REVIEW AND INVENTORY OF CURRENT UNDERWATER SOUND PROPAGATION MODELING METHODS

A report prepared by Maritime Way Scientific Ltd for the Joint Industry Programme on E&P Sound and Marine Life

JIP Topic – Sound Source Characterisation and Propagation

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About the E&P Sound & Marine Life Programme

The ocean is filled with a wide variety of natural and man-made sounds. Since the early 1990s, there has been increasing environmental and regulatory focus on man-made sounds in the sea and on the effects these sounds may have on marine life. There are now many national and international regimes that regulate how we introduce sound to the marine environment. We believe that effective policies and regulations should be firmly rooted in sound independent science. This allows regulators to make consistent and reasonable regulations while also allowing industries that use or introduce sound to develop effective mitigation strategies.

In 2005, a broad group of international oil and gas companies and the International Association of Geophysical Contractors (IAGC) committed to form a Joint Industry Programme under the auspices of the International Association of Oil and Gas Producers (IOGP) to identify and conduct a research programme that improves understanding of the potential impact of exploration and production sound on marine life. The Objectives of the programme were (and remain):

1. To support planning of E&P operations and risk assessments
2. To provide the basis for appropriate operational measures that are protective of marine life
3. To inform policy and regulation.

The members of the JIP are committed to ensuring that wherever possible the results of the studies it commissions are submitted for scrutiny through publication in peer-reviewed journals. The research papers are drawn from data and information in the contract research report series. Both contract reports and research paper abstracts (and in many cases full papers) are available from the Programme’s web site at www.soundandmarinelife.org.

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Review and Inventory of Current Underwater Sound Propagation Modeling Methods

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Prepared for Joint Oil & Gas Industry Programme (JIP) on Sound and Marine Life

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Editorial

This report has received final review and editing by J. Theriault of Ocean Environmental Consulting. Only minimal editing has been performed to add E&P Context. The general material has been left unchanged.
Executive Summary

Maritime Way Scientific Ltd is pleased to present to the Joint Oil & Gas Industry Programme (JIP) on Sound and Marine Life a detailed review and inventory of underwater sound and sub-bottom propagation models.

This report is a critical review and assessment of current sound propagation models and their application to offshore E&P activities, which includes identification of potential areas of further development for current sound propagation models to improve the effectiveness and/or accuracy of methods to estimate the properties of the underwater sound field.

Currently, the E&P Industry employs high-fidelity propagation models to provide the received sound levels throughout the ocean environment where marine animals are likely to be found. The goal of this report was to identify the best combination of underwater acoustic models for use by the E&P industry for environmental evaluation and marine animal disturbance mitigation. This goal has been accomplished by providing comprehensive critical and objective analysis of 28 of the currently available underwater acoustic propagation models and application models and the required supporting data (marine physical and marine animal databases). An important result of achieving this goal is the ability to identify gaps and weaknesses in propagation modeling, databases and exposure modeling.

The report is written in six (6) sections and supplemented with five (5) appendices. The sections of this report are described below.

SECTION 1
As a starting point to the following sections it Section 1.1 presents the background - a basic description of acoustic propagation in the ocean and defining basic acoustic terminology. The objectives of the report are given in section 1.2. A high level description of the research methodologies are presented in Section 1.3. Section 1.4 simply provides the report organization.

SECTION 2
This section is divided into five distinct parts that build the fundamentals of acoustics that support our assessment of propagation models.

In Section 2.1 we provide a brief summary of the theory underlying many of the standard numerical models that have been developed for underwater sound applications. In particular, we focus attention on Transform Solutions (wavenumber integration, normal modes, and multipath expansions), Ray Solutions and Marching Solutions. The intensive theoretical development of Sec 2.1 is supported by further numerical details of the models shown in Appendix A.
Sec. 2.2 provides a comprehensive identification of the eight main classes of model system that exist today. This section is supported by the information received directly from the modelers we contacted, described in Appendix B.

Section 2.3 provides an evaluation and comparison of propagation and application models with respect to differing environmental conditions and model capabilities that are aligned with E&P efforts. The section concludes with a look at future plans that may be in the offing for existing models, and finally a look at models may exist in the near future, what we are calling horizon models.

Section 2.4 revolves around uncertainties in acoustic modeling predictions. The discussion starts with a detailed discussion of model prediction uncertainties and their causes (2.4.1). Here we briefly introduce the idea that the acoustic modeling community generally agrees that the current high-fidelity models are all capable of accurately representing the sound field, if the environment is well known. However at-sea propagation loss estimates are still notoriously unreliable, not through any inherent weakness in the models themselves, but because the ocean-acoustic environment is often poorly sampled. The challenges of modeling in shallow water environments is briefly covered (2.4.2). Section 2.4.3 describes a wide variety of techniques which are in use to model the uncertainties in modeling. Conceding that modeling uncertainty exists, Section 2.4.4 describes the method iterative calibration where measured values of transmission loss in near real-time are used to help align model environmental inputs with the observed acoustic data.

Section 2.5 summarizes the main acoustic characteristics of E&P sources and lists the most common sound exposure metrics.

**SECTION 3**

Section 3 is primarily devoted to a massive survey of environmental and marine life databases. The section begins with common definitions and terminology used throughout the section (3.1). Section 3.2 presents a discussion of physical parameter databases whose web sites are listed in Appendix C. The section describes the format and terminology of the databases and a summary of the numbers of physical databases and portals found as of 2013. We have concentrated on the physical parameter databases since these provide environmental inputs for the acoustic models. A severe shortage of databases containing information about the geo-acoustic parameters is of particular note. In addition, we found that despite the seemingly large numbers of databases available and their ‘global’ coverage, the actual selection of values for specific sites is sparse. Section 3.3 deals with marine animal databases whose web sites are listed in Appendix D. The development of this part is similar to App. C.

The last part of this section, 3.4, discusses the specific inputs required that are suitable for acoustic models. These must be derived from the physical databases by some kind of environmental conversion model that translates the physical parameters into the form of the input required by the acoustic model. Because these models are usually empirical, there is an associated variability. We show, for example, the variability of the Applied Physics Lab (University of Washington) high frequency environmental model outputs in terms of ± decibels (dB), which reveals an estimate of variability of 15 dB – 30 dB for bottom losses from soft sediments. We further provide a qualitative reliability rating of the Bottom Loss Upgrade (BLUG) low frequency database. For example, we show that over 50% of all the database entries in 1983 were obtained without the use of measured data.
SECTION 4
Section 4 contains a critical assessment of the models. In Section 4.1, the accuracy of the models is judged by model-to-model comparisons, and model-to-data comparisons. The consensus of the acoustic modelers is that all the high-fidelity models, when used within their regions of applicability, are capable of accurately computing the sound field when given the correct inputs.

We further describe that sound waves propagating in the ocean are very dependent upon and sensitive to the environment. We note that a high fidelity propagation model that represents the physics well will automatically show the same sensitivities in its output. This high sensitivity is not a failure of the acoustic model; it is a fact of propagation in the real ocean. Coupling this finding with the uncertainty in inputs provided by databases that are coarsely sampled or derived by estimate, it is clear to the authors that statistical measures of the probable spread in the transmission loss are vital.

Section 4.2 identifies the best suited acoustic models for E&P noise predictions. The section begins by itemizing the most important attributes the acoustic models must be capable of handling for the prediction of the impact the E&P activities will have on marine life. As the frequency range of all activity is so broad, this section summarizes the classes of models that are best suited for each portion of the range. The other required attributes are the capability to include source characteristics, spatial coverage and output metrics. Section 4.2 then presents an evaluation table in which the models are broadly equated to the attributes they can satisfy. Using this evaluation effort, specific recommendations for the best model choices for all aspects of E&P noise production are made. Sections 4.3 through 4.5 describe the findings of the gap analyses for propagation modeling, physical databases, and exposure modeling.

SECTION 5
Section 5 covers potential areas for further development. Section 5.1 presents a high level summary of ways in which propagation models can be improved. Section 5.2 identifies 24 development items based on the identified gaps, and places each one in three development areas (core propagation models, exposure modeling, physical parameter databases). Each development item is scored and ranked by an estimate of the feasibility of successful development, the likely costs of development, the potential timing of availability, the methods of assessment and ease of validation, and the perception of need and its urgency. From this ranking, four major topics, identified as vitally important, are identified.

A more comprehensive recommendation for further development is made by suggesting that a Decision Making Capability tool needs to be built (5.3). The design of this tool would focus on the requirements at each step along the chain of impact on marine life. The hub of this chain of effort is acoustic modeling. Many of the tools required (theory, practice, and modeling) exist for framing and pressing into service each element in that chain to completion. Focusing on exploration scenarios faced in regions of E&P activity would direct the Decision Making Capability development. Sections 5.4 and 5.5 suggest options for project outreach, training, and a more condensed, user friendly, version of this report.

SECTION 6
The references cited in this report are provided in this section.
SUMMARY
The major accomplishments of this report are:

i. An in-depth evaluation of current acoustic model capabilities to meet E&P noise prediction requirements;

ii. Specific recommendations for the models best suited to all the different types of E&P activities;

iii. An extensive listing of web sites containing physical and animal databases;

iv. The identification of gaps in modeling output, physical databases and exposure models;

v. Top four most urgently needed recommendations for future development.

This report has identified seven (7) models that may be well suited to being used as core propagation models in exposure application software. These models are BELLHOP, ORCA, KRAKEN, RAM, TRACEO, and WAVEQ3D AND MOCASSIN. The selection of these models is based on the evaluation chart with considerable weight being given to models that are freely available and whose developers are currently active. These models provide the capabilities necessary for most of the modeling requirements of E&P activities.

FUTURE RESEARCH RECOMMENDATIONS
Based on the rankings in Section 5, there are four areas that emerged as of paramount importance. These four areas comprise our recommendations for the most urgently needed future development:

i. Core model selection criteria: To prevent potential errors from employing core propagation models outside their regions of applicability. There is a clear need for robust, automated selection criteria for determining which model to choose for any given environment and source frequency band;

ii. Improved, statistical, measures of sound exposure: Develop ways to provide a statistical characterization of the sound exposure levels that will ensure a more accurate basis for risk assessments. This must include the calculation of the statistics of the propagated sound field, the estimation of the underlying variability and uncertainty in the environmental inputs, and the incorporation of statistics into exposure metrics; Create a universally accepted metric for evaluating exposure that includes the statistics of the propagated sound and standardize the metric calculation techniques;

iii. Improved ambient noise: Improve the modeling of the ambient noise field and data based noise descriptions by including directionality and spectra from all noise sources, including ongoing E&P nearby activity; and
iv. **Improved ease of use:** Ensure core models provide more targeted outputs that are specifically designed for exposure metric requirements and provide more user friendly access to the core models for the exposure application developer.

**DISCLAIMER**

This project is a result of a comprehensive and very complete survey of the models identified by the authors and contributors to support the aims of this report for the Joint Oil & Gas Industry Programme (JIP) on Sound and Marine Life. The authors were asked to make a critical assessment of current sound propagation models and their application to offshore E&P activities. Relying on our experiences and expertise in the fields of ocean acoustics modeling theory and applications, we made statements and offered opinions to support the objectives. We acknowledge and understand that these views and opinions expressed in this report may not be shared by other experts. We acknowledge that these assessments are intended to stimulate further debate and move the field forward to a clearer understanding of the critical issues and relevant science progress in propagation modeling.

This report was prepared as an account of work sponsored by the Joint Oil & Gas Industry Programme (JIP) on Sound and Marine Life. Neither the JIP Group or Maritime Way Scientific assumes any legal liability or responsibility for the accuracy, completeness, or any third party’s use or the results of such use of any information, or process disclosed. Reference herein to any specific modeling system or process does not necessarily constitute or imply its endorsement, recommendation, or favoring by JIP. The views and opinions of authors expressed herein do not necessarily state or reflect those of Joint Oil & Gas Industry Programme.
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Section 1 - Introduction

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Section 1

1 INTRODUCTION

1.1 Background

The oil and gas exploration and production (E&P) industry is subject to stringent environmental regulations in regard to their activities underwater. In particular, prior to engaging in any activity that employs acoustic sources directly (e.g., air-gun survey, side-scan sonar surveys, acoustic telemetry and positioning systems) or that produces acoustic energy as a byproduct (e.g., drilling, dredging, pile driving), the industry’s principals must complete an Environmental Assessment (EA). Among other things, the EA is required to contain documented evidence concerning the potential for E&P acoustic operations to adversely affect resident marine life (including mammals, fish, and invertebrates).

![Oil platform, offshore platform and oil rig](image)

This large ocean platform has facilities to drill wells, to extract and process oil and natural gas, and to temporarily store product until it can be brought to shore for refining and marketing.

Numerous techniques to assess methods of resource localization are used. One method involves venting high-energy air pressure into the water from which the resulting acoustic echo returns can then be studied to show ocean bottom geological structures associated with petroleum deposits. These surveys can last for months and involve not only sonar activity but also the use of other water column systems.

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used to assess ocean bottom characteristics and properties. All these sound-making devices have potential noise impacts on marine life.

Generally speaking, the principles of acoustic propagation in the ocean and acoustoelastic propagation in the ocean floor are well understood. However, site-specific propagation characteristics can be complicated by local temporal phenomena and variations in spatial properties. Since in situ measurements are expensive, logistically difficult, and do not provide the overall coverage required, the E&P Industry is motivated to use acoustic models to produce complementary synthetic data. Given the restrictions mentioned above, and the paucity of historical acoustic data in the regions of interest, the acoustic evidence contained in an environmental assessment can only be reasonably and practically generated using synthetic means i.e., acoustic modeling.

1.1.1 Characteristics of E&P sound

E&P operations generate sound in many different ways. Seismic surveys are the dominating source of sound, but pile driving for construction purposes are also frequently used. Active sonar systems for measuring water depth and other features are used on most vessels, but the sound levels generated by these operations are much less than the before mentioned sources and therefore not often treated as a possible negative impact on marine life.

1.1.1.1 Seismic surveys

Marine seismic surveys are used to map hydrocarbon deposits in the geologic strata below the sea floor. Seismic vessels tow a large arrays of receivers (hydrophone streamers) and a source that generate a strong sound pulse of very short duration. Most surveys today use airguns as the source. The airgun is a device that in a controlled manner can release high pressure air into the sea, thereby generating the required pulse. Seismic sources are made up of 20 – 40 airguns deployed in an array that have an area of a few 10's of meters. The release of air from the airguns are synchronized to give a sharp pulse in the downward direction. Due to the physical size, the output from the source array has a characteristic directivity. In the horizontal direction the sound level will be much lower than in the vertical direction.

The sound pulse generated by the seismic source propagates down into the geologic strata below the sea floor, and be reflected and refracted by the variation in acoustic impedance at the geologic interfaces. The reflected / refracted data are received by the hydrophone streamers and after signal processing an image of the geology in the area can be created.

High frequencies are attenuated much more than low frequencies resulting in pulses received at a distance are dominated by the low frequency part of the source signal.

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2 The term model in ocean-acoustics has been defined as “computer algorithms and codes that produce numerical results”[1].

3 Further information can be found in IOGP / IAGC report no. 448 “An overview of marine seismic operations” (April 2011) (http://www.ogp.org.uk/pubs/448.pdf)
The propagation velocity of the sound in the subsurface is higher than in water, and therefore – at some distance from the source - the sound pulses from the geologic interfaces will reach the receiver before the water-borne arrivals. This is a feature not normally recognized in sound propagation modelling, and will be an important aspect of comparisons between modelling results and actual measurements.

Due to the sound propagating through the subsurface, it is also important to notice how the sound is recorded. There may be a significant difference between measurements using hydrophones suspended in the water-column and when the hydrophones are placed (or in other ways directly connected) to the sea floor. Again, this is a parameter not often considered when reporting sound levels at a distance from the source – especially in shallow water.

1.1.1.2 Pile driving

Pile driving for construction work is also an important sound source in E&P operations. A large “pile” (steel tube, often with several meter diameter) is hammered into the sea floor by pneumatic or gravity hammers.

The sound generated during pile driving will originate both from the pile, but also from the sea floor that will vibrate in a significant radius around the pile.

Since pile driving have a direct connection with the sea floor, sound propagation through the sea bottom and underlying geological layers will be substantial, and often stronger than the sound propagation through water. When assessing sound levels at a distance from pile driving operations it is therefore important to report how the hydrophone is deployed during the recording.

1.1.1.3 Sonar systems

Active sonar systems cover a wide variety of systems, from simple fish finding gear to large military installations. The E&P industry uses active sonar systems for depth measurements, for profiling of the uppermost layers in the sea floor and to search for objects that may interfere with the operations.

Sonar systems often use high frequencies, from 10's kHz to several 100's kHz. Due to the high frequencies it is possible to generate the sound in very narrow beams, and therefore modelling of the sound from sonar systems must take the directivity into consideration.

1.1.2 Acoustic Propagation in the Ocean

From an acoustic modeling point of view, oceanic environments are complicated layered structures comprised of air, water, sediment, and basement components (see Figure 1-2 below).
Section 1 - Introduction

The propagation of acoustic energy within the ocean is typically modeled by finding solutions to linearized hydrodynamic equations involving pressure, particle velocity, density, and sound speed. Under the assumption (for now) that density and sound speed do not depend on time, the acoustic pressure, $P(r,t)$, as a function of three-dimensional position vector, $r$, and time, $t$, is a solution of:

$$\rho\nabla \cdot \left( \frac{1}{\rho} \nabla P \right) - \frac{1}{c^2} \frac{\partial^2 P}{\partial t^2} = -4\pi S$$

(1)

where $\rho(r)$ and $c(r)$ are the density and sound speed, respectively, $S(r,t)$ defines the source of acoustic energy, and $\nabla$ is the gradient operator in the coordinate system defined by $r$.

Of course, the solutions of Eq. (1) are subject to initial conditions imposed at the source and to boundary conditions imposed at any interface. The various techniques employed in the solution of Eq. (1) are summarized and assessed in subsequent sections of this report.

1.1.3 Acoustic Intensity

For the purposes of this introduction, consider the images below in Figure 1-3. This figure illustrates the issue at hand; that is, for a given E&P activity, what level of acoustic intensity would be experienced by marine life at some range from the source.

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4 As detailed in Jensen, F., Kuperman, W., Porter, M., & Schmidt, H. (2011), Computational Ocean Acoustics [2], the development of most underwater acoustic numerical models begins with the solution to the wave equation.
On the left, Figure 1-3-a, presents an intensity map of the coherent pressure field due to an idealized harmonic point source of unit amplitude in an unbounded and homogeneous ocean, i.e., a much simplified ocean where $\rho$ and $c$ are independent of position. For such a case, the acoustic intensity decreases with inverse square of the range, $r^2$, away from the source (i.e., spherical spreading). Given a known source level, it is an easy and straightforward calculation to determine the pressure variation that marine life would experience at any range from the source.

On the right, Figure 1-3-b, presents a second intensity map (in logarithmic scale) for the same harmonic point source in a more realistic ocean confined by physical boundaries. In this example the ocean environment is comprised of three layers: the air layer above the ocean surface, a layer of water (100 m deep), and the bottom sediment layer – often referred to as a “Pekeris waveguide”\(^5\). The axes in Figure 1-3-b indicate a vertical slice of ocean (single azimuth from the source) with depth along the vertical and range from the source along the horizontal, respectively. In this example, the water depth is 100 m, and the water column is cylindrically symmetric. The source frequency (100 Hz) is low enough such that a small number (< 20) of acoustic wavelengths fit within the depth, leading to modal propagation. The acoustic intensity at all ranges and depths is indicated by the color map. Red colors indicate higher acoustic intensity (less loss) and colors towards the blue indicate lower acoustic intensity (more loss). Note the high degree of variation in acoustic intensity with both range and depth in this bounded, shallow, segment of the ocean.

The first point we wish to make is that addition of physical boundaries introduces much more complexity to the sound field. Thus, in such an environment, the intensity of acoustic energy experienced by marine life in this case is very dependent on both range and depth in the water column (and not just range as is the case in Figure 1-3-a). Second, and more important, is the fact that a modern numerical model was required to generate the data shown in Figure 1-3-b.

\(^5\) Realistic ocean environments are much more complicated than a Pekeris waveguide. For example, the sound speed, sea surface, bathymetry, and bottom composition are by no means uniform, rather they all vary spatially. Variations in sound speed result in refraction and focusing effects whereas spatial variations in the boundaries cause scattering and reflection loss. Spatial variations in bottom composition also affect bottom reflection and, consequently, contribute to the loss of acoustic energy away from the source. It is important to note that these reflection and scattering processes are typically angle and frequency dependent. Additionally, it may not be realistic to treat the ocean bottom as a fluid i.e., the sediments support shear, in which case, conversion from compressional (pressure) waves in the water to shear waves in the sediment needs to be treated. Spectral changes in the propagated sound field may occur due to such factors as absorption and scattering effects. Finally, both the sound speed and the sea surface description almost surely vary temporally.
1.1.4 Complex Sources, Environments, and E&P Operations

In addition to the complexity of the ocean environment, the acoustic sources employed in E&P operations are much more complex than harmonic point sources. An understanding of broadband, pulsed sources with sophisticated directional properties is required in order to cover all activities that typically includes either direct acoustic stimulation (air gun) or indirect stimulation (pile driver); frequencies from 10’s of Hz through 10’s of kilohertz are necessarily involved. From an acoustic modeling point of view, a suitable model is one that can handle, subject to the restrictions associated with Eq. (1), a variety of acoustic sources in a complex ocean environment that includes spatial and temporal variability. Fortunately, as will become apparent in this report, there are a number of candidate models that can provide acoustic field prediction data pertinent to E&P operations – unfortunately, no one model appears capable of providing coverage over all source frequencies and environment complexities.

1.1.5 Terminology

Underwater sound propagation is based on the physical principles of theoretical acoustics and has been studied extensively since the Second World War. The theory is now so well developed that it can provide a detailed description of how sound travels in the ocean. It is useful to review some of the terminology associated with underwater sound propagation.

Sound waves in fluids are pressure waves and represent the displacement of the medium as a wave passes along the direction of propagation. The amplitude of an acoustic wave is measured in units of micro-Pascals (μPa) and is often referred to as the sound pressure level (SPL). The relationship between frequency, $f$, wavelength, $\lambda$, and sound speed, $c$, in a medium is given by $c = \lambda f$.

Figure 1-3 shows an example of standing waves in a waveguide as a result of a continuous wave signal. The short duration (and broadband) of sound from seismic surveying or pile driving doesn’t result in the same interference pattern.

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Figure 1-3 Acoustic intensity due to source, $S$, in simplified ocean structures: a) an infinite uniform ocean, and b) a Pekeris waveguide. 
In what follows we present some of the basic terminology pertinent to a discussion of acoustic modeling.

**ACOUSTIC PRESSURE**, $P$, refers to the force per unit area that a sound wave exerts by the particle motions of the medium through which the wave passes. This is the fundamental quantity that propagation models calculate. The pressure is a complex quantity; that is, it has amplitude and a phase.

**ACOUSTIC INTENSITY**, $I = P^2 / \rho c$, is the amount of energy per second (power) crossing a unit area. It is obtained from the square of the acoustic pressure divided by the acoustic impedance, the product of the density, $\rho$, and the sound speed, $c$.

**DECIBELS**, dB, is a logarithmic scale used throughout acoustic research and practice to represent ratios of acoustic pressure or intensity. The values of these ratios are often too large or too small and therefore cumbersome to deal with in a convenient manner. The logarithmic scale of the decibel converts these ratios to a more convenient scale of values to work with on a routine basis. The ratios are calculated relative to a reference value. For example, the acoustic sound intensity level, expressed in dB is written as, 

$$ \text{SIL} = 10 \log_{10} \left( \frac{I}{I_{\text{ref}}} \right) \text{ dB re } I_{\text{ref}} $$

where ‘re’ means ‘referenced to’ the reference intensity value, $I_{\text{ref}}$. Both $I$ and $I_{\text{ref}}$ must have the same units, therefore decibels are always dimensionless (which is why statement of the reference value is critical).

**Sources**

**POINT SOURCE** is a term used to describe a mathematically abstract source in which the interaction with the surrounding medium occurs at a point i.e., the pressure wave is being injected into the water at a point. This type of source is often used to represent sources in the development of acoustic models.

**SOURCE LEVEL**, $SL$, is a measure of the source intensity expressed in decibel units,

$$ SL = 10 \log_{10} \left( \frac{P_o}{P_{\text{ref}}} \right)^2 \text{ dB re } P_{\text{ref}} @ R_o = 1 \text{ m} $$

where $P_o$ is the rms pressure at the reference distance $R_o = 1 \text{ m}$. By convention the reference pressure is $P_{\text{ref}} = 1 \mu\text{Pa}$ (one micropascal). The pressure is squared in order to compare acoustic intensities. The assumption in this equation is that the source is a point source.

Practical sources are not point sources but have physical extent (spatially distributed). Therefore that while the reference distance is 1 m, this does not mean that the pressure is $P_o$ at 1 m. In fact, if the source dimensions are 1 m or greater, the measurement of pressure is impossible. This apparent dilemma is often the cause of great confusion when interpreting the meaning of source level. In actuality, the source level for a distributed source (see below) must be measured in the far field (see below) and corrected for propagation losses between the source and measuring receiver. The value of $P_o$ at $R = 1 \text{ m}$ is inferred as though the source were a point source (for the moment ignoring the angular directionality of the source).
**SOUND PRESSURE LEVEL**, SPL, although it is referred to as a *pressure* level it is the decibel ratio of a measured *sound intensity* as compared the intensity of reference pressure, \( P_{\text{ref}} \). By convention the reference pressure is \( P_{\text{ref}} = 1 \, \mu\text{Pa} \).

\[
SPL = 10 \log_{10} \left( \frac{P}{P_{\text{ref}}} \right)^2 \, \text{dB re} \, 1 \, \mu\text{Pa}.
\]

**DISTRIBUTED SOURCE** is a term used to describe a source that has spatial extent i.e., all practical sources. Distributed sources exhibit directionality (see below).

**SENSOR ARRAY** is a term used to describe a collection of sources (receivers) that act in concert with one another to produce (or measure) acoustic pressure. They may be regarded as one form of a distributed source. Sensor arrays exhibit directionality (see below).

**DIRECTIONALITY** is a term used to describe the dependence of any acoustic parameter (e.g. source output) on angle. Note, the dependence could be on an angle in the vertical plane or an angle in the horizontal plane. Quantities that do not depend on angle are referred to as being **OMNI** or **OMNI-DIRECTIONAL**. Sensor arrays and distributed sources, in general, have directional properties that need to be accounted for.

**NEARFIELD** (and Farfield, see below) are terms referring to positions relative to a source (or a scatterer) for which the spatial extent of the source affects (or not) the resultant acoustic field. For a point source, the near field is comprised of those ranges less than one-quarter wavelength. For distributed sources, the near field distances are given approximately by the length or area of the source in comparison to the wavelength,

\[
R_{\text{NF}} \approx \frac{L}{\lambda} \quad (\text{linear source})
\]

and,

\[
R_{\text{NF}} \approx \frac{\text{Area}}{\lambda} \quad (\text{planar source}).
\]

For ranges less than \( R_{\text{NF}} \) the acoustic pressure varies rapidly due to summing contributions originating from different position on the source, each of which have a unique phase value, creating an interference pattern. In the near field small changes in position can lead to large changes in the acoustic pressure.

**FARFIELD** Beyond the range \( R_{\text{NF}} \) (see NEARFIELD, above) the phase difference from each contribution on the source are nearly the same, the interference pattern vanishes, and small changes in position do not create large changes in acoustic pressure. Therefore, calibrations must be carried out in the far-field.

**TRANSMISSION LOSS**, \( TL \), represents the reduction in acoustic intensity at any position (e.g. range, azimuth, and depth) as compared to the intensity of the source (this is also referred to as propagation loss). The transmission loss is given in decibels by,
\[ TL(r, \theta, z) = SL - SPL(r, \theta, z) \text{ (dB)}. \]

By convention, the transmission loss is positive, with larger positive values indicating higher losses. In reality the \( SPL \) value includes all accumulated losses due to reflection, scattering, absorption, and spreading.

**PLANE WAVE** refers to an idealized wave of constant amplitude, fixed frequency, and zero curvature. The wave fronts (surfaces of constant phase) are of infinite extent and perpendicular to the direction of propagation. They are a useful mathematical construct in the development of acoustic models.

**REFRACTION** is a term used to describe the bending of the wave front because the sound speed is not spatially constant. Refraction is a critical component that influences the complexity of the sound field. Sound channels formed about a local minimum in the sound speed can cause the energy to be trapped and propagate to long ranges with little loss. Caustics, formed where the refracted waves intersect, are regions where the acoustic intensity is enhanced. Shadow zones, which are regions with little acoustic energy, form when the refracted waves diverge around a local maximum in the sound speed.

**MULTIPATH** is a term used to describe propagation conditions for which the different components of the acoustic energy, propagating from the source to a receiver, experience different conditions or “paths” (i.e., directly, by reflection off an interface, by refraction caused by the sound speed profile). The ability to handle multipath is a critical component of any useful propagation model.

**Spectral Properties**

**NARROWBAND** is a term that is used to describe the transmission or reception of acoustic signals that involve a “narrow” band of frequencies e.g., harmonic

**BROADBAND** is a term used to describe the transmission or reception of acoustic signals that involve a “broad” range of frequencies e.g., impulsive sources are by definition broadband.

**DISPERSION** is a term used to describe the dependence of some aspect of the propagation on either time or frequency. For example a finite-duration pulse that is spread out over time due to the effects of the propagation is said to be “time-dispersed”. Whereas, certain frequency components of that same pulse might propagate energy with a difference speed from certain other frequency components resulting in “frequency dispersion”.

**Displays**

**FULL FIELD DISPLAY** is a term used to describe the display of the total acoustic field (usually in color) in two dimensions i.e., either range and depth or range and azimuth. Note, it is possible to produce a full-field display in three-dimensions although this is not often done.

**COVERAGE DISPLAY** is a term used to describe a display (usually color) of \( TL \) versus range and azimuth. This is of interest to the E&P problem since it provides a comprehensive account of
acoustic levels over a wide area. Note, this kind of display could also be produced in three dimensions.

**Water Column Properties**

**SOUND SPEED PROFILE (SSP)** is a term used to describe the dependence of ocean speed of sound with depth. Note, sound speed can also vary as a function of range i.e., typically one encounters different SSP's at different ranges. The largest changes in the sound speed are governed by the vertical profiles of water temperature and salinity over the depth of the ocean. The sound speed is affected by temperature by about four times as much as for salinity. The pH is also required, though its effects on the sound speed are much less than for temperature or salinity, and an average value (8.1) often suffices. Many empirical formulas are available to compute the sound speed from temperature, salinity, pH, and depth.

**SPREADING** is a term that refers to the changing shape of the wave fronts as they leave the source; spreading contributes to TL. Geometrical spreading losses are due to a mix of factors. In a ‘theoretical ocean’ without horizontal boundaries, a point source produces spherical waves and the geometrical spreading losses obey an inverse-square (spherical) law as -20 log10 R (see Fig. 3 above and associated discussion). Ocean boundaries confine acoustic energy and the spreading of high frequency signals tends to obey a “cylindrical” law as -10 log10 R at long range. Low frequency signals (such as the main energy from seismic signals) will follow a “spherical” spreading out to distances of more than 10 km. Propagation models that are based on solution to Eq. (1) inherently account for basic spreading effects (and a lot more).

**ABSORPTION** (in water) is a term that refers to the loss of sound energy during the passage of the wave through the water and is caused by friction and molecular absorption in the propagation medium. Molecular relaxations in the naturally occurring salts of the ocean also remove energy from propagation sound waves. Attenuation models used to predict this loss are all empirical and depend on the square of the frequency of the sound. The ocean pH serves to moderate these losses by lowering the loss as the water becomes more acid. The loss is normally added to the intensity with the spreading loss term. Loss is typically quoted as a positive number in units of nepers (natural logarithm, loss per meter), dB/m, dB/λ, or dB/m/kHz.
Boundary Effects

**REFLECTION** is a term used to describe the interaction of acoustic energy with a planar boundary. The plane wave reflection coefficient is used to represent, analytically and numerically, the reflection of a plane wave (amplitude and phase) from an infinite, plane interface between two different media. Note, using plane waves, it is possible to represent the reflection from a stack of layers as if it occurred at a single interface – this procedure is often used in model development and data analysis.

**SCATTERING** (also called diffraction), is a term that is used to describe the interaction of acoustic energy with an object or a rough boundary. Scattering may be thought of as the non-specular component of reflection from a rough surface, or the redirection of energy along a direction other than the incident direction. A full accounting of multiple scattering effects is complicated—typically, from an acoustic modeling point of view, scattering effects are considered to be an "integrated" effect and are applied as a complex coefficient that acts at a point or scattering center.

**SURFACE LOSS** is a term used to quantify the interaction of acoustic energy with the water/air interface at the ocean surface. The sea surface is a nearly perfect reflector of sound from underwater sources, chiefly due to the very large difference in acoustical impedance between air and water. However, the ocean surface is affected by the action of wind across its surface, which creates surface waves. Depending upon the source frequencies, this 'rough' surface redirects some of the energy incident at one angle over many reflected angles (scattering), removing a portion of the down-range propagating source energy and thus leading to a loss. Therefore, knowledge of the wind, or wave surface height statistics are important to account for this loss.

**BOTTOM LOSS** is a term used to quantify the interaction of the sound with the water/sediment interface. The ocean bottom presents itself as a boundary which is penetrable by sound and comprised of energy absorbing sedimentary material. Much more energy can be lost through to the ocean bottom than to the atmosphere.

Bottom Properties

**SEDIMENT LAYER** is a term used in propagation modeling to describe the uppermost layering in the ocean bottom. Since the impedance mismatch between the water and the ocean bottom allows energy to penetrate into the ocean bottom, the characterization of the sediments is important particularly since the sediments support shear waves (then they must be modeled as being elastic layers – a much more complicated modeling problem). It should be noted that the sediment layers are a very complex system of geologic deposits, and therefore the impact of the sediment layers on modelling results can be significant.

**BASEMENT LAYER** is a term used in propagation modeling to represent the deeper bottom materials and can be important from a modeling point of view because most models must be configured to dissipate energy in this layer and not let it return to the water column. It should be noted that in geological terms the basement layer will be found at great depth in areas where seismic operations are undertaken, and in most cases a proper use of sediment layers will be sufficient to handle the energy considerations in the model.
**Compressional Wave** is a type of wave that represents compression and expansion in elastic media. In underwater acoustics, water does not support any shear (the definition of a fluid) thus, the compressional waves are identical to pressure waves.

**Shear Wave** is a type of wave that represents a medium’s ability to support strain (torque). Fluids (water) do not support shear but sediments can and certainly, the more-dense basement layers do. Shear introduces an added level of complexity into the development of propagation models.

**Modeling Terms**

**Range-Dependence** is a term used to describe an ocean environment that changes with range e.g., sloping bathymetry, different bottom sediments and/or different SSP’s at different ranges.

**Full Field Model** is a term used to signify that a particular model computes the \( P(r, t) \) by working with the total field at any point in the waveguide. Most models can produce full-field results but a full-field model is cast (and executed) in terms of the total field.

**2D Modeling** is a term used to describe the modeling of acoustic energy in a range and depth slice i.e., in a vertical plane. \( TL \) as a function of range at a particular depth (or for a range of depths) is the standard propagation model output.

**Nx2D Modeling** is a term used to describe a method for computing acoustic coverage results in range and azimuth. Essentially, 2D fields (in range and depth) are computed along \( N \) azimuthal radials emanating from the source position. The environment on each radial is extracted from the full environmental description but the acoustic solution does not account for any coupling between azimuths (or out-of-plane interactions).

**3D Modeling** is a term that implies solutions to Eq. (1) account (usually approximately) for coupling of acoustic energy in azimuth. Typically, the 3D calculations employ an \( Nx2D \) strategy to get the field on \( N \) azimuthal radials and then process these component fields further to obtain an approximation to the 3D field which includes coupling effects.

**Sensitivity** is a term used to describe the dependence of a particular acoustic output parameter on the inputs. For example, the sensitivity of the acoustic prediction to environmental parameter error is of interest simply because it is extremely difficult to obtain a comprehensive environmental data set for input.

### 1.2 Objectives

The goal of this report is to identify the best combination of models for use by the E&P industry for environmental evaluation and marine animal disturbance mitigation. A comprehensive, critical and objective analysis of currently available, underwater acoustic propagation models has been compiled and presented herein. Of particular note, is the fact that these models depend critically on physically meaningful environmental data as input – hence, some emphasis is given here to identifying the location...
and availability of such data (marine physical databases, marine animal databases, and environmental translation models).

Finally, it should be noted that high-fidelity models such as those discussed here can only be expected to predict physical phenomena that are supported by the available environmental data – if the environmental description is limited (usually the norm in most cases simply because it is expensive to obtain geophysical data) then the acoustic predictions themselves must be subject to interpretation. Thus, some attention is devoted to identifying those models that will facilitate investigations of the sensitivity of the numerical predictions to environmental uncertainty so that significance can be attached to acoustic predictions when the environment is not well known.

Acoustic model surveys are not new [1, 3-7]. Recently, two very comprehensive surveys have been compiled and reported by Etter [8-9]. This survey differs in two very important aspects:

1. the focus is placed on E&P activities and environmental assessment issues, and
2. the inclusion of a complete and global set of environmental and marine animal databases (to be used with the acoustic models) is the first of its kind (to the authors knowledge)

This report will be of use to all E&P industry stakeholders where underwater sound is an issue. The E&P internal stakeholders include industry policy makers, regulators and technical leaders (survey managers, environmental compliance officers, geophysicists, etc.). Outside stakeholders (non E&P) include government decision and policy makers, governmental regulators, governmental monitoring networks, and non-governmental environmental organizations. This report provides detailed guidance with respect to the suitability of high fidelity acoustic models, modeling techniques, and the databases required to support them.

