Modelling Underwater Noise for Indian Marine Mammal Conservation

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Abstract - The escalating concern over the impact of underwater noise emitted by ships on marine mammals has garnered increasing international attention within the realm of marine conservation. Collaborative efforts between numerous countries and the International Maritime Organization (IMO) are underway to tackle this pressing issue, particularly focusing on noise reduction from commercial shipping. Ships produce significant noise through various operations such as engine functioning and propeller cavitation, posing a threat to the delicate auditory capabilities of marine mammals like whales, dolphins, and seals. This noise disrupts vital functions like communication, navigation, and feeding, leading to behavioural changes, habitat displacement, and even physical harm.

This paper focuses on the Indian coastline and the critically endangered Indian Humpback whale. It analyses numerical models to understand how underwater noise propagates and affects marine life. It identifies common challenges and knowledge gaps. Importantly, the paper emphasizes the need for further research on underwater sound propagation specific to the Indian coast. This knowledge is crucial for effective protection of marine mammals in the region.

Keywords: Humpback whale; IMO; Marine Mammals Protection; Ocean modelling; Sound Propagation; Underwater Noise.

1. INTRODUCTION

The underwater realm serves as a vibrant and intricate ecosystem, teeming with diverse life forms that rely heavily on sound for survival. Marine mammals, in particular, utilize sound waves as their primary mode of communication, navigation, and sensory perception [1]. However, the natural acoustic landscape of this hidden world is no longer solely shaped by the symphony of natural sounds. Human activities such as shipping, offshore drilling, and naval operations significantly influence the underwater soundscape.

Among these activities, the noise generated by commercial shipping stands out as a substantial source of underwater noise pollution, potentially causing profound consequences for marine mammal populations. The International Maritime Organization (IMO) has acknowledged the growing problems related to underwater radiated noise (URN) pollution caused by ships and has revised its guidelines to address the adverse effects on marine life (2023 IMO Guidelines on URN, IMO MEPC.1/Circ.906 [2]). These revised guidelines encompass a ship's design, construction, modifications, and operation, and can be applied to any ship. Recognizing the complexities of ship design and the need for diverse approaches to reducing URN, the Indian Register of Shipping (IRCLASS) has also taken a proactive step and released Guidelines on Underwater Radiated Noise and Measurements, in July 2023. This specifies URN notations that ship owners can adhere to for vessel certification [3].

Ship traffic is accountable for the steady increase in ambient noise at low frequencies (10–1000 Hz) across numerous ocean regions, with a reported rate of increase as high as 3 dB/decade [4], [5]. The origin of ship noise can be attributed to various sources associated with vessel operation, including engine propulsion, propeller cavitation, and the interaction of the hull with water. This noise encompasses a broad spectrum of frequencies and can propagate over vast distances within the marine environment. When this noise overlaps with the sensitive auditory systems of marine mammals, it can have significant ramifications for their behaviour, physiology, and overall ecology [4].

Chronic exposure to elevated levels of ship noise can further influence the distribution patterns and habitat utilization of marine mammals [1], [6]. Species inhabiting coastal areas or frequenting regions with high shipping traffic may alter their behaviour to avoid areas with intense noise levels, leading to modifications in their distribution and habitat preferences. Such displacement can have cascading effects on marine ecosystems, impacting predator-prey dynamics, community structure, and overall ecosystem function.

Understanding how sound travels underwater in the Indian Ocean, with its unique layers and varying freshwater inputs, is crucial for studying marine life communication and the impact of human-made noise. This knowledge can guide efforts to protect marine animals. Quieter ships, reduced speeds in sensitive areas, protected zones, and real-time noise monitoring are all strategies that can help minimize acoustic disturbance and safeguard marine mammal populations in Indian waters.

2. DIVERSITY AND DISTRIBUTION OF MARINE MAMMALS IN THE INDIAN REGION

The Indian Ocean supports a rich and diverse assemblage of marine mammals, encompassing a variety of taxonomic groups. Cetaceans (whales, dolphins, and porpoises) are the most prevalent, with estimates suggesting the presence of 30-35 species in Indian waters[7]. These include baleen whales (filter feeders such as blue whales and fin whales), toothed whales (e.g., sperm whales, bottlenose dolphins, and spinner dolphins), and beaked whales (known for their deep-diving habits). Additionally, dugongs, sirenian mammals related to manatees, are also present.

2.1. Legislative Protection

India recognizes the ecological significance of marine mammals and has incorporated them within the ambit of the Wildlife Protection Act of 1972. This act offers legal protection to all marine mammal species within Indian territorial waters.

