ITTC Quality System Manual
Recommended Procedures and Guidelines

Underwater Noise from Ships, Full Scale Measurements

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7.5 Process Control

7.5-04 Full Scale Measurements

7.5-04-04 Hydrodynamic Noise

7.5-04-04-01 Underwater Noise from Ships, Full Scale Measurements

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Abstract:

The purpose of this document is to provide guidance on the available procedures and methodologies for measuring underwater noise from full-scale surface ships in deep water and shallow water. Special requirements for measurement in shallow water, such as detailed description for ship parameters，requirement for test site and hydrophone deployment are listed. Multiple methods for assessing propagation loss in shallow water based on empirical and test are provided.

Underwater Noise from Ships, Full Scale Measurements

1. PURPOSE OF THE GUIDELINES

The purpose of this document is to provide guidance on the available procedures and methodologies for measuring underwater noise from surface ships. For the purposes of this document underwater noise is defined as the sound generated by a ship as measured in terms of sound pressure levels. Current interest in measurement of surface ship underwater noise is driven by recognition of the importance of anthropogenic (human-made) noise in the ocean and its environmental impact. In addition, ship underwater noise has an influence on the operation of hydroacoustic equipment. The current guidelines only address the measurement of underwater ship noise and does not comment on the impact of such noise.

It is noted that the subject of measuring under water radiated ship noise is currently being extensively examined by many different International Committees and Organizations with various standards having been issued and numerous others in the drafting phase. Reference to these standards is provided in Section 2. The extensive level of activity on this topic is due to both potential differences in national interests and the broad range of ship types, operating conditions, and oceanic environments that need to be addressed. Ship types can range from relatively small vessels to ultra large container ships. Vessel speeds can range from relatively slow, in near-shore and congested waters, to unrestricted full-speed in open oceans. Oceanic environments can range from relatively shallow water, where the sea bottom plays significantly in noise levels, to deep ocean conditions for which the bottom plays no role.

Much of the material provided in this guideline is drawn from the currently available publications. It is recommended that this guideline be revisited and updated periodically as further International Standards for this topic are published and when National and International requirements for ship underwater noise monitoring and regulation are established.

2. NORMATIVE REFERENCES

Ship-generated underwater noise, as previously stated, is a topic of extensive interest due to recognition of its possible environmental impact and the potential of new regulatory measures. As such, a large body of publications related to this topic has been developed over the last few years. For purposes of this guidelines, the salient publications can be categorized into three groupings:

- National/International Standards;
- Rules of Classification Societies;
- Guidelines in the form of Good Practices.

A listing of those found most informative is provided in Table 1.

Table 1: Publications Related to Underwater Noise from Ships

National/International Standards
• ANSI/ASA, 2009, Quantities and procedures for description and measurement of underwater sound from ships, Part 1: General requirements, ANSI/ASA S12.64-2009/Part 1
• 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
• ISO 17208-2:2019. Underwater acoustics – Quantities and procedures for description and measurement of underwater sound from ships – Part 2: Determination of source level from deep water measurements.
• ISO/DIS 17208-3:2024. Underwater acoustics – Quantities and procedures for description and measurement of underwater noise from ships – Part 3: Requirements for measurements in shallow water (under development in ISO/TC43/SC3)
• ISO 18405:2017 Underwater acoustics – Terminology.
Rules of Classification Societies
• DNV GL, Class Guideline DNVGL-CG-0313, 2022, Measurement procedures for noise emission
• BV, 2018, Underwater Radiated Noise (URN), Bureau Veritas Rule Note NR614
• RINA, 2017, Amendments to Part A and Part F of "Rules for the Classification of Ships" - New additional class notation: "DOLPHIN QUIET SHIP" and "DOLPHIN TRANSIT SHIP"
• ABS , 2021, Guide for the Classification Notation- Underwater Noise and External Airborne Noise
• Lloyd's Register, 2018, ShipRight - Design and Construction - Additional Design and Construction Procedure for the Determination of a Vessel's Underwater Radiated Noise
• CCS, 2018, Guideline for ship underwater radiated noise
• KR,2021, Guidance for underwater radiated noise
Guidelines in the form of Good Practices
• AQUO D3.1, 2014, Task T3.1, WP 3: Measurements, European URN Standard Measurement Method
• National Physical Laboratory, 2014. NPL Good Practise Guide No. 133, Underwater Noise Measurement
• AQUO and SONIC, 2015, Guidelines for Regulation on UW Noise from Commercial Shipping, Prepared by: Bureau Veritas, DNVL GL
• JASCO Applied Sciences, 2022, Towards a Standard for Vessel URN Measurement in Shallow Water.

The first document listed in Table 1 is the earliest Standard issued that addresses measuring underwater ship noise with the second being essentially an update. The documents in Table 1 should be referenced for further information and detail not provided in this guideline.

It is noted that the rules (that include limit values) for underwater radiated noise of commercial ships vary between the various class societies. The report of the 29th ITTC Specialist

Committee on Hydrodynamic Noise (2020) provides a review.

3. MEASUREMENT REQUIREMENTS AND PROCEDURE

3.1 Introduction

Documentation and reporting of test site information is critical to the resulting usefulness of noise measurements. There needs to be sufficient information to allow appropriate test configuration and site/environmental related corrections to be made to measurements to arrive at test site independent noise source levels. This provides noise source levels which can be used with noise propagation models to estimate ship noise impact when the ship is operating at other locations or in other oceanic environments. The discussion in other sections of this document addresses issues related to necessary corrections.

Described in this section on Measurement Requirements and Procedures are: a description of ship noise components and their variation with ship speed; characteristics of the test site; measurement configuration; testing configurations; environmental conditions such as sea state and associated weather conditions; and ship configuration.

3.2 Characteristics of Ship Radiated Underwater Noise

The report by the Specialist Committee on Hydrodynamic Noise for the 27th ITTC (2014) describes many characteristics of ship underwater radiated noise that are important in establishing measurement guidelines. Particularly important is that ship underwater noise is generated by different ship-related mechanisms, each varying differently in strength with ship speed. Figure 1, which is an adaption from Carlton (2012), illustrates this point. For this illustration ship noise source mechanisms have been grouped as being; (1) propeller noise, (2) flow noise, and (3) machinery noise. The relative level and possible character of each of these sources for a specific vessel depends on the type of ship, the type of propulsion system used, and the degree that noise quieting features are incorporated in the design. As illustrated, at low ship speed the dominant source is machinery noise which generally increases slowly in level with ship speed. At higher speeds underwater noise is dominated by propeller noise, particularly for speeds above cavitation onset. Flow noise, which is noise generated by flow over the ship hull and hull-mounted components, may be a contributor to underwater noise in the mid-speed range but is not a controlling source at any speed.

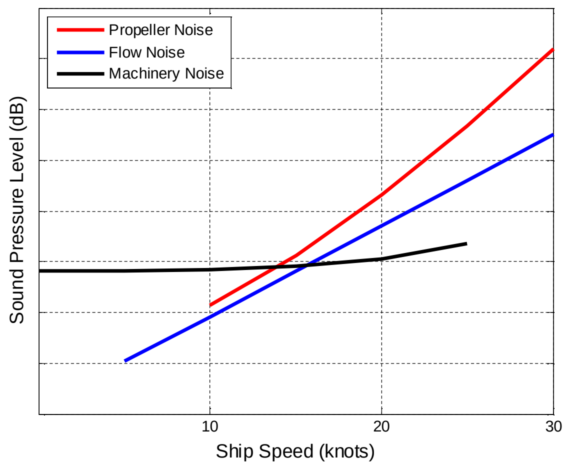

Figure 1: Illustration of variation of ship underwater radiated noise contributors with ship speed.

These characteristics need to be considered when conducting underwater noise measurements. For example, testing periods with low ambient noise levels are needed if underwater levels at low ship speeds are to be measured. If testing is to identify speed of cavitation onset then attention needs to be given to avoid ship and seaway conditions that might alter cavitation onset.

Ships generate continuous noise over a wide range of frequencies (Figure 2), from 1 Hz up to about 100 kHz (Bretschneider et al., 2014), although frequencies up to 20 kHz are the ones typically studied. The spectrum contains tonal, narrowband and broadband components, with the highest source levels typically found at low frequencies – below the 10th harmonic of the blade passage frequency (BPF). Both tonal and broadband sound are important in the context of environmental impact on marine animals (Cruz and al. 2021): the former can generate the highest levels, while the latter radiates more sound energy in total over a large frequency range. Broadband noise is therefore more likely to radiate at frequencies which coincide with those used by marine animals.

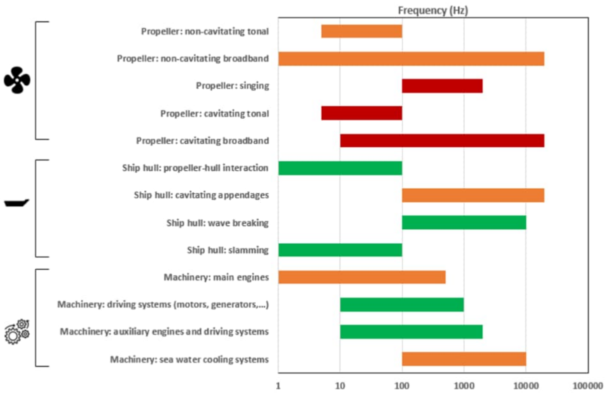

Figure 2:Overview of continuous underwater noise sources from ships, in terms of frequency range and expected contribution to URN (Bretschneider et al., 2014): red –high contribution; orange –medium contribution; green –low contribution. Tonal sources occur at harmonics of the propeller blade passing frequency, as well as ship hull natural frequencies in the case of propeller-hull interaction noise.

