac{r}{r_0}\right)^{0,95} * \left(\frac{f_0}{\Delta f}\right)^{0,5})$	$1\mu\mathrm{Pa}\,.\,\mathrm{m}^{0.95}$ / √Hz
MSL	ISO 17208-2	> 150m	$\mathrm{MSL} = \mathrm{RNL} + \Delta L$	1µPa . m
	LR	> 150m		

p_0: 1µPa; r_0: 1m; f_0: 1Hz; SPL: Sound pressure level; RNL: Radiated noise level; MSL: Source level; ΔL: Average RNL correction (see ISO 17208-2)

Table 6: Detailed procedure to demonstrate the resulting reference values to be employed per notation

2.5. Notations limits

None of the published standards or classification societies' notations that cover vessel URN levels are mandatory. ANSI ASA S12.64 and ISO 17208-1 just aim to provide testing and reporting procedures for the characterisation of vessel URN levels and therefore, they do not define any limit curve that needs to be met. However, classification societies usually provide such curves together with their notations on voluntarily basis, to certify if a certain vessel meets their requirements. Nevertheless, environmental consciousness and public pressure about underwater noise pollution are promoting local and international initiatives that will end up in mandatory noise levels restrictions, probably in the coming years.

In general, there are two threshold curves types defined in the classification societies notations. Figure 2 gathers the limit curves for the studied notations.

Some classification societies provide additional categories, for example, DNV defines qualification curves for Seismic, Acoustics, Fishery, and Research vessels. Regarding research vessels, ABS provides a limit curve as well. Since the vessel to be tested in SATURN's URN tests belongs to this category, these two limit curves (DNV and ABS) are shown in Figure 2. These limit curves are inspired by the ICES 209 (Mitson, 1995), where this document additionally provides a solid base (and its details) to justify those threshold values. On the other hand, BV allows using ICES 209 limits for fishery research vessels.

Regarding the URN results representation, only Bureau Veritas employs a different representation than the spectrum. This representation is the result of applying a bandwidth correction to the decidecade band spectrum as explained by equation (*8*).

$$L_{\mathrm{RN},f} = L_{\mathrm{RN}} - 10\log_{10}\left(\frac{B_i}{1\mathrm{Hz}}\right)\ \mathrm{dB} \tag{8}$$

$L_{\mathrm{RN},f}$: Radiated noise spectral density for a certain decidecade;
B_i : Total bandwidth for a certain decidecade.

As already mentioned in section 2.4, most of these curves cannot be compared because they use difference reference units or reporting metrics. Just those that share these two requisites are plotted using the same colour (see Figure 2). Exact curve values for Figure 2 are available in table format in Annex 1: Tables for URN limits.

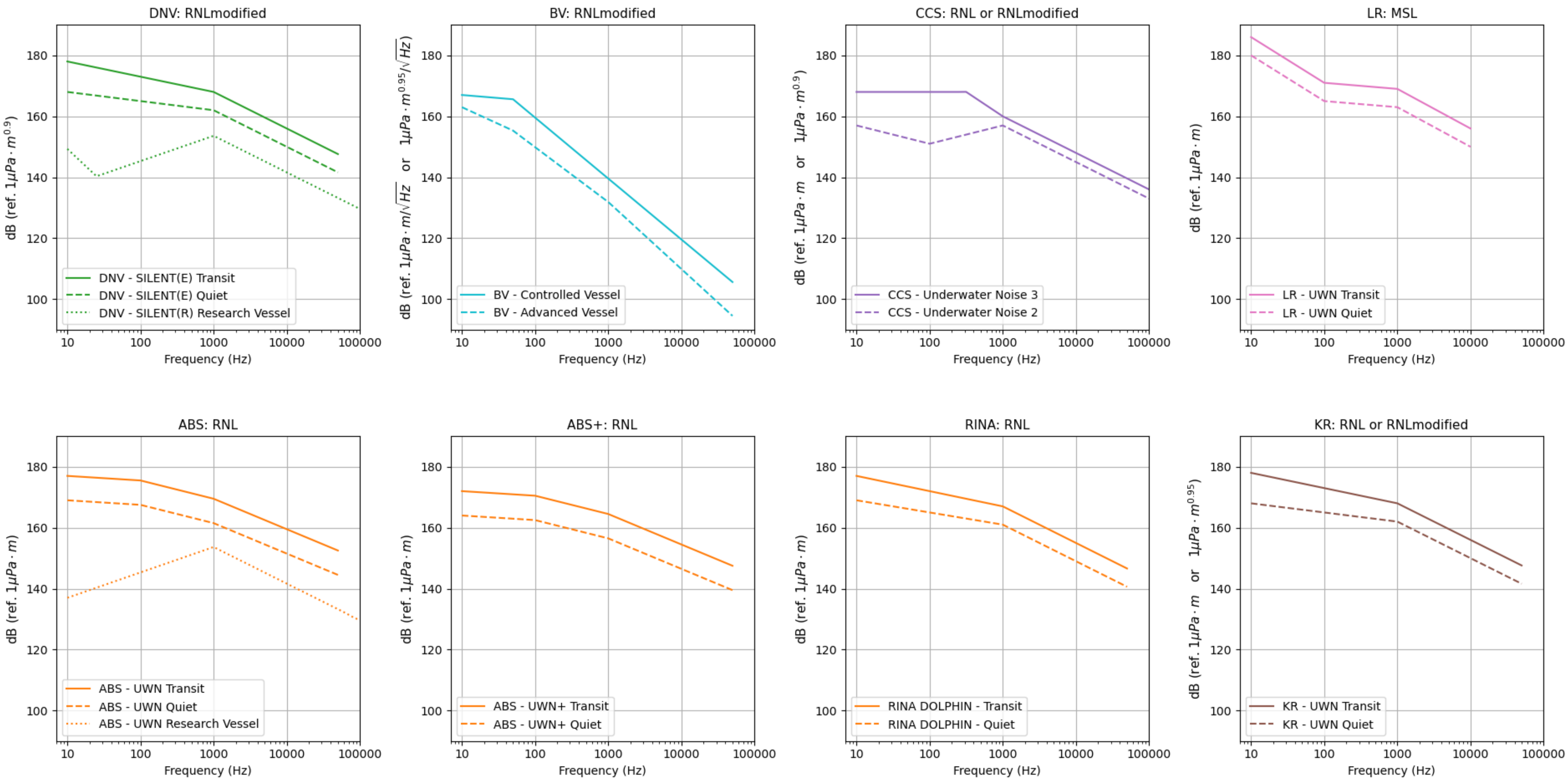

Figure 2: Limit curves per classification society expressed in decidecade band

3. Underwater sound propagation modelling

3.1. Introduction

Acoustic propagation models have been widely used since the 1970s in a broad range of applications (Wang, et al., 2014). During the last few years, the confidence in the use of propagation models has increased and its use has become more common due to, among others, the advances in computational acoustics, the available bathymetry databases, and the improvements in computational resources.

The propagation models studied in this report focus on the obtention of the noise level reduction caused by geometrical spreading and environmental factors. The spreading rules are described through the wave equation, which can be solved by different methodologies. The environmental factors include water sound profile and its attenuation, surface influence (roughness, bubbles, etc), and seabed (sediment properties, bathymetry, etc). All these environmental factors are not only geographic location dependent, but also frequency dependent.