2.2. Challenges in Marine Mammal Conservation

Despite legislative safeguards, there are significant challenges in ensuring the effective conservation of marine mammals in India. A major concern is the lack of a standardized protocol for responding to stranded marine mammals. Stranding events (refer to Figure 1, and Figure 3), where marine mammals become beached or entangled in fishing gear, are unfortunately becoming increasingly common along the Indian coastline. The absence of a standardized protocol hinders a coordinated and efficient response to these events, potentially compromising the chances of rescuing or rehabilitating stranded animals. The Central Marine Fisheries Research Institute (CMFRI), a leading tropical marine fisheries research institute established by the Indian government, maintains extensive records and databases. Additionally, the Marine Mammal Research & Conservation (MMRC), a group founded by Indian and international marine mammal scientists, has created a website [5] containing a database of marine mammal sightings and strandings along the Indian coast for the past decade.

Out of the 30-35 cetaceans species around along the Indian coastline, one specific species of Arabian Sea humpback whales (ASHWs) has been of interest to many researchers because this species which once used to dominate the Arabian Sea between Oman and India has been listed as “Endangered” on the International Union for Conservation of Nature’s Red List, refer Figure 2.

2.3. Acoustic Detection of Arabian Sea Humpback Whales in Indian Waters

To enhance the study of the Arabian Sea humpback whale presence in Indian waters, Madan M. Mahanty et al. [8] from the National Institute of Ocean Technology (NIOT) developed a noise measurement system for time-series data collection in shallow waters. This system was deployed along the west coast of Cochin, India, from January to May 2011. The study focused on analyzing repeatedly produced sounds with specific patterns, noting their fundamental frequency, range, and duration. A total of 1208 data sets were recorded, with only 10 exhibiting characteristics similar to humpback whale vocalizations. These candidate sounds were categorized into groups A-C and P-S based on their characteristics, as presented in Table 1. Details on the occurrence and associated frequency range were also included.

Building on this work, Maia L. D'Souza et al. [9] from the Indian Institute of Science Education and Research (IISER) conducted passive acoustic monitoring (PAM) along India's west coast in 2019. Their study analyzed data collected over a 77-day period with 5 hours of deployment, totaling 707.5 hours (1,415 recordings of 30 minutes each). The analysis identified 39,767 humpback whale call units, categorized into 11 call types (A-J). Information on occurrence and associated frequency for each call type is documented in Table 2.

Figure 1: Standing of Humpback whale ©www.marinemammals.in – photo by Dipani Sutaria recorded dead near Gujarat in Sep 2017

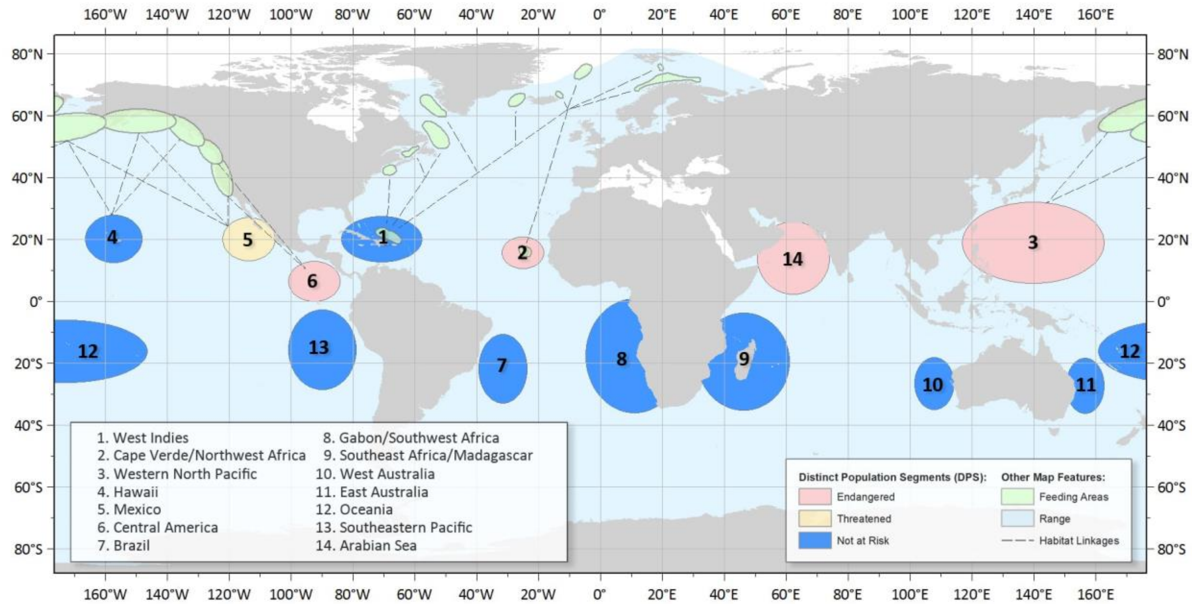

Figure 2: Map showing locations of the 14 distinct population segments of humpback whales worldwide©www.fisheries.noaa.gov