The specific objectives and questions this project was asked to address are:

- What is the current acoustic modeling capability for the wide range of possible sound sources and environments (included but not limited to frequency, range dependence and sediment interaction)?
- Are the acoustic models available, robust and user friendly?
- Are the acoustic models proven against real data?
- What is the current availability of databases (physical and marine animal) and in situ measurements to support model evaluations?
- Which acoustic models are best suited to be used in Oil and Gas E&P environmental evaluations?
- What are the most promising new approaches and how close are they to fruition?

The value of this inventory and critical assessment is that it allows the underwater acoustic modeling community to better focus efforts in areas where gaps are identified. Furthermore, the report is intended to provide an understanding of the tools available to the E&P industry policy makers, decision makers, and acoustic practitioners (engineering managers, survey mangers, etc.) who must choose and use acoustic models to conduct and perform risk assessments.
1.3 Methodologies

1.3.1 Propagation Model Surveys

The propagation model survey and assessment included extensive literature searches of published research articles, books, monographs, conference proceedings, workshop proceedings, and benchmark datasets.

A detailed questionnaire was prepared and sent to each of the developers of the chosen acoustic models for their critical review and editing. The questionnaires were designed to provide an in-depth analysis of the model with regard to solution physics, maturity of code, spectral properties, spatial properties, temporal properties, input environmental models required, output metrics, source representation, and any enhanced capabilities beyond just propagation. These questionnaires are presented in Appendix B. The information returned in these questionnaires was compiled and put in tabular form to be included in this report.

Finally, we would like to state up front that it is likely (almost inevitable) that we have missed "someone’s" model or misrepresented slightly "someone else’s" model. For this we apologize – there is no intent to promote one model over the other since as modelers ourselves we appreciate the dedication, hard work, and passion that goes into “everyone’s” model.

1.3.2 Locating Databases

There were two major phases of search and information gathering.

a. The first phase employed a web search to build an initial listing of databases and to obtain precursory information for each list entry – this established the baseline data for the second phase, and gave the authors a feel for the global database landscape.

b. The second phase involved revisiting each database source to find the remainder of the sought information. The primary search tools used were a World Wide Web (‘web’) search using Google search, Google Advanced search, and World Wide Science (http://worldwidescience.org/). Additionally, any acoustic model documentation, research literature, and/or, webpages that contained references (links) to related organizations and databases were also used.

1.4 Report organization

In addition to this introductory section, this report is organized into four main sections as listed below. Within these sections, the 8 deliverables defined in the RFP are presented.
1.4.1 Report Sections

**MWS Proposal Deliverables 1 & 2:**
**Section 2** Detailed summary of underwater and sub-bottom propagation models and supporting databases
- 2.1 – Review of standard model algorithms and solutions
- 2.2 – Identification of models
- 2.3 – Detailed comparison of propagation and application models
- 2.4 – Uncertainty in Predictions
- 2.5 – E&P source characteristics and sound exposure metrics

**MWS Proposal Deliverable 5:**
**Section 3** Marine database survey
- 3.1 – Common database descriptions and accessibility
- 3.2 – Physical parameter databases (Ref: Appendix C)
- 3.3 – Marine animal databases (Ref: Appendix D)
- 3.4 – Environmental models linking databases to model inputs

**MWS Proposal Deliverables 3 & 4:**
**Section 4** Critical assessment and review of acoustic models that may be used in the E&P industry
- 4.1 – Accuracy and sensitivity of surveyed models
- 4.2 – Identification of best suited E&P models
- 4.3 – Gaps in propagation modeling
- 4.4 – Gaps in physical databases
- 4.5 – Gaps in exposure modeling

**MWS Proposal Deliverables 6 & 7:**
**Section 5** Potential areas for further development
- 5.1 – Ways to improve propagation models
- 5.2 – Recommendations on new model or database development
- 5.3 – Recommendations on the development of a Decision Making Capability
- 5.4 – Project outreach & workshop(s)
- 5.5 – Modeling handbook

**MWS Proposal Deliverable 8:**
Peer review paper – in progress. Mid-project a paper and oral presentation were given at the Third International Conference on the Effects of Noise on Aquatic Life, August 11 - 16, 2013, Budapest, Hungary (Appendix E).

**Section 6** References
1.4.2 Report Appendices

The report contains the following six appendices that support the analysis and conclusions reached in the main body of the report:

Appendix A - Theoretical and Numerical Details of Select Acoustic Models
Appendix B - Models Library
Appendix C - Marine Physical Parameter Databases
Appendix D - Marine Animal Databases
Appendix E - Conference Paper
Appendix F - Report Authors Biographies
Section 2 - Detailed Summary of Underwater and Sub-bottom Propagation Models

Prepared for Joint Oil & Gas Industry Programme (JIP) on Sound and Marine Life

Solicitation Number: JIP 08-08

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Section 2

2 DETAILED SUMMARY OF UNDERWATER AND SUB-BOTTOM PROPAGATION MODELS

This section contains an extensive overview of underwater sound propagation models, including those that are currently available, potential new techniques and methods currently in development. Note, Section 2.1 below (and Appendix A) contains mathematical details that distinguish different model solution techniques. The reader not interested in such details, can skip directly to Section 2.2 where different models are identified according to the different solution techniques (but without the mathematical detail). The section concludes with comparative information about the models (as supplied by developers) and assessments regarding their suitability to the E&P problem set.

2.1 Review of Standard Model Algorithms and Solutions

In this section we provide a brief summary of the theory underlying many of the standard numerical models that have been developed for underwater sound applications. Historically, the motivation for developing the models has been the defense industry (navy, primarily) but the models themselves can and have been used to support marine mammal mitigation efforts.

Like naval sonar applications, the E&P operations involve a wide range of frequencies and environmental conditions – thus, different numerical approaches for computing the acoustic fields are required since no single numerical model can span the full range of conditions encountered. As noted previously, one of the prime objectives of this report is to identify/recommend acoustic models that are “best” suited to the E&P problems. In order to fully appreciate the recommendations, a basic level of understanding of the differences between the models is required and is presented herein.

Each propagation model is based on a specific representation of the field that solves the linearized acoustic wave equation shown in Eq. (1). The hierarchy of acoustic models is shown below in Figure 2-1. In this section we present the basic concepts underlying the various “standard” approaches to solving Eq. (1). In particular, we focus attention on:

- Transform Solutions (wavenumber integration [10], normal modes [11, 12], multipath expansion [13, 14]),
- Ray Solutions (overlap with multipath expansion techniques [15, 16]), and
- Marching Solutions (parabolic equations [17, 18, 19, and 20]).

These solution techniques are representative of the most widely used models in the underwater acoustics community (some representative model acronyms are given in the figure for each solution technique).

Different representations (solutions) have evolved because each is better suited to handling specific subsets of the operational/environmental conditions e.g., low versus high frequency or shallow versus deep water. Fortuitously, the conditions that determine the applicability of the different models overlap and thereby provide opportunities to compare and benchmark the solutions against each other since we should expect the models to produce similar and reliable predictions in such cases. Note, though we have tried to categorize the models according to solution technique, the boundaries between the models become blurred in some cases. For example, ray models that employ eigenrays in the calculation of the acoustic field are, to all intents and purposes, multipath expansion models even though they are derived...
from a different viewpoint. In other cases, the so-called “hybrid models” [21-22] utilize different field representations (rays, modes, PE) for different angular (wavenumber) components of the solution.

Because we present details of the individual models themselves, we do not discuss the theoretical or numerical details of any of the hybrid models in this report. Energy flux models [23-25] are similar in some sense to hybrid models since they can be cast in terms of modes or rays depending on the particular problem at hand. These models, though not new, are gaining in popularity and consequently we recognize this model type as a separate entity in Figure 2-1.

For completeness and as illustrated in Figure 2-1 above, we recognize the so-called “gridded solutions” to Eq. (1), in Section 1. These solution techniques involve either finite difference [26] or finite element [27, 28] algorithms applied to the solution of the wave equation directly (i.e., in time and space). The models are very powerful but tend to be resource-intensive (both in terms of computation time and storage) and also tend to be somewhat specialized in the type of problem to which they have been applied (e.g., scattering by buried objects). The gridded solutions have not (at least, not yet) achieved what one might call “main stream” acoustic model status and, moreover, appear to have somewhat limited scope in the context of the E&P problem. Consequently, we do not provide details concerning the underlying theory or numerical implementation herein.

Finally, with a view to the E&P problems we provide comments on each model solution type with respect to modeling of complicated sources, range dependence, 3D (three dimensional) effects, and environmental sensitivity. For reference, in what follows, we expand on terminology introduced in

Section 2 - Detailed Summary of Underwater and Sub-bottom Propagation Models
Section 1. As is illustrated below in Figure 2-2, we show a source located in an upslope 3D wedge environment (to the left of the figure). The source has directional properties in both the vertical (elevation) and the horizontal (azimuth) angular domains. With respect to range-dependent propagation in the center of the figure we show a plan view of the waveguide showing $N$ radials emanating from the source position—the source directionality is illustrated using the “green lobed” construct.

As discussed below, the models must be able to account for source directionality in both the vertical, $\psi$, and in the horizontal (azimuth), $\theta$. For coverage (area) type acoustic studies that are pertinent to the E&P industry, the modeler would typically execute what is known as $Nx2D$ modeling in which a number, $N$, of 2D (two dimensional) models are run at equispaced azimuths (the radials) covering the full 360° or angular sector desired. In $Nx2D$ modeling, there is no coupling of energy in azimuth (i.e., $\partial/j\partial \theta = 0$) and the $N$, 2D modeling problems (illustrated by the images for select radials) are solved independent of one another. Each 2D problem potentially involves the solution of a range-dependent problem in range and depth.

As illustrated, this is often performed using some sort of “staircase” or step-by-step procedure involving a sequence of range-independent sections pieced together to approximate the range dependence. These 2D problems change to match the environment along each of the radials. Note we illustrate range-dependent bathymetry – if other environmental parameters are range-dependent then a staircase approximation may not be sufficient i.e., some sort of interpolation in range might be required. Finally, we would like to point out that full 3D modeling is built up from the $Nx2D$ sequence by invoking procedures that model the coupling of energy in azimuth. Typically, a much more dense $Nx2D$ sequence is required to capture the 3D effects.
The directionality of the source is either the result of physical transducer size and geometry in relation to the wavelength of interest, or it may be a result of the shaping of a wave front through electronic manipulation of transmitting or receiving phase across an array of transducers. If the latter, the approach to calculating the directional effects is often referred to as beamforming. In acoustic modeling, beamforming is usually performed by an external program, and the resulting beam patterns, which are functions of frequency and propagation angle, are supplied as inputs to the model and are to be applied as a multiplier to the acoustic field.

As an example, consider the four beampatterns shown below in Figure 2-3. The image at top left is a 2D pattern at 200 Hz generated for a linear array of three hydrophones with $2/3\lambda$ spacing. Moving clockwise through the four images, we observe that as the number of elements increases, the beam pattern and directionality of the system becomes more refined. However a significant portion of the energy might be directed at undesirable angles through sidelobes. Note, for practical sources, the beampattern is three-dimensional—the beampattern images are equivalent to either a vertical or horizontal slice through such a 3D pattern; ultimately, the effect of source directionality must be incorporated into the modeled pressure field in the ocean waveguide.

![Figure 2-3 2D representations of the beampatterns from a set of four arrays](image)

Moving clockwise, each sample is generated for element spacing equal to 0.666$\lambda$: (a) 3 hydrophones, (b) 5 hydrophones, (c) 10 hydrophones, and (d) 20 hydrophones.

7 The beampattern directivity is a function of the number hydrophones and the acoustic aperture (length) of the array. By keeping the hydrophone spacing equal, increasing the number of hydrophones as in Figure 2-3 also increases the overall length.
Finally, with respect to environmental sensitivity, since it is impossible to know (measure) the environment (SSP, density, attenuation, bathymetry etc.) everywhere in space and time, a common approach is to:

- assign a probability distribution to each parameter (based on physics and historical data perhaps),
- randomly draw from these distributions to make model environments,
- run the model on each of these model environments,
- collect statistics on the computed pressure fields, and
- make assessments of the sensitivity of the acoustic field to environmental uncertainty

In what follows, for each model solution type, we indicate (by reference) the suitability for environmental sensitivity study.

### 2.1.1 Standard Solution Techniques

Eq. (1) is second-order partial differential equation whose solution depends on the specification of initial conditions (time evolution) and boundary conditions (spatial evolution). As mentioned above, the impetus for underwater acoustic model development has been largely derived from the navy and while current interest might lean towards active or broadband acoustics, traditional naval applications have been “passive” and focussed on listening for specific acoustic frequencies (or harmonics). Not surprising then that acoustic model development has been based on “harmonic” or frequency domain solutions.

The time-harmonic solution to Eq. (1) of Section 1 is obtained by defining the Fourier transforms of both the pressure and the source term. The transform relationships for the pressure are:

\[
p(\mathbf{r}, \omega) = \int_{-\infty}^{\infty} P(\mathbf{r}, t)e^{i\omega t} dt \tag{2}
\]

And

\[
P(\mathbf{r}, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} p(\mathbf{r}, \omega)e^{-i\omega t} d\omega \tag{3}
\]

Where \(\omega = 2\pi f\) is the angular frequency. With reference to Figure 2-1, and using the relationships expressed in Eqs. (2-3) applied also to the source term, it follows that the harmonic acoustic pressure (at frequency, \(f\)) is a solution of a reduced wave equation (or more formally, the Helmholtz equation). If we define a wavenumber parameter, \(k = \omega/c = 2\pi/\lambda\), then the reduced wave equation may be expressed: \(^8\)

\[
\rho \nabla \cdot \left( \frac{1}{\rho} \nabla p(\mathbf{r}, \omega) \right) + k^2 p(\mathbf{r}, \omega) = -4\pi S_\omega(\mathbf{r}) \tag{4}
\]

\(^8\)If the problem is broadband (e.g., impulse-type sources) then one would typically “synthesize” the broadband response by computing the solutions to Eq. (10) at as many frequencies as is required to build up the components of the Fourier Transform – this solution can be either analyzed directly in the frequency domain (averaging over frequency) or transformed back to the time-domain for further quantification and analysis i.e., time-delays.
Having transformed the problem to the frequency domain, we look to take advantage of other problem and environmental symmetries where possible. As Figure 1-2, above, suggests, although the ocean is complicated, it is fundamentally layered in depth and, thus, a reasonable solution path is one which first considers the layering to be range-independent i.e., constant thickness of layers. The idea being that the solutions in the more realistic ocean environments can be built up from the range-independent solutions directly or at least with modifications based on the knowledge gained in obtaining the range-independent solutions.

A further assumption used in obtaining the solution to Eq. (4) is that the source term acts at a point in the ocean layer since this allows the source to be represented mathematically as a delta function. Note, this is not a severe limitation since the acoustic fields due to distributed and, thus, more sophisticated sources can be built up from the point-source field by integration or by superposition. With this in mind, and in view of the fact the sound speed and density are functions of depth \( z \) only (a 1D medium is assumed), we can rewrite the Helmholtz equation in cylindrical coordinates:

\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial p}{\partial r} \right) + \frac{1}{\rho c^2} \frac{\partial^2 p}{\partial z^2} + k_0^2 N^2(z)p = -2S_\omega \frac{\partial(r)}{r} \delta(z-z_0). \tag{5}
\]

In Eq. (5) we have taken the rotational symmetry of the problem into account by recognizing that \( \partial/\partial \theta = 0 \), by specifying a point source at \( r = (0, z_0) \), and by integrating both sides with respect to \( \theta \). Here \( S_\omega \) denotes the spectral amplitude of the source at the given frequency \( \omega \). Also, \( k_0 = \omega/c_0 \) is a suitable reference wavenumber, \( n(z) = c_0/c(z) \) denotes the acoustic index of refraction, and the effects of absorption losses, \( \alpha \), in the medium can be treated by introducing a complex index of refraction, i.e., \( N(z) = n(z)(1 + i\alpha(z)) \).

In what follows we concern ourselves with several standard techniques associated with the solution of Eq. (5). Models based on these standard representations form the basis for mainstream modeling in underwater acoustics, and certainly of the models that appear best suited for application to the E&P application. In what follows, a brief outline of each model type is given below with supplementary details provided in Appendix A.\(^9\)

### 2.1.2 Transform Solutions

Previously, we used a Fourier transform to move from the time domain to the frequency domain, here we utilize a transform relationship that takes us from the space domain to the wavenumber domain. Assuming a range-independent, layered waveguide, the solution to (12) can be obtained by defining the following Hankel transform pair:

\[9\] The solution to the wave equation or the Helmholtz equation requires properties of the ocean which are the sound speed, bottom depth, surface elevation and roughness, and boundary properties or details of the underlying composition of the sediments. A broad overview [8-9] and extensive mathematical details can be found elsewhere [2].
In Eq. (6), \( J_0(kr) \) is the zero-order Bessel function of the first kind and \( G(k,z) \) is the so-called Green’s function. The details on the solution for \( G(k,z) \) in a layered waveguide are provided in Appendix A. In what follows, we assume that solution has been obtained, in which case the pressure field can be obtained via the inverse Hankel transform in Eq. (6) i.e., the solution, \( G(k,z) \), is transformed back to the space domain.

To assist with the clarity of presentation, we consider a simple layered Pekeris waveguide configuration shown in Figure 2-4 below. It consists of two homogeneous layers, namely

(i) a 100-m thick water column with sound speed, density, and attenuation parameters equal to 1500 m/s, 1.0 g/cm\(^3\), and 0.0 dB/\( \lambda \), respectively, and

(ii) an infinite ocean bottom with sound speed, density, and attenuation parameters equal to 1700 m/s, 2.0 g/cm\(^3\), and 0.5 dB/\( \lambda \), respectively.

Note, parameters in the ocean bottom are typical of a sandy ocean bottom [30]. By definition, the bottom layer is infinite; however, each acoustic model will have different method for terminating the computations at depth or for accounting for the fact that the layer is infinite i.e., the radiation condition.

Finally, we assume that the waveguide is being driven by an omnidirectional (non-directional), harmonic source, \( T_x \), at a depth, \( z_0 = 50 \) m, emitting a 100 Hz signal and received on omnidirectional receiver, \( R_x \), nominally at depth, \( z = 50 \) m also.

Figure 2-4 Shallow water “Pekeris” waveguide (\( f = 100 \) Hz) used for testing and comparison of long range transmission loss modeling.
2.1.2.1 Horizontal Wavenumber Integration

The theoretical details associated with the horizontal wavenumber integration solution in conjunction with Eq. (6) are presented in Appendix A. In practice, although the wavenumber integral in Eq. (6) is improper, the significant contribution occurs within a finite range of the wavenumber axis, \(0 < k_{\text{min}} < k < k_{\text{max}}\). The modulus of \(G\) for the configuration shown in Figure 2.4 is plotted below to the right in Figure 2.5 and clearly indicates that the major contributions to the wavenumber integral come from wavenumbers between \(k_{\text{min}} = 2\pi f / 1700 = 0.3696\,m^{-1}\) and \(k_{\text{max}} = 2\pi f / 1500 = 0.4189\,m^{-1}\).

This suggests that it may be amenable to evaluation by numerical quadrature. An efficient method of numerical integration is possible if the integral can be manipulated into the form of a finite Fourier transform so that the fast Fourier transform algorithm (FFT) can be used. In underwater acoustics, this approach was originally introduced as the fast field method [3] but now is usually referred to as the wavenumber integration method [2, 10, 29].

\[ p(r,z) = \frac{1}{2} \int_{-\infty}^{\infty} G(k,z) H_0^{(1)}(kr)dk \approx \int_{k_{\text{min}}}^{k_{\text{max}}} G(k,z)e^{ikr}\sqrt{k}dk \ . \quad (7) \]

Then, as outlined in the Appendix, if we discretize the wavenumbers according to \(k_{\text{max}} - k_{\text{min}} = (M-1)\Delta k\) and the range according to \(r_{\text{max}} - r_{\text{min}} = (M-1)\Delta r\), then subject to the constraint that \(\Delta r\Delta k = 2\pi / M\), an approximation to the exact representation in Eq. (14) is provided by the finite complex sequence,

\[ p(r_n,z) \approx \Delta k \frac{1}{2\pi i r_n} e^{ik_{\text{max}} r_n} \sum_{m=0}^{M-1} E_m e^{i2\pi mn / N} , \quad (8) \]
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where \( E_m = \sqrt{k_m G(k_m, z)} e^{imkr_{mn}} \). The above series has the desired form of a discrete Fourier series that can be evaluated rapidly using the Fast Fourier Transform (FFT) algorithm. The result of letting the \( m \)-point sequence \( \{E_m\} \) be input to a complex FFT routine is the complex sequence \( p(r_n, z) \) at \( M \) distinct range points \( r_n, n = 0,1,...,M-1 \). Only the first \( M/2 \) values are considered valid due to aliasing. For this procedure, \( M \) estimates of \( E_m \) and consequently \( G(k_m, z) \) as a function of \( k_m \) are required. The time-consuming part of this wavenumber integral method lies in the generation of this sampled depth-dependent Green's function. Further details on this approach, e.g., numerical stability issues, can be found elsewhere [2].

2.1.2.1.1 Source Modeling

Broadband sources can be easily accommodated using frequency synthesis whereas angular or directional properties can be incorporated as a "filter" in horizontal wavenumber domain [10] i.e., use the relationship between vertical and horizontal wavenumbers and the fact that vertical angle is associated with vertical wavenumber. Also, the method shows some flexibility in handling fully elastic sources that include shear – it is not clear that this is an issue in E&P marine life mitigation problems since interest lies primarily in water column energy.

2.1.2.1.2 Range Dependence

Range-dependence can be handled in this method either adiabatically [31] in the "spectral" sense or by breaking the problem into a sequence of range-independent sections [32-33] followed by solving the scattering problem at the vertical interfaces between sections by matching components in the spectral (wavenumber) domain. The scattering solution is approximate and compute-intensive but useful for "localized" discontinuities; it does not appear to lend itself to efficient range-dependent propagation modeling in a large ocean volume.

2.1.2.1.3 3D Modeling

This solution technique has been extended [34] to handle the solution of the reduced wave equation in three dimensions i.e., Eq. (5) with the \( \theta \) dependence back in. However, the solution does not account for environmental variability but rather the 3D nature of the sources.

2.1.2.1.4 Environmental Sensitivity

This solution technique has been used in conjunction with environmental sensitivity and geoacoustic inversion studies [35].

2.1.2.2 Normal Modes

In the previous section we indicated how wavenumber integration models obtain the pressure field via a direct and efficient (FFT) numerical integration of the inverse Hankel transform in Eq. (6). In this section we consider the implications of performing the integral analytically using the calculus of residues. Consider the \( k \)-plane representation of the Green's function (see Appendix A for details) and associated integration contour to the left in Figure 2-6 below. We observe a number of poles situated on the \( \text{Re}(k) \) axis (red dots) and a branch line defined by the blue contour. Provided the integration contour is chosen to enclose the poles on the positive \( \text{Re}(k) \) axis but exclude the branch line (see comments in Appendix A regarding branch lines) then the pressure field in the waveguide can be approximated by a "normal
mode” summation over the propagating modes plus an integral over the continuous spectrum of modes (corresponds to the branch line contribution).

Most normal mode acoustic models simply keep the propagating mode component to represent the field, well away from the source, in the oceanic waveguide as:

$$ p(r, z) = \frac{1}{\rho_0} \frac{2\pi i}{r} \sum_n \phi_n(z_0) \phi_n(z) e^{i k_n r} \sqrt{k_n}. $$

That is, the field at depth $z$ in Eq. (9) is proportional to a sum of the product of normal modes, $\phi_n(z)$ (evaluated at the source and the receiver depths), and the propagation factor, $e^{i k_n r} / \sqrt{k_n}$, where $k_n$ is the horizontal wavenumber associated with the $n^{th}$ mode. The normal modes are the natural vibrations of the system.

![Figure 2-6 Contour integration for the normal mode representation Propagation mode shapes, $\phi_n(z)$](image)

If a point source is located at the node of a particular normal mode, it will not be excited. Similarly, if a point receiver is placed at the null of a particular mode, that mode’s contribution to the total field will not be sensed. The functional dependence of the normal modes (at 100 Hz) in the waveguide shown in Figure 2-4 is shown to the right in Figure 2-6. In this simple case of an isovelocity waveguide, the eigenfunctions are sinusoidal i.e., $\phi_n(z) \sim \sin(k_n z)$ as illustrated in Figure 2-6 above to the right.

The boundary conditions at the surface and bottom lead to a specific definition for the vertical wavenumber $k_z$ that defines the depth function. The relationship between the horizontal and vertical wavenumbers ($k_n = \sqrt{c^2 - k_z^2}$) coupled with the boundary conditions at the ocean surface and the ocean bottom determine a “characteristic” equation whose solution yields the values of $k_n$ which are commonly referred to as the “eigenvalues”. The characteristic equation is typically transcendental (nonlinear) and requires special searching techniques to find the eigenvalue solutions—the methods for finding the eigenvalues typically distinguish the different normal mode models.
Not surprisingly, the horizontal wavenumbers corresponding to the peaks shown in Figure 2-4 (the wavenumber integration integrand) correspond identically to the horizontal wavenumbers of the modes shown in Figure 2-6; of course, this must be since the two methods are simply two different methods for dealing with the same inverse Hankel transform integral.

2.1.2.2.1 Source Modeling

Broadband sources can easily accommodated using frequency synthesis whereas angular or directional properties can be incorporated as a mode amplitude factor i.e., each mode can be associated with a particular vertical angle that, in turn, can then be related to vertical directionality [36].

2.1.2.2.2 Range Dependence

Range dependence has been handled in two different ways:

i. “Coupled modes” is a compute-intensive method [37] that involves partitioning the range-dependence into range-independent sections for the modes which can be found by the standard means. Solution is affected by solving the scattering problems at the vertical interfaces using a “mode-matching” technique – this method is similar in many respects to that alluded to above Section for the wavenumber integration method. Coupled modes are generally recognized as the benchmark solution for range-dependent acoustic waveguides but the method is not really amenable to coverage type problems (predictions over a wide area) associated with E&P operations.

ii. “Adiabatic modes” is simplification of the “coupled mode” formulation in which modes “adapt” adiabatically [2, 38] to the changes in waveguide properties – this means that there is no mode-coupling between modes (as there is in coupled modes). Of course, this implies that the changes in waveguide properties are not so severe as to cause mode coupling; under such conditions, the pressure field in the waveguide can be written as:

\[
p(r, z) \approx \frac{i}{\sqrt{8\pi r}} e^{i\pi/4} \sum_{n} \phi_n(0, z_0) \phi_n(r, z)e^{k_n(r)s} \frac{1}{\sqrt{k_n(r)}}.
\] (10)

In Eq. (10), the mode wavenumber, \(k_n(r)\), and mode function, \(\phi_n(r, z)\), are defined at range, \(r\), as if the waveguide was range-independent with the local properties. A comparison of Eq. (10) with Eq. (9) indicates that the adiabatic mode phase simply accumulates phase by summing all of the local contributions over range.

2.1.2.2.3 3D Modeling

Like the wavenumber integration technique, normal modes can be adapted to handle 3D directionality of sources but do not lend themselves to efficient and full 3D modeling.
2.1.2.4 Environmental Sensitivity

Normal mode codes have been used extensively for environmental sensitivity studies. They provide an efficient means of computing the field in a diverse set of underwater acoustic problems and thus are useful for Monte Carlo type investigations that might be associated with sensitivity studies.

2.1.2.3 Multipath Expansion

The multipath expansion technique also deals with the inverse Hankel transform in Eq. (6). In this case, a series expansion treatment of the Green’s function [39-40] (as shown in Appendix A) coupled with asymptotic evaluation of integrals results in a series solution. For the Pekeris waveguide shown below to the left in Figure 2-7 the series solution is particularly simple and can cast in terms of straight line paths and, to a very good approximation, products of plane-wave reflection coefficients occurring at the ocean surface and at the ocean bottom.

That is, the pressure field in the waveguide can be written as:

\[ p(r, z) = \sum_{v=0}^{\infty} \sum_{j=1}^{4} p_j^{(v)}(r, z), \]

where

\[ p_j^{(v)}(r, z) = \Gamma_j^{(v)} e^{i k_0 R_{jv}} e^{-\alpha R_{jv}}. \]

In Eq. 12, \( \alpha \) is the water attenuation in nepers/m and \( \Gamma_1^{(v)} = \Gamma_b^{(v)}(\theta_{1v}) \Gamma_t^{(v)}(\theta_{1v}) \), \( \Gamma_2^{(v)} = \Gamma_b^{(v)}(\theta_{2v}) \Gamma_t^{(v+1)}(\theta_{2v}) \), \( \Gamma_3^{(v)} = \Gamma_b^{(v+1)}(\theta_{3v}) \Gamma_t^{(v)}(\theta_{3v}) \), and \( \Gamma_4^{(v)} = \Gamma_b^{(v+1)}(\theta_{4v}) \Gamma_t^{(v+1)}(\theta_{4v}) \). Here \( \Gamma_j^{(v)} \) and \( \Gamma_j^{(v+1)} \) are plane wave reflection coefficients at the top and bottom interfaces respectively and are evaluated at specific angles that depend on ray index, \( j \). For a free boundary located at the ocean surface, \( \Gamma_t^{(\theta_{1v})} = -I \) independent

---

\( ^{10} \) The figure demonstrate waterborne acoustic propagation paths. At low frequencies and higher angles, the sound also propagates into the seabed.
of angle. Also, if we locate the Tx at a depth, \( z_0 \), and the Rx at a depth, \( z \), then the angles and path lengths involved are defined by analytic formulas; for example the formulae for \( R_{1v} \) and \( \theta_{1v} \) are given below:

\[
R_{1v} = \sqrt{r^2 + (2vH + z - z_0)^2}, \quad \theta_{1v} = \tan^{-1}\left(\frac{2vH + z - z_0}{r}\right).
\]  

(13)

The other formula can be obtained from the positions of the images of the source and receiver in the boundaries [2].

Apart from the reflection coefficients, the multipath solution for the Pekeris waveguide can almost be written down by inspection. Unfortunately, this is only possible in one or two simple cases (of which the Pekeris waveguide is one). Typically, in a realistic ocean, the full procedure outlined [39] in Appendix A must be used with a commensurate increase in numerical difficulty – for this reason, apart from the FAME [13] component of the Generic Sonar Model (GSM [14]), formal multipath expansion solutions have not been widely used in underwater acoustics. However, as we will see in the next section concerning ray solutions, multipath expansions find a certain commonality with ray techniques and thus are used extensively in that context.

2.1.2.3.1 Source Modeling

It is certainly possible to accommodate broadband sources by Fourier synthesis, to accommodate directional sources by applying angular filters at the source and receivers but the issue is the types of problems that can be solved with formal application of this method i.e., very limited.

2.1.2.3.2 Range Dependence

Recent work [41] has demonstrated that it is possible to generate range dependent solutions by a formal application of this technique.

2.1.2.3.3 3D Propagation

It does not appear possible to generate fully-coupled 3D solutions by a formal application of this technique. It would be possible to generate \( N \times 2D \) solutions to an extremely limited problem set.

2.1.2.3.4 Environmental Sensitivity

It would be possible to conduct environmental sensitivity studies for a very limited set of canonical problems but, in general, this method does not lend itself to efficient solutions in realistic ocean environments.

2.1.3 Ray Solutions

As mentioned in the previous section, formal application of the multipath expansion technique to an arbitrary oceanic waveguide is not easy, and, consequently, rarely if ever attempted. As it turns out, ray-theoretic treatments can be adapted to make use of a multipath-type representation of the field. Essentially, we begin by representing the acoustic pressure in terms of a series of ray paths each with an amplitude, \( A_0 \), and with a phase, \( r \), in the form,
Section 2 - Detailed Summary of Underwater and Sub-bottom Propagation Models

\[ p(r, z) = \sum_{m=0}^{\infty} A_m(r, z) \frac{e^{i \alpha r(z)}}{(ik)^m} \sim A_0(r, z) e^{i \alpha r(z)}. \]  \hspace{1cm} (14)

As shown in the Appendix, substitution of Eq. (14) directly into Eq. (5) (with the right-hand side set to zero) and collecting terms yields a set of equations that can numerically integrated to give the so-called "ray paths". Consider the waveguide shown below on the left in Figure 2-8. The ray paths (for range-independent sound speeds) can be found by integrating

\[ \frac{dz}{dr} = \tan \theta \quad \text{and} \quad \frac{d\theta}{dr} = -\frac{1}{c} \frac{dc}{dz}. \] \hspace{1cm} (15)

One can immediately see that vertical sound speed gradients play an important role in determining the behavior of these paths. A typical “ray diagram” is show to the right in Figure 2-8 and represents the field in a deep (H = 5000 m) ocean with the sound speed profile shown – the so-called Munk profile.

The range of grazing angles has been limited in the ray-trace to those angles ≤ ±14° – the rays are color-coded with those in red having launch angles ≤ ±5°, those in orange having launch angles in the range 5° to 10° and -5° to -10°, and those in yellow having launch angles > 10°. For reference the Munk Profile is given in analytic form as

\[ c(z) = 1500 (1+0.00737 (\hat{z} - 1.0+e^{-z})) \] where \( \hat{z} = \frac{2(z-1300)}{1300}. \)

To the acoustic modeler, a ray diagram, like shown to the right in Figure 2-8, is "seductively misleading" since, despite the relative ease in computing it and despite the obvious relevance to the propagation, it only represents a part of the story i.e., it is really only a manifestation of the \( r(r, z) \) factor in Eq. (14) above. The computation of the acoustic pressure from the ray diagram (e.g., according to Eq. (14)) has long been a distinguishing feature of many a ray code.

While all ray codes trace a fan of rays using the standard ray equations, the amplitudes are often determined numerically from rays that bracket a receiver. Some ray models attempt to locate eigenrays (multiple rays that connect a source to a receiver) which can be a difficult nonlinear root-finding problem. In either case, the expression for ray amplitude along a ray, \( A_0(r, z) \), becomes infinite at focal points where the cross-sectional area goes to zero or along caustics. In addition, due to refraction, there can be regions within a waveguide where rays emitted from the source do not reach a specific receiver location,
i.e., within shadow zones, and the amplitude goes to zero there (these regions are often adjacent to caustics). This unphysical behavior is the result of neglecting higher order terms in the derivation of the ray equation, with the result that diffracted energy is not taken into account.

It should be reiterated that ray models that attempt to represent the acoustic field as a sum of eigenrays (according to Eq. (14)) are essentially multipath expansions albeit derived from a completely different viewpoint.

Finally, we mention that Gaussian beam tracing is a method that attempts to address the above implementation issues. It retains the essential features of ray methods by approximating a given source by a fan of beams (central rays) that propagate through the medium according to Eq. (15) coupled with two additional equations that track beamwidth and curvature. The influence of beamwidth is described by a Gaussian distribution, or other symmetric function, about each central ray. The field at (r,z) is constructed by adding up (coherently or incoherently) the contribution of each beam at that position. Consequently, the computation of eigenrays is avoided, perfect shadow and caustic regions are eliminated, and the low-frequency applicability is improved. A numerical comparison of four variants of this finite-beamwidth method is provided in [42]. For more details on this approach, the reader is referred to the treatment in [2, 16].

2.1.3.1.1 Source Modeling

Since the computation of the rays starts at a point in space (and time) and then proceeds on the basis of a set of “launch angles”, it is a very easy and straightforward procedure to include a weighting on each ray that is angle dependent. Also, though not discussed in detail here, individual rays are non-dispersive; thus, pulse shapes (as a function of time) are preserved and this results in some flexibility in handling broadband sources with performing Fourier synthesis as in the other solution techniques.

2.1.3.1.2 Range Dependence

Range dependence in the sound speed profile (in the 2D sense) is formally handled by integrating all four ray equations as outlined in Appendix A i.e., Eqs. (A28-A29). Interaction with boundaries is straightforward and involves including the boundary slope (1D in this case) in the reflection calculations.

2.1.3.1.3 3D Modeling

Full 3D modeling is also possible using a ray theoretic approach simply by extending the “ray equations” to three-dimensions, that is:

\[
\frac{dx}{ds} = c\zeta(s), \quad \frac{dy}{ds} = c\eta(s), \quad \frac{dz}{ds} = c\zeta(s), \quad \text{and}
\]

\[
\frac{d\xi}{ds} = -\frac{1}{c^2} \frac{dc}{ds}, \quad \frac{d\eta}{ds} = -\frac{1}{c^2} \frac{dc}{dy}, \quad \frac{d\zeta}{ds} = -\frac{1}{c^2} \frac{dc}{dz}.
\]

Here, \([x(s), y(s), z(s)]\) define the ray trajectory in the three Cartesian coordinates \((x, y, z)\) and \([c\xi(s), c\eta(s), c\zeta(s)]\) define the local tangent to the ray. The initial conditions for each ray specify the source location and the slope of the emitted ray (measured positive downwards from the horizontal),
$x(0) = x_0$, $y(0) = y_0$, $z(0) = z_0$, and
\[
\xi(0) = \frac{\cos \theta_0 \cos \varphi_0}{c(0)}, \quad \eta(0) = \frac{\cos \theta_0 \sin \varphi_0}{c(0)}, \quad \zeta(0) = \frac{\sin \theta_0}{c(0)}, \tag{17}
\]
where $(x_0, y_0, z_0)$ are the source coordinates and $\theta_0$ and $\varphi_0$ are the ray launch angles in the vertical and horizontal directions respectively. Interaction with any boundary would also require that the reflection process accommodate 2D slopes—a straightforward adaptation.

2.1.3.1.4 Environmental Sensitivity

The efficiency by which the ray solutions are obtained (and in particular the beam methods) make them an obvious candidate for sensitivity studies where often the statistical properties of the sensitivity metric require that the model be run thousands of times i.e., Monte Carlo simulation.

