DIRECTIVITY OF UNDERWATER RADIATED NOISE FROM COMMERCIAL FERRIES AND IMPLICATIONS FOR MEASUREMENT APPROACHES

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1 INTRODUCTION

Anthropogenic underwater noise impacts on marine life are a growing concern worldwide. Vessel noise has been shown to impact marine life, altering an animal's ability to perform critical functions such as feeding, mating, communication, and navigation[1,2]. Research has shown there is generally a three decibel rise in background noise every ten years from shipping[3], though variations have been found in local areas[4,5]. With rising underwater noise comes the potential for disruption of marine life, impacts to populations, and degradation of overall ocean health.

These issues have been recognized by the international community. In August 2023, the International Maritime Organization (IMO) issued the "Revised Guidelines for the Reduction of Underwater Radiated Noise from Shipping to Address Adverse Impacts on Marine Life"[6]. The document highlights the need to reduce underwater noise, and discusses the interrelationships between energy efficiency, greenhouse gas reduction, and underwater radiated noise reduction. The document is part of the IMO's greater effort to identify how the commercial maritime industry can design and construct vessels with lower underwater radiated noise impacts on marine life while also meeting mandatory greenhouse gas emission reduction targets.

There is an associated effort to develop standardized, harmonized approaches to measuring underwater noise from vessels. Various standards have been established over recent decades by regulatory entities such as the American Bureau of Shipping (ABS), Det Norske Veritas (DNV), Lloyds, and others. These standards are generally similar in their overall approach, though the details of measurement and calculation procedures vary. The American National Standards Institute (ANSI) and the International Organization for Standardization (ISO) have developed standards for underwater noise measurements of vessels in deep water; these are ANSI S12.64 Part 1 and ISO 17208-1, respectively[7,8]. The two standards are largely identical; in the authors' experience, these are the most often used standards, especially when a specific regulatory body's method is not required.

The ANSI and ISO approaches are only intended for deep water measurements where the bottom does not interfere with the acoustic measurement of the vessel. However, such measurements are not practical in many situations; deep water may not be available within a reasonable distance of a vessel's home port, and/or the vessel may not be able to transit to deeper waters for logistical or operational reasons. There have been various attempts to develop a standard for shallow water measurements, though a standardized measurement methodology for shallow water is challenging. Most obviously, the reflection from the bottom is more likely to interfere with the direct path signal in shallow waters. At very large distances, multi-path propagation effects become important. As a result of these and other factors, the measured sound in shallow waters is typically not directly comparable to deep-water measurements without some sort of correction applied to the measurement.

This paper presents underwater noise data collected by the authors from various vessels operating in shallow and deep water to help inform the discussion of shallow water measurements. The data provides insight as to where measurements can be performed relative to the vessel to obtain valid data. The goal of this paper is to help inform methodologies that are practical for commercial vessels that can also help minimize errors which are inevitable in shallow water environments.

2 BACKGROUND ON MEASUREMENT APPROACHES

2.1 ANSI and ISO Deep Water Standards

ANSI S12.64 Part 1 and ISO 17208-1 measurements employ multiple hydrophones deployed at varying depths. The test vessel performs multiple transits past the hydrophones at a nominal distance. Diagrams of the basic test setup and vessel track are shown in Figure 1. At the vessel's Closest Point of Approach (CPA), the hydrophones are positioned 15, 30, and 45 degrees below the water surface plane. The nominal distance at CPA (d_{CPA}) is typically 100 meters.