Figure 3: Standing of Humpback whale ©www.marinemammals.in – photo by Harshal recorded dead near Maharashtra in Sep 2018

Table 1: Summary of acoustic parameters measured for each sound unit recorded by Madan M Mahanty et al. [6]

Unit Type	P	Q	R	S	A	B	C
	Up sweep Groan	**Low Gulps jumping**	**Tonal Up sweep**	**Tonal Down sweep**	**Down sweep**	**Up sweep**	**Down sweep**
Number of units for which acoustic features were measured	(n=9)	(n=8)	(n=10)	(n=11)	(n=12)	(n=12)	(n=12)
Duration (s)	1.87	3.68	1.01	1.1	1.19	1.47	1.67
Frequency range (Hz)	227-1160	96-128	1095-8810	390-8570	208-2954	195-781	98-270
Max fundamental frequency (Hz)	416.12	128.48	1404.45	698.76	463.87	341.38	158.9
Min fundamental frequency (Hz)	227.35	95.84	1095.47	390.43	207.9	195.28	98.07

Table 2: Summary of acoustic parameters of call unit types recorded; each value is reported as mean ± standard deviation by D'Souza et al *[9]*

Call Unit Type	Start frequency (Hz)	End frequency (Hz)	Minimum frequency (Hz)	Maximum frequency (Hz)	Duration (s)	Bandwidth (Hz)
A (*n* = 66)	629.44 ± 18.97	580.79 ± 30.34	509.67 ± 39.12	692.87 ± 31.14	5.5 ± 0.43	183.2 ± 57.82
B (*n* = 628)	280.85 ± 33.9	110.9 ± 43.83	68.03 ± 11.85	298.08 ± 27.73	1.19 ± 0.13	230.05 ± 30.7
D (*n* = 287)	941.64 ± 48.64	752 ± 30.1	706.75 ± 88.65	979.99 ± 103.99	4.46 ± 0.41	273.24 ± 56.51
F (*n* = 330)	280.72 ± 42.46	467.6 ± 50.85	248.27 ± 19.08	492.63 ± 55.67	4.91 ± 0.48	244.36 ± 57.87
G1 (*n* = 139)	241.98 ± 24.5	235.58 ± 18.85	113.12 ± 16.1	263.09 ± 22.48	1.32 ± 0.16	149.98 ± 29.22
G2 (*n* = 395)	100.76 ± 17.37	214.65 ± 21.02	66.11 ± 12.61	226.43 ± 18.23	1.5 ± 0.16	160.32 ± 23.49
H (*n* = 332)	495.38 ± 62.77	1,028.19 ± 77.12	487.52 ± 61.32	1,029.17 ± 83.45	1.2 ± 0.15	541.65 ± 81.76
I (*n* = 264)	994.73 ± 40.68	976.03 ± 23.84	869.24 ± 37.47	1,028.26 ± 42.58	2.25 ± 0.2	159.02 ± 46.52
J (*n* = 200)	420.56 ± 26.96	607.15 ± 29.22	362.32 ± 17.28	625.01 ± 25.72	1.7 ± 0.17	262.69 ± 33.94

3. UNDERWATER NOISE POLLUTION FROM SHIPS

Anthropogenic sound waves**,** primarily generated by the operation of ships and other offshore systems, pose a significant threat to the marine environment [1], [6], [10]. These continuous sound sources create a chronic issue for marine life that relies heavily on sound for communication, navigation, and feeding. While seismic exploration, military sonars, and fish-finders also contribute to underwater noise pollution, present discussion focuses on the dominant source: noise generated by ships in operation.

3.1. Categorizing Ship Noise:

Ship noise can be broadly categorized into three main types as shown in Figure 4:

- *Flow Noise:* As a ship moves through water, its hull disrupts the surrounding water, creating a pressure field and visible waves (ship wake) leading to noise. Flow noise is directly related to the ship's speed [11], [12].
- *Machinery Noise:* All rotating and reciprocating machinery onboard a ship contributes to machinery noise. This includes engines, generators, pumps, and other equipment. The combined effect can be very high sound power levels with significant vibrations. This noise propagates through the ship's structure and directly into the water. To mitigate this impact, resilient mounting and damping techniques are employed to absorb energy and reduce the overall noise level.
- *Propeller Noise:* The propeller located at the aft (rear) section, plays a critical role in noise generation. As the propeller blades rotate through the wake field, they create pressure fluctuations that translate into pulses of sound energy. Propeller blades experience cavitation, where pressure changes cause bubbles to rapidly form and implode. This process generates intense noise, with both low and high frequencies. Propeller cavitation noise is the most ubiquitous sound [10], [13] generated at higher speeds. Wittekind and Schuster [14] explain that for a large ship low frequency noise is solely attributable to propeller cavitation at frequencies below 300 Hz as shown in Figure 5.