When propeller cavitation is present, this noise mechanism typically dominates, especially the broadband part of the spectrum. Since most merchant vessels use screw propellers for propulsion, and experience cavitation at their design speed, propeller cavitation is typically the focus of research activities on URN from shipping. Note that while propeller singing – vibration due to coherent vortex shedding from the trailing edges of the blades – may produce high noise levels, it does not occur often for merchant ships. Machinery noise, particularly from the main engine, remains relevant however, since it generates strong tonal noise at low frequencies, and is present over a wide range of vessel speeds.

3.3 Test site

3.3.1 Test site configuration

The procedures and methods for full-scale noise measurements are dictated by the objectives and purpose of the measurements program; for example, whether the measurements are made on commercial, military, or possibly research vessels. The ANSI and ISO standards listed in Table 1 provide measurement standards that depend on the quality of measurements needed. Specifications for three grades of measurement quality are provided: (1) precision grade, (2) engineering grade, or (3) survey grade. The AQUO WP-3 document listed in Table 1 recommends procedures for two grades of measurements: (A) for engineering purposes with high accuracy and repeatability, and (B) for comparison to noise limits with medium accuracy and repeatability. The URN procedures also address guidelines for both shallow water (A1/B1) and deep water (A2/B2) measurements.

Testing is generally done using either fixed or mobile measurement equipment with the latter more common due in part to the complexity and cost of fixed facilities. It is noted that some fixed sites also employ mobile equipment, particularly those that predominantly support measurements of military ships. On-board measurement equipment may also be used in addition to fixed and/or mobile range equipment.

The basic configuration for deploying hydrophone(s) for underwater noise measurements is; surface mounting where hydrophones(s) are suspended from a surface buoy or support platform; using a bottom anchor and subsurface riser buoy combination onto which the hydrophone(s) are attached; or, a configuration where the hydrophone is mounted in a cage resting on the sea bottom. Various configurations of bottom mounting are used due to unique issues at the testing site. The various existing guidelines recommend hydrophone deployment procedures that improve measurement accuracy and repeatability.

3.3.2 Test site water depth (deep vs. shallow)

Water depth at a test site is an important issue that affects the quality of measurements that can be obtained and the type of deployment system that is used. While preference is naturally for deep water test, for which the influence of bottom reflections on acoustic propagation are not significant, the off-shore waters of many countries consist on an extended continental shelf which is characteristically shallow water (Pang & Wu 2014). Further, the infrastructure needed to support measurements in deep water is more complicated and periods of low background noise (low sea state conditions) are less often.

A single definition of what constitutes shallow water does not exist and varies among the normative references. The requirement of 150 m or 1.5 times ship length is used in ISO 17208-2:2019 and by most of the class societies to define deep water. This recommendation is set in part to ensure measurements include acoustic contributions that may exist along the full length of the ship, bow-to-stern. The minimum water depth for noise measurements in shallow water vary between 30 m and 60 m, depending on class society.

It is noted that shallow water depth may also affect trim, sinkage and speed of the ship. The minimum water depth at which the effect is negligible is given by ITTC procedure 7.5-04-01-01.1 (2014). Consideration needs to be given to whether ship operational performance is impacted while operating in shallow water which could affect acoustic performance. Information on the influence of shallow water on speed and power trials are given in ITTC procedure 7.5-04-01-01.2.

Bathymetric information needed to numerically estimate propagation losses in shallow water should be acquired and sound speed profiles should be measured as part of the testing protocol both in shallow and deep water.

The AQUO D3.1 and BV documents listed in Table 1 provide very extensive reviews of the effects of acoustic signal transmission and bottom absorption/reflection in measurements of underwater noise. These documents should be referenced for more detailed information if needed. It is noted that an ISO procedure on noise measurements in shallow water is in development.

3.4 Measurement Configuration

Underwater noise measurements are made using a single hydrophone or multiple hydrophones comprising an array or string. If multiple hydrophones are employed, the hydrophone signals may be processed individually to provide a spatially distributed (incoherent) sampling of a ship noise or may be coherently summed in some fashion to form measurement beams that provide spatial discrimination, such as against sea surface ambient noise. Further discussions on hydrophones and data acquisition are provided below.

Supporting information regarding the way the hydrophones, and possibly on-board equipment, are used to measure underwater noise should be provided to allow measurements to be converted to range-independent estimates and to determine confidence levels for the estimates. Such information includes, in part the: manner by which hydrophone(s) are deployed and maintained in position; distance of each hydrophone from the surface and the bottom; manner of determining and maintaining position of hydrophone(s); hydrophone signal telemetry and recording procedures; method of determining position of the test ship relative to the hydrophones during entire period for which measurements are made; and, signal conditioning, processing and analysis procedures used to arrive at measured underwater noise levels. Information regarding the accuracy of each of these items should be provided so that cumulative uncertainty estimates can be made. Further guidance on estimating measurement uncertainties is provided in the Uncertainty Analysis section of these guidelines (Section 4.4).

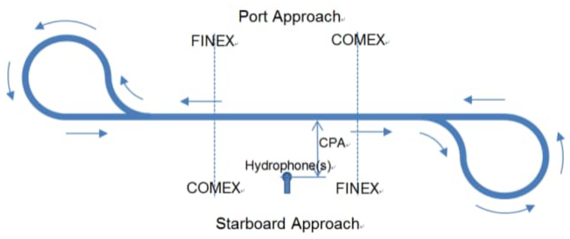

Figure 3: Path of ship during double run

The testing sequence for measurements of underwater noise entails the test ship sailing along a straight course past a sea surface reference point that is indexed to the location where the measurement hydrophone(s) are deployed. During the passage, the ship maintains a predetermined speed and equipment line-up. Data from the hydrophone(s) are continuously obtained during the period of vessel passage from a predetermined COMEX (start) to FINEX (end) of a test run (see Figure 3). The COMEX and FINEX positions of the ship along its track are set to provide the measurements needed to properly report underwater noise levels, as described below.

The test sequence given in Figure 3 is a standard arrangement recommended in many of the standards and guidelines. The track of the vessel is such that it passes the array with a closest point of approach (CPA) that is selected to meet specific test requirements. CPA is the closest horizontal distance the test vessel passes to the array index location as measured from the ship ‘acoustic centre’. The ship acoustic centre is a defined reference position on the ship which is meant to represent the location from which all underwater noise originates as if ship acoustic radiation is from a single point source. While specifying the acoustic centre to be at the location where most acoustic radiation originates is helpful, it is not critical since necessary corrections (principally for range corrections) can be made during post processing.

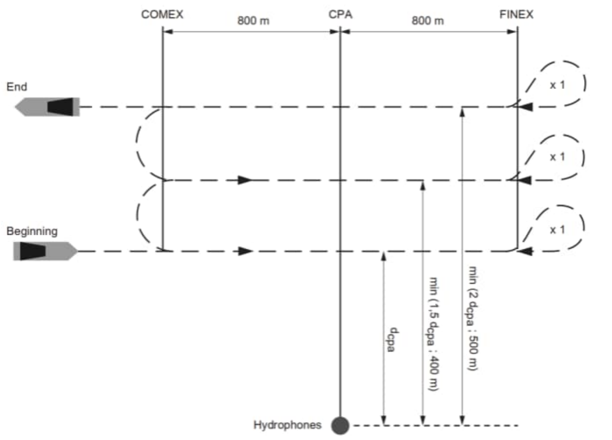

Figure 4: BV test course configuration.

The recommendations from the AQUO project, adopted in the BV rule, specifies an expanded series of such runs past the array to acquire data at multiple CPA to aid in accounting for propagation losses. The BV recommended run configuration is shown in Figure 4. A total of six runs are conducted. Test runs are made for both port and starboard aspect at three different CPA; i) 200 m or distance of 1 ship length, ii) 400 m or distance of 1.5 ship lengths, iii) 500 m or distance of 2 ship lengths. In case the ship gross tonnage exceeds 10000 GT, only two runs at CPA are accepted, or one run passing two hydrophone arrays at both sides of the vessel at CPA. In the latter case, the bathymetry should be flat and bottom sediment homogeneous.

Results from these varying CPA aid in assessing source-to-receiver propagation characteristics. Recognition is given of possible issues with excessively low signal-to-noise values for quieter ships at the greater CPA. Repeat runs at the closer CPA are recommended to help determine repeatability. Accuracy of CPA distance is given as +/- 10 m.