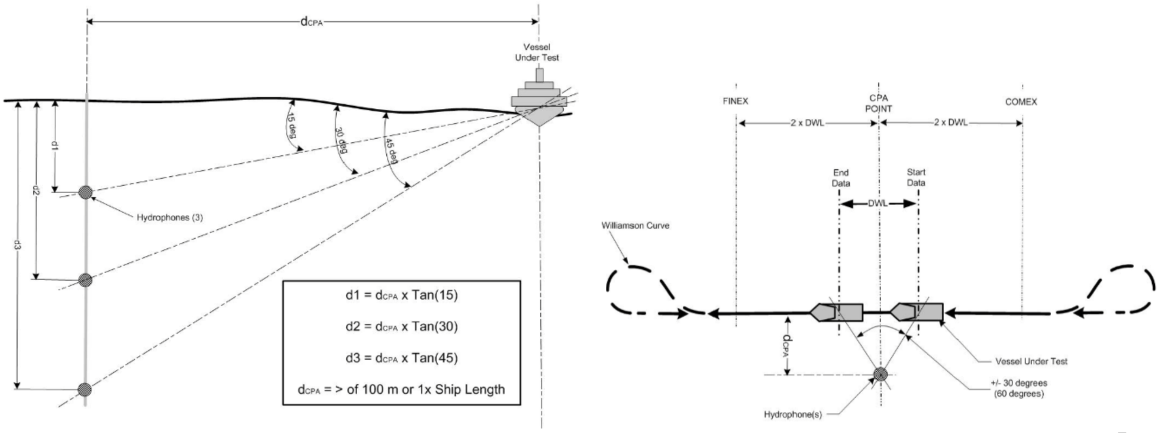

Figure 1: ANSI S12.64 Part 1 Hydrophone Arrangement (left) and Vessel Track (right)[7]

Variations in sound levels are expected at different locations through the water column due to potential differences in radiation directivity, as well as the phase-inverted reflection off the water surface. The use of multiple hydrophones at different depths creates a spatial average of these variations. While this approach is prudent to improve the accuracy of the measurement, the specific hydrophone arrangement shown in the ANSI and ISO standards is somewhat arbitrary. Alternative measurement angles could be used with similar accuracy as long as the measurement locations are reasonably far from the water surface, where the pressure would go to zero.

The selection of 15-, 30-, and 45-degree angles appears to be one of convenience. At a CPA distance of 100 meters, the lowest hydrophone is 100 meters below the water surface. In the authors' experience, this is a practical distance considering the effort required to put the hydrophone in that location, particularly when the hydrophones are suspended from the water surface. If an 80-degree receiver angle was required, the hydrophone would be at a depth of 567 meters. While possible, this is not particularly practical, and requires far greater water depths than the ANSI and ISO minimum water depths of 150-300 meters.

The ANSI and ISO measurement procedures imply the vessel will perform specific operations for the measurement of underwater noise. That is, the vessel is able to navigate past the hydrophones, turn around, and transit back, repeating multiple times. There is nothing that prevents the ANSI and ISO methodology from being used on an opportunistic basis, i.e. measurements of vessels during their normal operation, but it is less practical and the specific distance and angle requirements become difficult to obtain.

2.2 Potential Measurement Approaches for Shallow Water

Various approaches to measuring underwater noise from vessels in shallow waters have been proposed over the years. In most cases, the approach involves measuring sound at one or more positions on or near the sea floor, with a correction applied to account for propagation effects.

An example hydrophone arrangement is shown in Figure 2, which is taken from a recent document discussing possible shallow water measurement methods[9]. In this example, three hydrophones are installed on the sea floor at varying angles. The document allows for some flexibility in the placement of the hydrophones, though the closest hydrophone should have a minimum lateral distance to the vessel of 100 meters at CPA (r_{CPA1}). Given the other constraints discussed in the paper, this implies φ_1 would be 45 degrees or less. At this and greater distances, complex sound propagation with one or multiple reflections is likely.