This representation of the attenuation suffered by a certain noise in the modelled situation is referred as propagation loss (PL), and is used jointly with the measured sound pressure levels at a certain geographic location. As mentioned before, the use of the obtained propagation loss enriches the results obtained from experimental tests, allowing to represent the noise source through the use of SL. This procedure improves the accuracy of using the simple distance correction of the RNL metric and characterises the ship noise independently of the environment in which it is measured. SATURN task T2.2.2 aims to report the URN levels as described in different notations. Some of them state the need for using propagation models, and therefore, their use in the project is likely.

The use of propagation models requires a solid base in the related theory and a wide knowledge of their main limitations, restrictions of use, and particularities. This document does not pretend to explain in detail the theory about propagation models or the details of the physics behind the different methods, a good reference that gathers these details is the book *Computational Ocean Acoustics* (Jensen, Kuperman, Porter, & H., Computational Ocean Acoustics, 1997). However, a brief explanation of the most popular solutions is provided in the following subsection.

3.2. Propagation models for underwater environments

Models used for the characterisation of underwater sound propagation are generally split in two main categories: a) those which keep fixed the modelling parameters with distance and are commonly referred as range-independent and b) those that consider variations in the input parameters conditioned by distance and are commonly referred as range-dependent.

Currently, there are a wide variety of available propagation models that can be categorised based on their underlying method, resulting in the groups explained below (Jensen, Kuperman, Porter, & Schmidt, Computational Ocean Acoustics, 2nd edition, 2011). These propagation models solve the wave equation (Helmholtz equation) following different approaches and therefore their application is not valid for all scenarios. Their use is commonly conditioned by the frequency range and water depth. The following table summarises the suitability of every studied model according to frequency and water depth constraints (Wang, et al., 2014).

Shallow water - low frequency	Shallow water - high frequency	Deep water - low frequency	Deep water - high frequency
Ray theory	*Ray theory*	*Ray theory*	*Ray theory*
Normal mode	*Normal mode*	*Normal mode*	*Normal mode*
Wave number integration	*Wave number integration*	*Wave number integration*	*Wave number integration*
Parabolic equation	*Parabolic equation*	*Parabolic equation*	*Parabolic equation*
Energy flux	*Energy flux*	*Energy flux*	*Energy flux*

Green – suitable; Amber – suitable with limitations; Red – not suitable or applicable

Figure 3: Summary of propagations models suitability (source: Wang et al. [2014])

Although some models can be suitable for a certain frequency range and water depth, their computational cost could differ considerably. In some cases, these differences could even reach orders of magnitude in the running time, so considering this aspect is commonly a key point when choosing a certain propagation model. A brief description of the studied propagation models is provided below.

3.2.1. Ray method

Ray method is a geometrical high frequency approximation method. It solves the wave equation in the high-frequency limit by integrating Snell's law, following the analogy of optics, giving a physical picture of the acoustic paths. It considers seabed reflexion but omits sound diffraction (transmission of the sound from water to seabed) therefore, the use of this model is not suitable for low frequencies where diffraction of the sound occurs (typically below 200Hz). It can consider the variation of the propagation parameters caused by depth and distance, being considered a range-dependent model. It is commonly used for deep water and high frequencies, but it has a long run time and requires the use of large memory.

3.2.2. Normal mode

The normal mode method splits the solving of the wave equation in vertical and horizontal components, applying different approaches to solve the horizontal one. Depending on the solution of the horizontal component, the result can be range-independent, mildly range-dependent, and range-dependent, although it better fits for mildly range-dependent environments. As frequency increases, the number of detected modes increases exponentially, causing a proportional rise in the computational costs, making unsuitable the use of normal modes for high frequencies. At close distances, it should not be used because it ignores im-proper modes influencing the results at short distances. It is valid for both deep and shallow water, having a fast computational time and not requiring the use of large memory.

3.2.3. Wave number integration

The wave number integration method solves the wave equation using Green's function (Schmidt & Jensen, 1985). It provides an exact solution as it considers propagation modes and leaky and evanescent ones, so it is commonly used as a benchmark solution for other less exact techniques. It considers the ocean physical properties are just dependant on depth and, depending on the approximation used, it can be range-dependent or range-independent (this approach is the one used when using wave number integration as a benchmark model, and it is therefore its common use). Its memory requirements and running time are considered medium (compared with the rest of the studied propagation models).

3.2.4. Parabolic equation

The parabolic equation method proposes a totally different idea, it does not involve the computation of the field propagation from a source to a distant receiver. It assumes the propagation is one-way and splits the wave equation into incoming and outgoing solutions. It is suitable for range-dependent environments and it is applicable to deep and shallow water. Its computational cost increases with frequency, consequently, it is used below 1kHz, requiring high memory usage.

3.2.5. Energy flux

The energy flux method is a hybrid solution between rays and modes. It covers simple environments (flat bottom and constant sound speed) resulting in range-independent solutions, with some implementations for range-dependent environments. Its computation is very fast with considerable accuracy.

4. Propagation loss measurements

4.1. Introduction

In recent years, different studies focused on the propagation loss in underwater environments. Several authors addressed this topic from different perspectives, covering: the spherical spreading (Lee, et al., 2012) and (Seol, et al., 2015), the Lloyd's Mirror effect (Lafeber, Bosschers, de Jong, & Graafland, 2015) and (Tani, et al., 2019a), the bottom reflections (Lloyd, Lafeber, & Bosschers, 2018), the surface and bottom reflections jointly (Kleinsorge, Schemmink, Klose, & Greitsch, 2017), and the propagation loss from a theoretical perspective (Gaggero, et al., 2016). However just a few authors addressed propagation loss from an empirical point of view, although they finally represented transmission loss with the commonly used (and already mentioned) distance rule of $20\log_{10}(d/1\mathrm{m})\,\mathrm{dB}$ (Tani, Viviani, Hallander, Johansson, & Rizzuto, 2016b). Only a reference providing details of PL obtention from empirical tests was found (Johansson, Hallander, Karlsson, Langstrom, & Turesson, 2015), but neither the measurement details nor the post-processing methodology is explained, being impossible to assess the followed methodology. In this way, it was not possible to find any publication gathering how to properly measure PL from tests.

Regarding the available URN standards, neither ANSI S12.64 nor ISO 17208-1 require the use of the propagation loss and, therefore, they do not provide any details regarding this aspect. ISO 17208-2 mentions this term in Annex A (A.3), although further details to provide a complete context are missing. Regarding classification societies, some of them suggest the use of PL and propose obtaining it from tests, although neither the test procedure nor the post-processing activities are described in those notations.

Due to the lack of details aforementioned, a methodology for the PL obtaining from in-situ measurements is proposed in this section, where both the testing details and the post-processing activities are provided. As the SATURN project includes the performance of URN tests, this opportunity will probably allow testing the proposed methodology in a real environment for a ship, aiming to carry out the PL measurements under the same test conditions as for the URN tests: location, sea properties, distance between source and receiver, and depth.

Additionally, these results could be used for model calibration, by using the measured PL to adjust the model input parameters, such as the local geoacoustic properties of the seabed, for a better match between model and measurements.

4.2. Methodology

This section covers the details of the methodology proposed to obtain the propagation loss from in situ measurements. The suggested methodology is divided into: (i) instrumentation setup, (ii) underwater acoustic excitation, (iii) test procedure and (iv) post-processing activities. As the proposed methodology intends to explore both deep and shallow water, the aforementioned sections split their scope accordingly when needed.