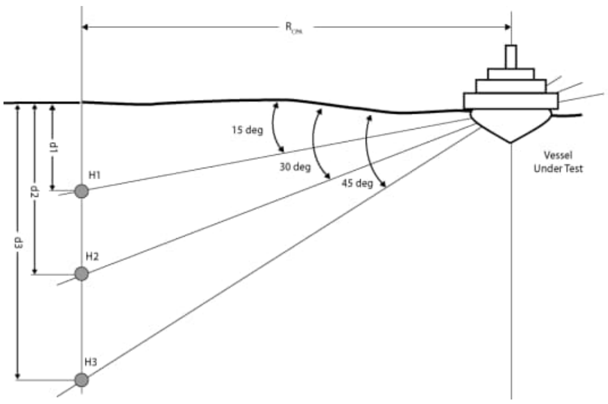

Figure 5: ANSI/ASA (2009) - Grade A and B hydrophone configuration

Due to the significant impact the air-water interface (sea surface) has on propagation characteristics of underwater ship noise, it is important that attention be given to the position of measurement hydrophone(s) relative to the sea surface. The deployment arrangement for hydrophones recommended in the ANSI and ISO standards depends on the grade of measurement needed. For the two higher grades (precision grade and engineering grade) it is recommended, as show in Figure 55, that a vertical string of three hydrophones be deployed at depths such that when the test ship is at CPA, the geometrical configuration of ship-to-hydrophones be such that the hydrophones are at angles of 15°, 30° and 45°, from the ship as measured from the sea surface.

Measurements from a single hydrophone positioned at the 45° depth can be used for the lowest grade measurements. For the higher grades, measurements from the individual three hydrophones are power summed, as described later, to reduce the influence of sea surface reflections (Lloyd mirror effect).

The ship track should provide the CPA and length of track appropriate to the grade of measurements as discussed earlier. If the single dominant noise source is propeller cavitation and testing is not done according to measurement grade specifications the minimum CPA recommendation can be relaxed but must be sufficiently large to ensure measurements are made in the acoustic far field (distance from source such that spherical spreading occurs, in absence of other losses). For long CPA tracks, signal propagation losses and possible resulting reductions in signal-to-noise need to be considered.

3.5 Testing Configurations

The manner and procedures followed for measuring underwater noise can vary due to site-specific requirements/restrictions, test objectives, and customer requirements. As such, information regarding testing procedures should be fully documented.

Ship underwater noise may vary with ship aspect requiring that measurements be made and reported as a function of ship aspect for a range of ship operating conditions (speed, machinery line-up, etc.). Here ship aspect refers to the azimuthal direction relative to the ship with bow, beam, and stern being cardinal aspects. Often only beam aspect is measured.

Beam aspect levels are generally defined as the average noise levels measured over the ship track covering ±30° of CPA. However, beam aspect is also reported as ±45° of CPA by various groups. If high accuracy estimates are needed, the continuous noise measurements over the beam aspect sector should be subdivided into short time intervals (typically 1 second) and individually corrected for propagation effects and then power averaged over the beam aspect sector to arrive at the estimate for beam levels. Lower grade estimates can be made based on a time average of levels covering the full period over which the ship is sailing the beam sector.

It is generally recommended that for each operating condition of interest, a minimum of two sets of measurements be acquired for both port and starboard aspects to allow for averaging and determination of any possible port-starboard asymmetry. For high grade measurements, as defined in the ANSI/ISO standards, it is recommended that three runs for each aspect and condition be obtained.

Port and starboard aspect measurements should be compared for difference in level. If the acoustic levels measured for the two sides are within (nominally) 3 dB of each other, the two levels should be averaged and reported as a single level. If levels are different by more than that amount, port and starboard levels should be reported separately.

During passage of the test ship past the hydrophone(s), operating conditions should be kept as constant as possible. Such operating conditions include ship speed, shaft RPM, propeller pitch (for controllable pitch propellers), ship power, rudder angle, and on-board equipment. Specifying the variation in these operating conditions that is acceptable is not possible due to dependence on ship size and ship type. However, acceptable variations in ship speed are generally ± 0.3 kn or within ± 2% of the target speed. It is noted that the proper ship speed for hydrodynamic noise sources is speed through water (STW) versus speed over ground (SOG as provided by GPS), and the acceptable variations in ship speed just cited are for STW. Acceptable variations in propeller shaft RPM are generally ± 2.4 % of the target RPM. For controllable pitch propellers, propeller pitch angles should be set before the start of the run and should not change during the noise measurements. While further studies of the variation of underwater ship noise with rudder angle are needed, a general guideline is to not operate the rudder or keep variations to within ± 2.0 degrees.

As illustration of changes in ship noise with manoeuvring conditions, Trevorrow *et al.* (2008) made measurements of underwater noise from an oceanographic research vessel for conditions when the vessel was conducting turning manoeuvres. From these carefully conducted tests they showed that even for relatively small turning rates, underwater noise levels increased.

If underwater noise measurements are conducted as part of contractually required speed-power trials then ITTC Recommended Procedures and Guidelines for Speed Power (S/P) Trials (7.5-04-01-01.1, 2014) should be followed. The recommendations and guidelines in that ITTC document are generally worthy of review and adopting as testing protocol.The ITTC Procedures 7.5-04-01-01.1 and 7.5-04-01-01.2 for conducting and analysing speed and power trials provides a listing of boundary conditions (location, wind, sea state, water depth, and current) that should not be exceeded in order to arrive at reliable speed/powering results. Correction methods for these boundary conditions are also given. If underwater noise is measured as part of speed/powering testing, attention must be given to limitations for these boundary conditions. However, as discussed, more restrictive limits to wind, sea state and current may be needed to ensure reliability of underwater noise measurements.

For commercial ships, sea trials including speed power (S/P) and manoeuvring trials are carried out at various main engine loads before delivery of the ships. Many times the effect of noise measurements on the cost and duration of sea trials is limited by conducting the noise measurements during the conventional sea trial program. It is recommended that if measurements of underwater noise are to be performed during S/P trials, runs at Contract and EEDI (Energy Efficiency Design Index, as formulated by IMO) power conditions be performed.

During speed power trials, at least five double runs (using three different power settings) for the first delivered ship and three double runs for sister ships including EEDI power are to be performed (ITTC 7.5-04-01-01.1, 2014). Manoeuvring trials are not mandatory for sister ships.

It is common in the case of a series of ships of the same type that measurement results of the first vessel represent noise performance of the other vessels. However, there are potential concerns with this approach due to possible ship-to-ship variability. Evaluations are currently underway to better understand both the variability that exists between sister ships and the reasons for this variability.

Variability of noise emissions between sister ships at sea trial are presumed to be due to variations within the manufacturing tolerance of a ship and environmental conditions existing during measurements of noise levels. The manufacturing tolerance of ships described in IACS REC 47 Rev.7 (2013) is ± 0.1% of LBP, breadth, and depth of ships. The manufacturing tolerance of propellers described in ISO 484-1 is ± 0.3% for diameter and ± 0.75% for mean pitch values in case of Class I.

3.6 Environmental Conditions

Environmental conditions at the time of underwater noise measurements can significantly influence the quality of results and thus need to be well documented. For example, information regarding water quality and characteristics may be needed to make proper range corrections, and sea state, wind speed and direction may have an influence on ship hydrodynamic performance, and hence acoustic performance. Ambient underwater noise, which sets a noise floor for ship underwater noise measurements, is a function of wind speed and wave height.

Variability of environment conditions that existed during standard speed trials for seven container ships was reviewed by Lee (2015). It was found that the range of wind speeds, wave heights and water temperatures were, 3.0~10.4 m/s, 0.4~1.7 m and 12.0~23.0 °C, respectively.

The most important environmental parameter to monitor is background noise. Background noise should be monitored during the conduct of all underwater noise measurements and reported. It is noted that while background noise levels are commonly reported in terms of Signal-to-Noise ratios (SNR) or equivalent Sea State levels (i.e. SS3 or in terms of equivalent Beaufort levels), for the purposes of documentation, background noise spectra (*SPL*) measured during the sea trials should be reported.

Depending on location and situation of the test site, it may be necessary to monitor and report water current at both the surface (affecting STW vs. SOG) and at the hydrophone(s) location. Water depth should be monitored and to the extent it is not constant, reported along with the reporting of underwater noise levels.

The final set of environmental parameters that are recommended to be monitored and reported as necessary are water temperature, density, and sound speed as a function of depth, and air temperature. Sound speed (vs. depth) profiles may be measured to support estimating propagation loss characteristics.

3.7 Ship Configuration

It is recommended that a maintenance inspection be made of the conditions of the propellers and hull as close in time to the testing period as possible, and preferably prior to testing to allow for any possible corrective actions. Particular attention should be given to the conditions of the propeller(s) and the possibility of excessive marine growth. Propeller fouling not only possibly reduces ship/speed relationship but can result in earlier cavitation onset and overall higher propeller noise levels. The pre-trial Ship Condition monitoring recommended in the ITTC Procedures 7.5-04-01-01.1 should preferably be followed. Results of this inspection should be included in the final reporting.

4. DATA ACQUISITION AND PROCESSING

4.1 Introduction

For underwater noise measurements, systems for accurate data acquisition, recording, processing, and displaying data from the hydrophone(s) are required. Such systems may comprise tape recorders, self-recording hydrophone(s), computer-based data acquisition systems or hardware-specific devices or combinations of these. The acoustic data processing system shall have a capability to; estimate background noise levels so that products such as background noise corrected levels and distance (range) adjusted levels can be provided; assess data quality and accuracy; and synchronize between hydrophone data and ship track position to allow range adjustments to measured levels.