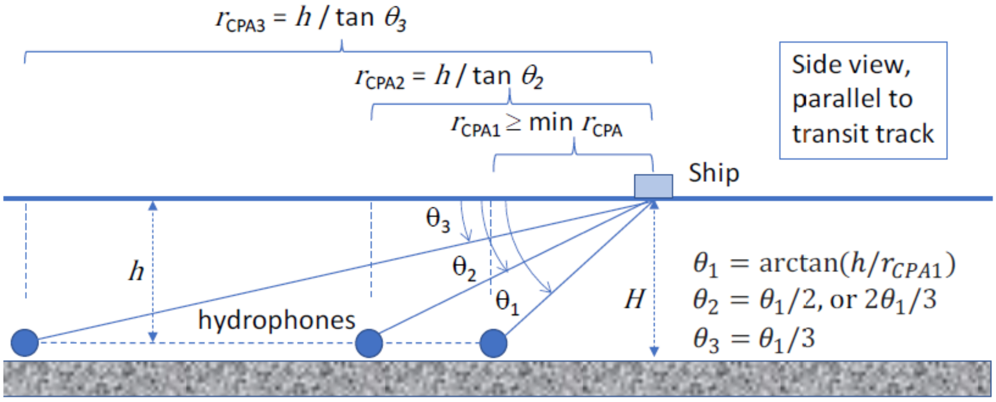

Figure 2: Potential hydrophone arrangement for measurement in shallow water[9]

The measured sound level at each hydrophone is corrected to a 1-meter "source level" in a free field environment to provide direct comparisons to the ANSI S12.64 and ISO 17208-1 methods. Since reflections and multi-path propagation are likely to be a factor for these measurement locations, the simple spherical spreading model used in the ANSI and ISO standard cannot be applied. A more complex sound propagation model must be used.

A complete discussion of sound propagation modeling is outside the scope of this paper. In brief, the transmission loss between a specific source-receiver pair is a function of their locations, water depth, acoustical properties of the sea floor (possibly through multiple layers of different media), sound speed profile, presence of surface waves, roughness of the bottom, and more. Long range sound modeling is a developed field, and there are a variety of tools available for performing predictions, many with impressive accuracy. However, it must be recognized that all models will have inaccuracies, and those inaccuracies will be exacerbated by poor, incomplete, or erroneous input data. Estimations of input data can and regularly are implemented when modeling sound propagation in complex environments. To create high accuracy models, one must know a lot about the specific local environment. Such information is not always easy to acquire.

This presents an issue for assessments that rely on modeling. Part of the intention of vessel measurements is to verify a vessel's noise is within specific limits or goals. While there are very few instances currently where noise limits are applied to commercial vessels, it is prudent to expect future regulation to apply acoustic metrics or impose limits. Therefore, uncertainties in the measurement process, such as an input quantity in an acoustic model, can lead to disagreement, legal battles, etc.

The approach represented in Figure 2 can be valuable when attempting to get a general sense of vessel noise, especially for vessels of opportunity. When multiple vessel passes can be obtained from a single vessel because the hydrophones have been installed along a transit route, the proposed approach can provide valuable information with simple estimations of the required modeling input parameters. However, care should be taken when establishing a standard measurement methodology; complex sound propagation models that rely on difficult to obtain parameters may lead to problems.

A different shallow water measurement approach has been used by the authors where measurements were performed directly beneath the test vessel. This approach was chosen for a particular project because it was convenient, simple, and minimized the influence of long-range propagation effects. As will be shown in subsequent sections of this paper, the influence of the bottom can still be identified in these measurements and would need to be corrected to allow for direct comparisons to deep water measurements. However, such corrections may be simpler than measurements collected at large distances from the test vessel.

3 MEASUREMENT APPROACH FOR FERRY UNDERWATER NOISE

3.1 Overview

The authors measured underwater noise from ferries performing normal operations in different locations in the United States. Several ferry classes were measured with lengths ranging from 80 to 140 meters. All ferries were double ended, with one propeller on each end. For all data presented in this paper, propeller cavitation is the dominant source of noise at all frequencies.

Hydrophones were temporarily installed along the ferry routes, some in ‘deep’ water and some in ‘shallow’ water. The ferries transited under controlled operating parameters when near the hydrophones to ensure data consistency. The hydrophones were installed for about a week, allowing data to be captured and averaged for many vessel transits.

