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Underwater Soundscapes: Ocean Acoustics, Noise Pollution, and Marine Life

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Introduction

The ocean is an acoustic world. Light fades within tens of meters, but sound can traverse ocean basins, weaving a dynamic tapestry that connects wind and waves, whales and ships, storms and seafloor. This book explores that tapestry in depth, introducing the physics that govern how sound is born, shaped, and absorbed in seawater, and examining how marine organisms rely on acoustic cues to communicate, navigate, forage, and survive. It also confronts the rapidly evolving reality that human activities now dominate many soundscapes, altering the conditions under which marine life has evolved.

Our aim is both technical and applied. We begin with fundamentals—how temperature, salinity, and pressure set the sound speed; why refraction focuses or defocuses energy; and how boundaries, bubbles, and biology scatter and absorb sound. Building on these principles, we present practical propagation tools—ray theory, normal modes, and parabolic equation models—alongside guidance on selecting appropriate models, validating results, and quantifying uncertainty. Throughout, equations and algorithms are paired with intuition, figures, and rules of thumb meant to travel from the desk to the deck.

Monitoring the ocean's soundscape requires careful measurement and analysis. We detail how to select and calibrate hydrophones and arrays, design sampling schemes, and apply contemporary signal-processing methods to detect, classify, and localize sounds of interest. The book distinguishes passive from active techniques, clarifies when each is appropriate, and explains how to manage data, metadata, and quality assurance to produce defensible, reproducible results. Case examples illustrate end-to-end workflows—from defining questions and performance goals to reporting findings and archiving datasets.

Human-generated noise—especially from commercial shipping, naval and fisheries sonars, seismic surveys, and coastal construction—now shapes many regions' acoustic environments. We synthesize the current understanding of how such sources alter behavior, mask communication, and can, at high exposures, lead to temporary or permanent hearing effects. Equally important, we emphasize context: species- and life-stage-specific sensitivities, habitat characteristics, and cumulative exposure over space and time. Our goal is to move beyond simple thresholds toward risk-informed assessments that integrate propagation modeling, empirical measurements, and species ecology.

Because science does not operate in a vacuum, this book bridges theory with regulation. Readers will find concise, practitioner-focused treatments of major policy

frameworks and guidance documents, including U.S. and international approaches to impact assessment, take authorization, and ship-quieting initiatives. We highlight how sound metrics—SPL, SEL, percentile levels, and cumulative dose—map to regulatory criteria, and how to structure permit applications, monitoring plans, and mitigation reports that are both scientifically robust and compliant.

Finally, we focus on solutions. Chapters on study design, operations, and mitigation present concrete strategies: quieting technologies for ships, planning tools that avoid sensitive times and places, soft-start and shutdown procedures, exclusion and buffer zones informed by real-time monitoring, bubble curtains and cofferdams for pile driving, and collaborative approaches that bring scientists, regulators, industry, and Indigenous and local communities to the same table. Looking ahead, we examine emerging opportunities—ocean observing networks, machine learning, and low-noise vessel designs—set against the backdrop of climate-driven changes that are reshaping temperature structure, ice cover, and biological sound sources.

Underwater Soundscapes is written for a broad audience: students entering the field, researchers expanding into applied work, regulators and consultants tasked with safeguarding marine life, naval and commercial practitioners seeking to reduce risk, and NGOs and community partners advocating for quieter seas. Whether you approach these chapters from the vantage of a laboratory, a ship's bridge, a policy desk, or a coastal village, we hope the integration of physics, biology, measurement, and management provides a durable guide to understanding, assessing, and improving the ocean's acoustic environment.

CHAPTER ONE: Fundamentals of Underwater Acoustics

Water is not merely wet; it is a waveguide with attitude. Where light surrenders after a few dozen meters, sound tightens its laces and sets off across entire ocean basins, bending around seamounts, lingering at depth, and arriving later than expected with stories to tell. This chapter establishes the physical bedrock on which everything else rests: how pressure disturbances become waves, how seawater's material properties decide their fate, and how we choose language and units that keep us from tripping over our own assumptions. We begin with continuity and motion, not as abstract relics, but as working tools that explain why a whale's moan can cross a basin while a clap dies within a hull.