4.2 Data Acquisition

4.2.1 Analogue-to-digital conversion (ADC)

The measurement system should be capable of covering at least the frequency range of a few Hz to 20 kHz with an appropriate sampling rate following Nyquist requirements and low-pass filtering to minimize aliasing. Resolution shall be at least 16 bits but if possible 24-bit to improve dynamic range performance.

4.2.2 Hydrophone information

The hydrophone(s) should have the bandwidth, sensitivity and dynamic range necessary to measure underwater noise from the ship under test. Usually, commercially available hydrophones of piezoelectric type are used for measurement of underwater noise. Hydrophone(s) should be omnidirectional across the required frequency range. The usable frequency range should cover from a few Hz to the upper limit of about 50 kHz or higher. The maximum operating pressure ranges between 40 and 100 atm, with the latter allowing measurements down to 1,000 m ocean depth. A built-in pre-amplifier can be of great importance to provide signal conditioning, particularly for transmission over long underwater cable.

Hydrophone sensitivity should be as high as possible and consistent with the usable frequency range. Typical values range between -165 to -215 dB re: 1 V/µPa.

The number of hydrophones employed for ship noise measurements varies depending on the application and typically vary between 1 and 10. The ANSI and ISO standards recommend the use of an array consisting of three hydrophones for higher grade measurements.

4.2.3 Calibration

System calibration can be undertaken either as a full system calibration, or a calibration of individual components. For full system calibration, the complete measurement chain (hydrophone, amplifiers, cabling, filters, signal conditioning equipment, and analogue-to-digital converter (ADC)) should be tested using known electrical input signals and/or a hydrophone-calibrator before deployment to ensure that the equipment fulfils specifications. For calibration of individual components, the instruments should be tested using known electrical input signals and a hydrophone-calibrator. The calibration should cover the full frequency range of use and be compliant to national or international standards such as ANSI S1.20-2012 or IEC 60565 (2006).

Electronic filters should be used for; anti-aliasing purposes; reduced influence of very low frequency parasitic signals; signal equalization across the frequency range; and, possibly amplification to condition signals before digitization. Filters must be characterized over their full operating frequency range.

Calibration of the hydrophone and recording system should be done with an overall uncertainty of about 1 dB (expressed at a 95 % confidence level). The calibration should be taken both before and after the measurements. Sensitivity does not need to be within a narrow tolerance band but needs to be known with accuracy.

4.2.4 System self-noise

System self-noise, or electrical noise, is a crucial parameter when measuring underwater noise. The system's noise equivalent pressure level should be calculated from the system electrical noise using the system sensitivity. The system noise equivalent pressure level should be at least 10 dB below the lowest noise level to be measured over the frequency range of interest.

4.2.5 Background noise measurements and auxiliary data

Background noise must be measured using the noise measurement system with the ship sufficiently far from the hydrophone (typically more than 2 km) and in a stationary condition so as not to contribute the background noise measurements.

Background noise should be periodically monitored and at a minimum measured and documented at the beginning and the end of each test period (typically day or half-day of measurements) unless traffic or weather conditions (wind, sea state) significantly change (e.g., wind variation > 5 knots). When weather conditions or background noise levels noticeably change, but not such as to prevent the execution of testing, new background noise measurements need to be obtained. Acceptable sea state levels for which ship noise measurements can be made are generally set as requiring that ship noise levels be a specified number of dB higher than background noise levels as discussed later.

To avoid contamination from noise due to the hydrophone mooring system, or flow over the hydrophones, careful design of the hydrophone support system is necessary. It is suggested to measure the acceleration of the hydrophone mount structure to assess the influence of vibrations on measured underwater noise. In general, it is recommended to record and document all auxiliary data that may be relevant, as described in **Errore. L'origine riferimento non è stata trovata.**, so that these may be used to assess data quality.

4.2.6 Mitigation of parasitic contaminating signals

In addition to the self-noise of the measuring system itself, the measured data can also be contaminated by noise originating from the platform or method of deployment. This is sometimes called “platform noise” or “deployment noise”, and excludes the electronic self-noise of the instrumentation. These parasitic signals are due to the deployment method for the hydrophone and recording system and its interaction with the surrounding environment (e.g. current, wave action, etc.). Care shall be taken in the design of the deployment systems to avoid contamination from these sources. Often, the presence of the contaminating signals is not easy to predict or to detect (even though it is present in the data). The platform-related deployment noise will in general add to the system self-noise and to the background noise.

A classic method of reducing flow noise is by use of an acoustically-transparent sonar-dome, which moves the turbulent fluid layer away from the hydrophone’s sensing element. Alternatives include locating the hydrophone close to the seabed where the current flow is reduced. The other main mitigation is to employ drifting systems where the system moves with the current and the relative motion of the hydrophone and medium is essentially zero.

The cable strum effect can be mitigated by use of bottom-mounted deployments, and by the use of mechanical fairings, often in spiral or helical form around cables and housings. If surface deployments are used, decoupling of the hydrophone from suspension cables using compliant couplings (for example, using elastic rope) will reduce the problem.

To minimize machine noise, avoid using metal moorings if possible; avoid metal coming into contact with metal (such as with shackles); avoid the use of chains in the moorings and supports; avoid placing hydrophone so close to the seabed that sediment can impact on the hydrophone; avoid hydrophones touching the support cables by attaching them with vibration isolators (compliant couplings).

If electrical noise because of ground loop pick-up is a severe problem, consider reverse coiling the cables on deck, or even keeping excess cable in a bucket of sea water.

It should also be noted that longer-term deployments may need servicing at intervals to remove biological fouling.

4.3 Data Processing. Reporting and Nomenclature

4.3.1 Definitions and Nomenclature

Measurement and reporting of ship underwater noise is an involved process and careful attention needs to be given to procedures and the use of established nomenclature in order for the reported information to be of use. ISO procedure 18405:2017 defines the terminology related to measurement of underwater ship noise. The definitions provided in those tables should be adopted as the protocol for ship underwater noise measurements and reporting. For reference, an abbreviated version of the most relevant terms and definitions is provided in **Errore. L'origine riferimento non è stata trovata.**. A few of the more important terms are discussed and described below.

The three most relevant terms to define and distinguish are: Sound Pressure Level (*SPL*), Radiated (Pressure) Noise Level (*RNL*), and Source Level (*SL*). All are expressed in dB relative to the reference pressure of 1 µPa. *SPL* is the sound pressure level measured by a hydrophone at the testing facility. Radiated Noise Level is the *SPL* adjusted by a distance normalization, often assuming spherical spreading, to an equivalent 1-meter distance. *SL* is the *SPL* corrected for spreading and propagation losses (e.g. Lloyd Mirror, absorption, sea bottom reflections, etc.). If a Lloyd Mirror correction (and distance correction) is applied to the SPL, the SL is sometimes referred to as monopole Source

Level. Each measure conveys different information and clarity in use is needed to avoid confusion. These terms and others are further discussed below. Note that in the literature different symbols may be used for *SPL*, *RNL*, and *SL*.

4.3.2 Underwater Noise Measurements

Underwater noise (*SPL*) measured from a test vessel shall be processed to allow corrections for background noise contamination and adjustments for distance normalized to obtain radiated noise levels (*RNL*). The processing of *SPL*s should be conducted by narrowband (typically 1 Hz) analysis in the frequency range between 20 Hz to 2 kHz and one-third-octave bands throughout the 20 Hz to 20 kHz frequency range (or higher). It is noted that narrowband processing is often performed over the full frequency range of interest. Similarly, the (equivalent) *SPL* of background noise pressure (p_n) shall be measured as described earlier, following the same analysis procedures and in the same bandwidths as the underwater ship noise. If *SL* are to be reported then the facility established procedures for correcting for propagation losses should be followed.

SPL (in dB) is the fundamental quantity used to represent underwater noise, and is defined in terms of a pressure ratio as follows[1]:

$$SPL = 10 \log_{10} \frac{\tilde{p}^2_{rms}}{p_0^2} \tag{4.1}$$

where SPL is the sound pressure level in dB, $\tilde{p}^2{}_{rms}$ is the mean-square of the acoustic pressure, and p_0 is the reference pressure (1 µPa in water). Note that the above can also be written as $20\log_{10}\left(\frac{\tilde{p}_{rms}}{p_0}\right)$ without ambiguity. The definition of standard statistical terms such as $\tilde{p}_{rms}$ and other spectral terms follow those provided in Bendat & Piersol (2011).

Of primary interest is the distribution of underwater sound as a function of frequency for which there are three commonly adopted formats. The first is that given by the above equation which is the 'Mean-Square Sound Pressure Level" (referred to as the 'Overall Sound Pressure Level', *OASPL*) and is a single value representing the total (frequency integrated) sound pressure level. The second is the "Narrowband Spectrum of Sound Pressure Level" (SPL_{NB}) which provides the distribution of *SPL* measured in narrow frequency bands of constant width. The most common and preferred bandwidth for such displays is 1 Hz and the resulting spectrum ($SPL_{1\text{-}Hz}$) is then termed a 'spectral density' (implicitly meaning a 1 Hz bandwidth). The third most common is to display *SPL* measurements in terms of proportional-band levels, with one-third-octave (OTO) bands being most common ($SPL_{1/3}$). In what follows, the explicit dependence on frequency of measurements expressed as spectra is not shown unless needed for purposes of definition and clarity.