The ferries were instructed to transit directly over the hydrophones. However, many events were also captured when the vessel did not travel over the hydrophone and instead transited at various distances to the side of the hydrophone. This data provides an opportunity to compare the underwater noise at various angles and compare it to the noise measured directly below the vessel.

In all cases, the data processing methodology of ANSI S12.64 was followed. All data presented in this paper is distance corrected to a 1-meter “source level” (as defined in ANSI S12.64) using a simple spherical spreading correction. The measured distance between the hydrophone and the vessel was used in all cases. No additional corrections for sound propagation have been used in the data presented here, including the data collected in shallow water. Care was taken to reject any data when other vessels were nearby and could influence the measurement results.

3.2 Hydrophone Setup

The water depth for ‘deep’ water measurements was 150 meters. A single hydrophone was positioned at a depth of 85 meters below the surface, moored to the bottom. The water depth for ‘shallow water measurements was 47 meters. The hydrophone was positioned roughly 1 meter above the bottom. A schematic of both test setups is shown in Figure 3.

3.3 Notes on Vessel Types

It is briefly noted that some ferries were diesel electric, while others were diesel geared. The primary distinction of note here is the diesel electric ferries always used the propellers on both ends for propulsion, while the diesel geared vessels only used the ‘aft’ propeller. All operating propellers produced cavitation, which dominated underwater noise levels. This means the diesel geared vessels had one dominant source, while the diesel electric vessels had two, one on either end.

4 MEASUREMENT DATA

4.1 Overview

The measured noise levels for a range of angles have been grouped and averaged for each vessel. Averaging of multiple vessel passes was performed in accordance with ANSI S12.64. The number of events available for each angle range is shown in the plots presented herein. There are typically more events within the 80- to 90-degree range than for smaller angles since this was the intention of the original measurement plan. The standard deviation of the presented data was calculated and found to generally be 1-2 dB below 10,000 Hz, and 2-3 dB at higher frequencies, with a few exceptions. All data is presented for ‘normal’ operating conditions except where noted. All data is presented in one-third octave bands, corrected to a 1-meter source level in accordance with ANSI S12.64.

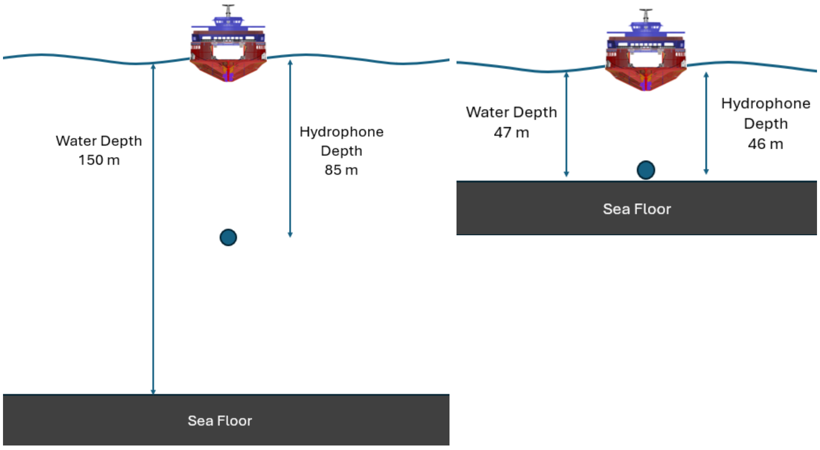

Figure 3: Schematic of Deep Water (left) and Shallow Water (right) Measurements, Not to Scale

4.2 Deep Water Results

Figure 4 through Figure 7 present the measured data for four vessels measured in deep water. Overall, the data shows remarkable similarity in the received levels. The data between 40 to 90 degrees is generally within 1-2 dB for all vessels with a few exceptions. The data collected between 20 to 40 degrees tends to have greater variations but is generally within 5 dB of the data at other angles.