2.1.4 Marching Solutions

The three “transform solutions” of the acoustic field described above (wavenumber integral, normal mode and multipath expansion), were derived formally from the integral transform solution to Eq. (5) for $p(r, z)$ – the solution obtained via manipulation of the depth-dependent Green’s function solution to Eq. (A1). Each of these representations led to efficient numerical procedures for computing the field due to a point harmonic source in range-independent waveguides. Extension to more complicated range-dependent scenarios is considerably less efficient with the exception of the adiabatic modes technique.

A popular and very useful alternative approach is provided by the so-called “marching solution” techniques in which the acoustic field, defined on a grid of points in depth, is marched out on a range grid as is illustrated in Figure 2-9 below to the left. This type of solution in underwater acoustics is referred to as a parabolic equation, or PE, solution. As a matter of interest, we present the PE field computed for the deep water Munk profile (ray diagram shown in Figure 2-8 above) to the right in Figure 2-9. The correspondence between the PE field and the ray field is quite remarkable on the one hand, given the differences in solution technique, but not so when we realize that both models work from the same basis equation i.e., Eq. (5).

Figure 2-9 Illustration of the grid for the PE model Full field image for a deep water waveguide supporting the Munk SSP profile
In Figure 2-1 we identified two different “streams” for the PE solutions, namely: (i) FFT PE’s [2, 17, 18] and (ii) Padé PE’s [2, 19, 20]. The distinction can be made on a number of different levels. Formally, the two approaches differ fundamentally in their treatment of the “vertical” differential operator that is integral to the PE solution – as their name suggests, FFT PE’s utilize FFTs to solve the vertical component whereas Padé PE’s utilize a finite difference (FD) development.

The FFT PE’s are typically classified as being “narrow angle” in their ability to accurately handle channels that only support grazing angles up to $15^\circ$ [43] and in some cases [17] up to $30^\circ$. Alternatively, the modern FD split-step Padé PE’s can handle very high grazing angles (approaching $90^\circ$ at the expense of more work i.e., Padé terms). In this report we focus primarily on the FD split-step Padé PE solution technique – the details of the analysis for both FFT PE’s and FD PE’s are presented in the Appendix A; the highlights for FD PE’s are reproduced below.

The split-step Padé PE represents the pressure field, $p(r, z)$, as an outgoing Hankel function (carrier wave) that is modulated by a slowly varying envelope function or reduced pressure, $\psi(r, z)$, as follows

$$p(r, z) \sim \psi(r, z) \frac{e^{ik_0r}}{\sqrt{k_0r}} ,$$  

where $k_0 = \omega/c_0$ is a suitable reference wavenumber. The solution for the reduced pressure is obtained at each range step by summing the solutions to a set of tridiagonal systems of equations (one for each Padé term $m = 1,..., M$ ) as,

$$\psi(r + \Delta r, z) = \psi(r, z) + \sum_{m=1}^{M} \psi_m(r, z) ,$$  

Where each partial component $\psi_m$ satisfies

$$\left(1 + B_{m,M}X \right) \psi_m(r, z) = A_{m,M}X \psi(r, z) , \quad m=1,...,M .$$  

In Eq. (20), $A_{m,M}$ and $B_{m,M}$ are related to the so-called Padé coefficients obtained by representing the propagator as a rational Padé summation approximation as

$$e^{ik_0X[1+\sqrt{1+X}]} \approx \sum_{m=1}^{M} \frac{1 + A_{m,M}X}{1 + B_{m,M}X} ,$$  

where,

---

11 It is important to note that the use of FFT’s introduces issues with respect to the handling of density jumps at the ocean bottom. Historically, the FFT PE’s broke onto the scene first but gradually, over the years, have yielded the stage to the more capable FD codes.
As shown in Appendix A, the propagator is obtained by factoring the reduced wave equation and retaining only the outgoing component. Since each partial component $\psi_m$ in Eq. (19) depends on the known value $\psi$ from the previous range step, it is seen that all $M$ components of $\psi_m\psi$ can be solved in parallel. Consequently, this representation can take advantage of multiple processors in a straightforward way.

### 2.1.4.1.1 Source Modeling

As indicated to the left in Figure 2-9, above, the PE solution requires a "starting field" be specified on the vertical grid at range zero i.e., $\psi(0, z)$ on the right-hand side of Eq. (20). Fortunately, there are several options available [2] that give the User some control over the angular content at the source. Self-starters are slightly more complicated to implement but provide the best match between starting field and the waveguide properties. Note, regardless of the choice of the starting field, it is always possible to arrange to transform the starting field sequence $\psi(0, z_m)$, $m=1,...2^N$ to the vertical wavenumber domain, apply a filter (representing vertical source directionality), and inverse transform to obtain a modified starting field $\hat{\psi}(0, z)$ that accounts for source properties.

The PE solution has been used extensively in E&P-related acoustic studies [45] and involves modeling of the air-gun source [46].

### 2.1.4.1.2 Range-Dependence

Range-dependent capability is strength associated with the PE solution technique and is naturally accommodated within the framework of the step-by-step marching procedure. That is, we let the environment change every range step and provided the change is not “too severe” then the PE field can naturally adapt to the environment. As it turns out, the types of range dependence that one can associate with continental shelf and littoral environments fit well within the bounds of “not too severe” provided that an energy-conserving adaptation [19, 47-49] can be made to the propagated field. Of course, once we allow the environment to change with range, and in particular each range step, then we must be cognizant of how we interpolate sparse environmental information (the usual scenario) onto the denser computational PE grid in range and depth.

### 2.1.4.1.3 3D Modeling

3D modeling is also a strength of the PE solution technique [49-50]. The development depends upon keeping the $\theta$dependence in Eq. (5) and, hence, in Eq. (22) above as:

\[
X_{3D} = N^2(z, \theta) - 1 + \frac{1}{k_0^2} \rho(z) \frac{\partial}{\partial z} \rho^{-1}(z) \frac{\partial}{\partial z} + \frac{1}{k_0^2 r^2} \frac{\partial^2}{\partial \theta^2} . \tag{23}
\]
There are several ways to handle the splitting of the operator $\sqrt{1+X_{3D}}$. One simple approach (for example) is based upon the fact that typically, the factor, $\frac{1}{k_0^2 r^2} \frac{\partial^2}{\partial \theta^2}$, is much smaller than the other terms in Eq. (23) and thus, for 3D modeling purposes, we can make the following approximation

$$\sqrt{1+X_{3D}} \approx \sqrt{1+X_{2D}} + \frac{1}{2k_0^2 r^2} \frac{\partial^2}{\partial \theta^2}$$

(24)

Where

$$X_{2D} = N^2(z, \theta) - 1 + \frac{1}{k_0^2} \rho(z) \frac{\partial^2}{\partial z^2} \rho^{-1}(z) \frac{\partial}{\partial z}.$$  

(25)

In this case, the field is propagated by (see Eq. (A38) of Appendix A):

$$\psi(r + \Delta r, z, \theta) = e^{ik_0 \Delta r \left( \frac{1}{2} \left( r k_0^2 \frac{\partial^2}{\partial \theta^2} \right) \right)} e^{ik_0 \Delta r \left( \sqrt{1+X_{2D}} - 1 \right)} \psi(r, z, \theta).$$

(26)

Numerically, the solution of Eq. (26) proceeds identically to that provided by Eqs. (19-20) above but for each azimuth, $\theta$. That is, the 3D PE field is marched out on the depth grid, one range step, at each azimuth. Then, the azimuthal operator in Eq. (26) can be applied at each depth in the waveguide i.e., either using an FFT approach or a finite difference approach one must solve $N_z$ “azimuthal” problems in order to correctly account for the full 3D coupling effects. Here $N_z$ is the number of grid points in depth used in the PE solution.

An example of the importance of full 3D coupling effects in a waveguide is shown above in Figure 2-10. The scenario is a shallow water wedge environment in the ocean bathymetry, initially at 380 m, tapers to
20 m over a distance of roughly 7 km. A 25 Hz source (exciting a single mode in the water column) is placed midway up the wedge. The top half of the color image shows the field at a depth of 36 m when 3D coupling is ignored. The lower half of the color image shows the same field when 3D coupling is included. Intuitively, we know that the sloped bottom must bend the propagating energy out towards the deeper water – this feature is clearly captured by the 3D calculations but not by the Nx2D calculations. Affirmation of the results are supplied by the line graph to the right of the figure (for receiver positions transverse to the up-down slope direction) which clearly show the effect of 3D coupling (horizontal refraction) that extends to 10’s of dB’s in level at range.

2.1.4.1.4 Environmental Sensitivity

The PE solutions are well-suited to environmental sensitivity studies and have been successfully used in this regard [51]. One feature of the PE that is often disregarded is the fact that field is computed at each grid point in depth (not just at the receiver position) every range step – this can lead to some efficiencies when computing sensitivity metrics.

2.1.5 Energy Flux Models

Energy flux models were originally derived from an attempt to extract “average” characteristics of the propagation in a shallow water refracting waveguide by examining the ray invariant [23],

\[ \int_0^H \sin \theta \frac{dz}{c} = T = \text{const.} \quad (27) \]

Or by examining the average transmission [24],

\[ \int_0^H p^2(r,z)dz \quad (28) \]

where \( H \) could be some depth in the water column or the depth of the water column itself. \(^{12}\)

To date the energy flux models depend upon having either a modal description or a ray description available for the particular waveguide of interest and are therefore dependent on those models with respect to source properties, range dependence, and 3D modeling.

As mentioned previously, energy flux models are an emerging force in the underwater acoustics community and while perhaps not well-suited to coverage-type studies they appear to be very useful in the analysis of specific propagation effects. Where energy flux models may find application in the E&P problem set lies in the environmental sensitivity where useful metrics may well be cast in terms of an “average” over range, depth, and/or angle.

\(^{12}\) The advantages of the technique appear to be mainly in terms of efficiency i.e., useful information provided very quickly. Recent advances in using the technique seem to center around including more “coherent” mode-interference effects [25] while keeping the overall efficiency high.
2.1.6 Summary

In the above sections we have attempted to provide some of the theoretical and numerical details that form the basis of the mainstream underwater acoustic models. To summarize,

- The wavenumber integral representation makes use of the FFT algorithm to numerically invert the Hankel transform of the depth-dependent Green's function with respect to horizontal wavenumber.

- Alternatively, the normal mode representation is obtained by applying contour integration methods to replace the integral along the real wavenumber axis with a sum of residues at the poles (modal wavenumbers) of the depth-dependent Green's function plus contributions from any branch line integrals.

- The multipath expansion representation relies on geometric ray concepts to partition the total field into various physical propagation components (refracted, surface reflected, and bottom bounce paths etc.) which are then evaluated asymptotically.

In contrast to these quasi-analytic representations (where we transform Eq. (5)), the ray solutions and the PE solutions are developed from considering Eq. (5) itself. Ray solutions derive from an attempt to find a series (or multipath type) solution to the Helmholtz equation directly.

One of the products of this approach is the ray diagram which is very useful and efficiently generated. Unfortunately, transitioning from traced rays to pressure is difficult in some cases for real ocean environments but beam methods appear to be a good option. The parabolic equation approach relies on factoring the reduced wave equation into incoming and outgoing components (with respect to \( r \) from the source). By neglecting the effects of the incoming components, the outgoing factor can be solved numerically, and very efficiently, using step-by-step marching methods.

2.2 Identification of models

In this section we put names to models that fall under the broad classifications defined in Section 2.1 above. Where applicable we provide supplementary information about each model or associated solution technique.

2.2.1 Wavenumber Integration

To reiterate (from Section 2.1.1), the wavenumber integration technique is a method used to numerically solve the wave equation. The steps needed to define the wavenumber integration technique are:

i. Obtain the depth-dependent Green's function for a single frequency at a dense sampling of horizontal wavenumbers for the layers and boundary conditions that describe the environment.

ii. Perform an inverse Hankel transform to change the Green's function's dependence from wavenumber to range. At this point we have a “harmonic” solution to our problem i.e., pressure as a function of range and depth at a specific frequency.

iii. Repeat steps i and ii at a sampling of frequencies in the bandwidth of the source (if necessary).
iv. Perform an inverse Fourier transform on the transfer functions from step iii to obtain the solution in time, range and depth (if necessary).

**OASES** [66] is a popular model that belongs in the wavenumber integration category. Note, OASES is an extension of the predecessor named SAFARI [10]. The OASES model contains a family of algorithms that include modules for elastic and poroelastic media and range dependence. Also, it can generate harmonic solutions, broadband solutions, and computes plane-wave reflection coefficients.

### 2.2.1.1 Advantages & Disadvantages

**The advantages of the wavenumber integration solution** are that arbitrary layer properties, including elastic sediments, can be easily accommodated and a time domain solution can obtained from first principles. Since wavenumber integration techniques can be configured to account for propagating part of the continuous spectrum, they are particularly well-suited and efficient for short-range time-domain problems where bottom interaction is important.

**The disadvantages to the wavenumber integration solution** are the large memory requirement and long computation times for broadband problems (for harmonic problems, the computation time is proportional to the number of layers and to the size of the transform used). There are also difficulties working with range dependent properties. For example, the OASES model employs a technique for range-dependence called spectral super-element [32] in which the environment is divided into a series of range-independent sectors, separated by vertical interfaces along which the field parameters are expanded in a series of orthogonal polynomials within each layer. The boundary conditions along the vertical interfaces can be expressed as a linear system of equations in the polynomial coefficients whose solution yields the two-way field in all elements simultaneously.

### 2.2.2 Normal Modes

As described in Section 2.1.2.2 above, normal modes are an alternative approach to solving the Helmholtz equation in two-dimensional stratified environments. In theory, the modal solution incorporates both the discrete spectrum of sums of modes and the continuous spectrum of modes; the latter stem from a branch-line integral in k-space. In the normal mode approach, the particular nature of the boundary conditions (problem dependent) is important in determining the best representation of the equations. Not surprising, techniques employed to evaluate these equations and the treatment of range dependence differentiate each of the normal mode models that are available today.

Normal mode models can also accommodate elastic sediments that support shear wave propagation. Elasticity can be important for several reasons. First, conversion from water-borne energy to shear waves (at the ocean bottom interface) and subsequent attenuation or leakage of the shear waves represents a loss mechanism that can be significant in a wide range of applications. Second, at low frequencies and for sources and receivers close to (or in) the ocean bottom, shear wave and interface modes of propagation may dominate.

**ORCA** [11] is a popular and efficient normal mode model that handles acoustoelastic layers with sound speed gradients. It can compute broadband TL in multi-layered acoustoelastic environments and it is largely automatic (the model can configure itself, if required, with regard to certain parameters). However, it has the weakness of being range independent.
Range dependence represents a somewhat complicated extension for normal mode models because of the redistribution of energy among the modes caused by the changing waveguide environment. For example, experiments have shown that sloping bottoms add energy to higher mode numbers in the case of up-slopes and to the lower mode numbers for down-slopes. As mentioned in Section 2.1.1, in the case of range-dependent bathymetry, the most common approach is to divide the bathymetry into range-independent segments or steps. Standard techniques are used to find the properties on either side of the vertical interfaces – however, a complicated mode-matching or mode coupling problem ensues in order to propagate the acoustic energy across these vertical interfaces. This coupling redistributes the energy from one mode into others using a coupling matrix and it is computationally intensive but extremely accurate. These types of models are used as benchmark models.

**COUPLE** [37] is a range-dependent normal mode model whose solution (considered a benchmark) contains a finite sum of discrete trapped modes and a continuous sum representing energy leaking into the half-space bottom. It offers three choices for range dependence: a two-way exact solution (coupled modes), a single scatter approximation and an adiabatic approximation.

**KRAKEN** [12] is a range-dependent normal mode model with a number of options for treating ocean-acoustic and acoustoelastic problems in range-independent, range-dependent or fully 3D environments. The modes are found by a fast finite difference method with impedance conditions for elastic boundaries. The version called KRAKENC handles complex loss mechanisms and leaky modes, and the version KRAKEL will compute elastic displacements and stresses.

Another approximation for handling range dependence in normal mode theory is to replace the coupling coefficients (as defined in COUPLE) by excitation coefficients that map the modes from one step to another.

**C-SNAP** [67] is a range-dependent, SACLANTCEN normal mode model designed to be easy to run and competitive in terms of execution time with existing PE algorithms. It treats the bottom as fluid sediment with varying sound speed overlying a solid half-space with elastic properties for losses only. Its mode calculations are based on the KRAKEN finite-difference method. It handles range-dependent bathymetry in a manner similar to COUPLE (staircase approximation) by defining “excitation coefficients” that propagate the acoustic field across the vertical interfaces.

As discussed in Section 2.1, perhaps the easiest method of handling range dependence is the adiabatic approximation which assumes there will be no coupling between modes. This approximation is sometimes referred to as the ‘conservation of mode number’, that is, the mode will retain its number and shape as the wave progresses down range. The eigenvalues are found by a range average (integral over range) of the eigenvalues in each range segment. The major difficulty with this approximation is that its validity for more severe range dependent environments has not been established; furthermore, it may prove difficult to mathematically determine this range of validity.

**POPP / PROLOS** [68] is a normal mode model package that calculate the modes numerically using a two-ended shooting method. It can include root-mean-square (rms) roughness at all layer interfaces. It has been successfully applied to bistatic reverberation and target echo calculations using modal group velocities and it handles range-dependence adiabatically.
PROSIM [69] is a SACLANTCEN normal mode model designed to predict broadband deterministic acoustic propagation with special attention to accuracy, robustness and efficiency. It uses a modification of ORCA as its core propagation engine. The output is the received energy level, channel transfer function and time series. PROSIM handles range-dependence adiabatically.

WKBZ [70] is a normal mode model that uses WKB eigenfunctions (up-going and down-going rays) for waveguide modes (summed coherently) and bottom-reflected modes (summed incoherently) to predict the smoothed average intensity. In the WKBZ model, ocean bottom layers are assumed to be fluid and range-dependence is treated adiabatically. 13

2.2.2.1 Advantages & Disadvantages

The advantages of the normal mode solution are that the modes can usually be computed efficiently and they give physical insight into the behavior of the acoustic energy in ducts and shadow zones (particularly at low frequencies and shallow water where there are few modes). Moreover, they can model complex sediment layering with elastic properties. Note, the mode sum (Eqs. (9-10)) and, hence, $TL$ can be computed coherently by retaining the phase of each mode or incoherently by ignoring individual mode phases. An incoherent $TL$ calculation is well-suited for comparisons with measured data that involve averaging over frequency, e.g., 1/3-octave band data. Not surprisingly, incoherent transmission loss is “smoother” than coherent $TL$ because the latter retains all of the fluctuations in the acoustic field.

The disadvantages of the normal mode solutions are twofold: (i) the mode eigenfunctions can be difficult to derive in closed form, and (ii) handling multiple layers or range dependence can be time intensive.

2.2.3 Multipath Expansion

As mentioned in Section 2.1.2.3 above, underwater acoustic models based on the multipath solution technique are rare–this is in part due to the fact that it has proven difficult to carry out the asymptotic evaluation of integrals associated with each path except in very specialized cases i.e., has not proved amenable to real ocean environments.

Integrated Mode [41] is an underwater acoustic model based on the multipath expansion technique that may prove to be the exception to the previous comments since it claims that it can handle range-dependent bathymetry, bottom type, and sound speed.

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13An interesting approximation for mode coupling coefficients for forward coupling is called the equivalent ‘wedge ocean’ described by [71]. The key technique is that a complicated bathymetry can be mapped to an equivalent wedge ocean by pre-computing local mode functions at all water depths in the scenario, and then using them in an order that traces the actual bathymetry. The excitation coefficients are constructed by cascading the coupling matrices at each step, making this technique much faster than the conventional one.
2.2.3.1 Advantages & Disadvantages

The advantages of the multipath expansion method are that the acoustic field can be examined in terms of “paths” with their own individual amplitude and phase–time delay along these paths is a natural product of the solution.

The disadvantages of the multipath expansion method lies in the rather limited problem set to which the method has been applied. There have been few models based on this technique although the Integrated Mode model could well constitute a breakthrough.

2.2.4 Ray Solutions

Traditionally, for operational usage, ray models have been relied upon to provide a fast visual description of the acoustic field i.e., the ray diagram. An interesting extension of the example shown in Figure 2-8 above is shown in Figure 2-11, below. The difference in the two figures is provided by the sea-mount in Figure 2-11 speed and clearly shows that the tracing can be extending to range-dependent environments. The ray solution technique is especially attractive for high-frequency, deep-water problems where normal mode (large numbers of modes) and parabolic equation models (large depth grid) are not as efficient. Of course, producing the ray diagram is the easy part–computing the field is another matter.

As discussed in Section 2.1.3 (and Appendix A), in conventional ray theory, the amplitude of the acoustic field associated with a ray is inversely proportional to the separation between two adjacent rays and it becomes infinite in a caustic where the sound rays are focused and their separation is zero. Consequently, conventional ray theory is almost never employed when a high fidelity prediction is required because of the somewhat coarse accuracy of the results and the instabilities around caustics. Additionally, conventional ray theory can predict false caustics due to strong discontinuities in slope from a poorly sampled sound speed profile.

GRAB [15] (Gaussian Ray Bundle) is a ray technique that can perform more consistently and smoothly in the presence of caustics by effectively expanding the zone of influence associated with an eigenray. The technique represents the acoustic field as a multipath expansion of eigenrays each of which is associated with a ray bundle of ordinary traced rays. These ray bundles are related to a specialized interpolation scheme that is designed to compute eigenrays [72]. The GRAB technique’s eigenray amplitude differs from conventional Ray theory in that it is weighted by a Gaussian distribution in depth, contributing some
energy to all depths i.e., as opposed to simply being related to the separation between two neighboring rays. Apart from a “smoother” behavior near caustics, GRAB models are subject to the standard limitation of ray theory.

**CASS/GRAB** [73] is a collection of models for the environment and for post-processing the acoustic field that utilizes the GRAB technique to compute eigenrays. CASS (Comprehensive Acoustic System Simulation) is an active and passive range dependent propagation, reverberation, noise and signal excess model which can provide a vast number of output metrics designed for Navy Fleet tactical use.

**SPADES** [74] (Sensor Performance and Detection Evaluation System) is a research propagation loss model using the GRAB technique. It propagates a set of ordinary test rays from the source and then uses a ray bundle interpolation scheme. Range dependence is handled and there are several options available for including surface roughness loss and scattering.

**WAVEQ3D** [75] (Wavefront Queue 3D) is a propagation loss model that is a derivative of the GRAB mathematical approach for 3D spherical/time coordinates, specifically formulated to provide a significant speed advantages to real-time, active sonar, simulation/stimulation systems in littoral environments at active sonar frequencies.

**FMM** [76] (Fast-Marching Method) is a new ray-based approach that employs a practical grid-based scheme for tracking multiple reflection and refraction phases in complicated 3D layered media. The program computes travel time and ray paths using a finite difference solution to the eikonal equation.

\[14\] The figure shows a source at a depth of 1000m. Seismic survey sources are towed at much shallower depths.
The goal of the program is to support tomography, refraction/wide angle reflection imaging and earthquake location. Figure 2-12 displays an example of a ray trace produced by FMM. The environment consists of a coast line, a sediment layer beneath the ocean, continental crust, oceanic crust subducting under the continent and part of the upper mantle. Seismic sources are represented by red diamonds, receivers by blue spheres. Two of the sources are on the ocean surface, another two are located in the subducting slab. An array of eight receivers is distributed over the land area. Velocity is laterally inhomogeneous in the continental crust. A selection of ray paths representing direct arrivals and reflections from the top and the bottom of the subducting slab is shown.

In an attempt to bridge some of the issues associated with the traditional ray methods and the more recent GRAB approach, some effort has been devoted to Gaussian beam techniques. These techniques involve a more rigorous mathematical solution to the Helmholtz Equation in which the field in the waveguide is represented by an expansion in terms of Gaussian beams. The beams center on the ordinary rays computed from the eikonal equation (i.e., Eq. (15)) but have a Gaussian dependence in the direction normal to the central ray. This is in contrast with Gaussian ray bundles in which a central ray (eigenray) is associated with a Gaussian dependence in depth. Gaussian beam ray models require that an additional pair of coupled equations (for the beamwidth and the beam curvature) be solved in conjunction with the ray equations.

These models exhibit superior behavior near caustics and in shadow zones when compared to conventional ray theory because the beams behave smoothly in these problem areas. Moreover, ray tracing is very sensitive to environmental interpolation (both boundary and volume), however the Gaussian beam technique can reduce that sensitivity significantly. In addition, the beam approach avoids the difficulties associated with finding eigenrays.
**BELLHOP** [16] is a Gaussian beam model that evaluates ray trajectories and amplitudes by numerical integration of the ray equations in conjunction with the Gaussian beamwidth and curvature equations.

**TRACEO** [77] is a Gaussian beam model that was developed to model propagation in complicated environments like wavy surfaces, range dependence in upper and lower boundaries (including compressional and shear velocities and attenuations) and range dependent variations of the sound speed. TRACEO has two rather unique features. First, it can model the field with objects, such as rocks, marine mammals or submarines, imbedded in the waveguide between the source and an array of receivers. The second unusual feature is the calculation of the particle velocity vector for each hydrophone in the receiving array. This has application to the vector sensor array used in match-field inversions techniques for seabed properties.

There are several application models (listed below) that use the either CASS/GRAB or BELLHOP.

**AIM** [78] (Acoustic Integration Model), uses BELLHOP and CASS/GRAB in a four-dimensional, individual-based, Monte Carlo statistical scheme designed to predict the exposure of receivers to any stimulus propagating through space and time. The unique capability of AIM is the animal movement engine, which moves the stimulus source and animal receivers through four dimensions (time and space) according to user inputs.

**ESME** [79] (Effects of Sound on the Marine Environment) workbench is an integrated computer application model that employs BELLHOP in the modeling of animal response to the sound fields produced by human activities; special emphasis is placed on naval sound sources such as sonar, explosives, and acoustic communications. ESME is a software simulation system designed as an educational and a basic research tool for the marine mammal research community and an aid for environmental planners who need to assess the potential impact of Naval training exercises on marine animals.

**QUONOPS** [80] is a noise management and forecasting system for natural and anthropogenic noise for environmental impact assessments. It is unique among applications in that it uses a Monte Carlo approach (in conjunction with BELLHOP) to handle variability and uncertainty in inputs and it produces probability density function maps as an output.

**SIMPLE** [81] is an application model that uses BELLHOP to produce the acoustic data for plots of sound-exposure level (SEL) and peak pressure ($P_{pk}$) due to a large choice of sources such as construction projects, air-gun surveys and shipping. The goal is to give non-experts a tool that produces a visual map of the sound exposure levels at marine mammal center frequencies of vocalization in complicated range dependent environments.

**WOSS** [82] (World Ocean Simulation System) is an application model library that uses BELLHOP to perform simulations of received intelligibility of underwater networks.

**VirTEX** [83] (Virtual Timeseries Experiment) is a channel simulator is designed for simulating acoustic modem performance by accurately modeling the effects of surface-wave and platform motion on acoustic modem packets.

**NAEMO** [84] (Navy Acoustic Effects Model) is the standard application model now used by the US Navy to estimate the potential acoustic effects of naval training and testing activities on marine mammals and
sea turtles. The acoustic predictions within NAEMO are provided by CASS/GRAB. Note, this model is not included in the Model Questionnaires in Appendix B because no information about it has been released.

**PCIMAT** [85-86] (Interactive Multisensor Analysis Training) is a multipurpose PC-based software system, comprised of acoustic models and tactical decision aids, used for both as a highly visual training tool to teach sensor employment for ASW and as a system performance prediction and sonar tactical decision aid for naval applications that involve acoustics. It couples scientific visualization with standard US Navy physics-based models (NSPE [87], RAM [20] and CASS/GRAB [73]) and high-resolution databases to enable simulation of complex physical interactions. It integrates training, mission rehearsal, tactical execution and post-mission analysis.

Stochastic Ray theory is a modeling technique in which Monte Carlo methods are used to construct random rays using a probability distribution of ray angles. This allows probability distributions to be estimated for acoustic field quantities providing some measure of confidence in the results when the inputs are not well known.

**MOCASSIN** [88] is a ray-based model designed specifically for problems involving environmental uncertainty. It is formulated for active sonar in shallow water with highly variable sound speed conditions and poor knowledge. MOCASSIN traces rays from a distribution of ray angles from each boundary reflection. It also smooth the sound speed profile gradients to eliminate any small internal sound speed ducts and it range averages the final transmission loss. It can be used for ASW operations, underwater communications and mammal protection.

### 2.2.4.1 Advantages & Disadvantages

**The advantages of ray models** are that they provide a useful picture (ray diagram) of the propagation in an efficient and timely manner. They also provide time delay information directly and are amenable to pulse-waveform and other broadband studies. Finally, ray models perform their best when the frequency is high and the water is deep.

**The disadvantages of ray models** are that conventional models have difficulty providing accurate predictions when wave effects such as diffraction and caustics are involved. In addition, ray models are not particularly well suited for investigating bottom interactions (shallow water) and low frequency propagation. Typically, underwater acoustic ray models do not model propagation in the sediments; however, sediment properties are taken into account through the plane wave reflection coefficient applied at the ocean bottom.

### 2.2.5 Marching Solutions

As discussed above in Section 2.1.4 (and Appendix A), marching solutions (PE methods) are based on the solution of a one-way wave equation. This implies that back-scattered energy (e.g., due to range-dependence) is negligible compared to the outgoing (forward propagating) energy.

The solution of the one-way equation is treated as an “initial value” problem in which an initial or “starting field” at \( r=0 \) is marched step-by-step in range by solving a second-order partial differential equation in the depth coordinate, \( z \). As discussed in Section 2.1.4, the depth equation involves the square-root of a differential operator (see Appendix A: Eqs. (A35-A38)); as such, it requires special treatment and the manner in which this is accomplished distinguishes the individual PE models – ultimately, an approximate
form that replaces the square-root operator by manageable terms is required. Some models approximate the square-root operator directly and some models approximate the exponential propagator itself. Once the square-root approximations have been made, the differential operator in $z$ must still be dealt with – some models use an FFT for this purpose and some models use finite-differences.

The split-step Fourier PE (FFTPE) uses an FFT approach to solving the depth operator and is, in general, a fast way of advancing the PE solution one range step at a time. It is computationally efficient for long-range, narrow-angle propagation problems with negligible bottom interaction i.e., the conditions in many areas of traditional naval interest for sonar performance predictions (during the 40 year time frame from 1950 to 1990). The Fourier transform method requires that the environment be continuous in range and depth, disallowing any abrupt changes in the sound speed or density, as would naturally occur across the boundary from the water to the sediment. Discontinuities such as this are smoothed over a few wavelengths on either side of the boundary, which unfortunately introduces some artificial constructs. In cases of strong speed and density contrasts, the computational grid must be made extremely fine and the advantage of computational efficiency is lost.

**MMPE** [17] in an FFTPE model that has been used to study the time varying field for communication channels with evolving surface shapes at frequencies from 8 to 50 kHz. It has also been applied to the estimation of variability and statistical parameters of path loss.

**PAREQ** [18] is an FFTPE model that employs automatic interpolation of environmental data with range. In addition to forward propagation studies, the model provides an approximation for reverberation as well.

Finite-difference PE (FDPE) approximations have received the bulk of the attention in recent years because the naval interest has shifted to shallow, littoral waters where some of the inherent limitations of the FFTPE's (narrower angle propagation and water-bottom interface problems) become accentuated. Finite-differences, in conjunction Padé approximations [61] (rational approximation of the operators), have been applied in dealing with the square-root operator itself (regular Padé PE's) and, more recently, with the exponential propagator (the so-called split-step Padé PE's).

**PECAN** [19] is an FDPE that computes the PE field using either regular Padé or the split-step Padé approximation. It features one-way, wide-angle propagation in range-dependent environments, either Nx2D or full 3D with coupling. It has some capability for shear in the ocean bottom and boundary roughness (ocean surface and ocean bottom).

**RAM** [20] is an FDPE that is based on the split-step Padé solution which naturally allows for larger range steps. Range dependence is handled by applying an energy-conservation correction as the acoustic parameters vary with range. Several application models discussed in connection with ray models in the previous section (i.e., AIM, ESME, PCIMAT, QUONOPS, and SIMPLE) all have a RAM component.

### 2.2.5.1 Advantages & Disadvantages

**The advantages of the PE models** are that: (i) the total acoustic pressure field is computed on a grid that covers the water column making the presentation of the acoustic field solution in range and depth (so called full field) a natural by-product of the computations, (ii) they handle range-dependence naturally by allowing the environment to change with each range-step in the solution (the PE solution appears to
handle continental shelf environments accurately and efficiently), (iii) the FFTPE’s are very efficient in
deep water where bottom interaction is less of an issue, (iv) the FDPE’s can accommodate very high angle
propagation and large range steps efficiently (iv) the FDPE’s are straightforwardly adapted to full 3D
modeling (with coupling in azimuth). An example of a typical PE output display is shown below in Figure
2-13 below and gives a clear and intuitive view of the strength of the propagation paths in range
dependent environments.\textsuperscript{15} Note, unlike the ray trace diagram, the PE full-field display is for the pressure
directly and therefore contains much more information than the ray counterpart.

![Typical full field transmission loss from PE output](https://example.com/figure2-13)

\textbf{Figure 2-13 Typical full field transmission loss from PE output [Personal Communication, McCammon 2013]}

\textbf{The disadvantages of the PE models} are that: (i) the efficiency is critically dependent on the treatment
given the second-order differential operator in the depth coordinate; unfortunately, this treatment is
frequency dependent (i.e., higher frequencies require more grid points in depth), thus, the PE models are
limited by the combination of frequency and/or waveguide thickness, and (ii) there is no hard and fast
rule as to the selection of grid sizes in range and depth–this makes full optimization of the models difficult
with respect to efficient computations for some problems i.e., adaptive grid-sizes add complexity to the
model.

\subsection*{2.2.6 Energy Flux}

The energy flux approach was originally \cite{23-24} based on the understanding that simple closed form
solutions for range averaged or frequency averaged transmission loss can provide a useful accounting of
propagation levels (in the average or mean sense) without taking explicit account of the discrete nature

\textsuperscript{15} Mostly, before the advent of the PE solution, ray traces were used to portray the possible ray paths but the
actual loss was only computed at a single depth in a range independent environment due to tactical runtime
limitations.
of the propagation paths, as is done in ray or mode theory. Modern usage [25] of flux methods seek to provide more fidelity by building in the ray or mode properties. The solutions appear to be quite tractable, and in the context of broadband active sonar where single frequency effects are smoothed out, these formulas explain the trends quite well.

**INSIGHT** [89] is a practical, versatile, energy flux approach to sonar performance prediction based on the addition of simple expressions for the acoustic components. It is a collection of incoherent intensity formulas for Lloyd’s Mirror, refraction, and bottom reflection, etc. that together can predict the broadband average intensity.

**INSPIRE** [90] is a semi-empirical model whose propagation component incorporates both geometric spreading and an energy-flow model in which the water column is represented as an acoustic duct with absorption dominated by hysteresis losses in the seabed. The variables are determined by fitting values to real-world data acquired from over 50 separate datasets taken at various locations around the UK. This model is designed to predict the levels of underwater noise from impact piling operations in shallow water areas, typically of 100 m depths or less, focusing primarily on coastal wind farm construction. The model has been expanded to also include modeling noise from seismic air guns.

### 2.2.6.1 Advantages & Disadvantages

**The advantages of the energy flux approach** are that it provides useful and rapid calculations of TL where the propagation conditions are dominated by numerous boundary-reflected multipath and when only the coarse characteristics of the acoustic field are needed. The computations are typically frequency independent and sonar features (beam patterns and bandwidths) are easily included. The method uses reciprocity and the evaluation of the ray invariant in range dependent environments to obtain simple algebraic formulas. The approach is very useful for predicting incoherent TL and reverberation in cases where there are a large number of modes because there is no requirement to find modes or eigenrays.

**The disadvantages of the energy flux approach** appear to be related mainly to difficulties in applying the method to specific and real ocean environments; hence the recent activity in trying to model propagation effects by incorporating more specific ray and mode characteristics.

### 2.2.7 Hybrid

Hybrid models have received attention, over the years, simply because no one underwater acoustic model has been able to cover the broad range of problems (in terms of frequency, water depths, bottom properties, etc.) facing those that use acoustics for underwater purposes. A hybrid model attempts to combine more than one solution technique (usually two) into a composite model in which each component model provides support in the regions of the solution space where the other models fail. Here we mention several published ideas even though many of them have not been formalized into functional acoustic models.

**Ray-Mode** [91] is a hybrid technique that utilizes the complementary features of ray spectra and mode spectra to provide a field representation with favorable numerical properties.

**Ray-PE** [92] is a hybrid technique is valid for high frequency sound propagation in depth-dependent and weakly range-dependent environments. The restrictions pertaining to these different modeling schemes
are complementary because Ray theory works well at large angles and for abrupt changes in medium properties where PE is deficient, while PE works well in the narrow boundary layer confining the multiple ray events. This hybrid can be regarded as either correcting the failures of ray acoustics in convergence zones where individual caustic transition functions are insufficient, or as removing the narrow-angle restriction from PE.

**HYPER** [93] is a hybrid PE-ray model that was developed to extend the PE model to higher frequencies by using a ray-based coordinate system that facilitated numerical calculations. However, it was subsequently found to exhibit ray chaos [94] when the underlying ray trajectories were chaotic.

**Adiabatic Mode-PE** [95] is a hybrid technique was developed for solving problems involving three-dimensional propagation in a thin spherical shell. The technique is based on the adiabatic mode approximation using Ray theory to determine the mode coefficients and using the PE to handle spatial variations in the acoustic properties.