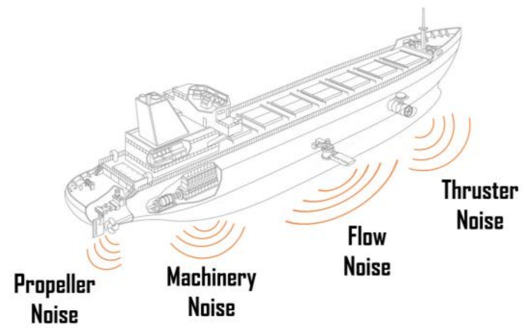

Figure 4: URN sources for a Ship

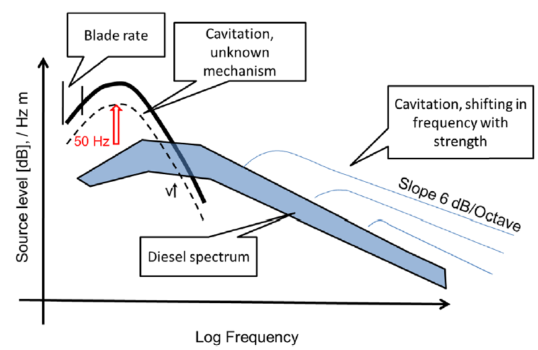

Figure 5: Generic sound spectrum of a commercial vessel [14]

4. OVERLAP OF FREQUENCIES

Humpback whales rely on sound for communication, with their songs and calls ranging from 20 Hz to several kHz. Unfortunately, this overlaps with the noise generated by ships, particularly the low rumble of machinery and broadband noise from propellers. The rumble of ship machinery, often falling below 500 Hz, creates a low-frequency assault that travels vast distances. This low-end thrum directly overlaps with the calls used by humpback whales for social interaction and coordinating feeding efforts. Adding to the problem is the broadband noise generated by ship propellers. Cavitation, the formation and collapse of bubbles around propellers, creates a cacophony of sound, with significant contributions at lower frequencies (less than 1000 Hz) for larger vessels. This broad spectrum of noise significantly overlaps with the core range (200 Hz to 1 kHz, refer to Table 1 and Table 2) used by humpback whales in their communications, particularly the intricate sequences sung by males, which are crucial for attracting mates. This "frequency collision" disrupts whale communication, potentially reducing calling rates, altering vocalizations, and causing stress.

By understanding the overlap between ship noise frequencies and humpback whale vocalizations, we can develop effective mitigation strategies.

Figure 6 compares humpback whale call unit frequencies with underwater radiated noise (URN) data measured from a ship. The figure also analyzes the ship's URN data in relation to its onboard machinery. This comparison involves measuring accelerations at the base of the machinery and then comparing it to URN levels under the same operating conditions.