4.2.1. Instrumentation setup

The instrumentation setup will vary depending on the water depth. For deep water it will be based on ISO 17208-1 and for shallow water it will follow the draft version of ISO 17208-3. The main difference in the proposed testing methodology compared with the mentioned standards becomes from the origin of the sound; an underwater sound source will be used instead of a vessel. This underwater sound source will produce a known excitation that will allow the characterisation of the environment, using the difference in the measured sound levels between the excitation source and the receiver.

Deep water

According to ISO 17208-1, three hydrophones will be used, following the same spatial distribution and any other instrumentation specification (see Table 1 for further details). ISO 17208-1 sets the acoustic centre of the vessel at the sea surface, however, using an underwater sound source at that location is senseless, therefore, the acoustic centre will be considered as in ISO 17208-2 standard; "0.7 times the ship's draft". Figure 4 shows the hydrophone array geometry to be reproduced in the PL test for deep water (described in ISO 17208-1), where the ship under test will be replaced by an underwater sound source.

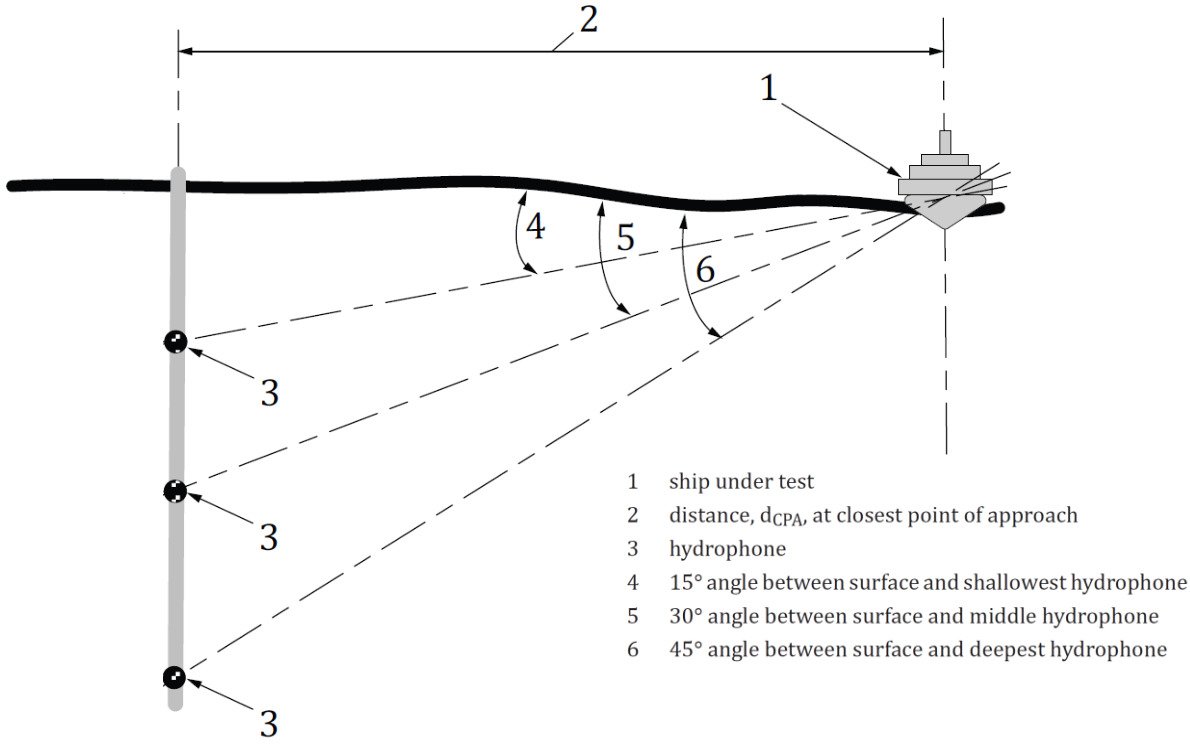

Figure 4: Hydrophone geometry for ISO 17208-1 (deep water) (Source: ISO 17208-1)

Shallow water

For shallow water, the instrumentation setup is based on the available draft version of ISO 17208-3. This standard recommends using three hydrophones (although it accepts using two), keeping a certain distance both from the water surface (minimum depth not specified yet) and the seabed (at least 2m above it). Precise details are pending to be confirmed as the currently available draft version does not provide the exact depth values yet. As described in the previous deep water section, the vessel is to be replaced by an underwater sound source, at the same depth defined above (0.7 times the ship's draft). Additionally, the preferable option is to use bottom-mounted hydrophones configurations in order to reduce platform-related self-noise (e.g., strum noise), however, the final setup would be conditioned by the available resources deployed for the SATURN URN tests and using a floating buoy to support the hydrophones is a likely scenario.

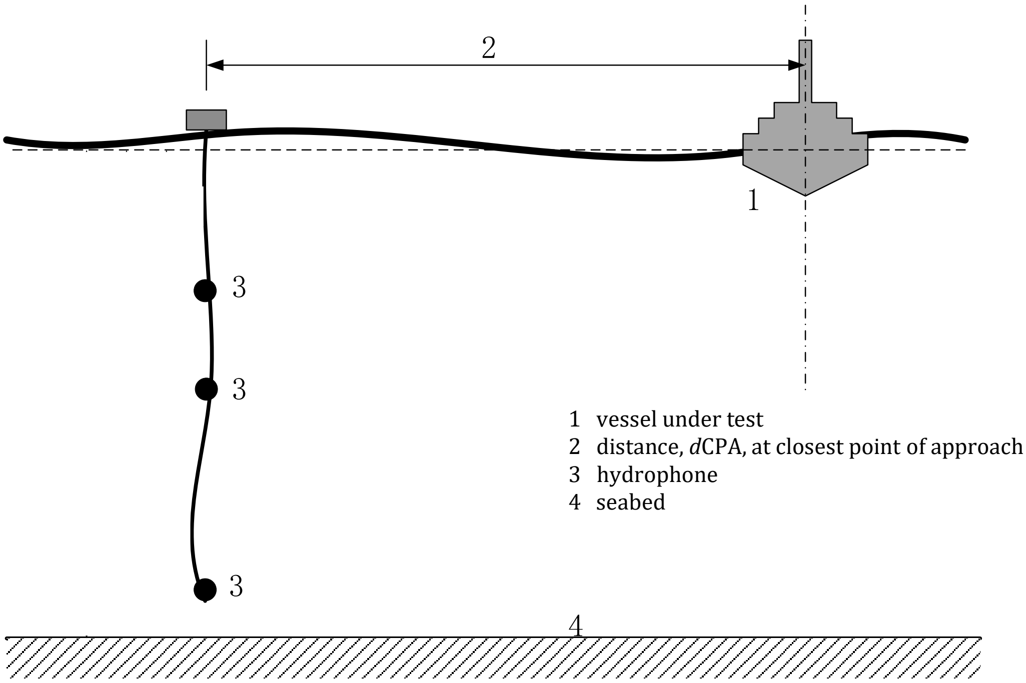

Figure 5: Hydrophone geometry for ISO 17208-3 (shallow water) (Source: ISO 17208-3 draft)

4.2.2. Underwater acoustic excitation

An underwater sound source will be used to produce a known acoustic excitation, trying to cover the wider possible bandwidth. The idea is to evaluate how the produced levels are damped due to the distance and the environmental influence (i.e., to measure propagation loss). The noise reduction (between source and receiver) will be obtained for the frequency range under study and will represent the propagation loss of the testing location. The excitation will try to produce the higher possible noise levels, producing a plain excitation either for the whole bandwidth frequencies (narrowband) or for each decidecade (band levels). Differences between the mentioned frequency scenarios are explained in the following sections of the document.