**CMPE** [96] is a coupled-mode-parabolic-equation hybrid model based on the normal mode model WKBZ. It uses a PE approach in a radial direction and normal modes to handle the depth dependence. Recently, the approach has been extended to three dimensions [97] and a faster method of obtaining mode functions has been described [98]. CMPE and WKBZ appear to be receiving continued improvements [99].

**Coupled Mode-PE** [100] is a hybrid model based on a generalization of the adiabatic mode PE that includes mode coupling terms and was developed to handle large-scale problems involving the coupling of energy between azimuths.

**RMPE** [101] is a ray-mode-parabolic-equation hybrid model. It uses normal modes in the vertical direction and mode coefficients in the horizontal direction that are found using a PE method.

### 2.2.7.1 Advantages & Disadvantages

The advantages of hybrid models are obvious in that, if successful, one achieves a single model with a wider range of applicability. Moreover, it is also conceivable that the hybrid model can be configured to be more efficient.

The disadvantages of hybrid models are that any issues with the component models, not alleviated by the combination of models, become entrenched in the hybrid model i.e., potentially, the number of problems with the hybrid model equals the sum of the number of problems with the component models. The fact that there are many hybrid models in mainstream use probably indicates that the technique is not generally very successful.

### 2.2.8 Gridded

The “gridded” class of models is capable of numerically solving the two-way wave equation in inhomogeneous fluid-elastic environments with complex geometry. These models are primarily used to study low and medium frequency scattering and reverberation from the ocean boundaries in seismology. There are three main techniques, all based on some form of direct discretization of the wave equation in Eq. (1), namely: (i) finite difference (FD), (ii) finite element (FE), or (iii) boundary element (BE).
NUCLEUS [102] is a modular FD software package designed for a wide range of applications in seismic exploration. Its module categories include marine survey design, marine source modeling, seismic modeling using finite differences and ray tracing, wavelet analysis, rock physics diagnosis, and interactive 2D seismic processing, data comparison and analysis. Modeling of the sound exposure level on marine life is a recent add-on with somewhat simplified assumptions.

GeoAcoustic_TDFD [26] is FD model that solves the wave equation (Eq. (1)) directly. It is designed primarily for scattering problems involving isolated scatterers and provides useful predictions of the time-evolution of the scattered fields.

CABRILLO [103] is an FD model that solves the wave equation (Eq. (1), Section 1) directly. It utilizes staggered grids and a pseudo-spectral method to compute propagation and scattering field components in acoustic, elastic, and poroelastic media. Staggered grids improve efficiency whereas the pseudo-spectral approach allows the spatial derivatives to be applied in the wavenumber domain.

FENL [104-105] is a FE program that computes the solution of the Helmholtz equation in an axially symmetric waveguide consisting of fluid layers overlying a rigid bottom. Standard Galerkin/ finite element techniques (non-uniform mesh grids) are employed to account for the interface conditions.

BEM [106] is a boundary element method used primarily to model the scattering effect of an obstruction in the ocean or to determine the acoustic field surrounding a sonar transducer.

2.2.8.1 Advantages & Disadvantages

The advantages of the gridded models are that they can model complicated spatial variability very well. They also typically provide time-domain characteristics of the field.

The disadvantages of the gridded models are that they tend to be computationally intensive and require highly detailed input. Since they solve for spatial and temporal variations of the acoustic field in the volume (the whole problem space at once) or on the boundary their application in ocean acoustics is limited either to the solution of special short range scattering problems or as a component in hybrid approaches to represent the scattering process. However, it must be noted that the finite difference method is commonly used in normal mode and PE models. The prime distinction is that the “gridded solutions5” employ finite differences on a “global” grid whereas the mode or PE solutions employ finite-differences “locally”.

2.3 Detailed comparison of propagation and application models

This section contains detailed descriptions of the models outlined in Section 2.2. In the tables that follow, the models are contrasted by a number of different attributes: physics approaches, spectral properties, spatial properties, inputs, and outputs. In this way, the specific capabilities of the models are compared, drawing extensively on the individual model questionnaires in Appendix C. 16

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16 Some of these models are on the Ocean Acoustics Library web site http://oalib.hlsresearch.com/ Other sources for these types of models include the ORFEUS Seismological Software Library in Europe, http://www.orfeus-eu.org/ and the Center for Wave Phenomena Software Library maintained by the Colorado School of Mines in the USA, http://cwp.mines.edu/.
2.3.1 Physics and/or Numerical Approach

2.3.1.1 Classes of Models

The propagation models that have been mentioned in Sections 2.2 are summarized in Table 2-1, classified by their solution technique i.e., according to the information provided in Sections 2.1 and 2.2. There are actually many more models in each of these classes.\textsuperscript{17} We have concentrated on models that are currently being used and considered to be the best in their class.

\textsuperscript{17} At one time, each university and Navy Lab with an acoustics or oceanographic program had in-house models; however, many of those have not been maintained and are no longer in use today.
### Table 2-1 Physics and/or numerical approach of acoustic models

<table>
<thead>
<tr>
<th>Class</th>
<th>Advantages</th>
<th>Weaknesses</th>
<th>Regime of Applicability</th>
<th>Propagation Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ray theory</td>
<td>Fast, visual, naturally range dependent and frequency independent</td>
<td>Difficult to obtain levels from rays traced into sediments and rays do not model diffraction</td>
<td>High frequency or deep water $h/\lambda &gt; 10$, range dependence</td>
<td>BELLHOP, GRAB, FMM, MOCASSIN, SPADES, TRACEO, WAVEQ3D</td>
</tr>
<tr>
<td>Parabolic Equation</td>
<td>Naturally range dependent, provides 2D acoustic field</td>
<td>Difficult to apply beam patterns or compute time dispersion or channel impulse responses. Must use approximations for complex sediments.</td>
<td>Low frequency, ducted or deep water, range dependent environments</td>
<td>MMPE, PECAN, RAM</td>
</tr>
<tr>
<td>Normal Modes</td>
<td>Accurate, physically intuitive, good for complex sediments</td>
<td>Most do not model near field and accurate range dependence is difficult and very time consuming</td>
<td>Low frequency, shallow water, layered sediments</td>
<td>COUPLE, C-SNAP, KRAKEN, ORCA, POPP/PROLOS, WKBZ</td>
</tr>
<tr>
<td>Wavenumber integration</td>
<td>Accurate, good for complex sediments</td>
<td>Computationally intensive requiring expert users and range dependence and beam patterns are difficult</td>
<td>Low frequency, short range, time domain problems</td>
<td>OASES</td>
</tr>
<tr>
<td>Finite difference/finite element</td>
<td>Accurate, good for complex sediments</td>
<td>Computationally intensive requiring expert users and range dependence and beam patterns are difficult</td>
<td>Short range, low frequency</td>
<td>NUCLEUS (for seismic applications)</td>
</tr>
<tr>
<td>Energy Flux</td>
<td>Fast, physically insightful</td>
<td>Only valid for simple cases and only gives coarse descriptions of the field</td>
<td>Broadband average intensity</td>
<td>INSIGHT, INSPIRE, NUCLEUS (for marine exposure)</td>
</tr>
<tr>
<td>Hybrid Models</td>
<td>Potential to overcome physics limitations of component approaches</td>
<td>Not generally very successful</td>
<td>Depends on the hybrid</td>
<td>HYPER, CMPE, RMPE</td>
</tr>
</tbody>
</table>
A schematic (not to scale) of the relative computer resources needed for these classes of models as a function of frequency is shown in Figure 2-14.

Notes:

i. The models that are fastest and require the least memory requirements are the low-fidelity Energy Flux models followed by the Ray models.

ii. They are drawn vertically to indicate that their run time is independent of frequency. Next, in order of computer resource and run time are the Normal Mode models and Coupled Normal Mode models whose run times vary linearly with frequency.

iii. The Wavenumber Integration and Finite Element/Finite Difference models require still more time and storage but also increase linearly with frequency.

iv. Finally the parabolic Equation solutions are shown as taking roughly the same resources as Normal Mode models at low frequencies but having run times that increase with the square of frequency.

2.3.1.2 Approximations and Limitations

Many of the respondents to our survey have listed approximations and limitations in the questionnaires in Appendix C that are inherent in the specific mathematics of their model. That is, these limitations and approximations are in addition to the model class limitations, which for example, is a high-frequency restriction on Ray theory solutions and the usual PE limitations of forward waves only, reference wavenumber and PE square root operator approximation. The model developers’ descriptions are listed in Table 2-2.
### Table 2-2 Specific approximations and limitations of models in addition to their class restrictions

<table>
<thead>
<tr>
<th>Class</th>
<th>Model</th>
<th>Approximations and Limitations</th>
</tr>
</thead>
</table>
| Ray theory     | BELLHOP | 1. Neglect of the beam displacement for rays emerging from the bottom.  
                  |         | 2. The Gaussian width is found by numerical solution to two differential equations. It is fixed in caustic regions to $\pi\lambda$.  
                  |         | 3. Bellhop will produce some artifacts for receivers very close the surface or bottom. |
|                | CASS/GRAB | 1. GRAB sorts the traced rays into families with like number of boundary interactions and turning points and then power averages the ray properties for each family to generate an eigenray representative of that ray family. Test rays are typically 0.1° to 0.01° apart in launch angle.  
                     |         | 2. Ray normal is approximated as the vertical distance between ray and receiver. Ray tracing is closed-form parabolic arcs.  
                     |         | 3. The Gaussian width is estimated from the depth spacing of adjacent rays of the same type. It is fixed in the caustic regions to $2\pi\lambda$.  
                     |         | 4. GRAB does not trace leakage rays.  
                     |         | 5. Shadow zones are sharply defined.  
                     |         | 6. Sound speed channels that trap only a few (or no) modes are not well treated. |
|                | FMM     | Sound field levels are not computed. |
|                | MOCASSIN | 1. The sound speed profile is smoothed (low pass) by a running average of length 7$\lambda$.  
                     |         | 2. The horizontal sound speed variability is described stochastically by a diffusion constant.  
                     |         | 3. Ray intensity is accumulated incoherently in a receiver window with a vertical extent defined by the user (this is not an eigenray solution). |
|                | SPADES  | 1. No propagation in sub-bottom layers.  
                     |         | 2. The test rays are 'marched' out range step-by-range step – at each range step estimates are made of the 'eigenrays' using the GRAB procedure.  
                     |         | 3. Surface roughness loss and scattering is handled in 'average sense' by associating a loss with each ray as it interacts with a surface (formal multidimensional scattering theory on a ray to ray basis is not applied). |
|                | TRACEO  | 1. Ray normal is approximated as the vertical distance between ray and receiver.  
                     |         | 2. Ray tracing and Gaussian beamwidth is found by numerical integration.  
                     |         | 3. Avoid vertical segments where a smooth variation is followed by an isovelocity layer, as such segments introduce unrealistic artifacts from an inaccurate calculation of the sound speed gradients. |
|                | WAVEQ3D | 1. Ray tracing is by numerical integration. Eigenrays found by second order Taylor series in vector form.  
                     |         | 2. 3D cross terms in product of azimuthal and vertical rays are ignored.  
                     |         | 3. The Gaussian width is given by the sum of squares of the variance of the ray beamwidth and $2\pi\lambda$ (this provides a caustic limitation with no sudden transition). |
| Parabolic      | MMPE    | 1. Mesh size based on size of transform, ocean depth and acoustic wavelength. |

---

Section 2 - Detailed Summary of Underwater and Sub-bottom Propagation Models
<table>
<thead>
<tr>
<th>Class</th>
<th>Model</th>
<th>Approximations and Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2. Transition at bottom must be a smoothly varying continuous function to avoid artificial reflections, aliasing and noise in the recurrent FFT calculations. MMPE uses a hyperbolic tangent function to smooth the profile over the interface.</td>
</tr>
<tr>
<td></td>
<td>PECAN</td>
<td>1. Up to 7 terms in the Padé approximation.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Energy conservation correction.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Three choices of treatment for the lower boundary.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. The stability constraints introduce a small amount of artificial attenuation which can be significant for propagation in deep water to very long ranges.</td>
</tr>
<tr>
<td>Normal Mode</td>
<td>COUPLE</td>
<td>1. A background model of the environment, assuming no loss, is first computed. Then the Galerkin method is used to approximate the real eigenfunctions with complex coefficients.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. An artificial absorber is employed at the bottom of the physical sediment.</td>
</tr>
<tr>
<td></td>
<td>C-SNAP</td>
<td>1. Limited to outgoing waves (one-way propagation).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. The true coupling coefficient is replaced with that of excitation coefficients.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Neglects the contribution of the continuous spectrum.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. Losses treated by perturbation approach.</td>
</tr>
<tr>
<td></td>
<td>KRAKEN</td>
<td>1. Losses treated by perturbation approach.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Accepts tabulated surface and bottom losses or boundary conditions for free, rigid or homogeneous half-spaces.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Elastic media attenuation and leaky modes only computed in KRAKENC.</td>
</tr>
<tr>
<td></td>
<td>ORCA</td>
<td>1. Range independent.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Mode functions are analytically given by Airy Functions or exponentials.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Fluid problems: trapped modes found on real k axis. Losses treated by perturbation approach. May be inaccurate at short ranges or for large material attenuations.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. Elastic problems: trapped and leaky modes found in complex k-plane.</td>
</tr>
<tr>
<td></td>
<td>POPP/PROLOS</td>
<td>1. Adiabatic range dependence.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Modes calculated using two-ended shooting method.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. RMS roughness included at all layer interfaces.</td>
</tr>
<tr>
<td></td>
<td>WKBZ</td>
<td>1. Adiabatic range dependence.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Mode functions are exponentials.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Waterborne modes are summed coherently. Bottom interacting modes are summed incoherently.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4. Shadow zones and cross-duct leakage are not well modeled because there are no evanescent tails of modes (no leaky modes).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5. Sound speed profiles with multiple minima and elastic bottoms are not well modeled.</td>
</tr>
<tr>
<td></td>
<td>OASES</td>
<td>Spectral - super-element approach to range dependence is a hybridization of finite-element and boundary element methods.</td>
</tr>
<tr>
<td>Wavenumber integration</td>
<td>INSIGHT</td>
<td>1. Range independent.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Based on addition of component closed form solutions to particular events, all assumptions in these various solutions will apply.</td>
</tr>
</tbody>
</table>
2.3.2 Spectral Properties

2.3.2.1 Frequency Range of Operation

The frequency at which the classes of models are considered valid or fast enough to be employed are described in Sections 2.1 and 2.2. High frequency models are usually ray models which are assumed to be valid whenever the ratio of water depth $h$ to wavelength $\lambda$ is much greater than unity ($h/\lambda \gg 1$). An additional limitation on ray theory is that at low frequencies traditional expressions of bottom loss as a dB/bounce parameter are misleading and simplistic because they imply that the sound field is acting on a single spot, rather than spread over a large volume. Since rays are not split on reflection, geophysical models which use layered sediments are necessary.

Low frequency models are usually based on normal modes, the PE, or wavenumber integration. These models have run time and memory storage requirements that are limiting factors, not the physics. In Table 2-3, the specific statements from the developers concerning their suggested frequency ranges are listed.

<table>
<thead>
<tr>
<th>Model</th>
<th>Suggested Frequency range</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIM</td>
<td>50 Hz – 100 kHz (i.e. based on the characteristics of the individual propagation models employed, not AIM per se)</td>
</tr>
<tr>
<td>BELLHOP</td>
<td>$h/\lambda &gt; 20$</td>
</tr>
<tr>
<td>CASS/GRAB</td>
<td>$h/\lambda &gt; 10$</td>
</tr>
<tr>
<td>COUPLE</td>
<td>Program limited to 400 modes</td>
</tr>
<tr>
<td>C-SNAP</td>
<td>The maximum number of modes supported is 500. Therefore, the frequency limit (ideal case) would be of the order of $f_{\text{max}} = 250 c/H$ (H being the sum of depths of the water and the sediment layer).</td>
</tr>
<tr>
<td>ESME</td>
<td>Using BELLHOP, the suggested lower bound is any scenario where the water depth is less than 20 wavelengths. RAMGeo can operate in water shallower relative to wavelength, for example low frequency (&lt;1 kHz) sources in shallow (10-100 m) water. RAMGeo can also operate in deeper water, with the tradeoff of longer computation time.</td>
</tr>
<tr>
<td>INSIGHT</td>
<td>Sonar frequencies</td>
</tr>
<tr>
<td>INSPIRE</td>
<td>10 Hz to 175 kHz</td>
</tr>
<tr>
<td>KRAKEN</td>
<td>The developer suggests an upper frequency of about 20 kHz is reasonable, and states that typically if such frequencies are computed, BELLHOP is preferred. For most users, run time dictates the upper frequency limit, as the number of modes being computed is proportional to the frequency. In cases of range dependence, this is particularly important because KRAKEN must compute modes at each range sample point.</td>
</tr>
<tr>
<td>MMPE</td>
<td>No limitation from a physics standpoint.</td>
</tr>
<tr>
<td>MOCASSIN</td>
<td>Consistent with Ray theory limitations.</td>
</tr>
<tr>
<td>NUCLEUS</td>
<td>10-250 Hz depending on accuracy of source signature</td>
</tr>
<tr>
<td>OASES</td>
<td>No limitation from a physics standpoint.</td>
</tr>
<tr>
<td>ORCA</td>
<td>No specific range given in users guide.</td>
</tr>
<tr>
<td>Model</td>
<td>Suggested Frequency range</td>
</tr>
<tr>
<td>-----------</td>
<td>------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>PCIMAT</td>
<td>Pretty close to 1 Hz to 100 kHz using two core models. Above 100 kHz, there is no reason CASS cannot run, but there aren’t any PC IMAT applications (like mine warfare imaging) for sensors that work above about 20 kHz.</td>
</tr>
<tr>
<td>PECAN</td>
<td>No formal restriction for range independent waveguides but realistically &lt; 500 Hz in general; for shallow water and short ranges it might be feasible to get up to a few kilohertz (problem becomes very large and memory and storage are issues). For range dependent waveguides I would expect the restrictions to tighten a bit depending on the severity of the range dependence simply because I expect step sizes to be ‘smaller’ for range dependent waveguides.</td>
</tr>
<tr>
<td>POPP/PROLOS</td>
<td>Mode cutoff to several thousand modes; e.g., up 10 kHz in shallow water.</td>
</tr>
<tr>
<td>PROSIM</td>
<td>10 Hz to 10 kHz.</td>
</tr>
<tr>
<td>QUONOPS</td>
<td>A few Hertz to tens of kilohertz.</td>
</tr>
<tr>
<td>RAM</td>
<td>Run time will dictate the frequency range.</td>
</tr>
<tr>
<td>SIMPLE</td>
<td>10 – 90,000 Hz with RAM and BELLHOP.</td>
</tr>
<tr>
<td>SPADES</td>
<td>Typically, for range independent waveguides, need to be &gt; 100 Hz in general; for shallow water and short ranges that lower frequency limit might go up. Note, beam displacement becomes an issue as frequency or sound speed in the ocean bottom goes down.</td>
</tr>
<tr>
<td>TRACEO</td>
<td>This model has demonstrated good results for the h/λ ratio values as low as 3.</td>
</tr>
<tr>
<td>VirTEX</td>
<td>Limited to the Bellhop frequency limitations on low frequency operation.</td>
</tr>
<tr>
<td>WAVEQ3D</td>
<td>f &gt; 150 Hz or h/λ &gt; 10</td>
</tr>
<tr>
<td>WKBJ</td>
<td>Frequencies higher than the duct cutoff frequency.</td>
</tr>
<tr>
<td>WOSS</td>
<td>Ray tracing is not advisable for modeling very low-frequency wave propagation; however, within the common operating bands used by available hardware, the approximations inherent in the ray tracing technique are verified to a satisfactory degree of accuracy.</td>
</tr>
</tbody>
</table>

### 2.3.2.2 Broadband Capability

Broadband is the term used to refer to the generation of propagation loss at a large number of frequencies, $TL(f)$, to adequately sample the bandwidth of the source in order to perform time series modeling of pulses. The frequency dependence in ocean propagation comes through the attenuations in the water and sediment and the wave trapping ability of a waveguide at particular frequencies.

Traditionally and typically, underwater propagation models have been run assuming a single frequency continuous wave (CW) source. To study the propagation of pulses, the bandwidth of the pulse is divided into sub-pulses characterized by a center frequency and the models are run repeatedly for each sub-pulse. Generally this frequency sampling must be programmed by the user as separate runs with his choice of core propagation model; however there are some models that specifically advertise themselves as having an internal broadband capability. These models are listed in Table 2-4.
### Section 2 - Detailed Summary of Underwater and Sub-bottom Propagation Models

#### Table 2-4 Internal broadband capabilities of the models and applications

<table>
<thead>
<tr>
<th>Model</th>
<th>Frequency sampling technique</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIM</td>
<td>Divides bandwidth into 1/3-octave bands and runs at each center frequency.</td>
<td>SEL</td>
</tr>
<tr>
<td>CASS/GRAB</td>
<td>Divides bandwidth into bins, uses mid or mean frequency by user choice.</td>
<td>SEL</td>
</tr>
<tr>
<td>C-SNAP</td>
<td>User defined frequency array in input.</td>
<td>SEL</td>
</tr>
<tr>
<td>ESME</td>
<td>Performs range averaging to approximate frequency averaging in 1/3-octave bands.</td>
<td>SEL</td>
</tr>
<tr>
<td>INSIGHT</td>
<td>Performs range averaging to approximate frequency averaging.</td>
<td>SEL</td>
</tr>
<tr>
<td>INSPIRE</td>
<td>Inherently broadband because of its empirical derivation.</td>
<td>SEL</td>
</tr>
<tr>
<td>NUCLEUS</td>
<td>User defined resolution.</td>
<td>SEL</td>
</tr>
<tr>
<td>OASES</td>
<td>Divides bandwidth linearly or logarithmically and runs at each center frequency.</td>
<td>SEL</td>
</tr>
<tr>
<td>ORCA</td>
<td>Uses derivatives to track eigenvalues through bandwidth. Step sizes are adjusted adaptively.</td>
<td>SEL</td>
</tr>
<tr>
<td>PCIMAT</td>
<td>Divides bandwidth into 1/3-octave bands and runs at each center frequency.</td>
<td>SEL</td>
</tr>
<tr>
<td>PROSIM</td>
<td>Performs log interpolation of eigenvalues computed for highest frequency.</td>
<td>SEL</td>
</tr>
<tr>
<td>QUONOPS</td>
<td>User choses bands (1/3-octave, octave, etc.).</td>
<td>SEL</td>
</tr>
<tr>
<td>SIMPLE</td>
<td>User choses bands (1 Hz, 1/3-octave, octave, or custom).</td>
<td>SEL</td>
</tr>
<tr>
<td>VirTEX</td>
<td>1-50 kHz bandwidth for communication simulations.</td>
<td>SEL</td>
</tr>
<tr>
<td>WAVEQ3D</td>
<td>Produces band-limited impulse response from multiple frequencies.</td>
<td>SEL</td>
</tr>
<tr>
<td>WOSS</td>
<td>User defined resolution.</td>
<td>SEL</td>
</tr>
</tbody>
</table>

An interesting approach to forming a broadband transmission loss is described in [71]. By this technique, a broadband result can be constructed by a single transmission loss calculation at the band’s center frequency, by shifting the range with the ratio \( f/f_c \) prior to addition. This technique has been generalized to the range dependent case using normal mode expressions. The cases demonstrated show a robust and accurate method of obtaining a broadband signal using a center frequency calculation that ought to be applicable to any of the classes of solution technique. Harrison and Harrison [221], cited by [71], describe a method whereby the continuous wave transmission loss may be converted to a broadband plot by range averaging using a sliding, variable width, window.

### 2.3.2.3 Temporal Capability

The modeling of the propagation of a pulse in time requires the calculation of the dispersive character of the environment. Even for a single frequency, each propagation path or mode in the ocean will have a different arrival time, causing the signal to be spread in time at the receiver.

For ray solutions, the time domain solution has a particularly simple form because ray theory can compute the travel time of each ray. Assuming a narrow spectrum and ray amplitude independent of frequency, then each ray making up the received signal is just a scaled and delayed replica of the source signal. The different travel times of the rays provide the pulse dispersion. The resulting acoustic field at the desired range can then be used to construct the received channel impulse response. An example of

---

18 These outputs were not specified in the questionnaires and therefore have been inferred by the authors.
the measured and modeled channel impulse response [107] computed with BELLHOP is shown in Figure 2-15.

For normal mode solutions, each mode has an associated group velocity (obtained from the characteristic equation) that provides the speed of transport of the energy in that mode. Using this, the acoustic fields can be readily sorted by the arrival time associated with each mode.

For the PE and wavenumber integral techniques considered in this survey the field in is not separated in time directly. They must compute a well sampled frequency distribution of the pressure and perform an inverse-FFT to construct the received time series. There are direct time domain solutions using parabolic and wavenumber integration techniques as discussed elsewhere [2], however the consensus in the underwater acoustics community is that 'most problems of practical importance in underwater acoustics clearly favor the Fourier synthesis technique’ for computational efficiency.

Figure 2-15 Comparison of measured (top) and the BELLHOP modeled (bottom) channel impulse response [107]
Listed in Table 2-5 are the propagation and application models in this survey that can provide the quantities necessary to readily produce a time series output. Models in the survey that are not listed in this table (COUPLE, C-SNAP, MMPE, PECAN, RAM) will require user programming and post-processing of inverse FFT’s to produce a time series output. The model INSIGHT removes time dependence by averaging over the pulse length in order to produce the signal as a function of target range only.

<table>
<thead>
<tr>
<th>Propagation Model</th>
<th>Temporal calculation technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIM</td>
<td>Ray travel time</td>
</tr>
<tr>
<td>BELLHOP</td>
<td>Ray travel time</td>
</tr>
<tr>
<td>CASS/GRAB</td>
<td>Ray travel time</td>
</tr>
<tr>
<td>ESME</td>
<td>Ray travel time</td>
</tr>
<tr>
<td>FMM</td>
<td>Ray travel time</td>
</tr>
<tr>
<td>KRAKEN</td>
<td>Modal group velocity</td>
</tr>
<tr>
<td>MOCASSIN</td>
<td>Ray travel time</td>
</tr>
<tr>
<td>NUCLEUS</td>
<td>Wavenumber Transform</td>
</tr>
<tr>
<td>OASES</td>
<td>Wavenumber Transform</td>
</tr>
<tr>
<td>ORCA</td>
<td>Modal group velocity</td>
</tr>
<tr>
<td>PCIMAT</td>
<td>Ray travel time</td>
</tr>
<tr>
<td>POPP/PROLOS</td>
<td>Modal group velocity</td>
</tr>
<tr>
<td>PROSIM</td>
<td>Inverse FFT of broadband transfer function</td>
</tr>
<tr>
<td>QUONOPS</td>
<td>Ray travel time</td>
</tr>
<tr>
<td>SIMPLE</td>
<td>Ray travel time</td>
</tr>
<tr>
<td>SPADES</td>
<td>Ray travel time</td>
</tr>
<tr>
<td>TRACEO</td>
<td>Ray travel time</td>
</tr>
<tr>
<td>VirTEX</td>
<td>Ray travel time</td>
</tr>
<tr>
<td>WAVEQ3D</td>
<td>Direct integration of ray equation in time domain</td>
</tr>
<tr>
<td>WKBZ</td>
<td>Modal group velocity</td>
</tr>
<tr>
<td>WOSS</td>
<td>Ray travel time</td>
</tr>
</tbody>
</table>

2.3.3 Spatial Properties

2.3.3.1 Range Dependence

Range dependence is a particularly important aspect of acoustic modeling in the world's oceans. All of the environmental descriptors (sound speed, bathymetry, bottom composition, surface sea state, etc.) are not static in time and space and can change at range scales far shorter than the desired range of propagation prediction. Thus, it is vital that an acoustic model adapt the propagated pressure wave to the changing environment as it evolves outward.

The knowledge of the sound speed profile is a critical factor in the prediction of the transmission loss because it controls the refraction of sound as it travels throughout the water column. Usually, when
modeling transmission loss in range-dependent environments, a lot of attention is paid to the sampling of the bathymetry but very little is spent on the mapping of the changes in the sound speed profile with range. Assumptions are made that SSP measured at a source location is good enough for a whole geographic region of interest. But in just a few kilometers the profile may be changed due to different surface conditions such as local rain storms, solar heating and wind that will affect the mixed layer. Even if another profile taken further away is available, a stair-step change in the environment is often deemed sufficient although this is not always the case as we will demonstrate by example in a later section of this document.

In Table 2-6 we summarize the range dependent capability of propagation models and find that almost all the models discussed in Section 2.2 have some form of capability (the exceptions are INSIGHT and ORCA which have no range dependent capability). Details of the types of interpolations employed are listed in the table. Application models contain the range dependence techniques of their core propagation models and are currently all being run in N×2D.

### Table 2-6 Range sampling techniques of range dependent propagation models

<table>
<thead>
<tr>
<th>Propagation Model</th>
<th>Range Dependence Technique</th>
<th>2D or 3D</th>
<th>Bathymetry sampling</th>
<th>Sound speed sampling in range</th>
<th>Bottom properties sampling</th>
<th>Surface state sampling</th>
</tr>
</thead>
<tbody>
<tr>
<td>BELLHOP</td>
<td>Ray trace</td>
<td>2D</td>
<td>Linear or curvilinear interpolation</td>
<td>2D bilinear quadrilateral interpolation</td>
<td>Stair step</td>
<td>Interpolated altimetry, stair step properties</td>
</tr>
<tr>
<td>GRAB</td>
<td>Ray trace</td>
<td>2D</td>
<td>Linear interpolation</td>
<td>Triangular interpolation</td>
<td>Stair step</td>
<td>Stair step</td>
</tr>
<tr>
<td>COUPLE</td>
<td>Full coupled mode, single scatter, or adiabatic</td>
<td>2D</td>
<td>Stair-step</td>
<td>Stair step or simple range interpolation</td>
<td>Stair step or simple range interpolation</td>
<td>Not provided</td>
</tr>
<tr>
<td>C-SNAP</td>
<td>Single scatter coupled mode</td>
<td>2D</td>
<td>Stair step</td>
<td>Stair step</td>
<td>Stair step</td>
<td>Stair step</td>
</tr>
<tr>
<td>FMM</td>
<td>Ray trace</td>
<td>3D</td>
<td>Yes, method not provided</td>
<td>Yes, method not provided</td>
<td>Yes, method not provided</td>
<td>None</td>
</tr>
<tr>
<td>KRAKEN</td>
<td>Single scatter, or adiabatic modes</td>
<td>3D or N×2D</td>
<td>Stair-step</td>
<td>Stair step</td>
<td>Stair step</td>
<td>Stair step</td>
</tr>
<tr>
<td>MMPE</td>
<td>One way Parabolic</td>
<td>2D</td>
<td>Linear interpolation</td>
<td>Linear</td>
<td>Linear</td>
<td>None</td>
</tr>
<tr>
<td>MOCASSIN</td>
<td>Ray trace</td>
<td>2D</td>
<td>Linear interpolation</td>
<td>Stochastic diffusion constant</td>
<td>Stair step</td>
<td>Stochastic angle change</td>
</tr>
<tr>
<td>NUCLEUS</td>
<td>Numerical integration (seismic)</td>
<td>3D (seismic)</td>
<td>Not provided (seismic)</td>
<td>Not provided (seismic)</td>
<td>Not provided (seismic)</td>
<td>None</td>
</tr>
</tbody>
</table>

2D refers to a single slice in range and depth, N×2D refers to N independent slices, each at a different azimuth, 3D contains true azimuthal coupling between bearings.
### Section 2 - Detailed Summary of Underwater and Sub-bottom Propagation Models

<table>
<thead>
<tr>
<th>Propagation Model</th>
<th>Range Dependence Technique</th>
<th>2D or 3D</th>
<th>Bathymetry Sampling</th>
<th>Sound Speed Sampling in Range</th>
<th>Bottom Properties Sampling</th>
<th>Surface State Sampling</th>
</tr>
</thead>
<tbody>
<tr>
<td>OASES</td>
<td>Spectral super-element or single scatter</td>
<td>2D</td>
<td>Stair step</td>
<td>Stair step</td>
<td>Stair step</td>
<td>Not provided</td>
</tr>
<tr>
<td>PECan</td>
<td>One way parabolic</td>
<td>3D or N×2D</td>
<td>Bivariate linear interpolation</td>
<td>Bivariate linear interpolation</td>
<td>Bivariate linear interpolation</td>
<td>Rough surface using Kirchhoff approximation</td>
</tr>
<tr>
<td>POPP/PROLOS</td>
<td>Adiabatic modes</td>
<td>2D</td>
<td>Stair step</td>
<td>Stair step</td>
<td>Stair step</td>
<td>Not provided</td>
</tr>
<tr>
<td>PROSIM</td>
<td>Adiabatic modes</td>
<td>2D</td>
<td>Stair step</td>
<td>Stair step</td>
<td>Stair step</td>
<td>Not provided</td>
</tr>
<tr>
<td>RAM</td>
<td>One way parabolic with energy-conservation correction</td>
<td>2D</td>
<td>Linear interpolation</td>
<td>Stair step</td>
<td>Stair step</td>
<td>None</td>
</tr>
<tr>
<td>SPADES</td>
<td>Ray trace</td>
<td>N×2D</td>
<td>Linear interpolation</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>TRACEO</td>
<td>Ray trace</td>
<td>2D</td>
<td>Linear interpolation</td>
<td>Bi-dimensional barycentric cubic interpolation</td>
<td>3 choices for interpolations</td>
<td>Altimetry and properties with 3 choices for interpolations</td>
</tr>
<tr>
<td>WAVEQ3D</td>
<td>Ray trace</td>
<td>3D</td>
<td>Piecewise cubic Hermite polynomial (PCHIP)</td>
<td>Nearest neighbor, linear, or PCHIP</td>
<td>Nearest neighbor</td>
<td>None</td>
</tr>
<tr>
<td>WKBZ</td>
<td>Adiabatic modes</td>
<td>2D</td>
<td>Stair step</td>
<td>Stair step</td>
<td>None</td>
<td>None</td>
</tr>
</tbody>
</table>

#### 2.3.3.2 Additional Spatial Characteristics

In Table 2-7 we list the model’s capabilities for other spatial characteristics. The ability to include beam-patterns of both source and receiver is important for correctly shaping the angular distribution of the acoustic field. The functional form of the sampling of the sound speed profile with depth is often of interest when comparing different classes of models; the choices usually made include \( c \)-linear, \( 1/c^2 \)-linear, and splines. The applicability of the solution to near field predictions (within one quarter wavelength of a point source) is important for short range operation and the ability to model propagation in the sub-bottom is important for low frequency, steep-angle propagation.
**Table 2.7 Additional spatial characteristics of models and applications**

<table>
<thead>
<tr>
<th>Models and applications</th>
<th>Beamforming capability</th>
<th>SSP functional form for depth sampling</th>
<th>Near field applicability</th>
<th>Sub-bottom propagation</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIM</td>
<td>Yes</td>
<td>1/c^2-linear</td>
<td>Yes</td>
<td>Yes with RAM and KRAKEN</td>
</tr>
<tr>
<td>BELLHOP</td>
<td>Source only - User supplied table</td>
<td>c-linear, 1/c^2-linear or cubic spline</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>CASS/GRAB</td>
<td>Yes</td>
<td>1/c^2-linear</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>COUPLE</td>
<td>No</td>
<td>1/c^2-linear</td>
<td>Yes with continuous field</td>
<td>Yes</td>
</tr>
<tr>
<td>C-SNAP</td>
<td>No</td>
<td>1/c^2-linear</td>
<td>Only ranges greater than one water depth</td>
<td>No</td>
</tr>
<tr>
<td>ESME</td>
<td>Sources only - using beamwidth and tilt angle</td>
<td>1/c^2-linear</td>
<td>No</td>
<td>Yes with RAM</td>
</tr>
<tr>
<td>FMM</td>
<td>No</td>
<td>Cubic spline</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>INSIGHT</td>
<td>Yes</td>
<td>c-linear</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>INSPIRE</td>
<td>No, impact piling produces omnidirectional noise.</td>
<td>None</td>
<td>Yes to 30 – 50 m</td>
<td>Because INSPIRE is semi-empirical, this is included implicitly in the geometric spreading term.</td>
</tr>
<tr>
<td>KRAKEN</td>
<td>Via post-processing</td>
<td>c-linear, 1/c^2-linear or cubic spline</td>
<td>Yes with careful setup of inputs</td>
<td>Yes</td>
</tr>
<tr>
<td>MMPE</td>
<td>Line array pattern using length and D/E angle of main lobe</td>
<td>c -linear</td>
<td>Yes</td>
<td>Yes, into two sediment layers</td>
</tr>
<tr>
<td>MOCASSIN</td>
<td>Source: beamwidth and tilt angle or weighted curves Receiver: Directivity index</td>
<td>c-linear</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>NUCLEUS</td>
<td>Yes: airgun strings and seismic streamers with hydrophone/geophone groups</td>
<td>Not provided</td>
<td>Yes</td>
<td>Yes (seismic)</td>
</tr>
<tr>
<td>OASES</td>
<td>Yes in OASM</td>
<td>1/c^2-linear</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>ORCA</td>
<td>Source only-Gaussian choice with beamwidth and tilt angle input</td>
<td>1/c^2-linear</td>
<td>Yes with ‘leaky’ modes</td>
<td>Yes</td>
</tr>
<tr>
<td>PCIMAT</td>
<td>Cookie cutter with top-hat and flat side lobes</td>
<td>c-linear or 1/c^2-linear</td>
<td>Yes</td>
<td>Yes with RAM</td>
</tr>
</tbody>
</table>
### Models and applications

<table>
<thead>
<tr>
<th>Models and applications</th>
<th>Beamforming capability</th>
<th>SSP functional form for depth sampling</th>
<th>Near field applicability</th>
<th>Sub-bottom propagation</th>
</tr>
</thead>
<tbody>
<tr>
<td>PECAN</td>
<td>Yes, by changing the starting field</td>
<td>c-linear</td>
<td>Yes with more Padé terms</td>
<td>Yes - treated as fluid layers with complex density</td>
</tr>
<tr>
<td>POPP/PROLOS</td>
<td>Via post-processing</td>
<td>(1/c^2)-linear</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>PROSIM</td>
<td>Source only-Gaussian choice with beamwidth and tilt angle input</td>
<td>(1/c^2)-linear</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>QUONOPS</td>
<td>Provides sound pressure along moving source and/or receiver arrays for external beamforming</td>
<td>c-linear, (1/c^2)-linear or cubic spline</td>
<td>No</td>
<td>Yes with RAM</td>
</tr>
<tr>
<td>RAM</td>
<td>No</td>
<td>c-linear</td>
<td>Yes with self-starter</td>
<td>Yes</td>
</tr>
<tr>
<td>SIMPLE</td>
<td>Source only - user has choices (e.g. air gun)</td>
<td>Uses core model sampling</td>
<td>Yes</td>
<td>Yes with RAM</td>
</tr>
<tr>
<td>SPADES</td>
<td>Source &amp; receiver: (\sin X/X), shaded (\sin X/X), HLA, table</td>
<td>c-linear</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>TRACEO</td>
<td>Receiver only - array shape choices</td>
<td>c-linear, (1/c^2)-linear or barycentric cubic</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>VirTEX</td>
<td>Source only - User supplied table</td>
<td>c-linear, (1/c^2)-linear or cubic spline</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>WAVEQ3D</td>
<td>No</td>
<td>c-linear, (1/c^2)-linear</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>WKBZ</td>
<td>Via post-processing</td>
<td>c-linear</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>WOSS</td>
<td>Choices for transducer types</td>
<td>c-linear, (1/c^2)-linear or cubic spline</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

### 2.3.3.3 Particle Velocity

Several of the surveyed models and applications have indicated the ability to compute particle velocity as an output. These models are AIM, BELLHOP, KRAKEN, MMPE, OASES, ORCA, and TRACEO. The TRACEO model in particular highlights the capability of calculating the particle velocity vector for each hydrophone in the receiving array for application to modeling the vector sensor array used in matched-field inversion techniques for seabed properties.