The definition for a narrowband spectrum is a direct adaptation of the definition of sound pressure level given above but with the replacement of the $\tilde{p}^2{}_{rms}$ with $\tilde{p}^2(f,\Delta f)_{rms}$ which is the mean-square pressure measured in the bandwidth Δf centered about frequency *f*;

$$SPL_{NB}(f,\Delta f) = 10\log_{10}\left(\frac{\tilde{p}^2(f,\Delta f)_{rms}}{\tilde{p}^2{}_0}\right) \tag{4.2}$$

with subscript '*NB*' meaning narrowband. If the bandwidth Δf is 1 Hz then it is a spectral density and the subscript '*1-Hz'* may be used.

[1] Note that ISO standard 18405 :2017 on Acoustic Terminology uses the symbol L_p to denote SPL in equations. In this document, acronyms were kept in equations for ease of reading. The symbols given in the ISO standard are given in **Errore. L'origine riferimento non è stata trovata.**.

One-third-octave bands are a class of frequency bands with bandwidths that are proportional to the centre frequency (f_n) of the band. The progression relationship for OTO bands is $f_{n+1}/f_n = 2^{1/3}$. This progression does not occur periodically within a decade and for convenience a series of 'preferred/standard' OTO centre frequencies have been established. When sound pressure levels are provided as OTO band levels this is stated explicitly and the term $SPL_{1/3}$ is used. It is acceptable for data to be processed in 1/10th decade bands and either reported as such or reported at being OTO band levels. The difference in bandwidths between the two is sufficiently small to make this acceptable.

While conversions between SPL_{NB} levels and $SPL_{1/3}$ levels are possible special care needs to be taken to prevent erroneous results. $SPL_{1/3}$ levels can be estimated by summing SPL_{NB} levels over the frequency band covering each OTO band. However, there needs to be a sufficient number of SPL_{NB} values within the OTO band to properly represent the OTO band. On the other hand, estimates of SPL_{NB} levels can be made by subtracting $10\log_{10}(\Delta f_{1/3})$ from $SPL_{1/3}$ levels to arrive at an $SPL_{1\text{-}Hz}$ level. However, this is only valid if the levels within the $SPL_{1/3}$ band are uniform in frequency. Similarly, if levels within a given SPL_{NB} are constant, these levels can be converted to $SPL_{1\text{-}Hz}$ levels by subtracting $10\log_{10}(\Delta f_{BW})$ from the SPL_{NB} levels, where Δf_{BW} is the bandwidth of the narrowband levels.

Calculation of the average sound pressure level SPL_{AVG} using SPL levels from individual hydrophones is given as:

$$SPL_{\text{AVG}} = 10\log_{10}\left[\frac{1}{N}\sum_{i=1}^{N}10^{(SPL_i/10)}\right] \quad (4.3)$$

where, SPL_{AVG}, is the average sound pressure level (in dB), SPL_i is the level (in dB) for the i-th hydrophone, and N is the number of hydrophones.

The above method can also be applied to calculate an aspect averaged SPL when levels over the aspect are measured in increments, such as every 1-second. For this, SPL_i is the individual 1-second SPLs that are measured.

4.3.3 Correction for background noise

Background noise corrected radiated noise, SPL_p' , shall be calculated as,

$$SPL_p' = 10\log_{10}\left[10^{\left(\frac{SPL_{p_{s+n}}}{10}\right)} - 10^{\left(\frac{SPL_{p_n}}{10}\right)}\right] \quad (4.4)$$

where SPL_p' is the SPL (dB) of the test ship after subtracting background noise, $SPL_{p_{\text{s+n}}}$ is the SPL (dB) as measured on range which contains contributions from the test vessel noise and background noise, and $SPL_{p_{\text{n}}}$ is the SPL of the background noise (dB) at the hydrophone when the test vessel is not present (see earlier section for discussion of measuring background noise).

As a metric of background noise contamination, the difference in level, ΔSPL (expressed in dB), between underwater sound pressure levels measured during the ship trials and underwater background noise levels, is calculated as,

$$\Delta SPL = SPL_{p_{\text{s+n}}} - SPL_{p_n} = 10\log_{10}\left(\frac{p_{\text{s+n}}^2}{p_{\text{n}}^2}\right) \quad (4.5)$$

If the value of ΔSPL is less than 3 dB, the background noise is considered too high in comparison with the measured sound pressure level and the measurement for the test ship is regarded as "contaminated" and discarded. If ΔSPL is greater than 10 dB then no adjustments for background noise contamination is necessary. However, if ΔSPL are in the range of $\Delta SPL \geq 3$ dB and ΔSPL <10 dB, background noise corrections to the measurements should be made following equation (4.4). Note that ΔSPL is a function of frequency and hence so will be the application of equation (4.4).

4.3.4 Correction for propagation loss

The ship's radiated noise source level, *SL*, is calculated from the measured $SPL_p^{'}$ as,

$$SL = SPL_p^{'} + PL \tag{4.6}$$

where *PL* is the 'propagation loss' which accounts for all changes in pressure level during propagation from the source (ship) to the receiver (hydrophone). Formally, *SL* is effectively the level of noise an equivalent monopole source would make in an unbounded ocean at 1 m from the source. *PL* results from numerous effects; geometrical spreading losses; absorption losses; and, sea surface and sea bottom reflection effects. If possible, *PL* should be measured at the test range and that value used for converting measured *SPL* to *SL*. Otherwise, standard estimations or numerical modelling results are needed to determine *PL*.

The radiated noise level, *RNL*, of a ship only accounts for geometrical spreading losses. Assuming spherical spreading,

$$RNL = \mathrm{SP}L_p^{'} + 20\log_{10}\left[\frac{r}{r_0}\right] \tag{4.7}$$

where r_0 is the reference distance of 1 m and r (in meters) is the distance between the test ship acoustic centre and the locations of the hydrophone(s). Based on practical experience, alternative spreading loss formulations are in use such as $18\log_{10}[r/r_0]$ in the DNV-GL rule and $19\log_{10}[r/r_0]$ in the BV rule for shallow water.

One method to quantify and account for propagation losses is to execute the AQUO project's recommended test protocol of conducting trials for multiple CPA. Such testing essentially uses the test vessel as an acoustic source from which source-to-receiver propagation characteristics can be determined.

An alternative to conducting multiple CPA runs to determine PL is to use a known source that is towed along the same path as the target ship. Either a set of single frequencies or broad band noise can be used as input to the known source. It is important to tow the source at the depth of the acoustic centre of the test ship in order to properly replicate surface and bottom reflection effects.

There are a number of empirical relationships for estimating sound absorption which should be accounted for, particularly at higher frequencies (tens of kHz range). One example is the deep water model by Thorp (1965).

Effect of sea surface and sea bottom reflection are not specifically losses but are propagation path related and are describe separately below.

4.3.5 Correction for bottom and free surface effects

For hydrophones deployed from the sea bottom in a fixture with hydrophone height above the bottom less than 0.2 m, reflections could affect measurements. In this case the suggested correction factor, arising from the assumption that all incident energy is scattered and redistributed into the water with no transmission into the bottom, is to reduce levels by 5 dB (Jensen *et al.* 2011; Urick 1983).

Measurements of underwater noise from a ship is affected by ship noise reflected from the sea surface and can exhibit a spatially-dependent constructive/destructive pattern (Lloyd mirror) resulting from the coherent sum of the direct and reflected signals. The complex interference pattern that forms is a function of both source and receiver locations and the conditions of the sea surface, all of which are difficult to fully and accurately account for during field measurements.

To minimize the influence of sea surface reflections it is recommended that reported ship noise levels be calculated as the power average of the background corrected *RNL* levels measured at each of the three hydrophones in the vertical array of hydrophones described earlier (for example, ANSI/ASA 3-hydrophone average). This provides a spatial averaging that greatly reduces constructive/destructive effects.

Urick (1983) derived a relationship to account for surface reflections that is based on source and receiver geometry and is a function of a surface reflection coefficient, μ. That relationship, expressed in the form of a propagation loss term, PL_{LM} (LM being Lloyd mirror) is,

$$PL_{LM} = -10\log_{10}\left[1 + \mu^2 - 2\mu\, cos\left(\frac{2kd_s d_r}{r}\right)\right] \tag{4.8}$$

for which μ is the surface reflection coefficient ($\mu \leq 1$), k the acoustic wavenumber ($k=\omega/c_0$; c_0 speed of sound in water), r the range (source-to-receiver distance), d_s the depth of the acoustic source, and d_r the depth of the receiver.

For a perfectly reflecting surface (μ=1) two extrema occur. First, when the surface reflected contribution at the measurement point is exactly out of phase with the direct path signal and total cancellation occurs. This occurs when the cosine term equals 1 and PL_{LM} goes to minus infinity. Second, when the surface reflected path contribution at the measurement point is exactly in phase with the direct path signal and the two add coherently resulting in the pressure doubling. This occurs when the cosine term equals -1 and the PL_{LM} is 6 dB.