Newton and Euler would feel at home here, though they might blink at modern sonar screens. Acoustic propagation in fluids rests on mass conservation and momentum conservation, expressed respectively as a continuity equation and a momentum equation that links pressure gradients to fluid acceleration. For small disturbances in a quiescent, uniform medium, these collapse into a wave equation in which pressure oscillates in space and time. The derivation is straightforward: linearize, neglect squares of small quantities, assume isentropic motion, and assume gravity plays no role in the fast alternations of sound. The result is a second-order partial differential equation that supports plane, spherical, and cylindrical waves alike. From it we extract phase speed, or sound speed, as the square root of the ratio of the bulk modulus to density, a definition that binds stiffness and inertia into a single number with outsized consequences.

Real seawater is seldom quiescent or uniform, yet the same wave equation guides us if we allow the coefficients to vary smoothly with position. Temperature, salinity, and pressure—often called the state variables—determine density and compressibility. A warmer parcel of water is lighter and more compliant, tending to increase sound speed, while higher pressure at depth squeezes water into greater stiffness, increasing sound speed further. Salinity, though important, plays a smaller role in open ocean waters than in estuaries or briny basins. These dependencies are not additive ornaments; they set gradients that refract sound, sometimes trapping it in layers where it can travel hundreds of kilometers with little loss. The UNESCO sound speed equation, adopted internationally, codifies these relationships so that a single formula can translate sensor readings into reliable predictions.

Units matter because the ocean does not care about our convenience. Sound pressure is measured in pascals, but the span from a quiet sea to a seismic array exceeds many

orders of magnitude, so we use logarithmic decibels referenced to a standard pressure, historically one micropascal in water. This choice is not universal in all disciplines, so vigilance prevents disasters in conversion. We also work with intensity, particle velocity, and energy density when conservation and dissipation come into play. Frequency hertz describes cycles per second, wavelength meters describes spatial period, and wavenumber radians per meter ties the two together via the sound speed. These quantities interlock like gears: change one, and the others shift, altering how beams spread, how boundaries reflect, and how receivers hear.

The idealized plane wave simplifies life by assuming infinite extent and uniform fronts. In that limit, pressure and particle velocity stay in lockstep, and specific acoustic impedance is simply the product of density and sound speed, a number known as characteristic impedance. Real waves diverge, however. A point source creates spherical waves in which curvature introduces reactive components, and near the source, pressure and velocity can be out of phase. As distance grows, the wave settles into a locally plane character, and geometric spreading dominates. Understanding this progression is essential for estimating how loud a call will be when it reaches a distant listener, and why shallow water with its hard boundaries behaves more like a duct than an open sea.

Reflection and transmission at boundaries follow from continuity of pressure and normal velocity. At the sea surface, the acoustic pressure must nearly vanish because air is compliant and cannot sustain significant pressure fluctuations against water. The result is an almost perfect phase-reversal reflection, with a coefficient near minus one. At the seabed, the story varies with geology. Hard rock reflects strongly, sediments can absorb and scatter, and a fluidlike mud can support shear in a poroelastic sense, converting acoustic energy into heat and motion. Each interface shapes the sound field by adding multi-path arrivals, phase shifts, and amplitude modulations that depend on grazing angle and frequency.

Scattering arises when boundaries or volumes depart from smoothness. A calm sea surface viewed at centimeter wavelengths is a riot of facets, each redirecting sound in proportion to its slope spectrum and the physics of bubble entrainment. The seafloor is rougher still, with ripples, boulders, and burrows that create a chorus of weak arrivals. Volume inhomogeneities, from internal waves to plankton swarms, can scatter or focus energy, sometimes turning a quiet patch into a noisy one. Describing these processes requires statistical models of roughness and random media, yet the core idea remains simple: irregularities redirect energy, and the amount redirected rises sharply when roughness exceeds about one tenth of a wavelength.

Absorption converts acoustic energy into heat through mechanisms that would surprise a casual observer. Classical Stokes-Kirchhoff viscosity and thermal conduction account for some loss, but in seawater, relaxation processes dominate. Magnesium sulfate and boric acid ions respond sluggishly to pressure changes, exchanging energy

with the acoustic field in a frequency-dependent dance. At low frequencies, absorption is slight, allowing blue and fin whales to chatter across ocean basins. At high frequencies, absorption tightens its grip, limiting echolocation range and turning broadband clicks into muted whispers. The total loss per distance therefore depends on frequency, temperature, salinity, and pressure, often summarized by empirical formulae that balance rigor against practicality.