A brief theoretical treatment of particle velocity is provided in Appendix A.

### 2.3.4 Environmental Databases / Descriptions Required

All acoustic models require the same basic descriptions of the environment. This includes the sound speed profile, the bathymetry, the bottom composition (or bottom reflection coefficient) and the surface state (or surface reflection coefficient). Most of the application models have direct links to databases that...
will supply some of these quantities given the desired latitude and longitude, while in most of the propagation models, the user must manually provide environmental data in an input file.

Table 2-8 lists the basic input requirements for each of the models. Included in this table is the listing of elastic sediment inputs which will indicate which models handle shear waves, either as a propagating wave or as a loss mechanism.

Table 2-8 Basic environmental inputs and bottom representation for models and applications

<table>
<thead>
<tr>
<th>Model</th>
<th>Sound speed input</th>
<th>Bathymetry input</th>
<th>Elastic parameter input</th>
<th>Mathematical bottom treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIM</td>
<td>GDEM or user input</td>
<td>DBDB-V, OAML 2002, or ETOP02</td>
<td>User input for sediment when using RAM</td>
<td>Reflection coefficient from CBLUG province, MGS province, or table.</td>
</tr>
<tr>
<td>BELLHOP</td>
<td>User input</td>
<td>User input</td>
<td>User input for complex reflection coefficient</td>
<td>Reflection coefficient from bottom boundary condition, fluid halfspace or table.</td>
</tr>
<tr>
<td>CASS/GRAB</td>
<td>GDEM</td>
<td>DBDB-V</td>
<td>No</td>
<td>Reflection coefficient looked up from sediment name.</td>
</tr>
<tr>
<td>COUPLE</td>
<td>User input</td>
<td>User input</td>
<td>No</td>
<td>Single fluid layer + absorbing sponge.</td>
</tr>
<tr>
<td>C-SNAP</td>
<td>User input</td>
<td>User input</td>
<td>User input in halfspace for losses</td>
<td>Single fluid layer overlying solid halfspace.</td>
</tr>
<tr>
<td>ESME</td>
<td>GDEM v3.0</td>
<td>DBDB v5.4</td>
<td>HFEVA database</td>
<td>BST v2.0 database.</td>
</tr>
<tr>
<td>FMM</td>
<td>User input</td>
<td>User input</td>
<td>User input in all layers</td>
<td>3D sediment and basement layers.</td>
</tr>
<tr>
<td>INSIGHT</td>
<td>User input</td>
<td>Flat</td>
<td>User input in halfspace for losses</td>
<td>Reflection coefficient from two layer sediment over solid halfspace.</td>
</tr>
<tr>
<td>INSPIRE</td>
<td>None needed</td>
<td>SeaZone Hydrospatial or GEBCO</td>
<td>No</td>
<td>Lossy medium with an upward refracting substrate.</td>
</tr>
<tr>
<td>KRAKEN</td>
<td>User input</td>
<td>User input</td>
<td>User input in halfspace for losses</td>
<td>Reflection coefficient from bottom boundary condition, acoustoelastic halfspace or table.</td>
</tr>
<tr>
<td>Model</td>
<td>Sound speed input</td>
<td>Bathymetry input</td>
<td>Elastic parameter input</td>
<td>Mathematical bottom treatment</td>
</tr>
<tr>
<td>-------------</td>
<td>-------------------</td>
<td>------------------</td>
<td>-------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>MMPE</td>
<td>User input</td>
<td>User input</td>
<td>User input in all layers</td>
<td>Two independent layers above the basement. The transitions of both speed and density across the interfaces are smoothed using independent hyperbolic tangents. Shear is incorporated using an equivalent fluid bottom approach.</td>
</tr>
<tr>
<td>MOCASSIN</td>
<td>databases</td>
<td>databases</td>
<td>No</td>
<td>Reflection coefficient looked up from porosity or other descriptors.</td>
</tr>
<tr>
<td>NUCLEUS</td>
<td>User input</td>
<td>User input</td>
<td>User input</td>
<td>Not provided</td>
</tr>
<tr>
<td>OASES</td>
<td>User input</td>
<td>User input</td>
<td>User input</td>
<td>Layers of poroelastic media with surficial roughness for each.</td>
</tr>
<tr>
<td>ORCA</td>
<td>User input</td>
<td>Flat</td>
<td>User input</td>
<td>Layers of viscoelastic media.</td>
</tr>
<tr>
<td>PCIMAT</td>
<td>GDEM</td>
<td>DBDB-V</td>
<td>No</td>
<td>Reflection coefficient using OAML routines (LFBL, HFBL, and sediment name look up.)</td>
</tr>
<tr>
<td>PECAN</td>
<td>User input or World Ocean Atlas</td>
<td>User input or Gebco</td>
<td>User input for losses</td>
<td>Layers of elastic sediments from Deck41 or user input.</td>
</tr>
<tr>
<td>POPP/PROLOS</td>
<td>User input</td>
<td>User input</td>
<td>No</td>
<td>Layers of fluid sediments with surficial roughness for each.</td>
</tr>
<tr>
<td>PROSIM</td>
<td>User input</td>
<td>User input</td>
<td>No</td>
<td>One sediment layer over fluid halfspace.</td>
</tr>
<tr>
<td>QUONOPS</td>
<td>MyOcean (offshore) and PREVIMER (coastal)</td>
<td>User input or ETOP01</td>
<td>User input for losses</td>
<td>Multiple layers, fluid-fluid or fluid-solid.</td>
</tr>
<tr>
<td>RAM</td>
<td>User input</td>
<td>User input</td>
<td>User input</td>
<td>Elastic halfspace + absorbing sponge.</td>
</tr>
<tr>
<td>SIMPLE</td>
<td>World Ocean Atlas 2005</td>
<td>SRTM30, NOAA coastal relief model, EEZ</td>
<td>User input for sediment when using RAM or for complex reflection coefficient</td>
<td>Reflection coefficient from sediment name or grain size.</td>
</tr>
</tbody>
</table>
Section 2 - Detailed Summary of Underwater and Sub-bottom Propagation Models

<table>
<thead>
<tr>
<th>Model</th>
<th>Sound speed input</th>
<th>Bathymetry input</th>
<th>Elastic parameter input</th>
<th>Mathematical bottom treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPADES</td>
<td>World Ocean Atlas</td>
<td>Gebco, ETOPO2, ETOPO5</td>
<td>User input for complex reflection coefficient</td>
<td>Reflection coefficient computed from Deck41 or user input.</td>
</tr>
<tr>
<td>TRACEO</td>
<td>User input</td>
<td>User input</td>
<td>User input for complex reflection coefficient</td>
<td>Reflection coefficient or boundary conditions.</td>
</tr>
<tr>
<td>VirTEX</td>
<td>User input</td>
<td>User input</td>
<td>User input for complex reflection coefficient</td>
<td>Reflection coefficient or boundary conditions.</td>
</tr>
<tr>
<td>WAVEQ3D</td>
<td>User input</td>
<td>ETOPO2, Coastal relief model, netCDF</td>
<td>User input for complex reflection coefficient</td>
<td>Rayleigh (with shear) Reflection coefficient from halfspace.</td>
</tr>
<tr>
<td>WKBZ</td>
<td>World Ocean Atlas</td>
<td>User input</td>
<td>No</td>
<td>Reflection coefficient from halfspace.</td>
</tr>
<tr>
<td>WOSS</td>
<td>World Ocean Database '09</td>
<td>Gebco03, Gebco09</td>
<td>No</td>
<td>Reflection coefficient from Deck41 database or sediment name.</td>
</tr>
</tbody>
</table>

Additional capabilities featured by some of the models in this survey include: source noise models, visual displays of results, and dynamic movement of source and/or receiver or mammal.

2.3.5 User Information

2.3.5.1 Availability of Model Code

The availability of any particular model or application depends primarily on the developer’s institutional or corporate affiliation and any corresponding restrictions from the funding sources. Table 2-9 sorts the models and applications by their availability to the general public. Note that the availability labeled as ‘commercially offered’ may mean ‘for sale’ or ‘offered as a service’. In the former case, the purchaser will own a licensed copy of the software; in the latter case, the software will be run under contract for the client.

<table>
<thead>
<tr>
<th>Availability</th>
<th>Models and Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free or open source</td>
<td>BELLHOP, ESME, FMM, KRAKEN, MMPE, ORCA, RAM, TRACEO, VirTEX, WAVEQ3D, WKBZ, WOSS</td>
</tr>
<tr>
<td>Commercially offered</td>
<td>AIM, INSIGHT, INSPIRE, MOCASSIN, NUCLEUS, OASES, PECAN, POPP/PROLOS, QUONOPS, SIMPLE</td>
</tr>
<tr>
<td>Classified for US Navy use only</td>
<td>CASS/GRAB, NAEMO, PCIMAT</td>
</tr>
<tr>
<td>Unknown</td>
<td>COUPLE, C-SNAP, PROSIM, SPADES</td>
</tr>
</tbody>
</table>
2.3.5.2 Primary Usage of Models and Applications

In Table 2-10 we present a listing of the models in our survey, classified by their current primary uses.

<table>
<thead>
<tr>
<th>Current Primary Uses</th>
<th>Models and Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active sonar performance prediction</td>
<td>AIM, BELLHOP, CASS/GRAB, PCIMAT, POPP/PROLOS, PROSIM, WAVEQ3D, SPADES</td>
</tr>
<tr>
<td>Simulation/stimulation tool</td>
<td>CASS/GRAB, PCIMAT, TRACEO</td>
</tr>
<tr>
<td>Array performance evaluation</td>
<td>ORCA, MMPE, MOCASSIN, QUONOPS</td>
</tr>
<tr>
<td>Environmental variability and Uncertainty</td>
<td>AIM, ESME, INSPIRE, MOCASSIN, NAEMO, NUCLEUS, QUONOPS, SIMPLE</td>
</tr>
<tr>
<td>Marine mammal noise exposure</td>
<td>AIM, C-SNAP, ORCA, PECAN, RAM</td>
</tr>
<tr>
<td>Matched field inversions</td>
<td>OASES, ORCA, PECAN, RAM</td>
</tr>
<tr>
<td>Naval tactical decision aide</td>
<td>BELLHOP, COUPLE, KRAKEN, MMPE, OASES, PECAN, RAM, SPADES, WKBZ</td>
</tr>
<tr>
<td>Research tool</td>
<td>CASS/GRAB, C-SNAP, INSIGHT, MOCASSIN, PCIMAT</td>
</tr>
<tr>
<td>Seismic exploration activities</td>
<td>NUCLEUS (seismic), OASES</td>
</tr>
<tr>
<td>Teaching tool</td>
<td>AIM, PCIMAT</td>
</tr>
<tr>
<td>Tomography and imaging</td>
<td>FMM, QUONOPS</td>
</tr>
<tr>
<td>Underwater network performance</td>
<td>MMPE, VirTEX, WOSS</td>
</tr>
</tbody>
</table>

2.3.5.3 Ease-of-Use

The following models: COUPLE, C-SNAP, MMPE, ORCA, PECAN, POPP/PROLOS, RAM, SPADES, WAVEQ3D, and WKBZ, are written in FORTRAN or C++ and have no graphical user interface (GUI). As stand-alone models, they are run from a command line interface with a run file prepared for a compiled executable. Output data is usually in the form of an ASCII or binary output data file. The user must find their own means to plot the output data.

Listed in Table 2-11 are the models and applications that have more sophisticated user interfaces and GUIs. The environmental databases attached to the models are listed in Section 2.3.4, Table 2-8. It might be assumed that any model that can be run with an interactive GUI and is linked to databases for supplying inputs will be user friendly. However, there are still many decisions and inputs that would require a trained operator. There are two models that specifically advertise their ease-of-use to non-experts:

The ORCA developer states in his questionnaire: “The model is unique among high-fidelity underwater acoustic propagation codes because it is largely automatic: the user does not need to guess at any obscure convergence parameters such as depth- or range-sampling resolutions.”

The SIMPLE developers state in their questionnaire: “The goal was to give even the non-expert user access right at their fingertips to everything needed to produce SEL and SPLpk, including bathymetry, sediment-type and -thickness information, ocean sound-speed profiles, source levels, marine mammal center-frequencies-of-vocalization, and the acoustic models themselves. It can be run in a default mode that makes sensible decisions for the user, or entirely with inputs supplied by the user.”
<table>
<thead>
<tr>
<th>Models and Applications</th>
<th>User Interface Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIM</td>
<td>PC or Apple/Mac GUI</td>
</tr>
<tr>
<td>BELLHOP</td>
<td>Matlab GUI or Command line interface</td>
</tr>
<tr>
<td>CASS/GRAB</td>
<td>Command line interface, output plotting with DISSPLA</td>
</tr>
<tr>
<td>ESME</td>
<td>Sparc or Windows GUI</td>
</tr>
<tr>
<td>FMM</td>
<td>Output plotting with OpenDX visualization package</td>
</tr>
<tr>
<td>INSIGHT</td>
<td>Windows GUI</td>
</tr>
<tr>
<td>INSPIRE</td>
<td>WYSIWYG PNG graphics of the impact range contours</td>
</tr>
<tr>
<td>KRAKEN</td>
<td>Matlab GUI or Command line interface</td>
</tr>
<tr>
<td>MMPE</td>
<td>Command line interface, MATLAB plotting available</td>
</tr>
<tr>
<td>MOCASSIN</td>
<td>MS Windows GUI written in C++</td>
</tr>
<tr>
<td>NUCLEUS</td>
<td>Linux platform and GUI in NUCLEUS+ framework</td>
</tr>
<tr>
<td>OASES</td>
<td>Plotting included in OASES Base (export) package</td>
</tr>
<tr>
<td>PCIMAT</td>
<td>Windows GUI, Visual Basic and Java</td>
</tr>
<tr>
<td>PROSIM</td>
<td>Output file plotting with pulse plotting package</td>
</tr>
<tr>
<td>SIMPLE</td>
<td>PC or Apple/Mac using Matlab GUI (p-code)</td>
</tr>
<tr>
<td>TRACEO</td>
<td>Matlab or Windows GUI</td>
</tr>
<tr>
<td>VirTEX</td>
<td>Matlab</td>
</tr>
<tr>
<td>WOSS</td>
<td>NS2/NS-Miracle support or command line interface</td>
</tr>
</tbody>
</table>

Table 2-11 The user interface type of GUI driven models and applications

It must be stressed that all of the high-fidelity models require an acoustic expert to correctly provide the inputs and choose the sampling parameters. For all the core acoustic models in application software, it is a built-in assumption during software development that the users will be some level of acoustic expert or trained practitioner.

For example, when using the PECAN model, the free parameters are the choice of source function, the choice of the number of Padé terms [19, 20], the choice of sampling depth and range step and the reference sound speed $c_0$, which controls the base phase in the solution. In this example, more ‘casual’ users will have little or no knowledge of the best source function or the number of Padé terms [108]. Given a blank slate, the user will require the advice of more experienced users.

As another example, when using the model BELLHOP, the user has choices of the functional form of the sound speed profile, the Gaussian representation, and the interpolation technique for the boundaries. Figure 2-16 shows the differences in BELLHOP’s computed ray trajectories, depending on the choice of interpolation technique, from a parabolic bathymetry. Reflection from a parabolic surface should produce parallel horizontal trajectories. In this case, the nearly correct behavior of the rays is shown on the left figure, which uses curvilinear interpolation because this method better represents the curved nature of the parabolic bathymetry.

The poor result shown on the right was computed using linear interpolation which is more suited to a facetted bathymetry. The effect of the linear interpolation on a curved surface is particularly striking for ray paths reflecting from the bottom at ranges less than 4 km. Clearly the user must be aware of the effects his input choices have on the result. These models cannot provide warnings to the users about the appropriateness of his choices.
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Figure 2-16 BELHOP ray trajectories after reflection from a parabolic bathymetry BELHOP bottom sampling choices: left - curvilinear interpolation and right - linear interpolation. [108]

An example of an opinion on ease-of-use appears in the SWAM'99 model-to-model comparisons [50], where the workshop organizer [50] noted that when comparing the models SAFARI (OASES), KRAKEN, RAM and ORCA: “There are numerous opportunities for errors, e.g., sound-speed profile representation (c or 1/c² linear), depth and range discretization, false bottoms (to have or have not; at what depth? see Figure 2-17), and source type (Green's function, spread of angles; point, or line)... It is nontrivial to run any of these models properly.”

Figure 2-17 Comparison of RAM run with and without a false, extra absorbing bottom at 25 Hz. (Tolstoy, 2001 [50])

Because most application software use more than one class of core model, the user needs an in-depth knowledge of each one in order to employ them correctly in the environments for which they are suited.
For example, Figure 2-18 displays the water depth selection criteria employed by the application model AIM. The developers (Frankel et al, 2002 [78]) state: “We would like to stress that AIM is a complex model with many inputs. Specific scientific and technical expertise is required to run AIM accurately and correctly. It is incumbent upon the user to ensure that the inputs are appropriate.”

![Figure 2-18 Water depth limitations imposed by AIM on its core propagation models (Frankel et al, 2002, [78])](image)

2.3.6 Specialties of Sound Exposure Models

The applications identified as sound exposure models are targeted to a specific purpose and are typically intended for large mammal studies. They usually feature interactive user interfaces and are internally linked to databases for inputs, relieving the user of the necessity to research databases and prepare input files herself.

The best classes of models for use by sound exposure application models are: rays, modes, and the PE. When used within their regions of applicability, a combination of these models will provide exposure predictions over the entire span of frequencies found in E&P sources. Ray models provide the fastest and most flexible computations, but for low frequency predictions, a PE or mode model will be required due to the frequency limitations of ray theory.

Almost all of the application models we have referenced for marine exposure predictions use a combination of these core models.

2.3.6.1 Exposure Application Models: Purpose and Specialties

In this survey we have identified ten application models that are specifically designed for marine sound exposure prediction. Unfortunately very little additional information could be found about four of the
models identified, NAEMO, NUWC Area Density Model, SAIC Model, and MONM, so they were not included in the questionnaires in Appendix B.

For completeness, we include them in Table 2-12 which lists the intended usage and special features of each of these models, along with their core propagation models.

Table 2-12 Marine mammal exposure applications’ purpose and specialties

<table>
<thead>
<tr>
<th>Application model</th>
<th>Purpose</th>
<th>Specialties</th>
<th>Core Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIM</td>
<td>Predict exposure from sonars, air guns, explosives, and sonic booms.</td>
<td>1) Monte Carlo statistics for animat positions and movement. 2) 4-D movement engine which programs the geographic and vertical movements of sound sources and simulated marine animals over time. 3) Wide choice of broadband sources. 4) 6 core propagation model choices.</td>
<td>RAM, CASS/GRAB, KRAKEN, BELLHOP</td>
</tr>
<tr>
<td>ESME</td>
<td>Animal response to sound produced by human activity with special emphasis on naval sound sources.</td>
<td>1) Time evolving simulations of populations of ‘animats’. 2) Stochastic simulation of species-specific behavior through defined behavioral states including aversion. 3) Direct prediction of the time series that the mammal receives. 4) Exposure histograms.</td>
<td>RAM, BELLHOP</td>
</tr>
<tr>
<td>INSPIRE</td>
<td>Predict the levels of underwater noise from impact piling operations in shallow water areas, typically of 100 m depth or less.</td>
<td>In theory, the INSPIRE model can be used to estimate underwater noise levels for any noise source for which good datasets of measurements are available.</td>
<td>Semi-empirical with geometric spreading and energy flow.</td>
</tr>
<tr>
<td>MOCASSIN</td>
<td>Has been used for computing risk radii for marine mammals.</td>
<td>Monte Carlo random ray tracing.</td>
<td>MOCASSIN</td>
</tr>
<tr>
<td>MONM 20</td>
<td>Noise contour maps from blasting operations.</td>
<td>1) Full waveform pressure timeseries via Fourier methods from the modeled transfer function. 2) Includes shear wave propagation.</td>
<td>RAM-s, FWRAM, BELLHOP</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Application model</th>
<th>Purpose</th>
<th>Specialties</th>
<th>Core Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAEMO 21</td>
<td>Estimates of takes for US Navy mid-frequency active sonar.</td>
<td>1) Multiple moving platforms with source choices. 2) Uses Navy Marine Species Density Database (NMSDD) to distribute species. 3) Duration of scenario based on representative training and testing activities.</td>
<td>RAM, CASS/GRAB, REFMS</td>
</tr>
<tr>
<td>NUCLEUS (exposure)</td>
<td>Predict exposure (SEL) from seismic exploration sources.</td>
<td>Realistic modeling of airgun pulse shapes and airgun array directivity.</td>
<td>Spreading laws</td>
</tr>
<tr>
<td>NUWC Area-Density Model</td>
<td>Estimates of takes for US Navy mid-frequency active sonar.</td>
<td>1) Field on 8 radials from multiple simultaneously operating sources. 2) Shallow, sloping or deep bathymetry. 3) Overlapping footprints gives CSEL. 4) Sum of animal densities in field times probability of behavioral change = number of takes.</td>
<td>CASS/GRAB</td>
</tr>
<tr>
<td>QUONOPS</td>
<td>Now-casting ocean noise, forecasting ocean noise, environmental impact assessment and decision making.</td>
<td>1) Approach and design is identical to weather forecasting, where measured data are used to calibrate the global prediction in a deterministic or statistical manner at basin scale. 2) AIS and operational oceanography data stream integrated. 3) Monte-Carlo approach in order to handle variability and uncertainty to produce Probability Density Function maps. 4) Geo-Time-deterministic prediction (4D data: latitude, longitude, depth, time).</td>
<td>RAM, BELLHOP</td>
</tr>
<tr>
<td>SAIC model 22</td>
<td>Estimates of takes for US Navy mid-frequency active sonar.</td>
<td>1) Define 5-20 different environments representing possible combinations and do acoustic modeling in each. 2) Histogram the SPL by depth.</td>
<td>CASS/GRAB</td>
</tr>
</tbody>
</table>


22 See Erbe et al (2012) [111]
2.3.6.2 Comparisons of AIM, ESME and SIMPLE

The following discussion represents the information and impressions that were gained by the co-author Craig Hamm during his visits with each of these three model developers. The authors are grateful for these generous opportunities.

2.3.6.2.1 Similarities Between Approaches

Each model’s user interface has a MS Windows (or similar) look and feel. They are using many of the same core propagation models and the output metrics are also similar. Each system is comprised of multiple user interfaces within the package. These may consist of tabbed interfaces, tables, graphs, pop-up windows, histograms, CPU status, TL plots, map plots, line graphs, etc. Despite best efforts to keep these user interfaces ‘friendly,’ for new users they can be somewhat overwhelming in terms of order of input, directory paths, input correction, run, pause, stop, analysis, saving output, etc.

2.3.6.2.2 Main Differences between Approaches

There are two main differences which really stand out among AIM, ESME and SIMPLE. These are the hardware requirements, and how animal behavior is treated.

**Computer Hardware:**

ESME is very processor intensive and requires a lot of random access memory. While the online recommendation for ESME states that a multicore or multiprocessor system with a minimum of 2GB or memory is needed, the development system (which we would expect to be leading edge) is running 12 i7 processor cores in parallel and using 12 GB of memory (May 2013).

At the other end of the spectrum, AIM and SIMPLE can run on good quality laptops with large, but reasonably normal, amounts of random access memory (2-4 GB, say). This is quite a difference. One would need to understand more deeply what the computational loads are to make a fairer comparison. On the surface, it appears as though ESME requires a more elaborate setup in relation to AIM and SIMPLE.

**Modeling of animal behavior:**

AIM computes exposure for tens of thousands of discrete individual animated animals or ‘animats’. Each animat has a constrained three-dimensional motion which is based on user inputs (ultimately based upon the most recent research data on the behavior of each species. AIM allows lateral and diving motions. AIM has the ability to model both avoidance and attraction to a sound source. It is not currently done for...
environmental assessments, because the parameters of avoidance/attraction are not known well enough. Furthermore, if animats are programmed to avoid the sound source, one opens oneself to the criticism or legal challenge that the impacts were underestimated by using avoidance behaviour. AIM continuously monitors the SEL of animats, and if the regulatory limits are breached AIM simulates the cessation of acoustic transmissions for the regulatory shutdown time, then resumes the transmissions, and repeats this process. AIM has the capability to output exposure histograms and various other statistical measures of the SEL, CSEL and SPL_{peak} values. This is quite a comprehensive modeling capability.

ESME uses the Marine Mammal Movement and Behavior (‘3MB’) program for the creation and simulation of animal movement and behavior within the ocean. The program permits a bounded stochastic simulation of animats, through defined behavioral states. For the version of ESME demonstrated to the author, animals are seeded throughout the simulation area with a uniform, user-specified population density specified in average number of animals per square kilometer. The default value is 0.01. Species can be repopulated, or their properties changed, via a context menu. Each species has predefined behaviors and modeling constraints that 3MB uses for animal movement, placement, diving profile behavior, podding behavior, and more. Twenty-one marine mammal species are currently supported.

SIMPLE allows the user to add mammals (about 125 species are available), but in a static distribution, there is no animat motion (perhaps we can refer to these as ‘anistats’). Anistats act as tagged receivers with characteristics of the modeled animal such as hearing sensitivity filters, etc. In one critique of animat modeling [225], the findings were that the static distribution method underestimates the number of behavioral harassments compared with the animat movement method.

<table>
<thead>
<tr>
<th>Table 2-13 Differences between exposure models AIM, ESME and SIMPLE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hardware Requirements</strong></td>
</tr>
<tr>
<td>AIM</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>ESME</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
Hardware Requirements

- 2GB memory and a multiprocessor or multicore system are strongly recommended for reasonable performance.

'Animats'

- Sound levels are computed on a regular grid of receivers. Implicitly, an animal is at each field point.
- Animats can be positioned individually, in pods, or from databases (OBIS-SEAMAP) at any of the receiver positions, or any other location.
- There is no accounting for any animal behavior/motion (static distribution).

2.3.7 Future Plans for Currently Available Models

Many of the models listed in section 2.1.2 have listed future plans for model improvements in their questionnaires. Those that have are listed in Table 2-14. We note that the most common future plan is to develop a true 3D capability.

<table>
<thead>
<tr>
<th>Models and applications</th>
<th>Future plans</th>
</tr>
</thead>
<tbody>
<tr>
<td>BELLHOP</td>
<td>3D version and range dependent bottom parameters expected in 2013.</td>
</tr>
<tr>
<td>CASS/GRAB</td>
<td>3D version of GRAB.</td>
</tr>
<tr>
<td>ESME</td>
<td>For 2013: new environmental databases, explosives modeling, and wideband source modeling (airguns, shipping noise).</td>
</tr>
<tr>
<td>INSPIRE</td>
<td>During 2013 INSPIRE will be developed to include an individual based model (IBM) system which will result in a more realistic representation of how receptors flee from noise sources when looking at cumulative metrics, such as Sound Exposure Levels (SELS).</td>
</tr>
<tr>
<td>MMPE</td>
<td>The model is currently being upgraded to compute 3D fields, both with flat surfaces and 2D rough surfaces. A version is also being tested that defines an air layer above the water, and does not presume a perfect reflector. Other modifications are being explored to improve the accuracy and efficiency of the model.</td>
</tr>
<tr>
<td>MOCASSIN</td>
<td>Inclusion of bistatic and multistatic calculations and new bottom models.</td>
</tr>
<tr>
<td>NUCLEUS (exposure)</td>
<td>Current development work is under way to implement more sophisticated sound propagation models. These will be capable of considering a depth-variable sound speed profile, range-dependent bathymetry, and viscoelastic absorption at the sea floor. It will also in the near future be possible to perform SEL calculations on synthetic data obtained from seismic full waveform modeling (FD, reflectivity).</td>
</tr>
<tr>
<td>PCIMAT</td>
<td>Incorporate a 3D capability for GRAB and error estimation for RAM. There are also plans to improve the model's broadband treatment and its beam pattern treatment.</td>
</tr>
<tr>
<td>Models and applications</td>
<td>Future plans</td>
</tr>
<tr>
<td>------------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>PECAN</td>
<td>Writing a user’s guide and adding a reverberation modeling capability.</td>
</tr>
<tr>
<td>POPP/PROLOS</td>
<td>Subprogram MODES regularly gets used in various applications: reverberation and clutter modeling; pulse propagation; code itself dates from 1978 and should be rewritten in Fortran 95.</td>
</tr>
<tr>
<td>QUONOPS</td>
<td>Improve description of input data: source levels, directivity, etc. Develop 3D or hybrid 2D/3D modeling.</td>
</tr>
<tr>
<td>RAM</td>
<td>Non-uniform sampling in depth to improve efficiency. Poroelastic PE treatment for compressional and shear sources in poroelastic sediment layers. Anisotropic elastic media treatment. Interface waves such as Rayleigh and Stoneley waves.</td>
</tr>
<tr>
<td>SIMPLE</td>
<td>A future goal is to add Scooter, SPARC, Kraken, Kraken3D, and Bellhop3D to SimplePlan.</td>
</tr>
<tr>
<td>TRACEO</td>
<td>Detailed comparisons with field data (where mismatch can be expected to become more relevant). Studies of backscattering issues (based on benchmarking against analytic solutions, backscattering-capable models, and/or available experimental data). Accounting for ray tracing in elastic layered systems. Three-dimensional field predictions. Code optimization, parallelization and cloud computing.</td>
</tr>
<tr>
<td>VirTEX</td>
<td>Extend this technique to other applications, especially long range, low-frequency propagation. Establish more direct links to the physical oceanography and associated models (NCOM, SWAN, WaveWatch III).</td>
</tr>
<tr>
<td>WAVEQ3D</td>
<td>WaveQ3D ray paths are parameterized in time to support the eventual development of a fast bistatic reverberation model for active sonar training systems. The theory is in place, but it will take time to implement. The uBLAS computational framework on which the implementation is based has a clear migration path to implementation on Graphic Processing Units. The developers are currently working with a sonar training system development project to replace their current implementation of FeyRay with WaveQ3D. This promises to provide concrete data for their speed hypothesis and answer lingering questions about the impact of this approach on training system outcomes.</td>
</tr>
<tr>
<td>WKBZ</td>
<td>Environments with multiple sediment layers will be taken consideration. Reverberation model and ambient noise model based on the WKBZ approximation will be developed.</td>
</tr>
<tr>
<td>WOSS</td>
<td>Official integration into Network Simulator 3.</td>
</tr>
</tbody>
</table>

### 2.3.8 Horizon Models - Those likely available in 2-3 years

Current models which may become available in the near future include RMPE and FDTD. As yet unnamed models may be developed based on some of the approaches mentioned in the above sections such as transport theory, closed-form intensity derivative, adjoint modeling, and ray chaos. In addition, the

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23 Some of the future plans for RAM have already been privately developed.
waveguide invariant is showing promise as a phenomenon predictor for broadband interference patterns.

i. **RMPE** [112] is a ray-mode-parabolic hybrid model. It uses Normal Modes in the vertical direction and mode coefficients in the horizontal direction that are found using a PE method.

ii. **FDTD** is a finite difference time domain model.

iii. **Transport theory** is a method of directly computing the evolution equations for the moments (mean intensities and fluctuations) of the propagating field arising from stochastic deviations in the waveguide properties [113].

iv. **Closed-form intensity derivative** is a technique [108] that relies on the ability to express the propagated incoherent intensity of the Gaussian Beam method in a differentiable closed-form equation.

v. **Adjoint modeling.** Methods based on adjoint models have been recently used to compute derivatives of the pressure field with respect to sound speed, density and frequency [114-116] for application to uncertainty modeling.

vi. **Ray Chaos.** A propagation model has been developed that may handle the chaotic case [117, 118] using a technique called polynomial chaos.

vii. **The waveguide invariant** [119] is a useful parameter for understanding the behavior of interference patterns that arise from broadband acoustic sources in shallow water waveguides. These interference patterns often appear in time-frequency plots (spectrograms) in the form of intensity striations as shown in Figure 2-19, whose properties are directly related to the environmental parameters that characterize the waveguide, such as the sound speed profile, bathymetry, sediment properties, and source/receiver depth.

The phase and group speed differences between closely spaced modes describe the horizontal and vertical spacing of the striations. The quantity known as the waveguide invariant is formally defined as the change of the phase velocity with respect to the change in the average group velocity for a group of closely spaced modes.

The waveguide invariant describes the dispersive propagation characteristics of an environment due to long range modal interference. For range independent waveguides, this parameter is approximately unity. For slow bathymetric range dependence, the parameter is approximately the ratio of the water depths at source and receiver. The assumptions in the derivation of the parameter are that the source spectrum is roughly flat across its band and that the spatial variations in the environment are sufficiently weak that the adiabatic mode approximation can be used. The receiver is assumed to be in the far field and the mode eigenfunctions functions are approximated by the WKB approximation (rays) in depth.
Figure 2-19 Pressure spectrogram data with waveguide invariant model predictions shown by circles [119].
The figure shows a pressure spectrogram over 70-170 Hz band from data collected in the SWellEX-3 experiment near San Diego, California in 1994. The three lines of interconnected circles superimposed on the figure are the waveguide invariant model’s predictions of the temporal evolution of the frequency content of the broadband interference patterns.

Thus far, waveguide invariant theory has successfully been applied to predict the temporal evolution of the frequency content of the broadband interference patterns [120,121] in an experiment using a broadband source on the continental shelf of southeast Florida in 2007. Future applications of the waveguide invariant involve signal processing algorithms for a Bayesian passive range and depth localization framework and for classification features.

2.4 Uncertainty in Predictions
The acoustic modeling community generally agrees that the current high-fidelity models are all capable of accurately representing the sound field if the environment is well known. However at-sea propagation loss estimates are still notoriously unreliable, not through any inherent weakness in the models themselves, but because the ocean-acoustic environment is often poorly specified. When an acoustic signal propagates in the body of the ocean, it exhibits intensity fluctuations, described as high intensity ‘ribbons’, that vary randomly both in space and time (in these respects it differs from seismic type propagation in the bottom where the intensity fluctuations are time independent and related to a deterministic geological structure). This problem is further complicated in exposure analyses because it is often necessary to estimate potential impacts to marine animals over large areas in shallow water.
2.4.1 Uncertainty in Modeling

In this section we provide some of the theoretical and numerical details that form the basis of the mainstream underwater acoustic models. To summarize:

i. The wavenumber integral representation makes use of the fast Fourier transform (FFT) algorithm to numerically invert the Hankel transform of the depth-dependent Green's function with respect to horizontal wavenumber.

ii. Alternatively, the normal mode representation is obtained by applying contour integration methods to replace the integral along the real wavenumber axis with a sum of residues at the poles (modal wavenumbers) of the depth-dependent Green's function plus contributions from any branch line integrals.

iii. The multipath expansion representation relies on geometric ray concepts to partition the total field into various physical propagation components (refracted, surface reflected, and bottom bounce paths etc.) which are then evaluated asymptotically.

iv. In contrast to these quasi-analytic representations (where we transform Eq. 5), the ray solutions and the PE solutions are developed from considering Eq. 5 itself.

v. Ray solutions derive from an attempt to find a series (or multipath type) solution to the Helmholtz equation directly.

One might legitimately ask: how do these methods stack up against one another?

To this end we present some results for the propagation loss as a function of range in the Pekeris waveguide (Figure 2-4, above) for a source at 50 m depth and a receiver at 75 m depth.

i. For a harmonic 100 Hz source, the propagation loss results are plotted versus range for models based on each of the wavenumber integration (WI), parabolic equation (PE), normal mode (NM), ray theory (RT), and multipath expansion (ME) techniques.

ii. We show close range results in Figure 2-20(a) and some longer ranges results in Figure 2-20(b).

iii. At short range we see very good agreement between the models – they track each other in amplitude and phase almost perfectly.

iv. At longer ranges we see some deviation of the RT and ME models from the WI, PE, and NM models. The deviation is primarily in phase and can be attributed to using plane-wave reflection coefficients to describe the interaction of rays with the ocean-bottom.
A second comparison between models (methods) is shown below in Figure 2-21 for a shallow water waveguide (200 m deep) with an upward refracting winter sound speed profile ($c(z) = 1500 + 0.15z$) over a bottom with properties: $c_B = 1600$ m/s, $\rho = 1.8$ g/cm$^3$, and $\alpha = 0.16$ dB/λ.