For sea trials, where sea surface scattering is influenced by sea state and bubbles, the Lloyd mirror interference pattern is only observed at low frequencies and not at high frequencies. The following formulation is proposed by ISO 17208-2:

$$PL_{LM} = \begin{cases} -10\log_{10}[4\sin^2(kd_s\sin\theta)] & kd_s\sin\theta \leq 3\pi/4 \\ -10\log_{10}2 & kd_s\sin\theta > 3\pi/4 \end{cases} \tag{4.9}$$

where θ corresponds to the depression angle of the hydrophone. For wind speeds above approximately 5 m/s, the effect of Lloyd mirror almost disappears for frequencies above 5 kHz and PL_{LM} is close to 0 dB (Audoly & Meyer 2017)

Note that as the test ship traverses the measurement track the geometry between the test vessel and fixed hydrophone(s) continuously changes and hence there are continuous changes in the relative contribution (constructive or destructive) from the surface reflected path to the measurements.

If the three hydrophone geometry is strictly according to ISO 17208-1, the following correction can be applied to the average noise level as published by ISO 17208-2:

$$PL_{LM} = -10\log_{10}\left(\frac{2(kd_s)^4+14(kd_s)^2}{14+2(kd_s)^2+(kd_s)^4}\right)\ \text{dB} \tag{4.10}$$

For the source depth d_s, ISO 17208-2 proposes a value of 0.7 times the ship draft, but other depths are in use as well depending on whether machinery noise or cavitation noise is dominant.

Alternatively, the propagation loss due to free surface and bottom can be calculated by numerical models. The Bureau Veritas Underwater Radiated Noise (URN) Rule Note NR 614 DT R02 E (2018) recommends the use of range dependent parabolic wave equation model RAM (Collins 1994; Collins *et al.* 1996), or a wave integration model, namely the Scooter/Fields model for low frequencies below 1,000 Hz (Etter 2013), and ray trace based models, namely Bounce or Bellhop models (Jensen *et al.* 2011), for higher frequencies. Other well validated models can also be used. The propagation models need as inputs sound-depth velocity profiles, noise source depth, hydrophone depth, and sea bottom characteristics. A numerical model that includes near field effects may be needed when ship underwater noise measurements are made for short source-receiver configurations.

4.3.6 Special requirements for shallow water

Ship Parameters

If the dominant contributor to underwater noise is the propeller (via propeller cavitation) then the ship-length criterion may be relaxed. Similarly, if underwater ship noise is due to only machinery and propeller noise contributions, then the ship length criterion may be reduced to being the distance between the machinery room and propeller, rather than being overall ship length.

The user defines the length L over which the ship is expected to radiate the dominant sound. Depending on the location of the dominant noise sound sources of the ship under test, this can be the overall length of the ship (from bow to stern) or the length of the aft part of the ship, where the propellers and the main engines are located. This length should be sufficiently larger than ship width and draft, hence it is required that length L is greater than 1/3 of the overall length of the ship.

$$L \leq L_{OA} \text{ and } L > L_{OA}/3 \quad (4.11)$$

Nominal depth(d_s) below the sea surface of the monopole point source from which the sound is considered to originate, and equal to 0.7 times the ship's draft(D), which is used for conversion of radiated noise level to equivalent monopole source level. The draft of the ship is considered to be the average of the stern and bow drafts.

$$d_s = 0.7D \quad (4.12)$$

The choice of the nominal source depth is somewhat arbitrary, and the choice of 70% of the mean draft represents a compromise. The value of the nominal source depth is to be reported alongside the equivalent monopole broadside source level value.

Test site

If the water depth is much smaller than the CPA distance, the water depth and seabed properties should be such that the lowest frequency of interest is at or greater than the shallow water cut-off frequency $f_{\min}$. The minimum depth $H_{\min}$ can be calculated from this equation, adapted from [Jensen et al, 2011, eq.(1.38)]:

$$H_{\min} = c_w/(4f_{\min}\sin\psi_c) \quad (4.13)$$

here c_w is the speed of sound in water, c_b is the speed of sound in the seabed and ψ_c the seabed critical angle $\psi_c = \cos^{-1}(c_w/c_b)$.

The user should be aware that shallow water effects can affect ship resistance and hence have influence on the ship radiated sound. ISO 15016: 2015 (Ships and marine technology — Guidelines for the assessment of speed and power performance by analysis of speed trial data) suggests that ship resistance for a ship of width B [m] and draft T [m] at speed V [m/s] is affected if the water depth is smaller than the larger of the values obtained from the two equations: $H_{\min} = 3\sqrt{BT}$ and $H_{\min} = (0.3\,s^2/m)\cdot V^2$.

The background noise at the test site should be low enough to permit measurement of the underwater sound of the ship under test over the frequency range of interest. That means that the background noise in the area (including the sound from ships passing at distance from the measurements site) should be at least 10 dB below the sound from the ship under test.

Hydrophone deployment

The deployment method shall meet the following criteria: The method shall enable the hydrophones to be positioned at a known depth in the water column (or height above the seabed); The method shall enable the hydrophones to be positioned at a known distance from the CPA of the vessel under test. The method shall provide mitigation from contaminating parasitic signals where required.

Use of multiple hydrophones is preferred, the signals recorded by the different hydrophones correspond with differences in propagation loss, leading to a more robust estimation of source level. In water depths greater than the CPA distance apply the hydrophone configuration specified in ISO 17208-1. This consists of an array of three hydrophones at depths corresponding with 15°, 30° and 45° vertical observation angles at CPA ('nominal hydrophone angle'). As a minimum, apply a single hydrophone at a depth corresponding with a nominal hydrophone angle between 15° and 45 ° .

In water depths smaller than the CPA distance, various configurations are possible: A single hydrophone in the lower half of the water depth, possibly bottom-mounted; A vertical array of three hydrophones, distributed over the water depth(Figure 6); A horizontal array of three bottom-mounted hydrophones, distributed between the minimum and maximum range for CPA distance. The CPA distance shall be greater than the acoustic ship length; The maximum distance between hydrophone(s) and ship track at CPA shall be limited, to avoid signal-to-noise problems and to reduce uncertainty associated with propagation loss estimation, It is advised to limit the CPA distance to a maximum of 5 times the local water depth; The minimum horizontal CPA distance for measuring small fast boats should be limited to achieve the minimum data window period that is needed for a reliable calculation of the SPL in the lowest frequency bands.

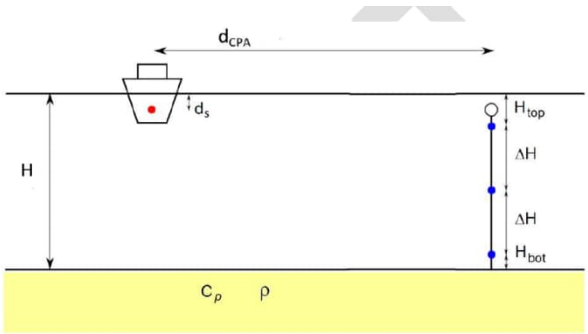

Figure 6: Proposed configuration for a vertical array in shallow water

Surface vessel based deployment and bottom mounted deployment are the most popular configurations in shallow water measurements (Figure 7). The vessel-based deployment method has the advantage that deployments can be quick and mobile, and a relatively large area can be covered fairly cost-effectively. The risk of losing instrumentation is low, the data can be monitored as they are acquired, and instrument settings can be adjusted in real time to provide the optimum settings for high quality data (for example to avoid saturation and distortion). This deployment method is suitable for measuring ship radiated sound, especially if there is a need to measure the acoustic field as a function of range from the source. Vessel-based deployments can suffer from certain types of platform-related noise.

For measurements in shallow waters, it is recommended to use bottom-mounted configurations. Static bottom-mounted systems are a good alternative to vessel-deployed systems. Multiple units may be used to obtain measurements as a function of range. A bottom-mounted deployment is preferable to a surface deployment to minimise parasitic signals from the influence of surface wave action, to keep the hydrophone away from the pressure-release water-air surface, and to minimise disturbance by surface vessels. Cost effective solutions for most deployments are autonomous recorders, which are archival and store data on memory cards or local drives with the data only available after recovery. Recovery requires either an acoustic release system or a surface buoy deployed from a seabed anchor, which enables the recorder to be hauled to the surface.

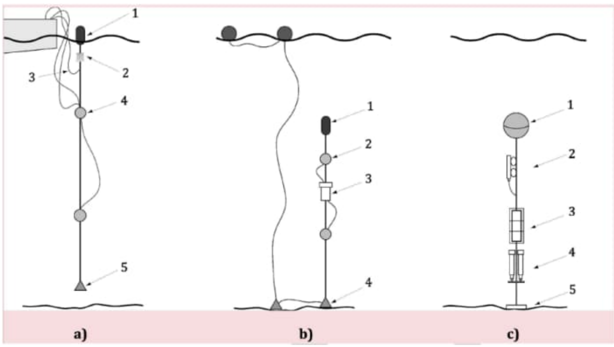

Figure 7: Examples of deployment configurations deployed from a) surface vessel, b) bottom-mounted with surface float, and c) bottom-mounted with acoustic release.