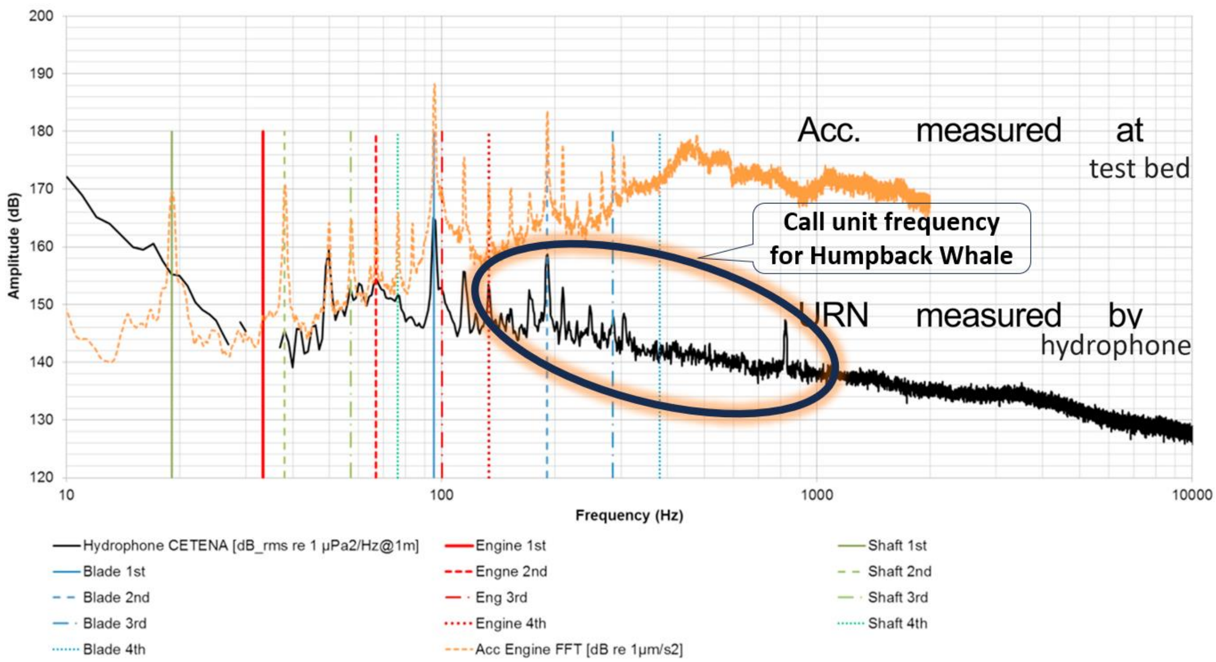

Figure 6: Overlap of Humback sound with the narrow band spectrum of the main engine acceleration compared with URN measurements for 2000 rpm [15]

5. NOISE PROPAGATION UNDERWATER

The ocean poses a significant challenge when it comes to modelling sound propagation. Unlike simpler environments, it is not a uniform medium. Instead, the ocean is a layered structure, a complex lasagna of air, water, sediment, and even rock (known as the basement) at the very bottom. Each layer possesses distinct properties that influence how sound travels through it (refer to Figure 7).

To understand sound propagation within this intricate system, researchers utilize a specific set of equations called linearized hydrodynamic equations. These equations account for factors like pressure, particle velocity, density, and most importantly, the varying sound speed within each layer. By solving these equations, scientists can predict how sound waves will travel, bend, and even be absorbed as they move through the ocean depths.

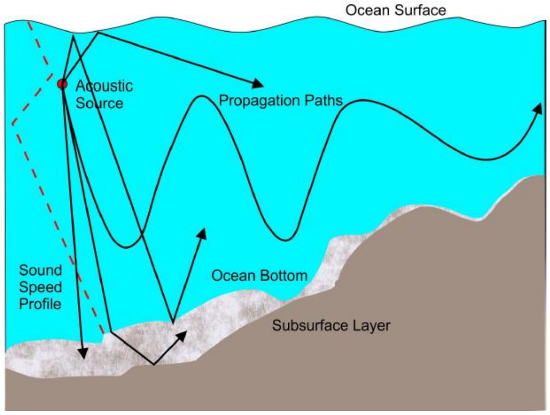

Figure 7: Visualizing Underwater Sound: Spatially Varying Environments Create Diverse Propagation Patterns[16]

5.1. Sound Speed Profile:

Underwater sound propagation, the transmission of acoustic waves through water, is a critical and intricate process underpinning various aspects of oceanography, including communication, navigation, and exploration. Several environmental factors significantly influence how sound travels underwater (refer to Figure 8 and Figure 9). These factors include:

- *Temperature:* Warmer water molecules have greater kinetic energy, allowing for faster sound propagation.
- *Salinity:* Similar to temperature, higher concentrations of dissolved salts in seawater lead to a denser medium, facilitating faster sound transmission.
- *Depth (Pressure):* Due to the increasing pressure with depth, sound speed generally increases as depth increases.

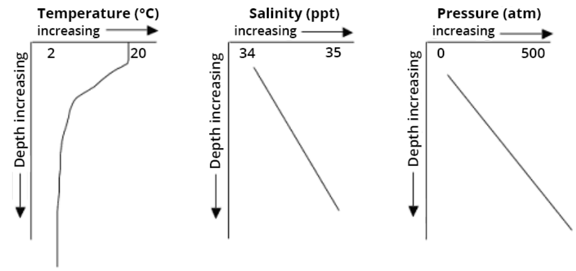

Figure 8: Depth profiles from the open ocean of temperature, salinity and density. Copyright University of Rhode Island.