In this instance, the models are not in such good agreement. The WI, PE, and NM models are very close; the RT model does not match the other models in detail very well at all – the general level is acceptably close.
The material presented in this section (and the Appendix) together with the results shown above in Figs. 2-20 and 2-21 (for relatively simple ocean environments) demonstrate that not only is the development of the models “a science” but that the choice and application of any method of these models to real world problems is itself “a science”.

Without some basic understanding of the parameters and the physics that drives each model, confidence in the acoustic product of any particular model is tenuous at best – it is always a good thing to have more than one model with which to compare results.
2.4.2 The Challenge of Shallow Water

During the cold war, most acoustic research was concentrated in the deep water regions of the world's oceans, because the perceived submarine threat was greatest there. When attention was finally given to shallow and littoral waters (circa 1990's), it was found that modeling shallow water environments for Navy system’s performance was much more difficult than the deep water predictions.

Why is shallow water much harder to model than deep water? There are many reasons.

i. Environmental information in databases, such as bathymetry, has a shorter shelf life – witness the redistribution of the sands after a storm.

ii. The bottom type and sound speed profile are inherently more variable than those in deep water due to coastal and fluvial runoff and human activity.

iii. The bottom sediments are different in character than those in deep water, they are generally deep layers of sands and muds that support a host of biological life, while deep water sediments are often ooze overlying bedrock. Shallow water sediments have a large range of roughness size distributions because of the shells, sand waves, and trash that litters the bottom.

iv. The water column and its boundaries cannot be easily separated, that is, individual interactions with the surface or bottom often cannot be distinguished in time. Instead there is an all-channel interaction. Some people have suggested defining a channel loss to replace the individual bottom and surface losses.

v. There is more marine life, often making the volume scattering strength in reverberation larger than the surface or bottom contributions.

vi. There is more shipping and industrial activity making the ambient noise higher and putting more transient spikes in the noise field.

In 2002, NATO conducted a study of the quality of their shallow water databases for bathymetry, sound speed profiles and bottom reflectivity called the NATO Standardized Oceanographic Database, NSODB. This study concluded that the “prediction is generally deemed unsatisfactory, due mainly to inaccurate environmental inputs from the NSODB. The bottom-loss information is found to be the weakest link, but also bathymetry and profile information can have adverse effects on the prediction accuracy.” [122]

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24 The usage and interpretation of the term littoral varies widely in oceanographic literature. Pre-1990 definitions point to a region that has a direct interface between the land and the open water and, in general, would extend no further than 5 km from shore. Usually between high and low water marks, and/or to depths of 200 m. Naval Doctrine Publication 1 describes Littoral as “Those regions relating to or existing on a shore or coastal region, within direct control of and vulnerable to the striking power of naval expeditionary forces.” (NDP-1 Naval Warfare, 1994). In 1999, the Naval Oceanographic Command at the Stennis Space Centre provided a USN definition of Littoral as the “region which horizontally encompasses the land/watermass interface from fifty (50) statute miles ashore to two hundred (200) nautical miles at sea; extends vertically from the bottom of the ocean to the top of the atmosphere and from the land surface to the top of the atmosphere.”
2.4.3 The Modeling of Uncertainty

Numerical studies using Monte Carlo realizations of sound fluctuations were demonstrated [123] using a full-wave model in a realistic shallow water environment including internal wave fluctuations and bottom roughness. Results of this study show that the sound intensity at distant receivers scintillates dramatically. Scintillation is a word used to describe rapid changes in intensity. The scintillation index (SI) is usually defined as the second moment of the intensity (the intensity variance) normalized by the square of the mean intensity. The mathematical form of SI will depend upon the probability distribution assumed for the intensity. A perfectly stable signal has a scintillation index equal to zero. When intensity fluctuations have a variance comparable to the average intensity, the index is near unity. The intensity variance increases rapidly with propagation range and is significantly greater than unity at ranges beyond about 10 km. The finding of a large scintillation index is a compelling reason for including uncertainty in sound field predictions.

A method must be found to account for all the potential uncertainties in the environment to which sound propagation is highly sensitive, or equivalently the uncertainties in the input parameters to which the acoustic model is highly sensitive. For practical prediction purposes in real ocean environments, some kind of statistical approach is necessary. The National Research Council [124] has stated:

"However, as with all models of the physical world, uncertainties in parameters and approximations in the modeling techniques are inevitable and must be accounted for using statistically valid means when interpreting the model predictions."

They also assert [124]:

"The quality of the estimate [of the acoustic field] is directly related to the quality of the environmental information used in the model. For example, in continental shelf waters, geoacoustic parameters such as compressional sound speed, attenuation and sediment density can significantly affect the acoustic propagation. Variability introduced in these parameters can substantially affect model predictions; propagation loss can be incorrect by as much as 20 dB as a result of inaccurate geoacoustic parameters."

The question is how to reasonably represent the TL for a given area while also acknowledging, examining, and accounting for these numerous environmental variables, and still capturing the overall effects of the proposed action or seismic air gun operations on the environment.

The most common statistical tool is Monte Carlo simulation. Of the models listed in Section 2.1 to Section 2.4, the ray model MOCASSIN employs Monte Carlo techniques to randomize the reflected ray angles from the surface. The Normal Mode model ORCA can perform Monte Carlo iterations to facilitate parameter studies of bottom and water column properties. The application model QUONOPS uses Monte Carlo techniques to produce the probability density function of the acoustic field from the variability of the bottom properties. The application model AIM uses Monte Carlo distributions to randomize the receiver (animat) positions but it uses a single deterministic solution for the acoustic field.

There are other methods of translating environmental uncertainty into TL predictions. The thrust of new research is toward understanding the sensitivity of acoustic models to the environmental variability and thus predicting its effect. Many of these approaches are described in the proceedings of a recent
Section 2 - Detailed Summary of Underwater and Sub-bottom Propagation Models

conference entitled The Impact of Littoral Environmental Variability on Acoustic Predictions and Sonar Performance, organized by SACLANTCEN in September 2002 [127].

Among the new research areas are: transport theory, closed-form intensity derivative, ray chaos, adjoint theory, a random ocean propagation technique and the principal component analysis. These are described below.

**Transport theory** is a method of directly computing the evolution equations for the moments (mean intensities and fluctuations) of the propagating field arising from stochastic deviations in the waveguide properties [113]. The theory expands the field in unperturbed Normal Modes and then obtains evolution equations for the mode amplitudes, accounting for mode coupling due to scattering from randomness in waveguide properties. Mode amplitudes are averaged with approximations for forward scattering, the short-range nature of the correlations between fluctuations (Markov approximation), a Gaussian distribution of randomness and the neglect of the cross-modal coherences (incoherent summation) [125, 126].

The resulting transport theory equations provide an approximation for the cross-mode coherence matrix. Transport theory scintillation index modeling has the potential to be just as accurate as but much faster than Monte Carlo techniques. Thus far, the theory has been successfully applied to sound speed fluctuations from internal waves [125] and to small-scale boundary roughness. [127, 128] Figure 2-22 displays a PE simulation (top) for total intensity obtained by averaging over the results for 50 rough surface realizations, and a transport theory result (bottom) with the modified SW06 profile [128] 25.

One of the applications for transport theory is to account for sea surface forward scattering as it affects propagation and reverberation in shallow water. The forward scattering leads to mode coupling. The most significant effect is on reverberation, even when the reverberation is dominated by scattering from the bottom. The predicted differences between transport theory predictions and the simple alternatives of either ignoring surface forward scattering or of using a coherent reflection loss at the surface can easily exceed 10 dB, so there is a lot at stake.

Some of the current research is directed toward using transport theory as the benchmark for developing effective surface loss models for the total field (coherent and incoherent scattering) that will replicate the transport theory results. This effective reflection coefficient can then be used in any ray or WKB mode model that can ingest range dependent surface reflectivity. The theory has also been extended to include broadband cross-frequency effects [129].

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25 The comparison between these two graphs is rather misleading because, due to the profile being used in this comparison, the field below the surface from 20 m downward is unchanged and both models agree in structure there. The surface roughness only affects the upper 20 m of water.
Closed-form intensity derivative is a technique that relies on the ability to express the propagated incoherent intensity of the Gaussian Beam method in a differentiable closed-form equation. The technique uses the expression for the standard error of a function of a random variable to obtain the variance in the transmission loss given the variances of the underlying uncertainties.

For example, let the random variable be a fluctuation in the sound speed, \( x \). Then the acoustic intensity, \( I \), is a function of this variable and the variance of the intensity, \( \sigma_I^2 \), is (to first order) directly proportional to the variance of the underlying uncertainty, \( \sigma_x^2 \), multiplied by the square of the intensity derivative with respect to the uncertainty, \( \frac{dI}{dx} \).

\[
\sigma_I^2 = \left( \frac{dI}{dx} \right)^2 \bigg|_{x=0} \sigma_x^2
\]  

(29)

This technique has been applied to the BELLHOP Gaussian beam equations [108].
Choosing a sound speed profile representation of either \( c \)-linear or \( 1/c^2 \)-linear, the equations for the Gaussian beamwidth can be solved in closed form, and therefore the derivative of the intensity can be evaluated in closed form. This technique provides a fast, exact expression for the variance of the intensity predicted by the BELLHOP model from small random changes in the sound speed profile.

The technique can be expanded to include variances produced by uncertainty in bottom properties and bathymetry. An example of the transmission loss field and the log of the intensity derivative field is shown in Figure 2-23. The left-hand plot displays the acoustic full field computed using BELLHOP at 1000 Hz over a shallow pyramid with a layered sound speed profile and the source at 30 m. The right-hand plot displays the spatial distribution of the log of the intensity derivative, assuming the randomness was in the surface sound speed.

By comparing these two graphs, we see that the intensity derivative with respect to the random component of the sound speed (right) is strongest in the regions near the strongest rays, in the surface duct and along the deeper refracting paths. This is because a slight change in the values of the SSP that define the ducts will cause the field to shift in space.

![Figure 2-23 Quantifying the uncertainty in BELLHOP transmission loss using the intensity derivative](image)

Figure 2-24 displays an estimate of the error in a \( TL \) slice at 150 m depth made using the intensity derivative shown above. The black line is the mean \( TL \) and the red lines are the \( TL \pm 1 \) standard deviation for a variance in the surface sound speed of 1 m/s.\(^{26}\) This example shows very localized error estimates caused by the specific geometry and single frequency nature of the example. In Section 4.1, the argument is made that sharp peaks and nulls will be smoothed by broadband source energy and therefore for application to that situation, these results should be range and depth averaged to provide a better estimate of the effect of uncertainty.

\(^{26}\) This is a crude estimate of the actual error bars made by simply adding and subtracting the dB value for \((1+\sigma_I/I)\). Correct evaluation would involve using the probability integral.
Ray Chaos refers to the chaotic behavior of rays in sound channels with range dependence [130, 131]. Chaotic ray behavior is characterized by the extreme sensitivity to initial and environmental conditions and is more pronounced in the shallow angle rays than in the steeper rays. Chaos in a strict sense cannot exist in wave solutions because these are solutions to a linear wave equation.

However these wave fields do exhibit the apparent randomness (see Figure 2-25) associated with chaos under conditions in which the corresponding ray trajectories are chaotic [132]. This apparent randomness and an associated limitation on our ability to make deterministic predictions (owing to our incomplete knowledge of the mesoscale ocean structure) are observable in the ocean. The metrics used to describe chaotic behavior are Lyapunov exponents and entropy rates.

A propagation model has been developed that may handle the chaotic case [117, 118] using a technique called polynomial chaos. This technique uses ensemble averages over the probability distribution of the
random variables written as series expansions of special orthogonal polynomials. For example, for Gaussian random variables, the appropriate polynomials are versions of the Hermite polynomials. The theory predicts two different behaviors of the mean field depending on the correlation length of the randomness as compared to the propagation range. However, Creamer [108] cautions that the calculation of the intensity variance and scintillation index using polynomial chaos is problematic because of convergence difficulties and the need for higher-order approximations.

**Adjoint modeling** is a technique of computing acoustic variability due to unknown environmental fluctuations by inverting the observed mismatch between measured and modeled acoustic data [133, 134]. An adjoint model is derived from a forward propagation model to propagate data-model mismatch backwards to the medium perturbations that were not being accounted for in the model. The adjoint model has particular relevance to inversion problems in which the unknown parameter space is much greater than the observation space. Methods based on adjoint models have been recently used to compute derivatives of the pressure field with respect to sound speed, density and frequency [114-116].

**Random ocean propagation** is solved using a new technique [135] for optimal modeling in horizontally stratified oceans with random sound speeds. The amplitude, phase and scattering of the sound wave are accounted for by decomposing the pressure into a deterministic component (solved by existing techniques) and a random component created by a perturbation. The solution for this component is based on spline filter theory that has previously been used for chaotic image enhancement.

**Principal component analysis** using Empirical Orthogonal functions (EOF) [136, 137] is a method of characterizing the sound speed profile in terms of polynomials representing the principal components. EOF decomposition is one of the most powerful methods for reducing the variability in the data into a few patterns. It provides a compact description of the spatial and temporal variability of data series in terms of orthogonal functions or statistical “modes” resulting from the decomposition of the data into eigenvalues and eigenvectors. Each set of EOF modes represents a standing oscillation pattern. A set of sound speed profiles (i.e. computed from multiple measurements of temperature over time using a thermistor string) can be represented by a set of EOFs that supply all the information necessary to reconstruct the most probable profile as well as the variability of the profile. This can provide the acoustic model with a realistic estimate of the mean environment and a measure of its variability.

### 2.4.4 Iterative Calibration: Ground-Truthing using TL Measurements

Very little material was found with respect to ‘ground truthing using TL-measurement.’ While this practice is common during U.S. Navy tests, no references are available in the open literature. A recent conference paper [138] describes a process permitting enabling near real-time corrections to the marine mammal protection zone boundary (also referred to as “shutdown radiuses). The process was demonstrated during a seismic survey, offshore the Astokh region of north-eastern Sakhalin Island, in the Russian Far East. The recency of this publication indicates that practice is relatively new.

The process is captured diagrammatically in Figure 2-26 below. The process described by Racca et al. [138] is divided into three phases:

- i. pre-survey activity in an office or laboratory;
- ii. the operation activity during the survey; and
- iii. post-survey data analyses.
Figure 2-26 Iterative calibration, data flow
Each phase is described below:

**The pre-survey portion** requires the acoustic model(s) to be run for a broad range of environmental inputs for the seismic survey area, and for the various source levels and source array characteristics that are anticipated during the field operation (blue boxes modeling-theme in Figure 2-26). These inputs may be divided into categories delineating various propagation regimes which are less or more favorable to propagation. Once the range of inputs are determined, the model(s) are run for all decided propagation cases and the model outputs, per-pulse SEL levels computed on the seafloor, are sorted and indexed into a library for later use in the field.

This results library mitigates the need to perform lengthy model calculations in when in the field. Corresponding to the propagation cases, a maps library (yellow boxes observer-theme) is produced indicating protection zone boundaries, or shutdown radii, based on some established regulatory criteria. **These maps are produced for use during the field survey by whale sighting observers who are trained and equipped with calibrated equipment for determining a whale’s observed position.**

**The field survey** portion necessitates bringing the results libraries of pre-computed per-pulse SEL to the field.

- A network of acoustic sensors is laid on the seafloor prior to seismic operations.
- The positioning of these sensors needs to be carefully planned in concert with the anticipated survey plan and the inputs used to create the results libraries.
- When the seismic transmission operation begins the acoustic modeling team determines, based on situational geometry, the appropriate hydrophone to monitor.
- Geometry and the actual seismic source parameters determine the case from the results library expected to best describe the propagation and bottom received level. The data selection also determines the corresponding protection boundary zone map to use.
- The choice of map is communicated to the whale observers.

As the survey progresses the received acoustic signals are monitored in real-time (brown boxes iterative-TL theme in Figure 2-26). In the paper by Racca et al. [138], if the received per-pulse SEL consistently deviated more than ±3 dB from the in-play library result, the library was searched for the new best match to the actual data and the new best match becomes in-play. When a new SEL case is in-play, the protection zone boundary map is updated to the corresponding case and the whale observing team is notified.

The whale observing team now operates with the new boundary. This process is done iteratively through constant monitoring and comparison of the actual bottom measured SEL (bottom measured transmission loss, TL) to the library result. This process, in-effect, iteratively ground-truths the pre-computed TL (which is embedded in the SEL estimates) with actual TL measurements. Each pre-computed case used during the survey is flagged for potential later post-processing (green box flagged data theme in Figure 2-26). In the event a marine mammal crosses the protection boundary, decision makers are notified. Note that during the survey all ship and seismic source positions are recorded for potential later use.

**The post-survey** portion utilizes all recorded field survey positional data and the acoustic model inputs (corresponding to the flagged propagation cases). This permits new acoustic model calculations to be
performed, providing such quantities as on-path (of the mammal) SEL levels, cumulative SEL levels, and any other processing deemed to be of relevance or interest.

2.5 E&P Source Characteristics and Sound Exposure Metrics

2.5.1 E&P Source Characteristics

Propagation models listed in Sections 2.1 to 2.4 assume a unity source level, and generally, the model user then supplies his specific source level and other source characteristics for post-processing. The possible exceptions are a source beam pattern which can be input to some of the models to be applied internally to shape the sound field, and the bandwidth of the sound, which can be input to some of the broadband capable models. For completeness we include here a short discussion of the E&P source characteristics.  

<table>
<thead>
<tr>
<th>Sound source</th>
<th>Source Level At 1 m re 1 µPa</th>
<th>Bandwidth</th>
<th>Main energy</th>
<th>Duration</th>
<th>Directionality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exploration and geophysical surveying</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Echo sounders</td>
<td>230-245 dB rms</td>
<td>11.5-100 kHz</td>
<td>Various</td>
<td>0.01-2 ms</td>
<td>Downwards</td>
</tr>
<tr>
<td>Sparkers, boomers, chirp sonars</td>
<td>204-230 dB rms</td>
<td>0.5-12 kHz</td>
<td>Various</td>
<td>0.2 ms</td>
<td>Downwards</td>
</tr>
<tr>
<td>Seismic airgun arrays</td>
<td>220-262 dB Peak-to-peak</td>
<td>5 Hz-15 kHz</td>
<td>10-120 Hz</td>
<td>10-100 ms</td>
<td>Downwards</td>
</tr>
<tr>
<td>Construction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Construction and Maintenance ships</td>
<td>150-180 dB rms</td>
<td>20 Hz-20 kHz</td>
<td>&lt;1 kHz</td>
<td>Continuous</td>
<td>Omnidirectional</td>
</tr>
<tr>
<td>Pile driving</td>
<td>220-257 dB Peak-to-peak</td>
<td>10 Hz-&gt;20 kHz</td>
<td>100-200 Hz</td>
<td>5-100 ms</td>
<td>Omnidirectional</td>
</tr>
<tr>
<td>Operation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drilling</td>
<td>115-117 dB</td>
<td>10 Hz--1 kHz</td>
<td>&lt;30-60 Hz</td>
<td>Continuous</td>
<td>Omnidirectional</td>
</tr>
<tr>
<td>Decommissioning</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Explosives</td>
<td>272-287 dB Zero-to-peak</td>
<td>2 Hz--1 kHz</td>
<td>6-21 Hz</td>
<td>&lt;1 ms</td>
<td>Omnidirectional</td>
</tr>
</tbody>
</table>

Table 2-15 Overview of E&P industry-related noises, reproduced from [140]

Oil and gas industry anthropogenic noise sources [139] may be broadly defined as coming from aircraft, construction activity, dredging, drilling, explosives used in construction, seismic exploration sound sources, shipping and small vessel noise, sites and production platforms, sonar and general acoustic devices and tools. Some broad information on sound sources found in Table 2-1 of [140].
Section 2 - Detailed Summary of Underwater and Sub-bottom Propagation Models

Table 2-15 notes:

i. The most common sources used for seismic exploration are air guns that produce high levels of low-frequency energy which will penetrate the seabed to considerable depths. They operate by releasing controlled volumes of high pressure air into the water creating an oscillating bubble.

ii. Most of the energy is concentrated below 500 Hz. Surface ducting conditions may enable the higher frequencies (500 – 4000 Hz) to propagate to considerable distances, though source levels in this band tend to be far lower than in the band less than 500 Hz. High frequency broadband transient signals have been observed near the airguns, but are hypothesized to be associated with the mechanical operations of the airguns. They have not been observed in the far field. The upper frequency bound of has been corrected from the original reference.

iii. An air gun array usually contains air gun elements with different volumes, which produce sound pulses with different amplitudes, damping rates and bubble pulse periods.

iv. This variability makes air gun array signature modeling complex and difficult [141]. The received level of air gun pulses depend not only on source-receiver range and on-axis air gun array source level, but also on array beampattern, sound speed profile, bathymetry and bottom properties.

v. A discussion of air gun arrays and signature modeling using AASM (Air gun Array Source Model) can be helpful [46]. A commercially available software package\(^{28}\), called GUNDALF\(^{TM}\), takes into account air gun interactions including non-linarites and interactions between sub-arrays. A number of papers related to air gun use in the Nova Scotia Gully Marine Protected Area were compiled and published in 2005 [142]. And for all types of modern seismic exploration source signature modeling, the model NUCLEUS\(^{29}\) from Petroleum Geo-Services is a popular industry tool.

2.5.2 Sound Exposure Metrics

The most common measures of the acoustic field that are provided by acoustic models are the sound pressure level (SPL) and the transmission loss (TL) which are required to solve the sonar equation for reverberation and signal excess, both important Naval metrics. However, in the evaluation of marine mammal noise exposure to impulsive sounds, several additional metrics are useful [143, 144, 241].

**Peak sound pressure level**, \(SPL_{pk}\), is the maximum of the absolute value of the instantaneous sound pressure \(p(t)\) during a specified time interval at the receiver’s location.

\[
SPL_{pk} = 20 \log_{10} (\max |p(t)|) \text{ dB re 1μPa} \tag{30}
\]

**Peak-to-Peak sound pressure level**, \(SPL_{pk-pk}\), is the difference between the maximum value and the minimum value of the sound pressure impulse \(p(t)\) during a specified time interval at the receiver’s location.

\[
SPL_{pk-pk} = 20 \log_{10} (\max p(t) - \min p(t)) \text{ dB re 1μPa} \tag{31}
\]

\(^{28}\) [www.gundalf.com](http://www.gundalf.com)

\(^{29}\) For articles on the Nucleus model search the web site [www.pgs.com](http://www.pgs.com) for ‘Nucleus’.
Root Mean Squared sound pressure level, $SPL_{rms}$, is the average of the squared pressure over some time window $T$ at the receiver’s location.

$$SPL_{rms} = 10 \log_{10} \left( \frac{1}{T} \int_{0}^{T} p^2(t) \, dt \right) \text{dB re 1μPa}$$  \hspace{1cm} (32)

For air gun pulses, the averaging time is commonly taken to be the approximate duration, $T$, of one pulse, which in turn is commonly assumed to be the time interval within which 90% of the pulse energy arrives. The received rms sound pressure level is typically ~10 dB less than the peak level. Also, because the duration is in the denominator, pulses that are more spread out in time (dispersion caused by multipath) have a lower $SPL_{rms}$ for the same total acoustic energy. The safety and disturbance criteria currently applied to most marine seismic surveys in Canada and the United States are based on the $SPL_{rms}$ metric.

**Duration, $T_{duration}$**, is the length of a sound event (in seconds), above the ambient noise level. A widely used definition is the interval between the 5% and 95% bounds of the time integral of the instantaneous sound pressure squared adjusted for the background noise and low-level reverberation assumed to be continuous. The value of $T_{duration}$ is not constant because the spreading of the pulse is spatially varying.

For example, in Figure 2-27, a broadband signal is sampled and the transfer functions are converted to a time series via an inverse FFT [69]. The figure compares the output versus time and receiver depth from two models. (Left: PROSIM and Right: C-SNAP, both high fidelity models) The signal is spread in time by different amounts depending on the depth of the sample.

![Figure 2-27 Comparison of received time series at 3km from PROSIM and C-SNAP, 100-1000Hz band, 1°up-slope bathymetry [69]](image)

**Sound exposure level, $SEL$**, is the decibel level of the time integral of the squared pressures over the duration of the sound (Erbe, 2011). The units are dB re 1 μPa²·sec, which is proportional to energy flux density for a plane wave propagating in an unbounded medium.
By definition, $SEL = SPL_{rms} + 10 \log_{10}(T_{duration})$. This measures sound energy rather than sound pressure and is commonly equated to sound exposure.

The metric can be used to characterize sounds of differing duration in terms of total energy for purposes of assessing exposure risk, however there is no consensus on how to form this metric and whether it is really the most appropriate one to use. We have found that some exposure modelers use a simple definition of $SPL_{rms}$ by just relying on using the source level expressed as an rms quantity. Others use a more rigorous definition by forming the channel impulse response and convolving it with the source waveform. In addition, the duration can be defined over different times, ranging from hours, days, months, even a year for some applications.

In order to take into account the different hearing capabilities and frequency ranges of different marine mammals, a frequency weighting factor called the M-weighting filtering process is often used. This term shapes the frequency spectrum by emphasizing the sounds most sensitive to the mammals, similar to A-weighted spectra for human hearing. This M-weighting filter is applied to the broadband pressure solutions before Fourier transforming to obtain the received pulse.

**Cumulative sound exposure level, $CSEL$,** is the energy sum of $SEL$'s from multiple individual sound events, assuming there is no recovery between sound impulses.

$CSEL = 10 \log_{10} \left( \sum_{n=1}^{N} \int_{T_n} p_n^2(t) \, dt \right)$

**Sensation level, $SnL$,** is a term that includes the hearing ability of a marine animal. To ‘hear’ a sound, the received SPL must be greater than the animal’s absolute hearing (receiving) threshold, $TH^{\text{re}}$ (a function of frequency). The difference between the received level and the hearing threshold is the sensation level.

**Particle velocity, $u$,** is the speed with which the water molecules move and for free travelling waves is related to the pressure divided by the acoustic impedance, $pc$. Using an electrical analogy, the pressure is the acoustic analog of a voltage and the particle velocity is the analog of the current. While marine mammal sensitivity to particle motion is poorly understood, it does provide another measure of the strength and effect of the acoustic field. However, marine vertebrates, mainly bony fish (including elasmobrancs), sense sound and fluid motion not by acoustic pressure but by particle velocity, through structures called the lateral line, which run along the surface of the animal. As listed in 2.3.3.3, only some acoustic models provide particle velocity as an output variable. It appears to the authors that all exposure regulations pertain only to marine mammals, without reference to species that rely on particle velocity. The authors are not aware of any regulatory standards or exposure metrics relating to particle velocity.

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30 This may also be considered the same as the minimum detectable signal in a sonar receiving system.
Section 3 - Marine Database Survey

Prepared for Joint Oil & Gas Industry Programme (JIP) on Sound and Marine Life

Solicitation Number: JIP 08-08

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Section 3

3 MARINE DATABASE SURVEY

This section contains the results of an extensive, world-wide, survey of the state of in situ data.

These data may be used to support underwater acoustic modeling efforts for assessing the impact of anthropogenic sound on marine animals. These data sets cover all physical properties of the ocean and a wide range of potentially impacted marine species.

![Figure 3-1 Global Marine Databases contain ocean floor definition, bottom properties, water column properties and ocean surface condition.](image)

More specifically, the physical data include:

- The ocean floor definition (shorelines, bathymetry),
- Bottom properties (geophysical, geo-acoustic, reflection, sedimentary history), water column properties (temperature and salinity),
- Ocean surface condition (winds and waves), and
- A few databases, which define the boundaries of marine, protected areas (MPAs) as these may be useful in the planning of exploration and production work near such sensitive areas.

The marine animal data include:

- Marine mammals and several other taxonomic groups that could be impacted by OGP activities, and

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31 Throughout this report, for simplicity, the use of the word 'ocean' should be taken to mean any major ocean basin, sea, or bay.
3.1 Common Database Descriptions and Accessibility

This section provides the definitions of database terminology and database accessibility as used in this report for both the Marine Physical Parameter and Marine Animal database survey.

3.1.1 Database Terminology

The terminology used in this report with respect to the database survey is defined in Table 3-1.

<table>
<thead>
<tr>
<th>Terminology</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Database</td>
<td>An organized collection of <em>in situ</em> marine physical or marine animal data, for a defined geographic region, covering a defined span of time.</td>
</tr>
<tr>
<td>Point of Entry (POE)</td>
<td>A website address (formally known as the universal resource locator, URL) from which one or more databases may be discovered. Points of Entry are identified as ‘Location’ in the database tables of Appendices C and D.</td>
</tr>
<tr>
<td>Portal</td>
<td>A single point of entry with the ability to query multiple databases through a common server. The databases may be stored locally, or may be distributed offsite among several institutions and data providers, connected through intranets or the internet. Portals usually offer some level of search capability of all connected databases.</td>
</tr>
<tr>
<td>Links Page</td>
<td>A point of entry which provides links (URLs) to other Points of Entry, but with no search capability of data at the listed Points of Entry.</td>
</tr>
<tr>
<td>Metadata</td>
<td>An overarching descriptive word. Simply, it is data about the data. Metadata is the “who, what, when and where” of the data. Metadata may include, but is not limited to such information as: the institution or researchers that collected the data, the physical or animal parameters that are recorded, the time the data were collected, the geographic origin of the data, contact information, the ship the data was collected on, the type of sensor, sensor calibration data, and so on. The metadata may, or may not, be attached to a widely accepted or local metadata standard.</td>
</tr>
<tr>
<td>Accessibility</td>
<td>Describes who has permission to obtain data. When permission is granted, data may be obtained by any number of means. Fast means of data acquisition are direct download from a webpage or ftp server. Slower means, though less common these days, may include ordering a Compact-Disc or DVD. The four main categories of accessibility used in this report are shown with their meaning in Table 3-2.</td>
</tr>
<tr>
<td>Availability</td>
<td>Refers to actual obtainability. All databases are considered available except in the following circumstances, and not limited to: database has been decommissioned, database is under maintenance, deployment of database is delayed, database system error, etc.</td>
</tr>
</tbody>
</table>
| *In situ*            | Refers to a parameter whose value is determined by experiment in its natural environment. Examples: temperature, salinity, pH, hydrostatic pressure, less

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32 This section of the report has covered a wide array of marine animals: mammals, reptiles (marine turtles), elasmobranchs (sharks and rays), tuna, and bony fish. Occasionally, marine animals such as polar bears, sea birds, and penguins appear in the data.
commonly direct measurement of sound speed. Another example is that of ambient noise which can be measured in situ.

3.1.2 Database Accessibility

In reference to the Accessibility item in Table 3-1, the sub-categories of Accessibility and their meaning as used in the database survey are provided below in Table 3-2, further elaboration is provided below the table.

<table>
<thead>
<tr>
<th>Accessibility</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open access</td>
<td>Members of the public may immediately obtain/download data for use.</td>
</tr>
<tr>
<td>Controlled access</td>
<td>Members of the public may obtain data after receiving permission (may involve registering with the data provider, membership, etc.)</td>
</tr>
<tr>
<td>Restricted access</td>
<td>Members of the public cannot obtain data.</td>
</tr>
<tr>
<td>Mixed access</td>
<td>Access to data is some combination of the above access types.</td>
</tr>
</tbody>
</table>

**OPEN ACCESS**: A large amount of data is open access. These are often data collected using public funds. The National Oceanographic and Atmospheric Agency (NOAA) in the United States of America (USA) is a good example of such a case. In some cases, for a single data provider, accessibility may vary depending on whether data or metadata are involved. Many databases have open access for their metadata, but controlled access for data. This is a logical policy, as metadata allows the user to discover the appropriate data. Once the correct data is identified, the user can seek permission to obtain the data.

**CONTROLLED ACCESS**: Often found with data providers who wish to know in the first instance who is accessing their data. This is accomplished by requesting some sort of registration. The registrations may request little information other than an email address, or they may request more information including the intended use. Another form of controlled access is due to moratoria on data. Moratoria are often imposed on data when a data owner is planning on publishing research based on that data and therefore require some exclusivity until the results are accepted for publication or actually published. Typical moratorium periods are one to two years.

**RESTRICTED ACCESS**: Common among private companies who have spent a great deal of money in collecting their data for a commercial purpose and for data owned by the military. Occasionally some military data are available. A military may make available a version of the data, which has been superseded by more recent, higher quality, data, or data with some other diminished scope.

**MIXED ACCESS**: Mixed access is common on many large portals or databases. Large databases and portals serve many data collectors and clients. Therefore not all data available through these points of entry will be under a common data access policy.

It should be emphasized that if a database is categorized as open access it does not necessarily allow the user to utilize those data free of all restrictions.  

33 Users of any database must ensure to check for any ‘terms of use’ attached to the database as restrictions may apply (e.g. the difference between public and commercial use). Furthermore, the dataset owner may wish to have the reference to the data stated in a specific manner. Some databases require user registration. Databases may contain caveats and warnings that the users should be aware of. For example, typically, databases or data atlases
3.2 Marine Physical Parameter Databases (Reference: Appendix C)

In this section a discussion of the format and content of the marine physical data database listing (Appendix C) is presented. This section also contains summary discussions of the physical parameter databases.

The list of databases provided in the appendices was valid as of the third quarter of 2013. No guarantee can be given that these links or databases will be maintained or visible thereafter. This may occur for several reasons such as merging with another database, losses of funding, closure of an institution, or a rare catastrophic failure. Conversely, new databases may appear, and are likely to disappear, as time progresses.

Because of complex data sharing and data-mirroring relationships between some large organizations, it was beyond the scope of this study to determine whether all the points of entry provide access to truly unique data. For example, some fraction of seabed data from the Scripps Institution of Oceanography (Scripps) may appear on their data servers, and in the National Geophysical Data Centre (NGDC). There are often delays in getting data from the primary providers of data (e.g. Scripps) to larger aggregators (e.g. NDGC), so it can be worth checking both points of entry for the complete picture.

3.2.1 Acoustic Modeling Parameters

When an investigator is tasked with performing a modeling exercise in a specified region the modeler will not need to digest the global scope of available data, but will need to seek all potentially relevant data for that particular region. Physical data are immediately relevant if they directly provide the quantitative values sought for use in an acoustic model, such as water temperature and salinity (or more directly, sound speed). When quantitative physical data are unavailable, descriptive data (noun, adjective) or illustrative data (imagery) are relevant since the quantitative data may be inferred (with increased uncertainty). An example of this may be when sediment density is unknown, or sediment grain size is unknown, but the sediment type ('sand', 'mud', etc.) is known, which may be converted through the use of look up tables from vetted sources.

Therefore, a wide variety of descriptive data parameters were admitted into the database search. Table 3-5 (below) indicates the physical data parameters relevant to acoustic modeling that were sought during the survey.

are not recommended for navigational purposes. Not all data are guaranteed to be free of errors or have been through a full quality control process. Users must check these policies, warnings, and other qualifiers as may occur and ensure they adhere to them. Once it is established that permission to use the data is granted the users of this data must also adhere to providing a citation to that data in accordance with the citation policy or example set by the data owner or institution.
3.2.1.1 Database Tables - Presentation and Organization

The marine physical parameter survey data are provided in a large table in Appendix C. To describe the table layout and the information contained within its rows, Table 3-3 presents a sample row from Appendix C. Each database, or point of entry, is described in two table columns. Note that each point of entry in the table is sequentially numbered. As necessary, these numbers are cross-referenced in other table points of entry. Insofar as possible the table entries are organized into blocks corresponding either to major institutions or geographic areas, e.g. NOAA, Asia, Mediterranean, etc.

Table 3-3 Sample row, Entry 4 of Table C.2 from Appendix C, Marine Physical databases

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter coverage: temperature and salinity profiles</td>
<td>Accessibility: open access</td>
</tr>
<tr>
<td>Meta: #tprofile, #sprofile, #global, #access_open, #dailyweekly, #current</td>
<td>Area coverage: global</td>
</tr>
<tr>
<td>Search capability: graphic interface, menu</td>
<td>Updates: to present, daily</td>
</tr>
<tr>
<td>Summary: Access to Argo float data has undergone the automated quality assurance procedures that are carried out by the U.S. NODC. The data are in NODC versions of ASCII text and NetCDF formats. Argo are data viewable through Google Earth™ via the Keyhole Markup Language (KML). Argo KML files are distributed as KMZ files, which are zipped KML files with a .kmz extension.</td>
<td></td>
</tr>
</tbody>
</table>

3.2.1.2 Marine Physical Databases - Table Entries

Using Table 3-3 as an example, the first column indicates the name of the database, and the database key owner or sponsor(s) in parentheses. The second column contains a list of properties for which information was sought during the search phase. These properties and their description are provided in Table 3-4. For key database properties metadata are assigned. The breakdown of the metadata for each property in Table 3-4 is described in detail in Table 3-5. A metadata item, or tag, is preceded by a ‘#’ mark.