It is interesting to note that the high-frequency data at 20- to 40- degrees for Vessel 1 is lower in level than the data collected between 40 to 90 degrees, while for Vessels 2, 3, and 4 it is higher. This result is unexpected, though consistent. Vessel 1 is the only diesel geared vessel that was measured in deep water, while Vessels 2-4 are diesel electric. As discussed above, this means that Vessel 1 has one effective source because it has one cavitating propeller, while Vessels 2-4 have two sources, one on either end of the vessel. This seems to produce a consistent result of slightly higher noise levels for the diesel electric 20- to 40- degree data. The cause of this discrepancy is unclear and is not the focus of this paper. The result can be used to highlight the fact that each vessel, or at least each vessel type, will have its own nuances in terms of the underwater noise that is created.

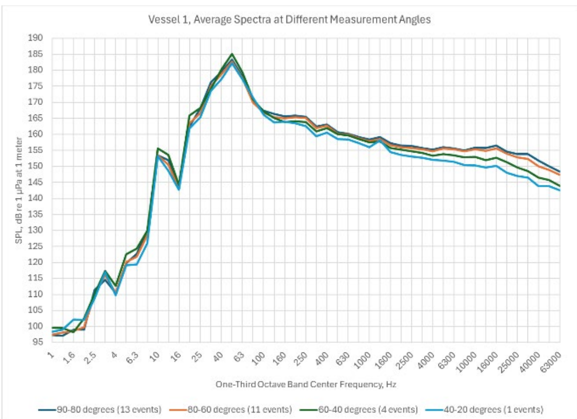

Figure 4: Vessel 1 (Diesel Geared) Radiated Noise vs. Measurement Angle, Deep Water

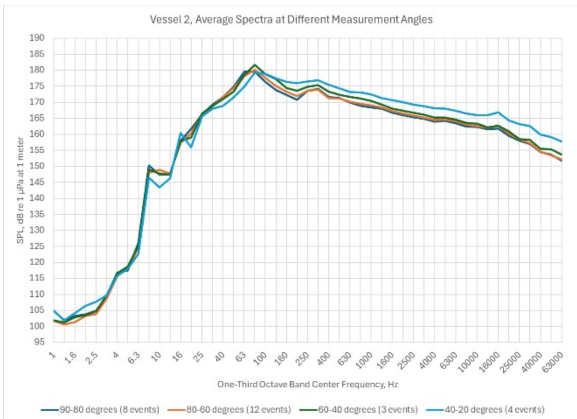

Figure 5: Vessel 2 (Diesel Electric) Radiated Noise vs. Measurement Angle, Deep Water

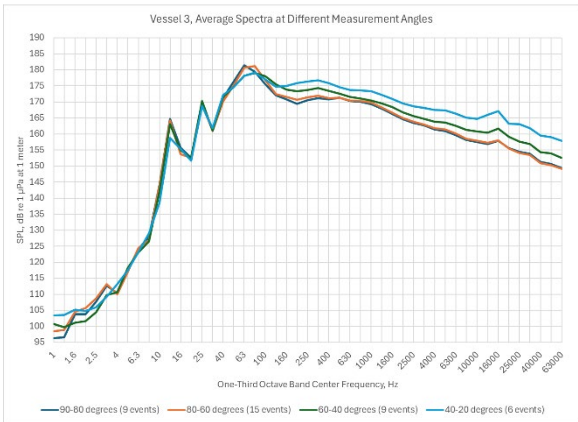

Figure 6: Vessel 3 (Diesel Electric) Radiated Noise vs. Measurement Angle, Deep Water

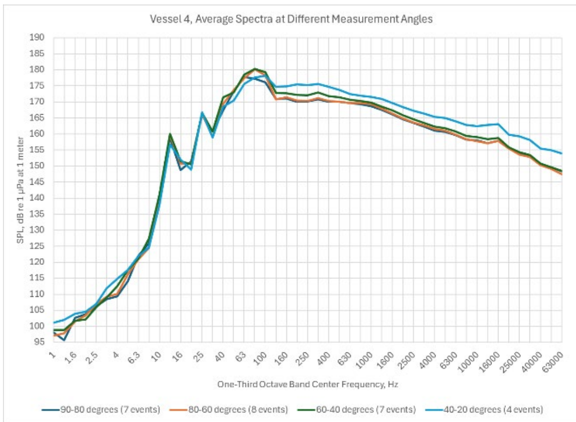

Figure 7: Vessel 4 (Diesel Electric) Radiated Noise vs. Measurement Angle, Deep Water