The underwater sound source will be externally controlled by a signal generator, producing the required excitation signal. Produced sound levels are intended to be monitored through a reference sensor, whether using a hydrophone to measure acoustic pressure, a specific transducer to measure particle motion or any other equipment considered valid (e.g., accelerometer placed on the radiating surface). This reference transducer will be used for the obtention of a transfer function between the excitation produced at this location and the sound levels measured at the receiver position. Figure 6 illustrates the mentioned setup.

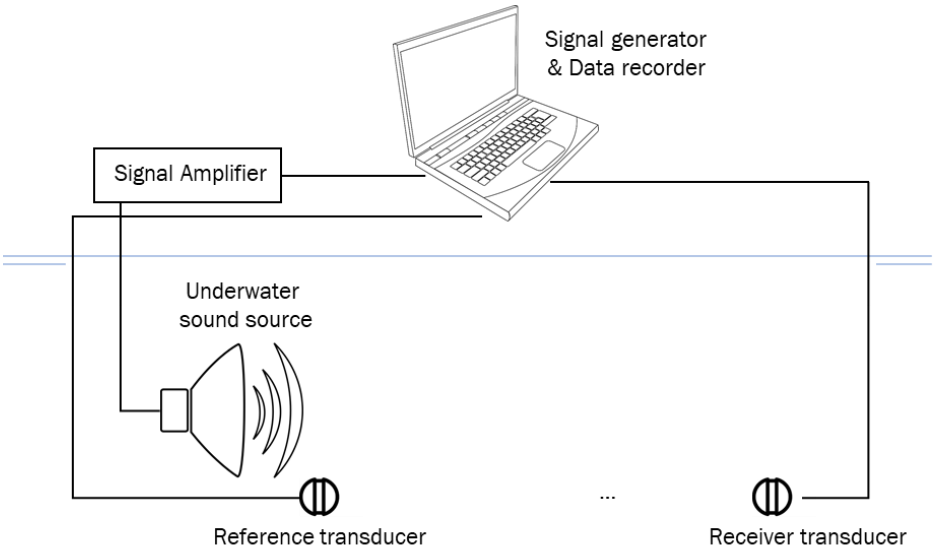

Figure 6: Simplified underwater sound source setup

The frequency resolution of the resulting propagation loss curve (which will represent the propagation factor – i.e., noise reduction – per frequency) will depend on the excitation methodology used: random noise or sine sweep. Both methods would allow the PL characterisation in decidecade bands, although it is intended to increase the frequency resolution as much as possible. Details for the two mentioned approaches are provided below.

Sine sweep

The sine sweep produces a tonal excitation whose spectral characteristics vary with time. It produces a certain sound level for a specific frequency and, as time passes, this frequency increases progressively. This methodology allows the excitation of the studied frequencies individually, where the frequency increment and the excitation time shall be configured for each frequency. The computation formula to produce the sine sweep is described in equation *(9)*. Figure 7 shows an example of a sine sweep signal in the time domain that could be used as input signal for the underwater sound source.

$$y = \sin(2\pi f_i * t) \tag{9}$$

f_i: excitation frequency. Its value increases in fixed steps every defined time interval (e.g.: steps of 1Hz every 10 seconds);
t: time array. It increases constantly according to a certain sampling frequency (time between samples).

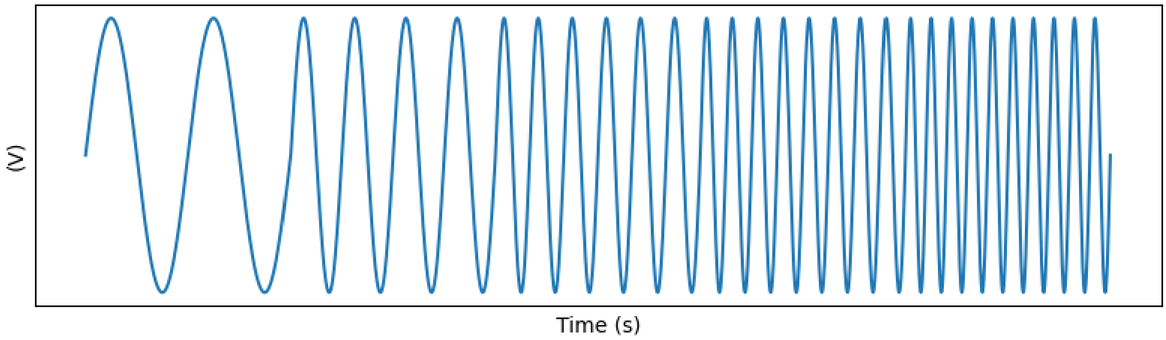

Figure 7: Sine sweep in time domain

The main drawback of using the sine sweep excitation is the time duration of a complete measurement, since every frequency is excited individually and it requires a sufficient excitation time. For example, if one desires to excite from 50 Hz to 20 kHz in 1 Hz steps of 5 s duration per frequency, the measurement time would be 162.5 minutes (1950[Hz]*5[s]). To optimise the testing time, some other strategies could be followed (e.g.: the use of a logarithmic frequency sweep). However, it is very likely that the required post-processing notably differs from the one detailed in section 4.2.4.

Pink noise

Another possible approach is to use pink noise as the input signal for the underwater noise source. The use of pink noise is very popular as it provides a frequency excitation that decreases with a slope of 3 dB per octave in the spectral narrowband representation and consequently, the sum of the produced excitation per octave band results in a plain response. This means that using pink noise produces a plain excitation if the frequency representation used is the octave band format. This approach would therefore, instead of exciting equally each frequency, excite equally each octave band. The plain excitation is reached as well when representing pink noise levels in one-third-octave bands (or decidecade as they can be used interchangeably). Figure 8 shows pink noise in narrowband representation while Figure 9 provides its decidecade representation.

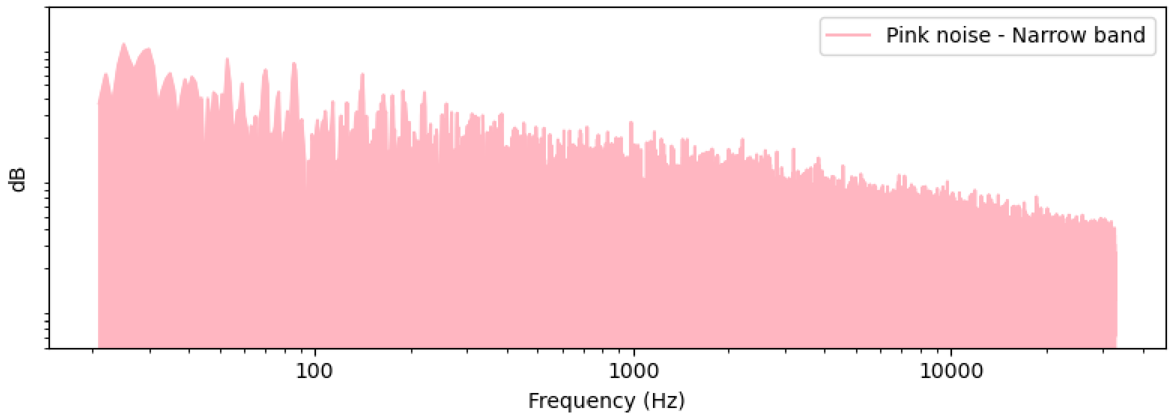

Figure 8: Pink noise in narrow band (bandwidth independent of frequency)