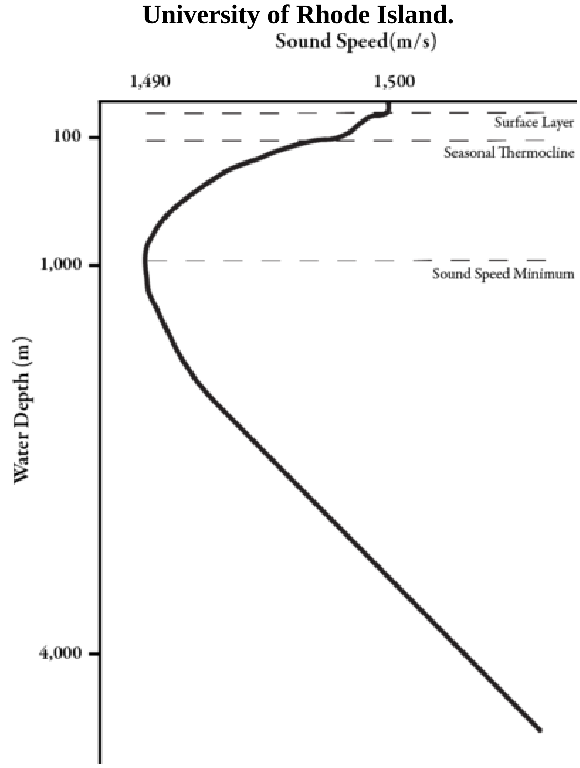

Figure 9: Profile of speed of sound in water. Note the sound speed minimum at 1000 meters. Copyright University of Rhode Island.

5.2. Propagation Loss:

The propagation loss mechanisms that significantly impact the intensity of sound waves as they travel through the ocean are as follows:

- *Geometric Spreading Loss:* Sound energy spreads outward from a source, resulting in a decrease in intensity over increasing surface area. This effect is most pronounced for small sound sources and constant sound velocity.
- *Absorption Loss:* As sound waves travel through

water, molecular interactions convert a portion of the sound energy into heat. This phenomenon weakens the sound wave and is frequency-dependent, with higher frequencies experiencing greater absorption.

- *Interface Losses:* Underwater boundaries like the sea surface and seabed cause sound energy to split between reflection and transmission. The energy loss at the interface is determined by reflection coefficients. The water-air interface can create the Lloyd's mirror effect, where reflected and direct sound waves interfere, affecting intensity. Additionally, sea surface roughness leads to scattering loss, weakening the reflected wave. Finally, the seabed's properties, especially unconsolidated layers, significantly influence reflection behaviour.

6. NUMERICAL MODELS USED FOR NOISE PROPAGATION

To predict how sound travels, researchers use different modelling techniques. Three main approaches exist: transform solutions (rearranging the sound wave equation for easier calculations), ray solutions (tracing the paths sound waves travel as they bend and bounce), and marching solutions (using equations to solve the sound wave equation step-by-step) as shown in **Error! Reference source not found.**. These techniques each have their strengths and are suited for specific scenarios. In some cases, there's even an overlap between these models, allowing to compare results and ensure accuracy.

Underwater sound field can be described by the Helmholtz equation (1):

$$[\nabla^2 + \mathrm{k}(r)^2]\emptyset(r, f) = 0 \qquad (1)$$

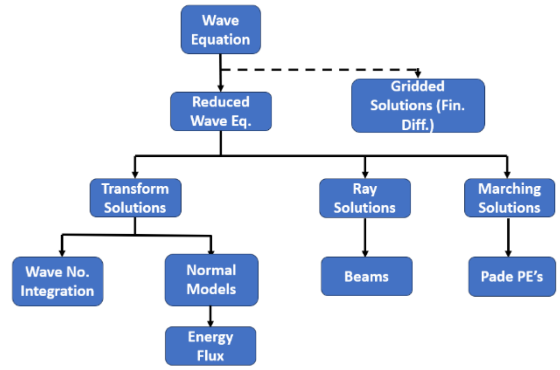

Figure 10: Different Propagation Modelling Techniques

Sound travels through the ocean in complex ways, influenced by factors like depth, temperature, and the seabed. To predict this behaviour, we use various methods based on the wave equation. Each solution, represented by the symbol $\phi(\boldsymbol{r},\ f)$, depends on the sound source and the underwater environment.

This section explores six popular propagation modelling methods. We'll discuss their advantages and limitations to help choose the most suitable approach for our specific needs.

6.1. Acoustic propagation models

Acoustic propagation models typically distinguish themselves by their chosen numerical methodologies. The subsequent sections will outline some of the most prevalent approaches.

6.1.1. Ray and Beam Tracing:

The ray method approximates solutions to the wave equation for high-frequency waves. It assumes a solution of the following form:

$$p = Ae^{j\emptyset} \qquad (2)$$

where A is amplitude and ϕ is phase (both dependent on source-receiver distance). Applied to the wave equation, this yields two separate equations.