Noise is the uninvited guest in every measurement. Ambient sound in the ocean arises from wind and waves, distant shipping, rain, earthquakes, and the creaks of ice. This background sets a detection floor that varies with location, weather, and time of day. Some noise fields are stationary to a good approximation; others fluctuate wildly. Knowing the statistics of ambient noise, particularly its spatial coherence, allows us to design arrays that suppress interference and enhance signals. Equally important is self-noise, the acoustic signature of our own platforms, which can blind us to the very phenomena we seek to study.

Sources radiate sound in patterns shaped by their geometry and motion. A monopole bubbles and expands symmetrically, a dipole arises from oscillating bodies that push water back and forth, and a quadrupole manifests in turbulence and shear. Real sources blend these types, and directivity determines who hears what. A ship's propeller cavitation lobes forward and aft, a seismic airgun fires a toroidal beam toward the seafloor, and a calling whale projects anisotropically depending on species and posture. Measuring source levels requires care, because near-field effects, reflections, and motion can distort readings, yet standardized procedures exist to report source levels in comparable ways.

Signal descriptors bridge physics and perception. Peak sound pressure level captures transients, while sound exposure level integrates energy over time, making it suitable for impulsive or cumulative assessments. Band levels and spectrum levels reveal where energy resides across frequency, critical for evaluating masking and hearing damage. Duration matters because many biological effects depend not only on maximum level but also on how long the sound persists. Metrics such as percentile levels and duty factor help translate complex time series into manageable summaries for models and regulations.

With foundations in place, we turn to how sound travels through realistic oceans. Ray theory visualizes energy as beams that refract with changing sound speed, turning upward in warm surface layers and downward in cold deep layers. In a uniform waveguide, rays bounce between surface and bottom, filling the duct with arrivals that interfere constructively or destructively depending on frequency and depth. Normal mode theory offers an alternative view: the field is a sum of discrete patterns, each with its own horizontal wavenumber and attenuation. At low frequencies, modes provide an efficient basis for long-range propagation, explaining how tones can persist across continents. Parabolic equation methods bridge the gap, handling range-

dependent environments with fewer approximations than ray tracing and less computational cost than full three-dimensional wave equations.

Dispersion adds another wrinkle. Because different frequencies travel at different speeds, broadband pulses stretch and chirp as they propagate. This effect can aid detection by separating signal from noise, yet it complicates communication and localization. In shallow water, dispersion can be pronounced, with low modes lagging high modes so severely that a sharp click becomes a drawn-out thump. Understanding dispersion is essential for designing waveforms, interpreting recordings, and estimating source characteristics from distant receptions.

Boundary interactions are not static; they depend on frequency, angle, and material properties. At high grazing angles, reflections tend to be dominated by specular returns; at low grazing angles, seabed roughness and sediment elasticity control scattering strength. The sea surface responds to wind and wave growth, altering its effective impedance and generating bubble clouds that scatter and absorb. These processes couple the air-sea boundary into the acoustic problem, so that storms not only create noise but also reshape propagation paths. Seasonal and regional changes in surface forcing therefore leave imprints on soundscapes detectable far from their origin.

Scattering from random media introduces uncertainty that grows with distance. Internal waves can refract sound into shadow zones or intensify it in convergence zones, creating flickering patterns that defy deterministic prediction. Volume inhomogeneities contribute to mode coupling, allowing energy to leak between patterns and altering attenuation rates. Statistical models help us quantify this uncertainty by treating the ocean as a random process with known correlation scales, yielding predictions of mean intensity and its variability. For practical engineering, such models guide decisions about how much safety margin to include in exposure estimates.

Attenuation accumulates along paths, often rising rapidly with frequency and depth due to relaxation absorption and scattering loss. Over short ranges, geometric spreading dominates; over long ranges, attenuation sets a limit on detectability. In the deep ocean's sound speed minimum, the convergence zone pattern repeats at intervals determined by the depth of the minimum and the sound speed profile, permitting remarkably efficient long-range transmission at frequencies below a few hundred hertz. In shallow water, interaction with the bottom controls loss more strongly, so sediment type and subbottom structure become central to predicting how far sound will go.

By the end of this chapter, we have assembled the concepts and vocabulary to describe how sound is generated, transmitted, and diminished in the ocean. The next chapters will deepen this picture by exploring sound speed structure, propagation

modeling, and the natural and anthropogenic contributions to the soundscape. Yet none of those advances would rest on firm ground without the fundamentals established here: wave motion, material properties, boundary behavior, and the metrics that let us compare very different sounds on common footing. With these tools, we can proceed to listen carefully, measure precisely, and interpret wisely.

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