Propagation loss correction

Multiple methods for assessing propagation loss are provided: Seabed-critical angle (SCA) method; Application of an empirical formula (as in ISO 17208-2); Application of a numerical model. Also, the propagation loss assessment may be supported by measurements at the test site with a controlled acoustic source.

1) Seabed-critical angle (SCA) method

The preferred calculation method for calculating the propagation loss for measurements according to this standard is the so-called seabed-critical angle (SCA) method [MacGillivray et al, 2023]. It approximates the propagation loss by a combination of contributions from the direct path and the first reflections from sea surface and seabed, depending on the grazing angle θ below the surface to the receiver at CPA and the seabed critical angle $(\psi_c = \cos^{-1}(c_w/c_b))$. $(\psi_c = \cos^{-1}(c_w/c_b))$. Here c_w is the speed of sound in water and c_b the speed of sound in the seabed. This estimation is derived based on the assumption that the water surface is an ideal pressure release boundary. The effect of wind on the sea surface is not considered in these formulae. The estimation of propagation loss is then obtained from the following formulae:

$$N_{PL}(f_n, d_{CPA}, h_i) = 10\log_{10}\left(\left(\sigma_1 + \frac{\psi_c d_{CPA}}{H}\sigma_2\right)\frac{r_i^2}{r_0^2}\right) dB$$

$$\sigma_1 = \left(\frac{1}{2} + \frac{1}{4(k_w d_s)^2 \sin^2\theta_i}\right)^{-1}$$

$$\sigma_2 = \left(\frac{1}{2} + \frac{3}{4(k_w d_s)^2 \sin^2\psi_c}\right)^{-1}$$

(4.14)

Where, $k_w = \frac{2\pi f}{c_w}$ the wavenumber in water, $r_i^2 = d_{CPA}^2 + h_i^2$ and $\theta_i = tan^{-1}(\frac{h_i}{d_{CPA}})$.

2) Empirical conversion formula

The following method is proposed for ship radiated noise measurements in shallow water. Although it may apply to other sensor geometry, it was designed for the case of measurements with a vertical array of 3 hydrophones, with the preferred geometry. This method adapts the approach of ISO 17208-2, for the calculation of source level from the radiated noise level measured by this array, to the shallow water environment. The proposed conversion is based on empirical correction formulae fitted to the results of numerical modelling [Meyer & Audoly, 2017-2020].

Calculate the band-integrated SPL spectrum from the sound pressures measured by the 3 hydrophones, following the procedure described in Clause 6. The corresponding root-mean-square sound pressures are noted p_1, p_2, p_3.

For each hydrophone, determine the product of the distance from the hydrophone to the ship reference point and the root-mean-square sound pressure: $p_{i,corr} = p_i . r_i$.

Here r_i is the slant range distance $r_i = \sqrt{(z_i - d_s)^2 + d_{CPA}^2}$, with d_s the nominal source depth, d_{CPA} the horizontal distance between the hydrophone and the ship reference point at CPA and z_i the depth of the hydrophones (i = {1,2,3}), all in metres.

Calculate the radiated noise level from the power average of these products for the three hydrophones:

$$L_{RN} = 10 \log_{10} \left(\frac{1}{3} \frac{p_{1,corr}^2 + p_{2,corr}^2 + p_{3,corr}^2}{p_0^2 r_0^2} \right) \text{ dB} \tag{4.15}$$

The calculation of SL is then obtained by applying a conversion term to the radiated noise level, using the following formulae, in which empirical parameters K and ε represent the effects of the sea surface and seafloor on sound propagation:

$$L_S = L_{RN} + \Delta L$$

$$\Delta L(f) = 10 \log_{10} \left(\frac{\varepsilon . K}{\left| \left(\frac{f}{f_0} \right)^2 + \frac{i}{Q} . \left(\frac{f}{f_0} \right) - 1 \right|} \right)$$

$$K = 2 \max \left(\sqrt{\frac{d_{CPA}}{H}} ; 1 \right),$$

$$f_0 = \frac{c_w}{2\pi . d_s} . \sqrt{K}, \quad Q = 0.75,$$

$$\varepsilon = 0.14\chi_z + 0.74, \text{ and } \chi_z = \frac{\rho_b . c_b}{\rho_w . c_w} \tag{4.16}$$

Where, f is the frequency [Hz], H is the local water depth [m], d_s the nominal source depth, d_{CPA} the horizontal distance between the hydrophone and the ship reference point at CPA , c_w is the sound speed in water [m/s], ρ_w is the water density [kg/m3], c_b is the compressional sound speed in the sediment [m/s], and ρ_b is the sediment density [kg/m3].

3) Propagation loss calculation using numerical modeling

Various numerical propagation loss modelling methods are available, see e.g. [Jensen et al, 2011; Wang et al, 2016, MacGillivray et al, 2022].

For the purpose of ship radiated sound measurements in shallow water, image source modelling offers the simplest approach. Due to the specific geometry, including a limited number of coherent image sources is considered sufficient [Wittekind & Schuster, 2022].

More detailed models, such as parabolic equation and wavenumber integration models, can be useful if detailed environmental information (such as geoacoustic properties of sediment layers) is available.

(4) Quantifying the acoustic environment using a controlled sound source

To calculate the ship's source level from the proposed measurements requires determining the propagation loss between the source reference position (at the assumed nominal source depth) and the hydrophone locations. A test run with a controlled sound source, deployed to the nominal source depth of the vessel under test, can be useful for either a direct measurement of propagation loss or for validation of calculated propagation loss. It is required that the source level of this sound source is known, either from previous calibration, or from direct monitoring of its output during the test. The test sequence for the controlled source runs should be equal to the test sequence for the vessel under test, and the same data processing should be applied. Pang (2023) conducted a model test using standard noise source in the lake.

The spreading may be described by "$\alpha \log_{10}(r)$" where α typically has a value between 10 and 20. The parameter $\alpha(f)$ is regressed from the function of measured sound pressure spectral level $L_p(f)$and the logarithm of distance $\log_{10}(r)$.

The empirical formula for source level is shown as below:

$$L_s(f) = L_p + 20\log_{10}(r_c) + \bar{\alpha}\log_{10}(r/r_c) + \Delta L(f) \quad (4.17)$$

Where, $\bar{\alpha}$ is the averaged propagation loss factor of frequency span 200Hz～2kHz, r is the surface distance, r_c is the critical distance, $\Delta L(f)$ is the corrections for surface reflection.

The correction formulae for deep water measurement are adopted here.

$$\Delta L(f) = -10\log_{10}\left(\frac{2(kd_s)^4+14(kd_s)^2}{14+2(kd_s)^2+(kd_s)^4}\right) \quad (4.18)$$

Where, $k_w = \frac{2\pi f}{c_w}$ the wavenumber in water, f is the frequency [Hz], d_s is the source depth [m], c_w is the sound speed in water [m/s].

Calculation of radiated noise level

The resulting source level spectrum can be converted to a radiated noise level similar to what would have been measured in deep water, according to ISO 17208-1. This conversion can be made by subtracting the correction given by the formula proposed in ISO 17208-2.

$$L_{RN} = L_s - \Delta L \quad (4.19)$$

4.4 Uncertainty analysis

4.4.1 Sources of uncertainty, variability, and error

Ship underwater noise measurements are subject to potentially large variations that need to be controlled or understood in order for the measurements to be of use. Numerous studies have been done to understand and quantify the source and impacts of these variations, particularly in support of drafting the various standards, classifications, and guidelines that are being issued. Attention is given to several publications that specifically address these issues. It is noted that while the terms variability, repeatability, and error are used somewhat synonymously, they can mean different aspects of results in a final level of uncertainty. It is further noted, but not expanded upon, that in uncertainty analysis a distinction is made between Type A uncertainty, which is uncertainty evaluated by statistical analysis of a series of observations and Type B uncertainty which is evaluated by non-statistical methods.

An extensive review of aspects that influence the uncertainty and repeatability of underwater noise measurements is provided in the AQUO document listed in Table 1. To estimate levels of uncertainty and repeatability, five measurements-related categories were considered:

1. Distance Measurement Accuracy;
2. Noise recording accuracy;
3. Propagation/Transmission loss;
4. Vessel;
5. Post processing.

The Vessel category covers issues of speed, propeller/machinery conditions, load conditions, and currents. A theoretical study of expected uncertainty for each category was made. The values for repeatability are identical as for the uncertainty but exclude contributions from noise recording and transmission. **Errore. L'origine riferimento non è stata trovata.** is a modified copy of the uncertainty and repeatability estimates provided in the AQUO document. In the original tables a distinction is made between deep and shallow water, but apart from the grade A U(D) term the numbers for the uncertainties are identical so they are not listed separately in **Errore. L'origine riferimento non è stata trovata.**. These theoretical estimates were found to be in general agreement to estimates based on review of a set of ship noise data.

An investigation into the repeatability of noise measurements was performed as part of the SONIC project by Humphrey *et al.* (2015). The standard deviation (70% uncertainty) of levels from a single hydrophone for several runs is between 1 and 2 dB, but it may increase significantly at low frequency for hydrophones deployed relatively close to the free surface. Systematic differences between hydrophones deployed at different depths were observed for frequencies below 1 kHz while for higher frequencies differences between hydrophones were of the same order as the variability for a single hydrophone.