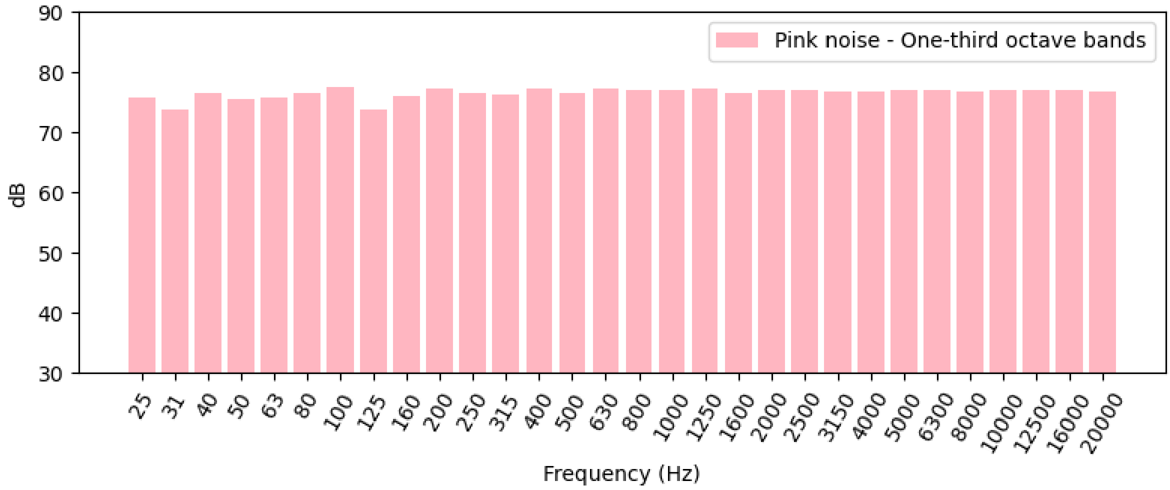

Figure 9: Pink noise in 1/10 decade band (bandwidth proportional to frequency)

The use of pink noise allows exciting all frequencies simultaneously, with a considerable reduction of the testing times compared with sine sweep excitation methodology. However, an important drawback of using broadband noise is that the excitation energy is distributed within the whole bandwidth, using lower energy per each exciting frequency than when using a sine sweep. As a consequence, this method provides a lower signal-to-noise ratio.

In this case, the excited bandwidth comprises 10 octave bands (from 50 Hz to 20 kHz) and, taking into account the noise levels reduction (3 dB per octave), the difference between the produced levels at the first and last excited frequency bands would reach -30 dB. This could be a problem if insufficient sound levels are produced at the higher frequencies If source levels do not exceed the background noise at the hydrophone location by 10 dB, the resulting measured levels would not be a precise representation of the produced noise levels by the source. If that is the case, pink noise should not be used as an excitation signal and instead using white noise could be a possible solution. White noise produces a flat signal in the narrow band representation, exciting with equal amplitudes the whole bandwidth and solving the abovementioned background noise issue possibly caused when using pink noise.

Another option could be considered regarding the reference transducer: to use an accelerometer placed on the radiating surface (providing and appropriate estimation of the volume velocity of the source, which is directly related with the free field source level). If ongoing investigations confirm that these approaches are feasible and indeed reduce uncertainties produced by measuring sound pressure through a hydrophone at the near field, their use shall be considered.

4.2.3. Test procedure

Propagation loss measurements are intended to be performed both for deep and shallow water. The planned deployments are inspired in ISO 17208-1 and ISO 17208-3 (the available draft) for deep and shallow water respectively. The specific details are provided below.

Deep water

The information provided in this section is based on the reference standard ISO 17208-1. Water depth and CPA distance (see Figure 5) must be identical. Background noise measurements will be required and, if measured noise levels when the source is active do not exceed loosely the background noise levels (at least greater than 10dB of the background noise), it will be required to reduce the source-to-hydrophones distance as much as needed in order to meet this requisite.

Once it is confirmed that the background noise is within the acceptable levels, the measurement shall start, using the underwater sound source to excite the environment according to the selected excitation approach (sine sweep or broadband noise). In case of using sine sweep excitation, the following parameters must be set: initial and end frequencies; conditioned by the source, frequency increment; conditioned by the user definition, amplitude per frequency; to properly equalise the frequency response of the underwater sound source, and the excitation time per each frequency step.

Shallow water

The main idea is to reproduce the same abovementioned underwater test as for ISO 17208-3, replacing the vessel under test with the underwater sound source. Details as CPA distance or water depth are pending to be defined and will be set during the coming months, as the ISO 17208-3 draft version will be further detailed. However, the underwater sound source configuration to be used will be the same as the one selected for the deep water measurements; reproducing the same excitation methodology and following the same location and transducer type for the reference sensor.

4.2.4. Post-processing

The following subsections detail the post-processing activities to be performed in order to get the PL results. As different approaches are considered for the excitation of the underwater environment, their common processing details are provided first and then, their specific considerations are detailed.

Background noise correction

One of the main concerns while performing these tests is to avoid background noise influence, whether by adjusting the excitation amplitudes or reducing the distance between source and receiver. If it is not possible to fulfil this requirement, results shall coexist with it, and the influence shall be assessed and mentioned.

Processing configuration

After performing the tests, raw time signals acquired by the hydrophones are to be processed to represent measured SPL (sound pressure level) in the spectral domain. To do so, time signals will be processed through the use of the Fourier transform according to the following parameters:

- Processing windows of 1 s; to obtain a resulting 1 Hz resolution
- Hann window; to avoid leakage
- 50 % overlap between consecutive windows; to avoid losing information caused by the Hann window
- Energy average between the resulting spectral representation of the processed windows

Sine sweep data present an important difference with the pink noise excitation; the measurements progress with time and, therefore, they must be considered as non-stationary. To properly process these data, the original raw time signal will be divided in consecutive slices (with the same duration as for the produced tones). Then, every slice will be processed separately (following the same procedure as the one detailed above) obtaining a set of consecutive spectral representations. This processing is commonly referred as spectrogram, where the spectra vary according to time. Once all slices are processed separately, the whole set will be merged using a spectral envelope: for every frequency, the maximum amplitude value will be kept. This procedure will provide the SPL per run and hydrophone.

On the other hand, as pink noise excites the whole bandwidth simultaneously, it is not required to slice the measured raw time signal, and the processing can be computed straight forward as described above (1 s processing steps, Hann window, 50 % overlap, and energy average) obtaining the SPL per run and hydrophone.

The same processing shall be performed for the reference sensor, applying any required additional computation to represent the noise produced by the source through the SL metric. This computation depends on the reference sensor signal magnitude (sound or vibrations), the distance between the radiating surface and the installed sensor, or the piston diameter. After obtaining the SL from the reference transducer data, the propagation loss per hydrophone results from equation (10).

$$N_{\mathrm{PL}}(f_i, k) = L_S(f_i) - L_p(f_i, k) \tag{10}$$

$N_{\mathrm{PL}}(f_i, k)$: Propagation loss for a certain frequency ($\mathrm{f_i}$) for the hydrophone *k;*
$L_S(f_i)$: Source Level of the source for a certain frequency (f_i);
$L_p(f_i, k)$: Sound Pressure level measured at the hydrophone *k* for a certain frequency (f_i).

Once propagation loss is obtained per hydrophone, a proper methodology shall be identified to obtain the final propagation loss for the test site.