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34 Following the entry number is the Point of Entry or database name (if it is 'named'), or, if there is no obvious name, a relevant moniker based on the major organization or major geographic region which hosts the data is used. In the example shown in Table 3-3 the database is the Global Argo Data Repository. Below the name the custodian of the point of entry is given in parentheses, in this case the National Oceanographic and Atmospheric Administration (NOAA), and its affiliate the National Oceanographic Data Center (NODC).
### Table 3-4 Description of marine physical database properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Provides a web link to the Point of Entry</td>
</tr>
<tr>
<td>Accessibility</td>
<td>Refers to the type of access as described in Section 3.1, in this case it has open access.</td>
</tr>
<tr>
<td>Parameter coverage</td>
<td>Lists the types of data the database contains, such as temperature and salinity profiles in the example above.</td>
</tr>
<tr>
<td>Meta</td>
<td>Provides the metadata keywords with a hash-tag (“#”). This facilitates parameter searches over all the entries in the table, and also facilitates the acquisition of metrics from the database table.</td>
</tr>
<tr>
<td></td>
<td>For example, one could search the Appendix C for all entries containing the words #tprofile, #sprofile, and this entry would be found (as well as any other points of entry with these metadata keywords).</td>
</tr>
<tr>
<td>Area coverage</td>
<td>Describes the regional span of the database, in the example, above, it is global. Global is used in this survey to indicate that data are accepted into the database from any location of Earth. However, it does not guarantee that coverage is complete, or that high data densities exist on the whole Earth. Points of entry that are not tagged with metadata keyword #global are considered to be “regional”. A region may be highly localized or may refer to one or two ocean basins, for example.</td>
</tr>
<tr>
<td>Search capability</td>
<td>Refers to the type of interface available to peruse the database. The entries can include interactive interfaces, customized search interfaces, tables, textual, or no search capability. In the example above, there are two search capabilities: and interactive map interface and a menu based search.</td>
</tr>
<tr>
<td>Updates</td>
<td>Provides two indications with respect to how relevant, temporally, the data are. The first is an estimate of the update period, i.e. approximately how often data are pushed to the database(s). Highly operational databases may be updated hourly, daily, or weekly. Points of entry within these update periods are tagged with metadata #dailyweekly. The second indication is an estimate (or better), of when data was last pushed to the database. The survey of databases in this study was concluded in late 2013. All data ‘last data’ from 2013 were tagged with metadata ‘current’. Data collected prior to 2013 were tagged with the metadata tag #before2013. Note, in some cases that data recently pushed to the database may have been under moratorium, and may have been collected one or more years prior to the present. For many databases determining exactly how old the most recent data are can be very laborious. In all cases, the best estimate was provided.</td>
</tr>
<tr>
<td>Summary</td>
<td>Provides additional narrative information of the point of entry or database. Much of this text is taken from the database description text provided by the data custodian.</td>
</tr>
</tbody>
</table>
### Table 3-5 Metadata description for marine physical parameter points of entry and databases

<table>
<thead>
<tr>
<th>Property</th>
<th>Metadata label (#) and description</th>
</tr>
</thead>
<tbody>
<tr>
<td>POE Type</td>
<td>#portal-links: if the point-of-entry (POE, i.e. web URL) is a portal or a links page</td>
</tr>
</tbody>
</table>
| Physical Parameters | #tprofile : vertical temperature profiles  
#sprofile : vertical salinity profiles  
#ice : ice coverage, ice thickness  
#wave : ocean surface wave data, ocean surface wind data  
#bathy : bathymetry  
#geodesc : geological or geophysical data which is descriptive  
#geophys : geophysical data  
#geoacoust : geoacoustic data  
#ssp : sound speed profile  
#sst : sea surface temperature  
#sss : sea surface salinity  
#sat : data acquired by satellite  
#timeseries : data recorded as time series  
#noise : data collected from underwater listening sensors  
#boundary : data which defines a legal boundary (state, national, protected areas, shorelines, etc.)  
#atlas : data which are presented pictorially over a geographic area  
#software : indicates that the point of entry leads to software, not necessarily a ‘database’  
#params_notdetermined : the parameters could not be discovered (e.g. language problem) |
| Coverage          | #global (if global; otherwise “regional” and no metadata) |
| Accessibility     | #access_open, #access_controlled, #access_mixed, #access_restricted, #access_notdetermined : As described in Table 3-2. |
| Update period     | #dailyweekly : Updated frequently, hourly, daily, or within one week.  
#monthly : Updated approximately once each month (1-2 months)  
#quarterly : Updated approximately once each quarter (3-6 months)  
#annual : Updated approximately once each year (7-12 months)  
#archive : Updates no longer occurring  
#update_notdetermined : Update period could not be determined |
| Last update       | #before2013 : Data were last pushed to the point of entry database(s) prior to 2013  
#current : Data were last pushed to the point of entry database(s) in 2013  
#last_notdetermined : Date of last update could not be determined |
3.2.1.3 Enumeration of Database Survey Findings

To summarize the snapshot of the databases listed in Appendix C, an enumeration of the findings, showing the number of points-of-entry that have been located for each metadata tag, is provided in Table 3-6.

**Table 3-6 Summary table for Appendix C, Table C.2. Numbers of entries for each metadata label (search tags are shown with the # symbol)**

<table>
<thead>
<tr>
<th>Topic</th>
<th>No. of POE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Points of Entry (POE) in Appendix C, Table C.2</td>
<td>168</td>
</tr>
<tr>
<td>#portal-links</td>
<td>54</td>
</tr>
<tr>
<td>#global</td>
<td>64</td>
</tr>
<tr>
<td><strong>Data Physical Properties</strong></td>
<td></td>
</tr>
<tr>
<td>Sea surface properties (#sst, #sss, #wave, #ice, #sat)</td>
<td></td>
</tr>
<tr>
<td>SST:</td>
<td>44</td>
</tr>
<tr>
<td>SSS:</td>
<td>14</td>
</tr>
<tr>
<td>Wave or wind:</td>
<td>49</td>
</tr>
<tr>
<td>Ice:</td>
<td>26</td>
</tr>
<tr>
<td>No. of POE with vertical profile data (#tprofile, #sprofile, #ssp)</td>
<td></td>
</tr>
<tr>
<td>Temperature:</td>
<td>81</td>
</tr>
<tr>
<td>Salinity:</td>
<td>80</td>
</tr>
<tr>
<td>SSP:</td>
<td>7</td>
</tr>
<tr>
<td>POE with seabed properties #bathy, #geodesc, #geophys, #geoacoust</td>
<td></td>
</tr>
<tr>
<td>bathy:</td>
<td>62</td>
</tr>
<tr>
<td>geodesc:</td>
<td>60</td>
</tr>
<tr>
<td>geophys:</td>
<td>25</td>
</tr>
<tr>
<td>geoacoust:</td>
<td>4</td>
</tr>
<tr>
<td>#noise</td>
<td>Noise: 6</td>
</tr>
<tr>
<td>#timeseries</td>
<td>39</td>
</tr>
<tr>
<td>#sat</td>
<td>30</td>
</tr>
<tr>
<td>#atlas</td>
<td>30</td>
</tr>
<tr>
<td>#boundary</td>
<td>13</td>
</tr>
<tr>
<td>#software</td>
<td>3</td>
</tr>
<tr>
<td><strong>Update period</strong></td>
<td></td>
</tr>
<tr>
<td>#dailyweekly</td>
<td>55</td>
</tr>
<tr>
<td>#monthly</td>
<td>38</td>
</tr>
<tr>
<td>#quarterly</td>
<td>14</td>
</tr>
<tr>
<td>#annual</td>
<td>32</td>
</tr>
<tr>
<td>#archive</td>
<td>39</td>
</tr>
<tr>
<td>#update_notdetermined</td>
<td>9</td>
</tr>
<tr>
<td><strong>Last database update</strong></td>
<td></td>
</tr>
<tr>
<td>#current</td>
<td>118</td>
</tr>
<tr>
<td>#before2013</td>
<td>50</td>
</tr>
<tr>
<td>#last_notdetermined</td>
<td>8</td>
</tr>
</tbody>
</table>
These findings are also displayed in a bar plot, Figure 3-2, and pie charts, Figure 3-3, that display the relative distribution of findings for global and regional coverage, update period, last data update, and accessibility.

In Figure 3-2, the data are sorted from left to right in descending order to illustrate the relative abundance of the parameter coverage found in the database ‘snapshot’ taken during this survey.
Figure 3-3 provides four pie charts indicating the relative proportions of selected metadata metrics for physical parameter databases and points-of-entry, Table C.2, Appendix C.

The top-left pie chart indicates when the database was last updated, and the bottom-left pie chart indicates how often the database is updated. Together, these two pie charts indicate some measure of database health. That is, are they abandoned, have they become archives, are data managers still actively maintaining the databases, is the data in this database relevant, is it likely to be around tomorrow, next year? The top right pie chart shows the geographic distribution of data, and the bottom right pie chart indicates the accessibility of the data.

As a general rule, all data categories are well represented, or better represented, inside a country’s exclusive economic zone (EEZ), as each country assesses their own natural resources (fisheries, oil and gas) through oceanographic and geologic research, showing relative numbers of information in Appendix C.
The main conclusions drawn from these figures are as follows:

- A large proportion (67%) of the marine physical parameter databases are current (updated within the study year).
- A large proportion (50%) of the marine physical parameter databases are updated frequently (daily to monthly).
- A large proportion (60%) of the marine physical parameter databases covers regional interests. Regional being defined as ‘very local’ to a particular ocean basin.
- A smaller, though significant proportion (40%) of the marine physical parameter databases contain data, which is sourced globally. Note, this does not always guarantee the data are well distributed over the globe.
- A very large proportion (80%) of the data is either full open access or controlled access, or mixed access.
- Industry and military data are, as expected, difficult to assess and are restricted access.

Databases that are both current and updated frequently are mostly associated with operational activities, though many databases are updated frequently with data that was collected long before being pushed to the database. Several database managers reported the delay between data collection and accessibility can vary widely from days to several years depending upon processing backlogs, moratoria, and any proprietary issues.

3.2.2 Physical Parameter Data Discussion

3.2.2.1 Data Gaps

Despite the lower values beyond ‘Geophysical,’ (Figure 3-2) the most serious data gap is primarily confined to geoacoustic data. While sound speed profile data are not in abundance, vertical temperature and salinity profile data in the water column are in abundance, tempering this apparent deficiency.

Not shown, as no databases were found, were transmission loss databases (that were comprehensive enough to catalog). However, these would only be sufficient for hindcasts, and with shifting climate these data, as well as any archived data, would be highly suspect in acoustic prediction work if accuracy is of key concern. Moreover, the odds are very low that transmission loss radial paths would match the bathymetry of current prediction scenarios. The authors, therefore, do not lament this lack of transmission loss data.

3.2.2.2 Vertical Profile Data

Less abundant are databases of measured or computed sound speed profiles (6 instances, meta: #ssp). In general vertical profile data, primarily temperature and salinity, are in abundance for the acoustic modeler. This is demonstrated by the approximately 80 discovered databases in the survey.35 From these two parameters the sound speed profile may be computed.

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35 Appendix C, Meta: #tprofile, #sprofile.
3.2.2.2.1 ARGO Vertical Datasets

One of the greatest additions to the vertical sampling of the oceans has been the international Argo program.  

Argo is comprised of approximately 3600 robotic floats (Figure 3-4 & Figure 3-5) which drift with the current and sample the top 2000 m of the ocean, and then relay the data via satellite to receiving stations and regional data centers. As described by Freeland et al. [145] for each float this occurs every ten days. This provides near real-time data for recently sampled positions, and this data is openly and immediately available for download by users, free of charge.

Currently, a float in the Argo inventory produces a new profile approximately every four minutes (11,000 per month), and in November of 2012 the one-millionth profile was measured. In comparison with the World Ocean Database, Argo is providing considerably more data and better coverage both spatially and seasonally (almost 50/50 split summer to winter). Notable Argo data gaps include the Arctic Ocean and the Canadian Archipelago, Hudson Bay, the Kuroshio Current region close to Japan and the northern North Atlantic. Within five years it is expected that some groups will deploy floats that will sample up to approximately 6000 m depth.

When taken at face value it would appear that the Argo program has solved all of the modelers’ demands for vertical profile data. Despite the immense amount and rate of data accumulation, and spatial temporal coverage offered by the Argo float program, a problem for acoustic modelers’ remains. That is, ideally, range dependent acoustic models require vertical profile data along particular map transects, preferably sampled within hours of each other, or days at worst. The Argo floats are at the mercy of ocean currents, and occasionally winds. In the best case the Argo repository may provide data, if lucky, along or near required modeling transects. However, the age of

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36 www.argo.net; see entries Appendix C, entries 4, 38, 74, 75, 148.
37 http://en.wikipedia.org/wiki/Argo_(oceanography)
each profile data could be random and uncorrelated with the snapshot of local conditions being attempted by the modeler (see Figure 3-5, for the Operational Cycle example).

It remains with the modeler to seek the most spatially and temporally coherent, and recent, set of vertical profile data from whatever the best sources are. Other data at higher resolutions are available but will tend to be more regional.

These sources may be from surveys directly associated with the industry and modeling activity, or from nearby academic research programs. Resources such as the World Ocean Database are more suited to 'acoustic climatology' as these data are very stale for practical purposes. Archival data should only be used in the most desperate of circumstances.

Figure 3-5 Normal Float Operational Cycle

http://www.argo.ucsd.edu/
### 3.2.2.3 Bathymetry

The quality and coverage of bathymetric data has never been so good for the acoustic modelers. Hydrographic surveys and methods are improving allowing large governmental and international organizations to continually improve the data sets.

The database survey indicates 62 found points of entry that contained bathymetric data from a variety of instruments (Appendix C, Meta: #bathy).

The best single set of global bathymetric data is the recent SRTM30Plus data (entry 42). SRTM30 resolution is 30 arc seconds, or approximately 1 kilometer. This data set now includes the Arctic. Bathymetric data from other methods such as multibeam surveys offer much higher resolution, but over much smaller areas. However, one may surmise that these areas are also areas of relative importance and so these data sources should be sought whenever possible. When high-resolution data cannot be found, then this data gap needs to be populated by acquiring new data.

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**As a rule of thumb for acoustic modelers, the desired bathymetric resolution required for an accurate range dependent modeling run should be on the order of a half wavelength.**

For propagation predictions over long ranges, tens of kilometers, SRTM30 data at 1 km resolution may suffice to capture the basic propagation features due to bottom slopes and gross features less than 2 km to 3 km in extent.

For propagation predictions in more confined regions, such as coastal waters, inlets, bays, and straits where the subtle bottom bathymetry may affect the propagation of sound, higher resolution data (e.g. multibeam bathymetry) should be sought by the modeler. These regions tend to be under resolved by measurement techniques designed to cover larger range scales (e.g. SRTM30). It is reasonable to assume that if high-resolution data do not already exist for a particular region, they will not be gathered at the request of acoustic modelers.

### 3.2.2.4 Bottom Properties

The bottom property data have been divided into three categories: geo-descriptive, geophysical, and geoacoustic.

These are each described, below.

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39 Shuttle Radar Topography Mission (SRTM)
3.2.2.4.1 *Geo-descriptive Data*

Geo-descriptive data provides qualitative information about the ocean bottom. In Appendix C, these data are found using the metadata tag #geodesc. Acoustic models do not readily ingest these data. These data include:

- Noun descriptors bottom type (texture: gravel, sand, mud, clay, rock; hard, soft, etc.)
- Folk codes
- Sea floor features (ripples, smooth, rocky, etc.)
- Geological history (geological era, rock lithology; core samples, sediment grabs)
- Habitat characteristics (often related to benthic flora and fauna)
- Sonar reflection and scattering data (could be digital or analog image data, charts with estimated reflection and scattering parameters/bottom roughness; seismic layering)

Due to the myriad ways in which the seabed can be measured and described, there is an abundance of descriptive geological data (60 entries in Table C.2). Seafloor descriptions may assist in determining mitigation strategies based on the marine fauna that are in an area due to specific benthic habitats, but that is outside the scope of the acoustic model input. Using information from the above types of data may assist in providing lower and upper bounds on seabed physical or seabed acoustic parameters when no other data are available.

However this is not sufficient for accurate acoustic modeling. These types of data should be used only in the last resort, or as a cross reference to a more trusted geophysical or geoacoustic data. It is useful to have overlapping geo-descriptive and geophysical data to assist in correlation in going from geo-descriptive to geoacoustic data.

3.2.2.4.2 *Geophysical data*

Geophysical data provides quantitative numerical information about all ocean bottom physical parameters, which are not specific to acoustics. From these data geoacoustic *models* can be employed to *infer* geoacoustic parameters such as compressional and shear sound speeds, and absorptive losses in the ocean bottom. In Appendix C these data are found using the metadata tag #geophys.

These data include:

- Grain size (and grain size distribution, grain size fractions)
- Porosity
- Density
- Sediment thickness
- Surface roughness
- Log shear strength

Database Library: In this point-of-entry/database snapshot:

- Twenty-five (25) databases (or points of entry) were found to provide geophysical data,
- With ten (10) of these found to have some degree of global (#global) scope entries: 13 (Trackline Survey), 18 (Global Sediment Thickness), 27 (Sediment Grain Size), 65 (via IEDA), 66
This leaves fifteen (15) databases of geophysical parameters, which are regional in scope (e.g. a particular coastline, sea, bay, etc.).

Due to the large deficiency in readily available geoacoustic data, it is in situ geophysical data that will be sought after the most for ingestion into acoustic models for modeling the bottom interaction.

Coverage is generally good, but as for vertical profile data (see above), the position associated with any actual datum may be not on the acoustic path, or the sampling is likely to be coarse with large inter-datum distances. Regional databases, as may lie inside an EEZ, may provide a higher data density and greater probability of providing data along, or near, acoustic propagation radials. Gaps in in situ data can only filled by comprehensive, and very expensive, physical sampling programs. Gaps are not likely to be filled any time soon without directed investments. Depending on the geophysical gradients between existing data, the modeler may be able to interpolate values along the propagation radial, and this is what is most often done now, out of necessity.

For seeking data in global databases, the NOAA/NGDC databases (entries 13, 18, 27) are excellent starting points. The BST database (Appendix C, Table C.3, entry 1) found in the public domain version of OAML database may also be of use. Otherwise, modelers should interrogate the regional databases.

3.2.2.4.3 Geoacoustic data

Geoacoustic data provides quantitative numerical information about all ocean bottom acoustical parameters. Ideally these data are measured in situ and their values can be ingested directly into acoustic models for determining propagation in the ocean bottom. 40

In Appendix C these data are found using the metadata tag #geoacoust. These data include: 41

- Bulk density (note, there is overlap with #geophys on this parameter)
- Speed of sound – compressional waves (P-Wave velocity)
- Speed of sound – shear waves
- Attenuation of sound – compressional waves
- Attenuation of sound – shear waves

In Table C.2 only four (4) geoacoustic databases were found during a search of non-naval databases (entries: 26, Drill Logs; 50, Sediment Texture Data; 53, usSEABED; and 163, Marine Sediment database and Australian Marine Spatial Information System).

40 As described by Bachman, Schey, Booth, & Ryan, 1996 [146] “A geoacoustic model is a tabulation of the acoustic properties of the seabed from the seafloor down to, and including, acoustic basement. These properties are compressional and shear wave speeds and attenuations, and density...”

41 Overall the availability and accessibility of geoacoustic data is very poor, as demonstrated in the database landscape snapshot captured from Table C.2 and summarized in Table 3-6.
Only table entry 26, the Drill Log database reports both global coverage (“global,” however does not necessarily mean high spatial density) open data access, as well as having frequent (monthly) data updates, and current as of 2013. The four databases are listed in Table 3-7, below.

Table 3-7 Listing of databases from Table C.2 containing geoacoustic data

<table>
<thead>
<tr>
<th>Table C.2 Entry</th>
<th>Metadata</th>
</tr>
</thead>
</table>
| 26              | Drill Log database  
#geodesc, #geoacoust, #global, #access_open, #monthly, #current |
| 49              | WHOI Archives – Sediment Texture Data  
#geoacoust, #access_open, #archive, #before2013 |
| 53              | usSEABED (U.S. coastal)  
#geoacoust, #access_open, #archive, #before2013 |
| 163             | Marine Sediment database and Australian Marine Spatial Information System (Australian waters only)  
#geoacoust, #atlas, #access_mixed, #quarterly, #current |

Table C.3 of Appendix C lists a selection of naval databases. While naval acoustic databases are more likely to contain geoacoustic data, however, access to data may pose problems as the best data tend to be classified.

The relative lack of geoacoustic databases should not be surprising. No truly *in situ* geoacoustic databases were found. *In situ* measurements can be found, however these tend to be individual studies captured in journal publications.

All geoacoustic data found in databases with any significant area coverage are derived from other *in situ* measurements, such from physical sampling techniques (such as cores and grabs) which are analyzed for geophysical properties, or from seabed acoustic reflection measurements. However, these sampling techniques are insufficient for the properties of deeper sediment layers, which become more important as the frequency decreases, offering deeper penetration of the acoustic energy. These measured properties, or acoustic responses, are then used as inputs to numerical empirical or theoretical physical models, which yield estimates of the geoacoustic parameters.

There is an enormous amount of literature for describing and modeling the relationships between the sediment physical properties, or acoustic response and the geoacoustic parameters.

In many instances the relationship between geophysical parameters and geoacoustic parameters is sufficient, but there are many caveats, as illustrated by the following abstract from a well-respected underwater acoustics institution (underlines by the present authors):

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42 See for example [146-149, 224] reports and dissertations, but not in databases with any appreciable geographic coverage. More recent work for *in situ* proposals and techniques are found in [150-152].

43 [153-156]
"The usefulness of environmental databases (bathymetry, sound-speed profile and bottom reflectivity) for sonar performance predictions in high-variability littoral waters has often been questioned. Thus it is conceivable that spatial and temporal averaging of sparsely sampled data could result in data holdings which do not capture some of the acoustically important environmental features required for accurate sonar predictions.

To address this issue on a larger geographical scale, SACLANTCEN has undertaken a study using the Allied Environmental Support System (AESS) as the prediction tool and the NATO Standard Oceanographic Data Base (NSODB) as the environmental representation. To quantify prediction errors in selected shallow-water areas as a function of bottom type, water depth, season, frequency, sonar/target depth, etc., SACLANTCEN's vast broadband transmission-loss database established over the past 30 years has been used as ground truth. Results from the Barents Sea, the Norwegian Shelf, the Iceland-Faeroe Ridge, the Baltic Sea, the English Channel and the Mediterranean Sea indicate that databank-based performance predictions in shallow water are indeed unreliable and that the weakest link is the bottom-loss information."[157]

In summary, it is unlikely that open access geoacoustic data will be present on a frequent basis, or with significant coverage. When available, the authors recommend using geoacoustic data with caution, taking care to understand the precise conditions (frequency, method, etc.) these data were collected under to ensure relevance to the present case being modeled. Otherwise, modelers must convert geophysical data, or acoustic reflection data, to corresponding geoacoustic parameters (if this is what the model requires) through the use of equations, models, and methods currently accepted by the scientific community.

For expediency, the Bottom Sediment Type database, BST V2.0, available from the OAML database (see Table C.3, entry 1) may provide adequate data and coverage.

3.2.2.5 Wind and Surface Wave

Of the 166 points of entry catalogued in the table of Appendix C (Table C.2), 49 of them contain data on either wind speed or surface wave height (Appendix C, meta: #wave). Obtaining data on the condition of the sea surface is generally not difficult at this time due to the large number of satellite observations, which are available.

Presently, the entire globe is covered by measurements of sea surface wind (which may be correlated to the wave statistics through empirical models not strictly in situ) or direct in situ measurement of surface waves by physical buoys. Sea surface data generally cover all seasons.

Of all the input parameters to acoustic models the sea surface description exhibits the highest variability in both space and time, owing to the vagaries of the local weather.
wave data should be considered 'historical' and therefore quite stale as the sea state can change within a matter of hours.

Examples of major databases (or providers) of satellite wind and wave data with global coverage include the:

- STAR,
- Global Observing Systems Information Center (GOSIC),
- Physical Oceanography Distributed Active Archive Center,
- Computational and Information Systems Laboratory (PO.DAAC),
- MyOcean,
- Centre ERS d’Archivage et de Traitement - ERS Processing and Archiving Facility (CERSAT),
- Earthnet Online (ESA), and
- British Oceanographic Data Centre and (entries 23, 40, 43, 93, 95, 97, and 120, Appendix C, respectively).

Coastal areas and exclusive economic zones (EEZ) tend to be better sampled due to the increased shipping and commercial activity in those waters. A majority of regional or national organizations deploy wave measuring buoys or calibrated coastal radar with near real time wave statistics data available.

Examples of major databases (or providers) in the U.S. are:

- NOAA (many entries within Appendix C), notably the Marine Environmental Buoy Database,
- Center for Operational Oceanographic Products and Services,
- National Data Buoy Center, Gulf Atlas, Asia-Pacific Data-Research Center (APDRC),
- IOOS US Data Portal (entries 3, 29, 30, 36, 57, 63, respectively).

European providers include:

- SeaDataNet,
- EMODNet,
- Mediterranean Marine Data,
- Iberia, Biscay, Ireland – Regional Operational Oceanographic System,
- BSH Marine Data, Baltic Sea Portal,
- Northwest European Shelf Operational Oceanographic System,
- Flemish Marine Data and Information Centre Portal (entries 84, 85, 86, 92, 99, 101, 102, and 108, respectively), and several others.

For current sea surface wave conditions, as could be useful for near real-time ground-truthing during at-sea activities, local forecasting organizations in developed nations provide hourly to daily marine forecasts for their marine regions (or may be estimated visually, though this will be subjective). Use of current meteorological data will prevent the use of stale data in these circumstances.  

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44 For planning purposes wave data may be estimated by utilizing wave atlases (e.g. Baltic Sea Portal, entry 101; Marine Data Online, entry 114; Canadian wave data, entries 133 and 134), or numerous other sources of archived wave data, such as may be held by many of the NOAA organizations. Suffice it to say, as for bathymetry, these data are becoming easier to obtain and they are highly accurate.
In scenarios where the acoustic propagation interacts with the sea bottom, uncertainties in the sea bottom properties will affect the acoustic propagation outcome much more than uncertainty in sea surface losses. An exception may be high frequency sonars that are interacting with the surface, in which case the surface effects may well dominate the losses. In cases of extreme weather, it may be assumed that wave height may restrict marine operations and therefore negate the necessity for modeling in this scenario.

### 3.2.2.6 Ice Cover

Acoustic modeling scenarios in the Arctic, Antarctic, marginal ice zones, and seas with annual ice cover are likely the most rare.

Nonetheless, acoustic predictions may be required as natural resource development opens up in sea ice zones. Depending upon the needs of industry in higher latitude ice-laden waters, acoustic models may be forced to include ice on the upper boundary condition of the acoustic channel.

The need to monitor high latitude regions of the world for ice presence and ice cover is driven by weather prediction, climate change research and monitoring and also for the navigational warnings and advice for mariners.

For these reasons alone it is quite easy to source ice cover data through the internet (Appendix C, Meta: #ice). A total of 26 points of entry were found to provide access to ice cover information. Much of the data is now sourced from polar satellites. Some of the best sources appear to be in the U.S.:

- GOSIC, PO.DAAC, and the NSIDC (entries 40, 43, and 45, Appendix C, respectively),
- The National Snow and Ice Data Center, entry 45, is very good, covering north and south polar sea regions. The information provided includes: sea ice charts, sea ice drift and velocity, sea ice concentration and extent, sea ice thickness, sea ice age, and others from ships, buoys, upward-looking sonar, and manned research stations,
- For NE Asian marginal seas, charts are available from the NEAR-GOOS Program (entry 143, Appendix C), and operational Arctic and regional data from Russia are available (entry 146, Appendix C),
- European ice data, in the form of charts, may be sourced from the Baltic Operational Oceanographic System (entry 107, Appendix C), and
- Arctic Regional Ocean Observing System (entry 109, Appendix C).

With commercial shipping being so vital, and with high-latitude coverage by satellites being so complete, there are few, if any, data gaps for sea ice location. Sea ice thickness is also now being measured by satellite. However, the capability of most acoustic models to handle sea ice remains an issue.
Moreover, non-fast ice will drift, making this solid upper boundary time varying and difficult to model. Ice keel depth and orientation should also be incorporated, though acquiring these data with sufficient resolution for the frequency range being modeled remains a challenge. Statistical techniques may be useful in these cases depending on the modeling scenario.

3.2.2.7 Satellite Data

Satellite data are found in Table C.2 using the metatag #sat. Thirty databases or points of entry were found to contain satellite data.

Satellite data are not in situ – they are derived from various models of electromagnetic spectrum reflection and backscatter.

However, these techniques have become sophisticated and the data can be useful for many purposes. Satellite data for ocean surface features is not normally imported directly into acoustic core models as a dataset. For example, when temperature and salinity profiles exist, the datum at the top of the water column is used from the profile data, not from a satellite data source.

It is recommended that sea surface temperature (Appendix C, Meta: #SST) maps, and sea surface salinity (Appendix C, Meta: #SSS) maps, be used to identify ocean fronts that may cross-modeling boundaries.

For all intents and purposes there are no geographical data gaps in the areas most likely to be required in acoustic modeling. Global SST and SSS are available, daily, from a variety of sources and should be consulted in areas prone to oceanographic fronts or high spatial contrast in any of the marine physical parameters.

3.2.2.8 Ocean Ambient Noise

In post processing, ocean ambient noise levels may be employed with the output of propagation models in order assist in passive acoustic monitoring, or in determining noise-limited ranges when making predictions for active acoustic monitoring, of marine species. Ambient noise data are in very limited supply; this is corroborated by investigators more familiar than the authors with the state of ambient noise research and data [158].

From the summary of Table C.2, our snapshot of database findings indicates only six (6) noise databases (Meta: #noise).

- Three of the six contain in situ data; the remaining database (Cetsound & SoundMapping, entry 41) is comprised of calculated noise levels (annual average).
It is well understood that there are more noise data sets, many exists in universities, navy labs and local hard-drives/servers. All the in situ databases appear to be region specific, the largest region found was the Baltic, and the others sampled the west coast of Canada. Finally, investigators may find data that are band-averaged (e.g. 1/3-octave bands) or frequency limited.

For the Cetsound & SoundMapping database, the noise estimates are based on the spatial distribution and density of oceanic vessel traffic, and GoMEx seismic surveys in the case of the Gulf of Mexico. Presently, Cetsound provide preliminary mapping products as images with the goal of making the underlying data available in subsequent releases. The data used to represent the average annual geospatial distribution of large commercial ships (specifically cargo ships and tankers >500 GT) derive from the World Meteorological Organization Voluntary Observing Ships Scheme (VOS). The specific data applied were collected from Oct 2004 to Sept 2005 [159].

The respected monograph by Etter [9] provides a listing of noise databases (e.g. SNHR, SNLR), however none of these could be found or accessed via the World Wide Web. Moreover, these databases are owned by the U.S. Navy, and therefore have restricted access (for example, the noise data in OAML, Table C.3 entry 1, are not available for public use).45

3.2.2.8.1 Noise Data Gaps

The National Research Council [124] noted that a major gap in existing noise databases is that no long-term (greater than a decade), systematically collected, ocean acoustic data set exists for any frequency band. Such an effort could supplement the ambient noise data sets that formed the basis of the empirical curves in widespread use (see Wenz [160] and Knuldsen [161] & Hildbrand [162]). Also concurs with this gap's existence.

In 2009, Hildebrand noted many gaps in the noise data. He indicated that more information is needed on surface ship noise spectra which should include frequency content, pressure time series, duration, repetition rate, directionality, etc. Furthermore, vessel noise measurements are within the frequency range of marine mammal echolocation (1 kHz to 100 kHz).

One of the gaps mentioned was that research should be conducted on how the level of anthropogenic activity (such as the types and numbers of vessels) is related to resulting noise levels (this has recently been partially addressed by Frisk [163]. Frisk demonstrated that observed ambient noise level increases over 1950-2007 are primarily attributable to commercial shipping activity, in the frequency band 25 Hz – 50 Hz, through the world fleet gross tonnage (which, over this period, is related to the world GDP).

Hildebrand suggests that better data are needed on noise source locations (surface ship geographic distributions) and that track lines for seismic profiling can be used. He also thinks that in regions with high source concentrations, physical environmental data, including local winds and wind-wave noise spectra, are needed to permit more accurate modeling of the relative contribution of anthropogenic noise and natural noise sources. For acoustic modelers, when ambient data cannot be found easily, the scientific literature may be surveyed for individual studies where the respective researchers hold that

45 It is reported (National Research Council, 2003, p. 125) [124] that NOAA’s Pacific Marine Environmental Laboratory (PMEL) Acoustic Program collects data from the SOSUS (Sound Surveillance System) data off the coast of the State of Washington since 1991, but neither metadata nor data are available online.
data. Otherwise, acoustic modelers must obtain new (or archived) *in situ* data from their sponsors or resort to empirical models, Wenz & Knudsen [160, 161] for example, to estimate ambient noise levels due primarily to wind and shipping (See Figure 3-6).

In some cases there may be data available from controlled access sources, such as from university programs, for example.
The typical sound levels of ocean background noises at different frequencies, as measured by Wenz (1962) [160]. This graph is therefore also referred to as the 'Wenz curves.' The sound levels are given in underwater dB summed over 1 Hz wide frequency bands, which is often written as dB re 1 µPa²/Hz. Reprinted with permission from National Research Council. 2003 [124]. Ocean Noise and Marine Mammals. National Academy Press, Washington, D.C. (as adapted from Wenz, 1962) [160] by the National Academy of Sciences.
3.3 Marine Animal Databases (Reference Appendix D)

In this section a discussion of the content of the marine animal database listing (Appendix D) is presented.

The same caveats as for physical databases apply: The list of databases provided in the appendices was valid as of the third quarter of 2013. No guarantee can be given that these links or databases will be maintained or visible thereafter; because of complex data sharing and data-mirroring relationships between some large organizations, it was beyond the scope of this study to determine whether all the points of entry provide access to truly unique data.

3.3.1 Parameters Surveyed

The databases listed in Appendix D may include any of the following data: species, location, population estimate, resident season, animal sounds (spectra/signatures/hearing range), etc. Marine animals by major taxa include: marine mammals, bony fish, marine reptiles (primarily turtles), cephalopods, elasmobranchs (sharks, rays, skates), and tuna. These follow the same layout and format of the table described in section 3.2.1 for the Physical parameter databases.

3.3.1.1 Table Presentation and Organization

To describe the table layout and the information contained within its rows, Table 3-8 presents an sample row from Appendix D, Multispecies databases. The first column contains the name of the database (if there is a unique name), and the major organization or sponsor of the data, or major geographic region, which hosts the data. In the example of Table 3-8 the organization is the European Ocean Biogeographic Information System. The second column contains a list of data properties for which information was sought during the search phase. Some properties are in common with the marine physical parameter listings (e.g. Location, Accessibility, Summary). Properties unique to the marine animal database survey and their description are provided in Table 3-9. For key database properties metadata are assigned. The breakdown of the metadata for each property in Table 3-8 is described in detail in Table 3-10. Again, a metadata item, or tag, is preceded by a ‘#’ mark.
Table 3-8 Sample row, Entry 11 of Table D.1 from Appendix D, Multispecies Databases

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accessibility:</td>
<td>Accessibility: open access for search, controlled access for data, but it doesn’t apply to all data sets</td>
</tr>
<tr>
<td>Meta:</td>
<td>Meta: #bonyfishes, #mammals, #reptiles, #elasmobranchs, others</td>
</tr>
<tr>
<td>Data subject:</td>
<td>Data subject: population, density, geographic distribution, strandings, sightings</td>
</tr>
<tr>
<td>Animal coverage:</td>
<td>Animal coverage: marine turtle, cetacean, seals, polar bears, fishes, marine birds</td>
</tr>
<tr>
<td>Area coverage:</td>
<td>Area coverage: all the continental shelf seas of Europe, from the Canaries and Azores to Greenland and North-West Russia, including the Mediterranean shelf, Baltic Seas and deep-sea areas</td>
</tr>
<tr>
<td>Seasonal coverage:</td>
<td>Seasonal coverage: all</td>
</tr>
<tr>
<td>Search capability:</td>
<td>Search capability: web form with basic and advanced search capabilities; also an interactive map tool</td>
</tr>
<tr>
<td>Updates:</td>
<td>Updates: last update March 2013; monthly updates</td>
</tr>
<tr>
<td>Summary:</td>
<td>Summary: The European regional node of the Ocean Biogeographic Information System. This distributed system to present biogeographic information integrates individual datasets on marine organisms into one large consolidated database, and can therefore provide a better understanding of long-term, large-scale patterns in European marine waters. The most recent version of the data will always be available through this search interface. Hosted and maintained by Flanders Marine Institute (VLIZ).</td>
</tr>
</tbody>
</table>

3.3.1.2 Table Entries Unique to Marine Animal Entries

Entry topics in Table 3-9 have the same definitions as those in the Physical Data shown in Table 3-4 and discussed in section 3.2.1.2. The following are the entries unique to the Marine Animal database table in Appendix D.

Table 3-9 Description of marine animal database properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data subject</td>
<td>Describes the type of information the site contains. In this example, one may find information about population, density, geographic distribution, stranding, and sightings.</td>
</tr>
<tr>
<td>Animal coverage</td>
<td>Lists the species that are included in the database. In this example, marine turtle, cetacean, seals, polar bears, fishes, and marine birds may be found.</td>
</tr>
<tr>
<td>Seasonal coverage</td>
<td>Lists the times of year that data cover, if known. Most databases cover all seasons. In many other cases it was difficult to ascertain if ‘all’ seasons were covered by the data.</td>
</tr>
</tbody>
</table>
All metadata used for the marine animal database points of entry are shown in Table 3-10.