Regression analysis applied to a large number of sea trial data involving cavitating propellers gave an average uncertainty estimate, at 95% confidence level, of 4.8 dB for a single dataset and 6.5 dB for combined data sets (Sponagle 1988). A single data set consists of noise spectra measured within a period of a few days and combined datasets consists of noise spectra for the same ship measured at different times over a period of several years.

4.4.2 Quantification and minimization of uncertainty

Independent of the testing protocol followed, uncertainty estimates for each of the five categories listed in the AQUO Standard should be made. The method of estimating the uncertainty should be clearly described.

Estimates of uncertainty resulting from data acquisition and processing systems can be made using standard procedures such as those provided by the ISO/JCGM documents listed at the end of this section. Adopting modern data acquisition procedures, dedicating particular attention to system maintenance, and performing scheduled calibrations should result in instrumentation errors being of marginal concern.

Measurements of underwater ship noise are greatly influenced by on-range environmental conditions which include: effects on source-to-receiver propagation characteristics (transmission); multi-path transmission due to sea surface and ocean bottom reflections; and, contaminating effects of background ocean noise. To minimize propagation-related uncertainty, range propagation characteristics should be well documented based on dedicated acoustic calibrations such as those from towed known source calibrations. Results of calibrations of this type should be included in reporting of underwater ship noise measurements to allow the customer to estimate the impact of this uncertainty when using the reported measurements. Procedures for accounting for background noise were provided earlier. To minimize this uncertainty, careful attention should be given to monitoring background noise and ensuring that for each underwater noise measurement there is a measurement of background noise representative of what existed during the ship noise measurement. If possible, the conduct of test runs should be conducted so that quieter ship conditions are tested during periods of lower ambient/background noise.

Repeatability issues may occur due to unintended deviations in ship operations (equipment line-up, speed, etc.) or due to variations resulting from changes in seaway conditions (currents, wave action, etc.). Uncertainty due to ship operations are minimized by careful attention to ship conditions and indoctrination of ship's crew as to the impact of ship operations on underwater noise. There is little control over uncertainty resulting from seaway conditions other than conducting tests only during favourable weather conditions, which is generally not possible. Careful documentation should be made of both weather and seaway conditions for all ship noise measurements so that the influence of this uncertainty can be assessed. To minimize seaway-related uncertainty it is recommended that multiple sets of measurements be made for each condition with the reported noise being an average of these individual results. Repeat tests are a principal method listed by all standards and best practices as a means to mitigate/quantify uncertainty.

Variations in the ship's acoustic source condition will affect the repeatability and reproducibility of SPL and SL measurements. These variations are highly case specific. Some conditions (machinery settings and propeller rpm, draft) can potentially be controlled by the use of rigorous measurement procedures. Environmental effects are mainly relevant for reproducibility, they may affect repeatability as well, for example speed differences at courses with and against the current and due to weather variations.

The averaging time will affect the SPL measurement, because the distance between ship and hydrophones varies during a run. The received sound pressure will vary with time because the lengths of the direct and surface reflected sound paths vary.

Overall uncertainty analysis should be done in accordance with the following regulations/recommendations:

JCGM100:2008: Evaluation of measurement data – Guide to the expression of uncertainty in measurement. (GUM guide)

JCGM104:2009: Evaluation of measurement data – An introduction to the "Guide to the expression of uncertainty in measurement" and related documents. (Introduction to GUM)

JCGM200:2012: International vocabulary of metrology – Basic and general concepts and associated terms. (VIM)

It is recommended that users determine their own assessment of uncertainty based on the guidance in this Clause and the methods described in the ISO/IEC Guide 98 3:2008, Uncertainty of measurement — Part 3: Guide to the expression of uncertainty in measurement.

5. REQUIRED AND RECOMMENDED DATA

In addition to the recommendations provided in Section 3, particulars of the test ship, measurement system, graphic of the measurement results and environmental condition shall be considered and reported along with the noise measurements.

Errore. L'origine riferimento non è stata trovata. provides a listing of data that is "Required" to be reported and data that is "Recommended" to be reported. If the latter are considered, the reliability and the quality of the measurements will be considerably improved.

The comparison between data of full-scale noise measurements and data of extrapolated model-scale cavitation noise measurements should preferably be performed using source levels for both datasets. This in order to exclude the effect of propagation which is notably different for the two measurements.

6. PARAMETERS LIST

6.1 Data Reduction Equations

Sound Pressure Level

$$L_p = 10\log_{10}\frac{\tilde{p}_{rms}^2}{p_0^2}$$

Propagation loss

$$PL = L_s - L_p$$

Propagation loss for spherical spreading in freefield

$$PL_{freefield} = 10\log_{10}(r/r_0)^2$$

Radiated noise level in deep water

$$L_{RN} = L_p + PL_{freefield} = L_p + 10\log_{10}(r/r_0)^2$$

Correction for free surface effects in deep water

$$PL_{LM} = -10\log_{10}\left(\frac{2(kd_s)^4 + 14(kd_s)^2}{14 + 2(kd_s)^2 + (kd_s)^4}\right)$$

Source Level

$$L_s = L_p + PL$$

Source Level in deep water

$$L_s = L_p + PL_{freefield} + PL_{LM}$$

oSurce Level in shallow water

$$L_s = L_p + PL_{shallow}$$

6.2 Definition of Variables

D	propeller diameter	(m)
p_0	reference sound pressure in water	(Pa)
L_p	sound pressure level	(dB, re. 1 μPa)
$L_{p,f}$	sound pressure spectral density Level	(dB, re. 1 $\mu Pa^2/Hz$)
f_{min}	lower frequency of band	(Hz)
f_{max}	upper frequency of band	(Hz)
Δf	frequency bandwidth	(Hz)
R	range	(m)
d0	reference distance	(m)
PL	propagation loss	(dB, re. $1/m^2$)
LS	noise source level	dB, re. 1 $\mu Pa^2 m^2$)
LRN	radiated noise level	(dB, re. 1 $\mu Pa^2 m^2$)

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8. KEYWORD:

ITTC, procedures, guidelines, underwater radiated noise, full-scale test, shallow water, deep water, propagation loss

9. TABLES AS ANNEX

Table 2: Computed estimates of the uncertainty U and repeatability R at 95% confidence level for the URN measurements procedure as given in AQUO D3.1 (2014).

Grade		A[1]	B[1]
Accuracy type		engineering	comparison
Distance accuracy measurement	U(D), R(D)	1 dB	1.5 dB
Noise recording accuracy[2]	U(H)	2.5 dB	4.3 dB
Transmission/Propagation loss[3]	U(TL)	3 dB	7 dB
Vessel	U(V), R(V)	1 dB	1.2 dB
Post Processing	U(PP), R(PP)	2 dB	2 dB
Total Uncertainty		4 dB	7 dB
Total Repeatability		1.2/2.3 dB	2/3 dB
[1]: In the original table a distinction is made between deep and shallow water, but apart from the U(D) for grade A, the numbers for the uncertainties are identical and are not listed separately in this table			
[2]: Due to fact that this uncertainty is only important for high frequencies, it is not accounted for in the final uncertainty of the measurement			
[3]: Note that some publications use the term ‘transmission loss’ instead of ‘propagation loss’. Propagation loss was adopted in (ISO 18405, 2017) and is therefore generally preferred.			

Table 3: Required and recommended data for reporting underwater noise measurements

	Required	**Recommended**
General information (Ship, propeller operating conditions)	Type of ship Main and auxiliary machinery equipment and resilient mountings Ship main particulars (length, draft fore/aft, breadth) Propeller main particulars (Diameter, number of blades, pitch, running pitch) Shaft immersion and number of shafts Known problems or concerns that may affect underwater sound levels Hull and propeller(s) inspection Engine power, RPM and ship speed for each run	IMO number Classification Year of construction Propeller design conditions Drawing of stern shape including arrangement of appendages Last date and means of hull and propeller cleaning Accuracy of ship operating conditions during testing; o Speed (kn) o RPM o Power setting o Pitch (for CPP)
Position and time of the measurements	GPS-coordinates of the measurement system and the test ship positions Depth of water	Distance to coast Sea bottom type/sediment type Date and time of measurement at each run
Environmental conditions	Water temperature Weather and sea-state	Wind speed and rate of rainfall Vessel traffic Sound speed profile / Variation of temperature/salinity with depth
Measurement system and Instrumentation	Deployment of the system Number of hydrophone(s) Position of hydrophone(s) Depth of hydrophone(s) deployment Review of data acquisition system Type, frequency range, directionality, sensitivity Data sampling rate Type and settings of amplifier and filters	Hydrophone manufacture, model number and sensitivity Field calibration method and results Factory calibration data

Measurements and processing	Description of ship track geometry Measuring period Integration period used for measuring level (i.e., ± 30°) Correction procedures applied to measured levels o Background noise o Range correction (spherical spreading, etc.) o Propagation loss (by absorption) o Surface effects (e.g. Lloyd mirror) o Bottom effects Underwater sound pressures o 1/3 octave band o Narrowband o Source levels Multiple hydrophone averaging Multiple run averaging Background noise level Results of uncertainty analysis (error bounds for reported levels)	• Vibration characteristics of ship hull • Time series