4.3. Potential application

The proposed methodology aims to empirically obtain the test site propagation loss to reduce the uncertainties caused by the current URN reporting metrics. As already mentioned, the most accurate approach requires the use of propagation models, caused by the highest number of factors considered (seabed, free surface, water column, etc) that the commonly used metrics do not include (RNL, $\mathrm{RNL_{MODIFIED}}$). This would lead to a richer description of the test site, intended to be used as well to:

- Study the differences between the updated URN metrics (aRNL, DSL) and the conventional ones (RNL, MSL) in deep and shallow water environments;
- Evaluate the accuracy of the results provided by propagation models used for the characterisation of the same test site.

In case this methodology allows to improve the current metrics accuracy, it would be necessary to evaluate its ease of use, the required investment in the specific instrumentation, the difficulty of performing the test, and the duration of the trials.

5. Conclusions

This report describes the fundamentals of URN, offering a breakdown of the most popular URN measurement procedures, whether coming from standards or classification societies. It additionally introduces the need of further definitions as, for example, for measuring vessel noise in shallow water, where an international standard is currently under development (ISO 17208-3). The specific details of the studied documents were summarised in table format, facilitating comparison between their measurement and post-processing activities, allowing its use in the coming SATURN measurement campaign (SATURN task 2.2.2). Additionally, the different evaluation curves defined for the classification societies are provided, including those defined for research vessels (as the ship used for the URN measurements belongs to this category). The objective of this representation is to highlight their great differences in shape and to remark that their direct comparison is not feasible because the lack of consensus in the reference units used per notation and URN metric. Their precise values are available at the end of this document (Annex 1: Tables for URN limits).

In section 3, underwater sound propagation models were introduced, explaining the main used propagation models, their advantages and some considerations that might be considered to guider their choice (e.g., frequency, accuracy, speed, computational cost, etc).

Finally, a methodology to obtain the propagation loss directly from measurements is proposed. This methodology pretends to result in the PL obtaining from tests, as its obtention is commonly suggested in the studied notations, but their details on how to finally obtain it are not provided. This topic is not widely documented in alternative bibliography neither, being another aspect that encourages the study of a possible empirical methodology. The results produced by this test would be used, among others, to evaluate the accuracy of the currently used (and some recently proposed) URN metric or to study a cost-effective solution for the characterisation of the vessel URN levels.

6. References

Ainslie, M., Martin, S. B., B. Trounce, K., Hannay, D. E., Eickmeier, J. M., Deveau, T. J., . . . Borys, P. (2022). International harmonization of procedures for measuring and analyzing of vessel underwater radiated noise. *Marine Pollution Bulletin*(174).

American Bureau of Shipping. (2018). *Guide for the classification notation: Underwater Noise.*

American National Standard Institute - Acoustical Society of America. (2009). *Quantities and Procedures for Description and Measurement of Underwater Sound from Ships – Part 1: General Requirements.*

ANSI. (2004). *Specification for Octave-Band and Fractional-Octave-Band Analog and Digital Filters.* USA, American National Standard Institute.

Audoly, C., Gaggero, T., Baudin, E., Folegot, T., Rizzuto, E., Salinas Mullor, R., . . . Kellett, P. (2017). Mitigation of underwater radiated noise related to shipping and its impact on marine life: A practical approach developed in the scope of AQUO project. *IEEE Journal of Oceanic Engineering*, 373–387.

Bloomfield, P. (1976). *Fourier analysis of time series: An introduction.* New York: John Wiley and Sons.

Bloomfield, P. (2000). *Fourier analysis of time series: An introduction. Second edition. Wiley series in.* New York: John Wiley and Sons.

Bureau Veritas. (2018). *Underwater Radiated Noise (URN). Rule Note NR 614 DT R02 E.*

Cruz, E., Lloyd, T., Bosschers, J., Lafeber, F., Vinagre, P., & Vaz, G. (2021). *Study on inventory of existing policy, research and impacts of continuous underwater noise in Europe. EMSA report EMSA/NEG/21/2020.* WavEC Offshore Renewables and Maritime Research Institute Netherlands.

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

Det Norske Veritas Germanischer Lloyd. (2019). *Measurement procedure for noise emission. DNVGL-CG-0313.*

Gaggero, S., Gaggero, T., Rizzuto, E., Tani, G., Villa, D., & Viviani, M. (2016). Ship propeller side effects: pressure pulses and radiated noise. *Noise Mapping, Vol. 3, no. 1*, 295-315.

International Organization for Standardization. (2016). *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.*

International Organization for Standardization. (2017). *ISO 18405:2017. Underwater acoustics – Terminology.* Geneva.

International Organization for Standardization. (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.*

Jensen, F. B., Kuperman, W. A., Porter, M. B., & H., S. (1997). *Computational Ocean Acoustics.* Springer (reprinted from 1994 AIP Press).

Jensen, F. B., Kuperman, W. A., Porter, M. B., & Schmidt, H. (2011). *Computational Ocean Acoustics, 2nd edition.* Springer.

Johansson, A. T., Hallander, J., Karlsson, R., Langstrom, A., & Turesson, M. (2015). Full scale measurement of underwater radiated noise from a coastal tanker. *MTS/IEEE OCEANS 2015 - Genova: Discovering Sustainable Ocean Energy for a New World*.

Kleinsorge, L., Schemmink, S., Klose, R., & Greitsch, L. (2017). Case study for the. *5th International Symposium On Marine Propulsors - SMP'17, Espoo, Finland*.

Korean Register. (2021). *Guidance for Underwater Radiated Noise. GC-37-E.*

Lafeber, F., Bosschers, J., de Jong, C., & Graafland, F. (2015). Acoustic reverberation measurements in the Depressurized Towing Tank. *4th International Conference on Advanced Model Measurement Technologies for the Maritime Industry AMT'15, Istanbul, Turkey.*

Lee, J., Jung, J., Lee, K., Han, J., Park, H., & Seo, J. (2012). Experimental Estimation of a Scaling Exponent for Tip Vortex Cavitation via Its Inception Test in Full- and Model-ship. *Journal of Hydrodynamics, Vol. 24, no. 5*, 658-667.

Li, D., Hallander, J., & Johansson, T. (2018). Predicting underwater radiated noise of a full scale ship with model testing and numerical methods. *Ocean Engineering, Vol. 161*, 121–135.

Li, D., Hallander, J., & Johansson, T. (2018). Predicting underwater radiated noise of a full scale ship with model testing and numerical methods. *Ocean Engineering, Vol. 161*, 121–135.

Lloyd, T., Lafeber, F., & Bosschers, J. (2018). Investigation and Validation of Procedures for Cavitation Noise Prediction from Model-Scale Measurements. *32nd Symposium on Naval Hydrodynamics, Hamburg, Germany*.

Lloyd's Register. (2018). *ShipRight. Additional Design and Construction Procedure for the Determination of a Vessel's Underwater Radiated Noise.*

Miglianti, F., Cipollini, F., Oneto, L., Tani, G., & Viviani, M. (2019a). Model scale cavitation noise spectra prediction: Combining physical knowledge with data. *Ocean Engineering, Vol. 178*, 185-203.

Mitson, R. (1995). *Underwater noise of research vessels: Review and recommendations.* ICES Study Group Report.

Registro Italiano Navale. (2021). *Rules for the Classification of Ships Part F. Chapter 13 - Other Additional Class Notations. Section 25 - Dolphin Quiet Ship and Dolphin Transit Ship.*

Robinson, S., Theobald, P., Hayman, G., Wang, L.-S., Lepper, P., Humphrey, V., & Mumford, S. (2011). *Measurement of Underwater Noise Arising from Marine Aggregate Dredging Operations: Final Report. Document Number 09/P108.* Marine Environment Protection Fund (MEPF).