However, the primary result is measured noise levels for these vessels are very consistent, regardless of measurement angle. This result implies that while measurements can be performed at the standard 15, 30, and 45 degrees that are dictated by ANSI S12.64 and ISO 17208-1, measurements collected directly below the vessel should be considered equally as valid.

It is important to recognize that this result may apply primarily to vessels where propeller cavitation is the dominant source. However, propeller cavitation is expected to be the dominant source for many commercial vessels, particularly those of greatest interest to IMO and other entities aiming to reduce acoustic impacts to marine life.

4.3 Shallow Water vs. Deep Water

The measurement data collected for this study allowed for a comparison of underwater noise from two different vessels of the same class – i.e. identical design – in shallow and deep waters. Figure 8 presents this comparison for a maximum speed operating condition, measured at angles close to 90 degrees. The similarity of the data is remarkable, especially when considering these data are not of the same vessel, but rather the same vessel class collected in two different environments. Differences in the measured source level are typically on the order of 2 dB or less (above 10 Hz), with the exception of a dip and peak in the shallow water data between 315-1250 Hz.

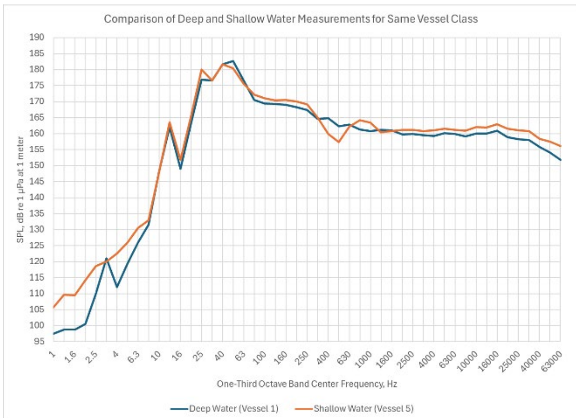

Figure 8: Comparison of Deep and Shallow Water Measurements for Same Vessel Class, 90-degree Measurement Angle

This dip-peak feature is believed to be caused by a reflection off the bottom. The hydrophone was located roughly 1 meter off the bottom. Assuming the speed of sound in water is 1500 m/s, destructive interference should occur around 375 Hz, and constructive interference would occur around 750 Hz. While not exact, there is reasonable correlation between these estimates and the dip and peak frequencies in the data.

The strong similarities between these data sets indicate measurements performed in shallow water directly below the vessel have the potential for compatibility with deep water measurements with minimal corrections. However, it must be recognized that these results may not be universal to all locations. The acoustic properties of the bottom are not known for the measurement location represented in these measurements. However, it is clear that this bottom does not produce strong reflections at all frequencies. For example, an acoustically hard surface would produce a 6 dB increase in level at low frequencies where the wavelength is large relative to the distance between the hydrophone and the bottom. However, the data shows very little if any amplification at these frequencies (250 Hz and below).

Different results may be seen for different locations due to differences in the sea floor, though a wide range of common sea floor types, including those composed of sand, silt, and clay, have similar densities and sound speeds[10]. This implies that measurements in many areas of the world may have similar results to those shown here, though a more comprehensive investigation would be needed to obtain high accuracy for any singular site.

The similarities between the deep and shallow water data are at least partially a result of the measurement location: directly below the vessel. There is apparently only one reflection of note off the bottom. At worst, this produces 'erroneous' results relative to deep water in a limited frequency range. At best, this limited impact simplifies the data correction process.