The first equation, focusing on phase, simplifies to the eikonal equation (a non-linear partial differential equation) by neglecting a term related to amplitude variation. Solving the eikonal equation numerically with initial launch angle and sound speed profile gives ray paths.

The second equation, the transport equation, determines amplitude. Ray-tracing models are limited by the approximation leading to the eikonal equation. This translates to limitations: small ray curvature relative to wavelength, small sound speed change over a wavelength, and small amplitude change over a wavelength.

6.1.2. Normal Modes

The normal mode method was introduced into the field of underwater acoustics by Pekeris [17]. The solution for a cylindrical coordinate system can be written as:

$$p(r,z) = \sum_{m=1}^{\infty} \emptyset_m(z)\emptyset_m(r) \qquad (3)$$

Normal modes are a way to understand sound propagation in underwater channels with flat seafloors and surfaces. These modes arise from the constructive interference of two plane waves, one traveling upwards and the other downwards, reflecting from the boundaries as shown in Figure 11 .

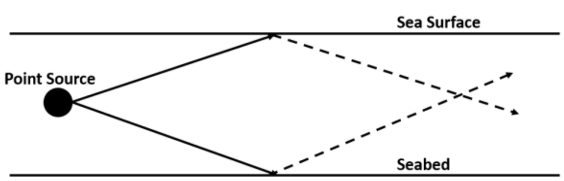

Figure 11: Two wave paths reflecting within an underwater channel, originating from a point source at opposite grazing angles.

The normal mode method is best suited for range-independent environments. For range-dependent scenarios, extensions like adiabatic mode theory or coupled mode methods are employed. Adiabatic methods are efficient when environmental changes are gradual, while full coupled methods handle significant variations but are computationally intensive.

A key advantage of normal modes is the ability to calculate the sound field anywhere between source and receiver. However, this method is most effective in shallow water channels with low-frequency signals. Finding contributing modes becomes challenging at high frequencies in deep water due to compressed vertical wavenumbers.

6.1.3. Wavenumber Integration

The wave number integration method, also known as the Fast Field Program (FFP), solves the wave equation for horizontally stratified media using the Green's function. This method integrates over wavenumbers using Fast Fourier Transforms, offering an efficient solution. While an approximation with Hankel functions limits accuracy at short distances, the wavenumber integration method is an exact solution compared to normal modes.

6.1.4. Parabolic Equation

The parabolic equation (PE) solution approximates underwater sound propagation by considering only outgoing waves. This transforms the problem into an initial-boundary value problem, allowing step-by-step calculation of the sound field from the source outward. The PE method has gained popularity due to its wide availability, ability to handle the entire water column and range-dependent environments, and compatibility with elastic boundary conditions (though computationally expensive). PE models can handle some high-angle propagation but are generally limited to lower frequencies due to increasing computational demands at higher frequencies.

The common PE approach is the split-step Padé expansion [18]. RAM (Range-dependent Acoustic Modelling) is a popular PE code utilizing the split-step Padé algorithm for efficiency and wide-angle propagation modelling. Users can balance speed and angular range by adjusting the number of Padé terms (more terms for wider angles, longer runtime). RAM can model low-frequency propagation in fully range-dependent environments.

6.1.5. *Energy Flux method and Finite difference / finite element*

Energy Flux Method:

A hybrid approach combining ray and mode theory. Analytic solutions exist for simple environments but extensions to complex scenarios with depth-dependent sound speeds and range dependence have been developed. These flux-based solutions offer high speed and handle diffraction, but they are not suitable for calculating the coherent acoustic field and often neglect high-frequency interference effects. In terms of accuracy and speed, they fall between ray and mode theories.

Finite Difference/Finite Element Methods:

Common numerical approaches in physics, Finite Difference (FD) and Finite Element (FE) methods involve discretizing the entire environment into a grid and solving the wave equation across space and time. However, their application in ocean acoustics is limited due to the computational cost associated with gridding vast oceanic regions with sub-wavelength resolution for most practical scenarios. These methods are typically reserved for problems like scattering or very near-source propagation, finding applications in pile-driving noise modelling and seismic generation of low-frequency modes in ocean sound speed minimum channels.

6.2. *Choosing Appropriate Model*

Choosing the right underwater sound propagation model depends on two key factors: frequency and environment. Explained below in brief:

High Frequency (Short Wavelength):

- If the sound wavelength is much smaller than ocean features (like water depth or mixed layer), use a ray tracing or beam model. These models track sound like rays of light.