Schmidt, H., & Jensen, F. B. (1985). A full wave solution for propagation in multilayered viscoelastic media with application to Gaussian bean reflection and fluid-solid interfaces. *Acoust. Soc Am.*, 77, 813-825.

Seol, H., Paik, B., Park, Y., Kim, K., Ahn, J., Park, C., . . . Kim, K. (2015). Propeller Cavitation Noise Model Test in KRISO Large Cavitation Tunnel and Its comparison with Full-Scale Results. *4th International Conference on Advanced Model Measurement Technology for the Maritime Industry, Gdansk, Poland.*

Tani, G., Aktas, B., Viviani, M., Yilmaz, N., Miglianti, F., Ferrando, M., & Atlar, M. (2019a). Cavitation tunnel tests for "The Princess Royal" model propeller behind a 2-dimensional wake screen. *Ocean Engineering, 172*, 829-843.

Tani, G., Viviani, M., Hallander, J., Johansson, T., & Rizzuto, E. (2016b). Propeller underwater radiated noise: a comparison between model scale measurements in two different facilities and full scale measurements. *Applied Ocean Research, Vol. 56*, 48-66.

Thomsen, F., Mendes, S., Bertucci, F., Breitzke, M., Ciappi, E., Cresci, A., . . . dos Santos, M. E. (2021). *Addressing underwater noise in Europe: Current state of knowledge and future priorities.* Future Science Brief 7 of the European Marine Board, Ostend, Belgium: ISSN: 2593-5232. ISBN: 9789464206104. DOI: 10.5281/zenodo.5534224.

Traverso, F., Gaggero, T., Tani, G., Rizzuto, E., Trucco, A., & Viviani, M. (2017). Parametric Analysis of Ship Noise Spectra. *IEEE Journal of Oceanic Engineering, Vol. 42, no. 2*, 424-438.

United States Department of Defense. (2014). *MIL-STD-810H. Method 514.8. Test Method Standard for Environmental Engineering Considerations and Laboratory Tests.*

Wang, L., Heaney, K., Pangerc, T., Theobald, P., Robinson, S., & Ainslie, M. (2014). *Review of underwater acoustic propagation models.* NPL Report. AC 12.

Annex 1: Tables for URN limits

Frequency	BV - Controlled Vessel	BV - Advanced Vessel	DNV - SILENT(E) Transit	DNV - SILENT(E) Quiet	DNV - SILENT(R) Research Vessel	CCS - Underwater Noise 3	CCS - Underwater Noise 2	LR - UWN Transit	LR - UWN Quiet	KR - UWN Transit	KR - UWN Quiet	ABS - UWN Transit	ABS - UWN Quiet	ABS - UWN Research Vessel	ABS - UWN+ Transit	ABS - UWN+ Quiet	RINA DOLPHIN - Transit	RINA DOLPHIN - Quiet
-	RNLmodified	RNLmodified	RNLmodified	RNLmodified	RNLmodified	RNL or RNLmodified	RNL or RNLmodified	MSL	MSL	RNL or RNLmodified	RNL or RNLmodified	RNL	RNL	RNL	RNL	RNL	RNL	RNL
Hz	dB (1µPa.m / sqrt(Hz) or 1µPa.m^0.95 / sqrt(Hz))	dB (1µPa.m / sqrt(Hz) or 1µPa.m^0.95 / sqrt(Hz))	dB (1µPa.m^0.9)	dB (1µPa.m^0.9)	dB (1µPa.m^0.9)	dB (1µPa.m or 1µPa.m^0.9)	dB (1µPa.m or 1µPa.m^0.9)	dB (1µPa.m)	dB (1µPa.m)	dB (1µPa.m or 1µPa.m^0.95)	dB (1µPa.m or 1µPa.m^0.95)	dB (1µPa.m)	dB (1µPa.m)	dB (1µPa.m)	dB (1µPa.m)	dB (1µPa.m)	dB (1µPa.m)	dB (1µPa.m)
10	167.0	163.0	178.0	168.0	149.3	168.0	157.0	186.0	180.0	178.0	168.0	177.0	169.0	137.0	172.0	164.0	177.0	169.0
12.5	166.8	161.9	177.5	167.7	147.1	168.0	156.4	184.5	178.5	177.5	167.7	176.9	168.9	137.8	171.9	163.9	176.5	168.6
16	166.6	160.8	177.0	167.4	144.7	168.0	155.8	182.9	176.9	177.0	167.4	176.7	168.7	138.7	171.7	163.7	176.0	168.2
20	166.4	159.7	176.5	167.1	142.5	168.0	155.2	181.5	175.5	176.5	167.1	176.5	168.5	139.5	171.5	163.5	175.5	167.8
25	166.2	158.6	176.0	166.8	140.3	168.0	154.6	180.0	174.0	176.0	166.8	176.4	168.4	140.3	171.4	163.4	175.0	167.4
31.5	166.0	157.5	175.5	166.5	141.1	168.0	154.0	178.5	172.5	175.5	166.5	176.3	168.3	141.1	171.3	163.3	174.5	167.0
40	165.8	156.4	175.0	166.2	142.0	168.0	153.4	177.0	171.0	175.0	166.2	176.1	168.1	142.0	171.1	163.1	174.0	166.6
50	165.6	155.3	174.5	165.9	142.8	168.0	152.8	175.5	169.5	174.5	165.9	176.0	168.0	142.8	171.0	163.0	173.5	166.2
63	163.6	153.5	174.0	165.6	143.6	168.0	152.2	174.0	168.0	174.0	165.6	175.8	167.8	143.7	170.8	162.8	173.0	165.8
80	161.5	151.6	173.5	165.3	144.5	168.0	151.6	172.5	166.5	173.5	165.3	175.6	167.6	144.5	170.6	162.6	172.5	165.4
100	159.6	149.9	173.0	165.0	145.3	168.0	151.0	171.0	165.0	173.0	165.0	175.5	167.5	145.3	170.5	162.5	172.0	165.0
125	157.6	148.1	172.5	164.7	146.1	168.0	151.6	170.8	164.8	172.5	164.7	174.9	166.9	146.1	169.9	161.9	171.5	164.6
160	155.5	146.2	172.0	164.4	147.0	168.0	152.2	170.6	164.6	172.0	164.4	174.3	166.3	147.0	169.3	161.3	171.0	164.2
200	153.6	144.5	171.5	164.1	147.8	168.0	152.8	170.4	164.4	171.5	164.1	173.7	165.7	147.8	168.7	160.7	170.5	163.8
250	151.6	142.7	171.0	163.8	148.6	168.0	153.4	170.2	164.2	171.0	163.8	173.1	165.1	148.6	168.1	160.1	170.0	163.4
315	149.6	140.9	170.5	163.5	149.4	168.0	154.0	170.0	164.0	170.5	163.5	172.5	164.5	149.5	167.5	159.5	169.5	163.0
400	147.5	139.0	170.0	163.2	150.3	166.4	154.6	169.8	163.8	170.0	163.2	171.9	163.9	150.3	166.9	158.9	169.0	162.6

Table 7: URN limits for different classification societies' notations - Table 1 of 3