4.4 Additional Shallow Water Results

Example shallow water measurement data from two vessels are provided in Figure 9 and Figure 10. The data shows similar trends to the deep water data; data at angles between 40 and 90 degrees are very similar, and the 20- to 40- degree data has more separation. Note that Vessel 5 is diesel geared, while Vessel 6 is diesel electric. Similar trends in the relative levels at high frequencies seen in deep water for diesel electric vs. diesel geared are seen here as well.

The other interesting element seen in this data is the dip-peak feature is seen to shift higher in frequency with increasing angle. This is further evidence that this feature is caused by the bottom reflection. At greater angles, the vessel is further from the hydrophone and the path length difference between the direct and reflected paths shrinks. This causes the alternating destructive and constructive interference frequencies to rise.

5 DISCUSSION AND CONCLUSIONS

Underwater noise measurements in shallow waters are challenging. The reduced water depth inevitably results in influences from the sea floor. Sea floor reflections are dependent on several factors including its acoustical properties. To create a 'deep water equivalent' source level, one must have detailed knowledge of these and other environmental parameters. This presents a challenge for standardization of underwater noise measurements in shallow water. While it would be ideal to include collection of the detailed acoustical properties of the sea floor as part of a standard measurement protocol, it is not practical in most cases due to reasonable budgetary limitations. However, there is a need for standard shallow water measurement methodologies to facilitate IMO's standardization goals. Compromises will likely need to be made to allow for and correct shallow water effects.

The data presented in this paper suggests that noise from propeller cavitation is largely omnidirectional at a vessel's CPA, and is very consistent between 40- to 90-degree angles. Overall, measurements collected directly under the vessel are no worse than measurements collected at the arbitrarily chosen 15-, 30-, and 45-degree angles stipulated in ANSI S12.64 and ISO 17208-1. In fact, there may be a preference for measurements under the test vessel due to the simplified arrangement and the potential for minimized impacts from the sea floor.

The authors do not intend to lay out the details of a new standard test methodology for shallow water within the context of this paper, though simplified procedures will be needed to facilitate measurements of all commercial vessels. The data presented will hopefully provide information relating to simplified options for shallow water measurements.

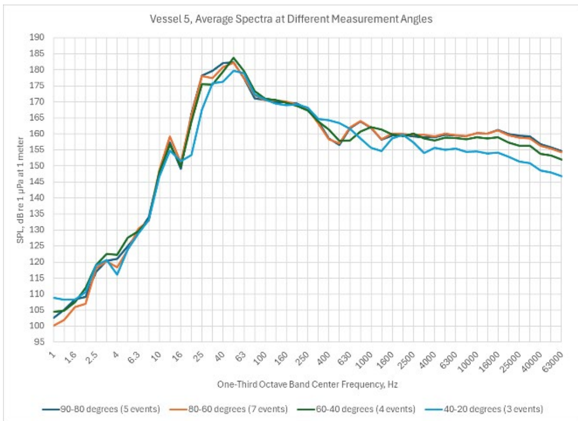

Figure 9: Vessel 5 (Diesel Geared) Radiated Noise vs. Measurement Angle, Shallow Water

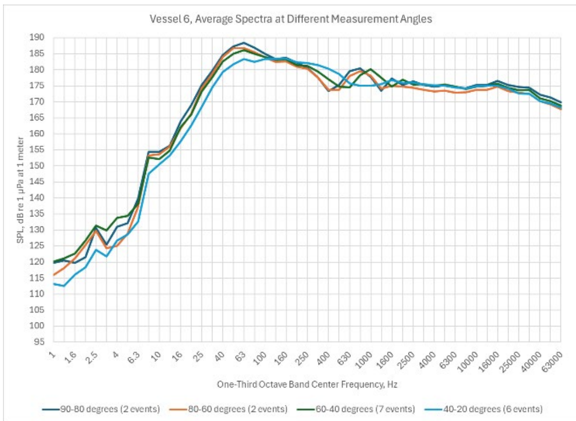

Figure 10: Vessel 6 (Diesel Electric) Radiated Noise vs. Measurement Angle, Shallow Water

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