Low Frequency (Long Wavelength):

- If the wavelength is comparable to ocean features, use a low-frequency model. The choice between two types of low-frequency models depends on the environment:
  - *Range-Independent:* If the ocean conditions don't change with distance, use a wavenumber integration model for better short-range accuracy.
  - *Range-Dependent:* If the ocean conditions change with distance, use a parabolic equation (PE) model (e.g., RAM). PE models are more practical for calculations across varying distances.

Table 3: Numerical approach of acoustic models' comparison

Numerical approach	**Advantages**	**Weaknesses**	**Limitation**	**Propagation Models**
Ray theory	Fast, visual, naturally range dependent and frequency independent	Difficult to obtain levels from rays traced into sediments and rays do not model diffraction	High frequency or deep water h/λ >10, range dependence	**BELLHOP,** GRAB, FMM, MOCASSIN, SPADES, TRACEO, WAVEQ3D
Parabolic Equation	Naturally range dependent, provides 2D acoustic field	Difficult to apply beam patterns or compute time dispersion or channel impulse responses. Must use approximations for complex sediments.	Low frequency, ducted or deep water, range dependent environments	MMPE, PECAN, **RAM**
Normal Modes	Accurate, physically intuitive, good for complex sediments	Most do not model near field and accurate range dependence is difficult and very time consuming	Low frequency, shallow water, layered sediments	COUPLE, C-SNAP, **KRAKEN,** ORCA, POPP/PROLOS, WKBZ
Wavenumber integration	Accurate, good for complex sediments	Computationally intensive requiring expert users and range dependence and beam patterns are difficult	Low frequency, short range, time domain problems	**OASES**
Finite difference/finite element	Accurate, good for complex sediments	Computationally intensive requiring expert users and range dependence and beam patterns are difficult	Short range, low frequency	NUCLEUS (for seismic applications)

Energy Flux	Fast, physically insightful	Only valid for simple cases and only gives coarse descriptions of the field	Broadband average intensity	INSIGHT, INSPIRE, NUCLEUS (for marine exposure)

7. CONCLUSION

Ship noise undeniably represents a significant human-made (anthropogenic) impact on marine mammal populations. The constant hum of maritime traffic disrupts their world in profound ways, affecting their behaviour, physiology, and the delicate ecological balance of the ocean. Understanding these complex interactions is critical. By delving deeper into how ship noise impacts marine mammals, we can develop effective mitigation strategies to preserve the acoustic integrity of marine habitats and ensure the long-term survival of these remarkable species.

While the focus of ship design has historically been on maximizing cargo capacity and speed, a crucial shift is underway. Today, environmentally friendly designs that minimize noise pollution are paramount for a healthy future. Quantifying the noise radiated by shipping traffic in specific regions is essential to grasp the true extent of this problem.

Sound propagation underwater is a complex phenomenon, far from the simple straight lines depicted in traditional models. Understanding the intricacies of how sound reflects, refracts, and diffracts is crucial. While this paper aimed to dispel common misconceptions about sound propagation (shallow water and low-frequency sounds, seabed reflection and sound spreading patterns), it also underscores the limitations of current models. Further research is needed to refine our understanding of sound propagation specific to the Indian coastline, considering factors like the unique bathymetry (underwater geography) and oceanographic characteristics of the region.

This deeper knowledge, coupled with advancements in underwater acoustics, will inform the development of more sophisticated sound propagation models. The factors like temperature, salinity, and resulting sound speed profiles (layered ocean concept) are key to developing robust sound propagation models. Techniques like ray tracing, normal modes, Snell's Law, and the software tools mentioned (wavenumber integration and parabolic equation models) offer a promising path forward.

For a more nuanced understanding of the impact on marine mammals, research must extend beyond general propagation patterns. Species-specific studies are critical. For instance, the majestic Humpback Whale, a vital part of the Indian Ocean ecosystem. Investigating how underwater noise travels in the areas frequented by these whales will provide crucial data for targeted mitigation strategies. Critically, it has been identified that the tonal frequency range of Humpback whale communication overlaps significantly with the noise generated by ship machinery and propellers. Further research in this area is vital to understand how this overlap disrupts their communication and develop mitigation strategies that minimize noise pollution at these specific frequencies.

In conclusion, while the current understanding of sound propagation presents challenges for modelling noise impacts, the work outlined here provides valuable groundwork. By prioritizing quieter ship designs, implementing effective mitigation strategies tailored to the Indian coastline and specific species like the Humpback Whale, and addressing the gaps in our knowledge of sound propagation in this region, we can work towards a future where the symphony of the ocean – vital for marine mammal communication and navigation – continues to resonate for generations to come.

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