Frequency	BV - Controlled Vessel	BV - Advanced Vessel	DNV - SILENT(E) Transit	DNV - SILENT(E) Quiet	DNV - SILENT(R) Research Vessel	CCS - Underwater Noise 3	CCS - Underwater Noise 2	LR - UWN Transit	LR - UWN Quiet	KR - UWN Transit	KR - UWN Quiet	ABS - UWN Transit	ABS - UWN Quiet	ABS - UWN Research Vessel	ABS - UWN+ Transit	ABS - UWN+ Quiet	RINA DOLPHIN - Transit	RINA DOLPHIN - Quiet
-	RNLmodified	RNLmodified	RNLmodified	RNLmodified	RNLmodified	RNL or RNLmodified	RNL or RNLmodified	MSL	MSL	RNL or RNLmodified	RNL or RNLmodified	RNL	RNL	RNL	RNL	RNL	RNL	RNL
Hz	dB (1µPa.m / sqrt(Hz) or 1µPa.m^0.95 / sqrt(Hz))	dB (1µPa.m / sqrt(Hz) or 1µPa.m^0.95 / sqrt(Hz))	dB (1µPa.m^0.9)	dB (1µPa.m^0.9)	dB (1µPa.m^0.9)	dB (1µPa.m or 1µPa.m^0.9)	dB (1µPa.m or 1µPa.m^0.9)	dB (1µPa.m)	dB (1µPa.m)	dB (1µPa.m or 1µPa.m^0.95)	dB (1µPa.m or 1µPa.m^0.95)	dB (1µPa.m)	dB (1µPa.m)	dB (1µPa.m)	dB (1µPa.m)	dB (1µPa.m)	dB (1µPa.m)	dB (1µPa.m)
500	145.6	137.3	169.5	162.9	151.1	164.8	155.2	169.6	163.6	169.5	162.9	171.3	163.3	151.2	166.3	158.3	168.5	162.2
630	143.6	135.5	169.0	162.6	151.9	163.2	155.8	169.4	163.4	169.0	162.6	170.7	162.7	152.0	165.7	157.7	168.0	161.8
800	141.5	133.6	168.5	162.3	152.8	161.6	156.4	169.2	163.2	168.5	162.3	170.1	162.1	152.9	165.1	157.1	167.5	161.4
1000	139.6	131.9	168.0	162.0	153.6	160.0	157.0	169.0	163.0	168.0	162.0	169.5	161.5	153.7	164.5	156.5	167.0	161.0
1250	137.7	129.8	166.8	160.8	152.4	158.8	155.8	167.7	161.7	166.8	160.8	168.5	160.5	152.5	163.5	155.5	165.8	159.8
1600	135.5	127.4	165.6	159.6	151.2	157.6	154.6	166.3	160.3	165.6	159.6	167.5	159.5	151.2	162.5	154.5	164.6	158.6
2000	133.6	125.3	164.4	158.4	150.0	156.4	153.4	165.1	159.1	164.4	158.4	166.5	158.5	150.0	161.5	153.5	163.4	157.4
2500	131.6	123.1	163.2	157.2	148.8	155.2	152.2	163.8	157.8	163.2	157.2	165.5	157.5	148.9	160.5	152.5	162.2	156.2
3150	129.6	120.9	162.0	156.0	147.6	154.0	151.0	162.5	156.5	162.0	156.0	164.5	156.5	147.7	159.5	151.5	161.0	155.0
4000	127.6	118.7	160.8	154.8	146.4	152.8	149.8	161.2	155.2	160.8	154.8	163.5	155.5	146.4	158.5	150.5	159.8	153.8
5000	125.6	116.5	159.6	153.6	145.2	151.6	148.6	159.9	153.9	159.6	153.6	162.5	154.5	145.3	157.5	149.5	158.6	152.6
6300	123.6	114.3	158.4	152.4	144.0	150.4	147.4	158.6	152.6	158.4	152.4	161.5	153.5	144.1	156.5	148.5	157.4	151.4
8000	121.5	112.0	157.2	151.2	142.8	149.2	146.2	157.3	151.3	157.2	151.2	160.5	152.5	142.8	155.5	147.5	156.2	150.2
10000	119.6	109.9	156.0	150.0	141.6	148.0	145.0	156.0	150.0	156.0	150.0	159.5	151.5	141.6	154.5	146.5	155.0	149.0
12500	117.7	107.8	154.8	148.8	140.4	146.8	143.8	-	-	154.8	148.8	158.5	150.5	140.5	153.5	145.5	153.8	147.8
16000	115.5	105.4	153.6	147.6	139.2	145.6	142.6	-	-	153.6	147.6	157.5	149.5	139.2	152.5	144.5	152.6	146.6
20000	113.6	103.3	152.4	146.4	138.0	144.4	141.4	-	-	152.4	146.4	156.5	148.5	138.0	151.5	143.5	151.4	145.4
25000	111.6	101.1	151.2	145.2	136.8	143.2	140.2	-	-	151.2	145.2	155.5	147.5	136.9	150.5	142.5	150.2	144.2
31500	109.6	98.9	150.0	144.0	135.6	142.0	139.0	-	-	150.0	144.0	154.5	146.5	135.7	149.5	141.5	149.0	143.0

Table 8: URN limits for different classification societies' notations - Table 2 of 3

Frequency	BV - Controlled Vessel	BV - Advanced Vessel	DNV - SILENT(E) Transit	DNV - SILENT(E) Quiet	DNV - SILENT(R) Research Vessel	CCS - Underwater Noise 3	CCS - Underwater Noise 2	LR - UWN Transit	LR - UWN Quiet	KR - UWN Transit	KR - UWN Quiet	ABS - UWN Transit	ABS - UWN Quiet	ABS - UWN Research Vessel	ABS - UWN+ Transit	ABS - UWN+ Quiet	RINA DOLPHIN - Transit	RINA DOLPHIN - Quiet
-	RNLmodified	RNLmodified	RNLmodified	RNLmodified	RNLmodified	RNL or RNLmodified	RNL or RNLmodified	MSL	MSL	RNL or RNLmodified	RNL or RNLmodified	RNL	RNL	RNL	RNL	RNL	RNL	RNL
Hz	dB (1µPa.m / sqrt(Hz) or 1µPa.m^0.95 / sqrt(Hz))	dB (1µPa.m / sqrt(Hz) or 1µPa.m^0.95 / sqrt(Hz))	dB (1µPa.m^0.9)	dB (1µPa.m^0.9)	dB (1µPa.m^0.9)	dB (1µPa.m or 1µPa.m^0.9)	dB (1µPa.m or 1µPa.m^0.9)	dB (1µPa.m)	dB (1µPa.m)	dB (1µPa.m or 1µPa.m^0.95)	dB (1µPa.m or 1µPa.m^0.95)	dB (1µPa.m)	dB (1µPa.m)	dB (1µPa.m)	dB (1µPa.m)	dB (1µPa.m)	dB (1µPa.m)	dB (1µPa.m)
40000	107.6	96.7	148.8	142.8	134.4	140.8	137.8	-	-	148.8	142.8	153.5	145.5	134.4	148.5	140.5	147.8	141.8
50000	105.6	94.5	147.6	141.6	133.2	139.6	136.6	-	-	147.6	141.6	152.5	144.5	133.3	147.5	139.5	146.6	140.6
63000	-	-	-	-	132.0	138.4	135.4	-	-	-	-	-	-	132.1	-	-	-	-
83000	-	-	-	-	130.6	137.0	134.0	-	-	-	-	-	-	130.5	-	-	-	-
100000	-	-	-	-	129.6	136.0	133.0	-	-	-	-	-	-	129.6	-	-	-	-

Table 9: URN limits for different classification societies' notations - Table 3 of 3