**Table 3-10 Metadata description for marine animal points of entry and databases**

<table>
<thead>
<tr>
<th>Property</th>
<th>Metadata label (#) and description</th>
</tr>
</thead>
<tbody>
<tr>
<td>POE Type</td>
<td>#portal-links: if the POE is a portal or a links page</td>
</tr>
</tbody>
</table>
| Taxa           | #bonyfishes: e.g. herring, flounder, plaice, cod . . .  
|                | #cephalopods: e.g. octopuses, squid ...  
|                | #mammals: marine mammals, e.g. cetaceans, pinnipeds  
|                | #reptiles: sea turtles                                              
|                | #elasmobranchs: sharks, rays, skates                                
|                | #tuna: tuna                                                         
|                | #atlas : data which are presented pictorially over a geographic area     |
| Coverage       | #global: (if global; otherwise “regional” and no metadata)              |
| Accessibility  | #access_open, #access_controlled, #access_mixed, #access_restricted, #access_notdetermined: As described in Table 3-2. |
| Update period  | #dailyweekly, #monthly, #quarterly : #annual, #archive, #update_notdetermined: As described in Table 3-5. |
| Last update    | #before2013, #current, #last_notdetermined: As described in Table 3-5.                                           |
3.3.1.3 Enumeration of Database Survey Findings

Table 3-11 provides a summary of the numbers of marine animal points of entry (or databases) found on the web.

Table 3-11 Summary of table for Appendix D showing numbers of entries for each metadata label

<table>
<thead>
<tr>
<th>Metadata label</th>
<th>No. Of POE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Points of Entry (POE) in Appendix D</td>
<td>61</td>
</tr>
<tr>
<td>#portal-links</td>
<td>9</td>
</tr>
<tr>
<td>#global</td>
<td>17</td>
</tr>
<tr>
<td>#allseasons</td>
<td>55</td>
</tr>
<tr>
<td><strong>Type of data</strong></td>
<td></td>
</tr>
<tr>
<td># mammals</td>
<td>48</td>
</tr>
<tr>
<td>#reptiles</td>
<td>25</td>
</tr>
<tr>
<td>#elasmobranchs</td>
<td>23</td>
</tr>
<tr>
<td>#bonyfishes</td>
<td>19</td>
</tr>
<tr>
<td>#cephalopods</td>
<td>8</td>
</tr>
<tr>
<td>#tuna</td>
<td>4</td>
</tr>
<tr>
<td>#atlas</td>
<td>9</td>
</tr>
<tr>
<td><strong>Update period</strong></td>
<td></td>
</tr>
<tr>
<td>#dailyweekly</td>
<td>5</td>
</tr>
<tr>
<td>#monthly</td>
<td>14</td>
</tr>
<tr>
<td>#quarterly</td>
<td>4</td>
</tr>
<tr>
<td>#annually</td>
<td>12</td>
</tr>
<tr>
<td>#archive</td>
<td>13</td>
</tr>
<tr>
<td>#update_notdetermined</td>
<td>17</td>
</tr>
<tr>
<td><strong>Last database update</strong></td>
<td></td>
</tr>
<tr>
<td>#current</td>
<td>30</td>
</tr>
<tr>
<td>#before2013</td>
<td>25</td>
</tr>
<tr>
<td>#last_notdetermined</td>
<td>6</td>
</tr>
<tr>
<td><strong>Accessibility</strong></td>
<td></td>
</tr>
<tr>
<td>#access_open</td>
<td>39</td>
</tr>
<tr>
<td>#access_controlled</td>
<td>5</td>
</tr>
<tr>
<td>#access_mixed</td>
<td>15</td>
</tr>
<tr>
<td>#access_restricted</td>
<td>2</td>
</tr>
<tr>
<td>#access_notdetermined</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 3-7 and Figure 3-8 (Pie Charts) displays the relative distribution of findings for global and regional coverage, update period, last data update, and accessibility.

As for marine physical parameters data discussion in Section 3.2.2, the numbers of points-of-entry (POE), or databases, that included particular parameters are shown in Figure 3-7. The data are sorted from left to right in descending order to illustrate the relative abundance of the taxa coverage found in the database ‘snapshot’ taken during this survey.

The results to indicate that marine mammals, marine reptiles (i.e. sea turtles) and elasmobranchs (i.e. sharks, skates and rays) are relatively well represented, with mammal data dominating. However, in speaking with marine biologists, surveying the literature and through conference attendance, the picture
for marine reptiles is not as complete as the figure indicates. There is an abundance of websites for conservation groups and enthusiasts of both marine reptiles and sharks, though most of these websites contain no data of any relevance. The case for marine reptiles is discussed more, below.

Figure 3-7 Summary showing sorted prevalence of available data by major taxa, from the survey in Appendix D (Table D.1)
Figure 3-8 provides four pie charts indicating the relative proportions of selected metadata metrics for marine animal databases and points-of-entry, Appendix D. The presentation of the chart is as above for marine physical parameter databases.

The main conclusions drawn from Figure 3-8 are as follows:

- Approximately half (49%) of the marine animal databases are current (updated within the study year). About 41% of the databases were last updated prior to 2013,
- Almost all (96%) of the found data fall into the categories of full open access, controlled access, or mixed access. Only 4% were restricted access (Industry and military data),
- Most (72%) of the marine animal databases cover regional interests. Regional being defined as from 'very local' to a particular ocean basin,
A smaller, though significant proportion (28%) of the marine animal databases contain data, which is sourced globally. Note, this does not always guarantee the data are evenly distributed over the globe, and

In contrast to marine physical databases, only a minority (28%) of the marine animal databases could be determined to be updated frequently (daily to monthly). It was much more difficult to determine (in 25% of the cases) how often a database was updated. Almost 40% of the databases were determined to be either archives (no more updates) or updated infrequently (annual).

As with marine physical parameter databases, several database managers reported the delay between data collection and accessibility can vary widely from days to several years depending upon processing backlogs, moratoria, and any proprietary issues.

3.3.2 Marine Animal Data Discussion

In this section a summary of the data and a discussion of knowledge gaps for marine life databases is provided. This summary is derived from the database survey (Appendix D) and augmented by broad literature search. The authors through attendance at the timely Third International Conference also gathered notes on the Effects of Noise on Aquatic Life, which was held in Budapest, Hungary in August of 2013. On the final day of the regular program several ‘breakout’ discussion groups, or roundtables, were convened in order to discuss data gaps. Participants came from a wide array of backgrounds, providing a broad perspective. Notes taken during these discussions and references to this conference are noted as ‘AN2013’.

3.3.2.1 Data Gaps

From Figure 3-7 marine reptiles appear to have good representation. However, in speaking with marine biologists, surveying the literature and through participation at the AN2013 workshops, the picture for marine reptiles is not as complete as the figure indicates. There are an abundance of websites for conservation groups and enthusiasts of both marine reptiles and sharks, though most of these websites contain no data of any relevance. The case for marine reptiles is discussed more, below. It is apparent from Figure 3-7 that cephalopods are highly under represented. Finally, tuna appear last in terms of database abundance; however, tuna are a highly regulated, high valued, fishery, which was the motivating factor for this specific search.  

3.3.2.2 Biogeographic & Seasonal

Several researchers have commented on the biogeographic gaps. Baseline population data are missing for many areas across many species. When estimates are available they are often based on small sample sizes [164]. The ocean is vast, and in many regions the weather can be severe during extended durations of the year.

Due to costs, resources, and the effort required to attain high coverage, regions outside the normal area of operations for the U.S. Navy are lacking in species density data [165]. Therefore

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47 Most of the tuna data are in atlas form from regulatory bodies (FAO Tuna Atlas, entry 58; Indian Ocean Tuna Commission, entry 59; The International Commission for the Conservation of Atlantic Tunas, entry 60).
population estimates usually more available and more reliable in fair weather seasons and for localized regions, such as being closer to existing shipping routes [166, 80]. However, as a counter example to this assertion, at the recent (7-9 January 2014) American Petroleum Institute’s Sound Exposure Modeling Workshop (Washington, D.C.) it was pointed out that the most recent data presently available for the Gulf of Mexico was collected in the 1990’s, nearly a quarter-century out of date.

Regions requiring extended journeys, such as remote regions of the Indian and Southern Oceans exhibit geographic gaps [167]. National Biodiversity Data Center [168] mention biodiversity gaps, where these gaps occur, and how biodiversity is changing over time, pointing to a lack of baseline data in many instances.

While there appear to be many databases/datasets on marine turtles, critical gaps exist. Beyond their use of beaches for there is a critical lack of in-water occurrence data for sea turtles. There is little assessment data of the general presence of turtles in an area. Many studies extrapolate turtle density based on numbers by counting nesting individuals or numbers of eggs, or by recording by-catch [165] 48. While there is biogeographic data on mature sea turtles, due to the extremely long lifespan of sea turtles, the major biogeographic gap relates to their location during their early years, until they are juveniles. Simultaneously, this is also a major life-stage gap. 49

Finally, it has been noted that there is a scarcity of data regarding both geographic and seasonal distributions of the characteristics of sounds generated by aquatic life, particularly within behavioral contexts National Research Council [124] and AN2013 Gaps Breakout Group.

3.3.2.3 Diving Behavior and Movement Databases

While diving behavior and movement data are not strictly inputs to propagation models, rather they are inputs to exposure models, they deserve mention.

Diving behavior databases may contain, for each species within the database, the following parameters related to the dive behavior: dive depth, dive time, bottom behavior, vertical dive rate, dive speed, dive angle, surfacing angle, surface behavior, dive activity budget, aversion and attraction behaviors (see for example, Marine Assessment Decision and Planning Tool (MADPT), Marine Acoustic Inc., proprietary database, pers. comm. Kathleen J. Vigness-Raposa). These data are used to provide bounds on stochastic models that simulate the motion of thousands of animated animals, so called animats, in the water column. Using the known position of any particular animat at any particular time the exposure to the sound field at that position is determined and stored in the exposure model’s internal database for later statistical exposure analyses.

The literature contains much data on the dive and movement behavior of many marine species. Here, examples are not provided but they are easily found via a web search. However, only one open access database, 3MB (described briefly in section 2.3.6.2.2) was located through web-based search. When

48 During the AN2013 conference, marine mammals and sea turtles Gaps Breakout Group, it was said for sea turtles: “Do not even know what is unknown” – this is quite an admission.

49 This is summarized in a quote found on the World Wide Web: “From the time they take their first swim until they return to coastal waters to forage as juveniles may be as long as a decade. This period of time is often referred to as the "lost years" since following sea turtles movements during this phase is difficult and their whereabouts are often unknown.” http://www.seeturtles.org/1402/life-cycle.html
further results were not to be found, many papers from the literature were scanned for possible references to such databases, with negative results. Finally, several marine mammal researchers were directly queried for the existence of such databases. The final inquiry was directed to Dr. Dorian Houser, Director of Conservation and Biological Research at the National Marine Mammal Foundation (San Diego, California).

Paraphrasing Dr. Houser, he indicated that the lack of openly-available dive behavior data is problematic when performing exposure modeling with simulated animals. Although there was an effort to develop a common database for marine mammal dive information over 10 years ago, the effort was unsuccessful in producing an openly-available database. This was largely due to individual researcher desires to maintain control on their dive data, but also in part because no acceptable long-term sponsors of the database were identified. Interfacing with individual researchers is still necessary to get raw data for behavioral analysis and the willingness of researchers to share data varies. However, aside from individual arrangements with the tagging community, the modeling community is still left with mining dive and behavior data from the literature.

3.3.2.4 Sound Reception and Sound Production

Southall, *et al.*, [144] noted the scarcity of data on many species with regards to direct measurements of hearing, and consequently he found the theories regarding species hearing capabilities were speculative and knowledge of marine mammal hearing was quite limited. More recently, it was noted that there remains a gap in data for species hearing, and that, routinely, sensitivity is inferred from indirect evidence [169]. A summary recommendation in a newly released report [239] by the National Marine Mammal Foundation (NMMF) is to increase both species representation and the sample size of subjects (as feasible) representing a species for temporary threshold shift (TTS), baseline audiometric studies, and other psychophysical studies. It was noted (Michel André, AN2013) that there are still large gaps in the understanding of sound perception.

An audiogram provides a measure of the threshold of hearing of a marine animal, in decibels (referenced to a unit of pressure), a function of frequency. Sample audiograms for a variety of marine species are shown in Figure 3-9, below. As described in Nedwell *et al.* [170] there are two main methods from which audiograms are obtained for fish and mammals:

- by behavioral responses to provided acoustic stimulus, and
- by means and by auditory evoked potential (AEP) measurements (by monitoring of the electrical activity of the animal’s hearing mechanism when the animal is presented with a sound stimulus).

It is worth noting that behavioral response studies require training the animals under test to participate in the experiment, AEP measurements do not. It was noted (J. Sisneros, AN2013) that there are large differences between behavioral thresholds and AEP (auditory evoked potentials) thresholds, and that AEP audiograms do not ‘equal’ the behavioral audiograms.

A further issue is a lack of data for audiograms and once obtained from one member of the species the data are applied to all members of that species, not accounting for animal age, sex, overall health,
previous life history etc. Nedwell et al. [170] noted the coarseness of the auditory level steps (2dB) and that some audiograms may not cover the entire hearing range of the animals under test.\footnote{50}

A report of the National Research Council [171] noted that data are needed to provide comparisons allowing an evaluation of how common hearing deficits may be among stranded animals; and asserted that the development of population-level audiograms requires the perfection and wide use of auditory evoked potential techniques (eliminating the need to train animals under test).

Another method of specifying the hearing of marine mammals is the M-weighting function, functionally described as zero-gain band pass filters: “In assessing the effects of noise on humans, either an A- or C-weighted curve is applied to correct the sound-level measurement for the frequency-dependent hearing function of humans. ... similar, frequency-weighted hearing curves were needed for marine mammals; otherwise, extremely low- and high-frequency sound sources that are detected poorly, if at all, might be subject to unrealistic criteria.[144].”

\footnote{50} Testing in tank environments present other problems as it is difficult to achieve a free field.

\footnote{51} http://www.dosits.org/animals/effectsofsound/howdoyoumeasureamarinemammalsreactiontosound/hearingsensitivitystudies/
However, they also note a lack of data when calculating M-weighting functions results in functions that are intentionally precautionary (i.e. wide), likely overestimating the functional bandwidth for most or all species. (Finneran, AN2013) noted that M-weighting is used for animals, but there are no standards for animals (only humans), and that M-weighting likely underestimates effects near the best sensitivity, and over estimates effects at low frequency, and suggested more data is needed at low frequency.

The auditory responses, discussed above, describe the hearing ability of marine animals with respect to frequency. Nedwell et al. [172] developed a measure that depends upon the frequency in its derivation, but removes the overt frequency dependence, and corresponds to the perception of sound by a particular species. The scale is denoted by: dB_{ht}(species). In short, dB_{ht} is the difference between the sound pressure level and the hearing threshold at any particular frequency. The sound level after the filter corresponds to the degree of perception of the sound by the species. For example, a value of dB_{ht}(species) = 10 dB could apply at any frequency for species. Because of the dependence upon the species audiogram, dB_{ht} will suffer the same inaccuracies as the parent audiogram [173].

Finneran and a variety of co-authors [226-238] have performed a considerable amount of research using both auditory evoked potentials and behavioral responses to study temporary threshold shift (TTS) over a range of impulsive and tonal acoustics sources. Research into the auditory weighting functions, hearing loss, subjective loudness level measurements and equal loudness contours, and the effects of fatiguing, are covered in the cited list papers. Most of this work was with bottlenose dolphins (Tursiops truncatus). A recent (2012) report by Finneran and Jenkins [237] provided criteria and thresholds for U.S. Navy acoustics and explosive effects analysis.

Further summary recommendations of the NMMF report [239] include:

- Increase the number of comparisons between psychophysical and electrophysiological estimates of hearing function within the same subject.
- More to standardize approaches, as both psychophysical and electrophysiological methods vary considerably among research groups. This will permit comparisons between related, but different, studies (e.g. equal loudness vs. equal latency) and those assessing the same thing (e.g. auditory evoked potential thresholds). To improve consistency between research groups agreement on fundamental components of research methods (e.g. the baseline frequency for loudness comparisons) was recommended.
- As there are no hearing measurements on mysticete whales, validated anatomical models are necessary for predicting mysticete hearing sensitivity. Models should be validated against behavioral or electrophysiological information from available species prior to extrapolation to species when no information exists. Highly recommended is the validation of peripheral and middle-ear models.

On sound production, there is a gap in knowledge on how animals make use of the many acoustic cues, including communication vocalizations, in the marine environment [124]; (AN2013 Gaps Breakout Group). As it is unknown what received sound levels are necessary for a marine animal to recognize and respond to social calls, our understanding the impact of masking effects of a particular type of noise in marine mammals is impeded. Masking effects caused by anthropogenic sources could potentially affect behavior and vital rates, depending upon the particular circumstances.
3.3.2.5 Metrics, Criteria, and Standards

One of the recurring themes encountered during the AN2013 conference in Budapest was that of suitable or appropriate metrics. Many questions arise, exposing knowledge gaps, such as:

- For spectra should narrow band (single frequency) levels be used or broad band levels?
- Should higher order spectral moments be considered?
- For time-based measures: peak levels, peak-to-peak, and root-mean-square (RMS), and the decibel, all need to be clearly defined within the context of exposure metrics. How do we measure the shape of the signal and does the shape affect the way the sound is perceived by the animal?
- Do we have the same issues for particle velocity metrics?
- While all of these ideas may be defined mathematically, the questions remain: Are these the correct metrics? Are there better metrics? What is the basis for choosing a particular metric?

Our attention turns to gaps in determining criteria of exposure. Southall [144] identified several deficiencies, including a lack of data to identify applicable, quantitative criteria for behavioral disturbance in response to multiple-pulse and continuous sounds, and limited data to construct marine mammal noise exposure criteria (including cumulative effects of repetitive or long-term noise exposure). They noted at the time a lack of specific data on the level of a sound pulse that would cause temporary threshold shift-onset for pinnipeds in water, for example.

It was noted at the AN2013 conference in Budapest (B. Casper, AN2013) that the criteria, once established in some manner tend to be coarse. To illustrate, an exposure of 185 dB may equate to no-injury, whereas 185.1 dB equates to injury. Participants of the AN2013 Gaps Breakout Group continue to describe a lack data for determining exposure criteria for marine life other than cetaceans and pinnipeds (e.g. invertebrates, fish, sea turtles, sirenians, sea otters, and polar bears). Furthermore the group agreed that criteria are more urgently needed for species that are considered threatened or endangered.

The establishment of appropriate standards remains a topic of much discussion in the mitigation community. Popper & Hastings [174] discussed the lack of standardization in results from studies employing various types of sound sources (e.g. seismic air guns, mechanical shock, and pile driving), noting that these sources exhibit distinctly different propagation mechanisms: air gun sounds propagate laterally primarily via waterborne paths whereas pile driving, for example, also propagates much energy via the substrate. Therefore, they posted that extrapolation of results cannot be applied to species to indicate damage and death without considering the type of stimuli.

These ideas were presented at the AN2013 conference where questions arose as to what the acoustic “source level” meant:

- How is source level defined when the source is coupled directly to the sea bottom’s substrate, or in close proximity to the sea surface and ocean bottom and its layers?
- During pile driving operations that also couple acoustical energy to the air above the water, is this being considered in the calculations of source level?
- Are all investigators using the same definitions for impulsive sources as for continuous sources?

Several investigators present at the AN2013 conference noted that there were many ways of expressing the same quantity (e.g. 1μPa²s /Hz =1μPa²/s² = (1μPa·s)²) depending upon which reference level was
chosen. The choices for reference levels or how they are expressed may render rapid comparison across datasets more cumbersome. 52

3.3.2.6 Species Vital Rates
There are many knowledge gaps with regards to the effects of sound during different life stages on the development and vital rates of marine biota. Little is known about how vital rates are affected by anthropogenic sound causing physiological or behavioral changes (J. Harwood, AN2013).

The long-term effects of exposure to impulsive sounds, such as pile driving, that may lead to death or induce a change in behavior that affects the survival rate at some time well after the exposure, are unknown according to Hastings & Popper [175]. They also highlighted the lack of in situ data on the effects of sound on developing larvae and eggs, noting that the sensitivity to mechanical stimulation varies with each stage of development. Popper & Hastings [174] mention the lack of data on non-mortality responses of fishes outside the ‘kill-zone’, which are not immediately apparent, yet may affect the population.

They describe non-mortality responses as including temporary injuries that heal, or injuries that lead to organ damage leading to slow death. They also offer a list of issues that need to be addressed to fill knowledge gaps for eggs and larvae.

3.3.2.7 Behavioral Changes

The effects of sound on behavior are important in the contexts of aversion (or attraction) of marine life to the source of the sound, as this affects the immediate exposure, and also within the context of longer term sound induced behavioral changes affecting species vital rates (e.g. how are the following affected: feeding, courtship, communications, movement to different habitats, etc.)

It was noted at AN2013 that when addressing challenges in studies of behavioral responses of whales to noise the sample sizes are low (Cato and Dunlop, AN2013). Previously, Shaffer & Costa [178] highlighted a lack of data that simultaneously examines diving behavior and sound exposure. Also in terms of short term impact, Hasting & Popper [175] noted the data gap on the immediate behavioral effect on fishes both near and far from the noise source. This knowledge gap in the acute and cumulative response of fish and invertebrates to sound was more recently mentioned [176] where this knowledge was found to be necessary to quantify any impacts resulting from sound-generating activities.

52 Normandeau Associates Inc., [176] and Moore et al. [177] both noted deficiencies in the standards and agreements on use of terminology. As an example, the U.S. Congress included such vague terminology as “small number,” “negligible impact,” “jeopardy,” and “adverse modification” in marine mammal laws and regulations in an effort to implement them across multiple types of activities. Another complaint is that terminology usage is often inconsistent and not always appropriate.
The National Research Council [171] noted a lack of data on long-term effects of ambient noise on marine organisms, where the effects include changes in hearing sensitivity and behavioral patterns. The long-term effects of pile driving on fish behavior and the cumulative effects of exposure to loud sounds have been identified as a knowledge gap by Hastings & Popper [175].

Several investigators [144, 167, 179, 240] and the investigators attending the AN2013 Gaps Breakout Group (2013) have indicated critical gaps in understanding the behavior of marine animals within the context of all the environmental variables. For example, if an animal is presumed to have reacted to the sound source, what activity was already taking place (e.g. courting ritual, grouping patterns, what other species were present and what were they doing)?

3.3.2.8 Methodology Used in Surveys
Where sightings data exist, or have been used to build population or density estimates, users are cautioned to ensure that these data have been corrected for expended level-of-effort (LOE) during the survey; furthermore, many surveys do not follow a regular sampling grid and surveyors often return to the same areas at the same time of each year where sightings are assured. This has the possibility to produce false negatives on population and density maps which may not explicitly differentiate between areas with no sightings versus areas where no sampling occurred.

The format of an 'annual survey' may also leave large seasonal gaps in regions that experience severe at-sea weather [180]. Halpern et al. [159] noted as much regarding the lack of homogeneity in data sets for marine animal observations. Fitch et al. [164] highlight that some observation methods are entirely ineffective for many species as detectability can depend upon the methods and the species being sought. Tagging of marine species with acoustic or radio transponders is labour intensive, slow, and remains a bottleneck for determining the behavior and location of many species (D. Mann, Frans-Peter Lam, AN2013). It is unclear how to address this gap.

While there is a plethora of acoustic pressure sensing hydrophones available in the commercial market, however, it is particle motion, which is sensed by many marine species. A clear gap is that calibrated detectors for particle motion (or velocity) are not widely available [176].

3.3.2.9 Physiological Effects
Investigators continue to note that successful extrapolation of data results between different species lack two critical elements:

1) Knowledge of differences in the hearing systems of different organisms, and effects of exposure to sound on such different auditory systems, and

2) Limited data on the precise nature of a stimulus (e.g., pressure and/or particle velocity) which might affect the hearing apparatus [174, 175] & participants of AN2013 Gaps Breakout Group.

Hastings et.al [175] reported a lack of data on the biochemical mechanisms of acoustic traumas and barotraumas, as well as their acoustic thresholds. The lack of data to support the acoustic exposure conditions required to induce physiological trauma directly was reported by Southall [144]. A specific example is the lack of data to support discrete, science-based injury criteria specific to beaked whales exposed to tactical, mid-frequency military sonar (ibid. p. 445). Regarding non-auditory injury, (ibid. p.
411) reported a lack of data for physiological harm to organisms due to exposure of underwater noise. Additionally, it is unknown whether behavioral reactions (e.g. atypical diving behavior) due to noise exposure may secondarily induce bubble formation and tissue damage.

Southall reported that gaps exist in both methodology and physiology. They reported a complete lack of information on the extent that post mortem artifacts introduced by decomposition before sampling, handling, freezing, or necropsy procedures affect interpretation of observed lesions [174].

For stranded marine mammals there is a lack of information on the interpretation of lesions observed, and of data on the received acoustic exposure conditions for animals involved in stranding events (unless the acoustic conditions for precipitating a stranding were planned, it would be an unlikely coincidence to also have recorded in situ receive levels in the vicinity of the marine animals location in order to plug this gap.) Moore et al. [177] reports that where physiological stress caused by noise exposure has been documented for fish in laboratory settings there are no relevant data on stress available for marine mammals.

3.3.2.10 Information Dissemination and Backlog

An interesting type of gap, or perhaps, inefficiency, exists in the manner in which information is made available. In this study the landscape of data held in databases was surveyed. However, for both marine physical and marine animal data the authors have found that much data resides in reports and literature. As an analysis based solely on database listings does not expose the full breadth of the data and knowledge gaps which exist. This is easily demonstrated by the present discussion of marine animal / biological data gaps that out of necessity required surveying the literature and available reports.

One would need to perform a species-by-species analysis, and this would not expose overarching gaps. Shaffer & Costa [178] point out this 'literature-based' dataset and suggest that this is responsible for some loss of information. In terms of visibility of the original data, this is quite plausible as publications offer a filtered version of those data.

The U.S. Department of Navy [222] and Scientific Advisory Group for Navy Marine Species Monitoring [223] suggest that a knowledge gap exists due to limited resources available to analyze a backlog of existing data.

53 Note a lack of data indicating whether a survey involved a professional fish pathologist to perform full necropsy and histopathology after a noise exposure event.
3.4 Environmental models linking databases to propagation models

The predictions from an acoustic model are only reliable if the inputs provided are accurate and in the correct mathematical format for the model. Many of the physical databases provide a description of the sediments and surface conditions however these parameters may not be utilized directly by the propagation models. Ray theory models require reflection coefficients rather than geophysical parameters.

Many models represent the bottom by a half-space with just one set of sediment parameters, which will require averaging or ignoring the data based sediment layers. Surface losses must be derived from the wind speed. And all acoustic models need sound speed profiles derived from temperature, salinity, depth.

In general, the inputs suitable for acoustic models must be derived from the physical databases by some kind of environmental conversion model. Very often, these environmental models are empirical, such as the surface loss equations, the conversion tables between sediment descriptions (such as silty-sand) and reflectivity, the various equations to convert ocean temperature to a sound speed profile and the calculation of water column absorption. The problem with using empirical equations is that they are really only reliable at the location and condition for which they are fitted, and extrapolation to other regions or conditions is dangerous.

A report on the high frequency empirical environmental models [181] lists estimates of the variability of their models, shown in Table 3-12. Estimates of variability like these are vital for determining the true range of prediction of a propagation model. This need was recognized by the temperature and salinity database developers of the Generalized Digital Environmental Model, variable resolution, GDEM-V [182]. They have constructed a companion database containing Temperature VARability versus depth (TVAR). TVAR is a four-dimensional model of ocean temperature variability with statistics for the mixed layer depth and the in-layer and below-layer gradients.

This suggests that all fundamental database parameters should be accompanied by a statistical measure of its range, in order that the environmental model that translates these values into usable acoustic inputs can provide these variability estimates to the modeler.

Table 3-12 Estimates of the variability of high frequency environmental models (Applied Physics Laboratory, University of Washington, 1994) [181]

<table>
<thead>
<tr>
<th>Type of environmental model</th>
<th>Area of application</th>
<th>dB variability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface backscatter</td>
<td>Wind speed greater than 16 kt</td>
<td>±4 dB</td>
</tr>
<tr>
<td>Surface backscatter</td>
<td>Wind speed less than 16 kt</td>
<td>±5 dB</td>
</tr>
<tr>
<td>Surface loss</td>
<td></td>
<td>-3 to +5 dB</td>
</tr>
<tr>
<td>Bottom backscatter</td>
<td>Rock and gravel</td>
<td>±10 dB</td>
</tr>
<tr>
<td>Bottom backscatter</td>
<td>Well characterized sand and silt</td>
<td>±3 dB</td>
</tr>
<tr>
<td></td>
<td>Poorly characterized sand and silt</td>
<td>±5 and ±10 dB</td>
</tr>
<tr>
<td>Bottom backscatter</td>
<td>Soft bottoms</td>
<td>From ±15 to 30 dB</td>
</tr>
<tr>
<td>Bottom loss</td>
<td></td>
<td>Error is the same magnitude as the loss,</td>
</tr>
</tbody>
</table>
The conclusion about environmental models that transform database parameters into quantities suitable for input to propagation models is that they may be the weakest link of the chain. In the next subsection, a U.S. Navy approach to providing bottom loss inputs from physical descriptions is presented to illustrate the problems associated with making these conversions.

### 3.4.1 Stainless Steel Bottom

A very famous (infamous) example of an environmental model, used extensively by the U.S. Navy, is the Navy Standard Low Frequency Bottom Loss database LFBL (formally called Bottom Loss Upgrade, BLUG) and its conversion model LFBLTAB, which derives bottom reflection coefficients from the BLUG database, for use between 50 Hz and 1000 Hz.

At the time of its creation, the BLUG database contained parameters for a thin sediment layer overlying a more substantial sediment layer overlying a basement half space [183].

There were 10 parameters in this database. In the research used to populate this database, inversions were made of transmission loss experiments at a range of frequencies. During the course of this experimental program, a profoundly anomalous region in the Hatteras Abyssal plain was discovered. There, the losses at 100 Hz were as much as 30dB at low grazing angles while the losses at 1600 Hz were only 4dB. Normally losses increase with frequency so why was this 1600 Hz loss so low?

Attempts to explain this anomalous behavior postulated either a 10m layer consisting of alternating subsurface layers of silt, sand or gravel 1-2 inches thick with high velocity; or a layer filled with gas hydrates. In any case, and whatever the cause, the only way the BLUG database and conversion model LFBLTAB could reproduce this behavior was to define an artificial very hard thin layer to give the correct high frequency resonances, and this was promptly dubbed the stainless steel bottom! Naturally, the U.S. Navy was unhappy with this moniker, and in the 90’s, the BLUG parameter list was increased to 15 to include a second layer with a frequency dependent term, but in reality the stainless steel layer was only pushed to the basement.

A major problem with populating the BLUG database was the scarcity of measured data. In the catalog of database values [184] the reliability of each data province was quantified for the topics of geoacoustic parameter confidence, measured data availability and overall parameter estimation.

Table 3-13 displays the ratings given to them in the four major ocean basins by percentage of the total number of database provinces in those basins. It is clear that the majority of the BLUG database entries were rated at the lower scales of reliability. Well over half were derived using no measured data.
### Table 3-13 Reliability ratings of BLUG database parameters from (Monet, Greene, & Spofford, 1983) [184]

<table>
<thead>
<tr>
<th>Rating</th>
<th>North Atlantic</th>
<th>Indian Ocean</th>
<th>Mediterranean Sea</th>
<th>North Pacific</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Geoacoustic parameter confidence (%)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fairly complete data from a drilling site</td>
<td>31.8</td>
<td>38.1</td>
<td>37.5</td>
<td>27.0</td>
</tr>
<tr>
<td>Less complete</td>
<td>30.1</td>
<td>38.1</td>
<td>25.0</td>
<td>35.0</td>
</tr>
<tr>
<td>Little or no geologic data</td>
<td>38.1</td>
<td>23.8</td>
<td>37.5</td>
<td>38.0</td>
</tr>
<tr>
<td><strong>Measured data available (%)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>At least 1 good site</td>
<td>28.3</td>
<td>0</td>
<td>12.5</td>
<td>3.1</td>
</tr>
<tr>
<td>Anomalous or marginal measurement site</td>
<td>14.2</td>
<td>42.9</td>
<td>18.8</td>
<td>14.3</td>
</tr>
<tr>
<td>No measured data</td>
<td>57.5</td>
<td>57.1</td>
<td>68.7</td>
<td>82.6</td>
</tr>
<tr>
<td><strong>Overall parameter estimation (%)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Good estimate</td>
<td>17.7</td>
<td>0</td>
<td>12.5</td>
<td>1.6</td>
</tr>
<tr>
<td>Some parameters have questionable accuracy</td>
<td>24.8</td>
<td>42.9</td>
<td>31.2</td>
<td>12.7</td>
</tr>
<tr>
<td>Canonical values used</td>
<td>57.5</td>
<td>57.1</td>
<td>56.3</td>
<td>85.7</td>
</tr>
</tbody>
</table>

In those regions that did have measurements, the automated Monte Carlo or synthetic annealing method for solving for the best fit of the parameters did not provide a unique solution. Lots of combinations of the 10 or 15 parameters could match the measurements. Because the solution has many minima, the one chosen by the automatic program may not have been a realistic physical set. So, even though the parameters had physical names like density and attenuation, they really weren’t.

A geoacoustic model is a model of the real sea floor with emphasis on measured, extrapolated, and predicted values of those properties involving sound transmission. In general, a geoacoustic model details the true thicknesses and properties of sediment and rock layers in the sea floor. In the case of BLUG however, the layering was restricted to just 2, which were not enough to correctly characterize the sediments. Additional problems with the BLUG inversions were that no shear was accounted for, which would be an important effect below 200 Hz in shale, chalk and sandstone types of sediments. Also, no roughness was used at interfaces, and flat layers were assumed. This caused too little loss at low grazing angles.

Finally, the frequency range of this low frequency environmental model did not extend to overlap the high frequency model, leaving a gap between 1 kHz and 3 kHz with no approved environmental model.
Section 4 - Critical Assessment of Acoustic Models for E & P Industry

Prepared for Joint Oil & Gas Industry Programme (JIP) on Sound and Marine Life

Solicitation Number: JIP 08-08

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Section 4

4 CRITICAL ASSESSMENT OF ACOUSTIC MODELS FOR E&P INDUSTRY

This section contains a thorough review and assessment of most of the models presented in Section 2 in terms of their accuracy, sensitivity to inputs, and fidelity. Information about specific models was compiled by a questionnaire sent to every model developer. Questionnaire can be found in Appendix B.

Models not listed in the tables below where found to be incomplete or the developer did not supply any relevant information in their questionnaires.

This section is broken into three main groups to provide the E&P Industry the best method of understanding suitable models, as follows:

i. Accuracy, sensitivity & fidelity of surveyed models (4.1);
ii. Identification of Best Suited E&P Models (4.2); and
iii. Gaps in: propagation modeling (4.3), physical databases (4.4), exposure models (4.5).

4.1 Accuracy, Sensitivity and Fidelity of Surveyed Models

4.1.1 Accuracy

Accuracy is obviously very important but, unfortunately, difficult to quantify. It is critical that models capture as much of the ‘important’ physics in the problem so as to represent what we see as the reality in the ocean. In order to gain trust in a model, its ability to capture the underlying physics needs to be established— we can do this directly by comparing to real data or indirectly by comparing with benchmark problems, which have been designed to expose certain physical aspects of propagation.

Model-to-benchmark comparisons are the gold standard. If we can establish that a model handles the benchmark problems then we ‘trust’ that it is going to produce reasonable results when applied to real ocean environments that match in some way the characteristics of the benchmark problem.

Model-to-model comparisons are good even when neither model is an accepted benchmark, particularly if the models are based on different methods for solving the acoustic propagation equations. In this case the chance of two different models introducing the same ‘bad’ physics or numerical artifacts into the problem is unlikely.

Model-to-data comparisons are obtained less frequently because, with the complexity and time-varying nature of the ocean environment and the costly nature of acquiring data at sea, it is very hard to compile a complete timely environmental description in the entire propagation region that the high fidelity models require. Moreover, our confidence in model-to-data comparisons is increased dramatically if the measured acoustic data (and supporting environmental data) is free of measurement bias and artifact i.e., the environmental data must be “smooth” in some sense and not contain unphysical transitions or data points.
The consensus of acoustic modelers is that all the high-fidelity models (when used within their regions of applicability) are capable of accurately computing the sound field when given the correct inputs.

4.1.1.1 Measures of Accuracy

Most of the models can produce point-wise accuracy for the test cases for which the algorithm and equation have been designed. In many cases, a mathematically derived error-term can be calculated based on the approximations employed by the solution classes. These terms provide the modelers with concrete methods to compare solution techniques, but they are not particularly useful for assessing accuracy against measurements.

Often, particularly in model-to-model comparisons, accuracy is judged simply by eyeballing the goodness-of-fit. For example, many model comparisons are said to be “within the thickness of the line”. Indeed, if two sets of results are within the “thickness of the line” no matter what the line width (within reason) it points to very similar phase and amplitude characteristics between the two model results i.e., a good thing.

For comparisons with measured data from all real ocean environments where the input data of the experimental site is often too coarsely sampled or not timely, the goal for predictions is to have a small uniform error, quantified as a ‘few’ decibels. Quantifying these errors typically consists of computing root-mean-square (rms, also RMS) errors in decibel level, arrival angle, arrival time, or range of onset of convergence zone.

Note, rms errors computed on the sound levels will bias the result due to the properties of the logarithm because differences between smaller energy values are non-linearly accentuated in the decibel. Furthermore, a slight misalignment of the phase structure or a perfect null can produce large rms errors, which are counter-intuitive.

In an effort to put the judgment of accuracy on a firm scientific footing, a method of field shift correlation has been developed [185].

- With this method, the acoustic field computed in the waveguide (hereafter referred to as the unperturbed field) is systematically examined in small “windows” gridded in range and depth.
- By perturbing the environmental inputs to the model, one can compute a “perturbed” acoustic field on the same grid in each of the small windows.
- Within each window, the perturbed field is shifted in range and depth (by grid units) and correlated with the original unperturbed field; the shifted perturbed field that yields the maximum correlation is then used to define an rms error with respect to the unperturbed field.
- This gives separate measures of the actual level change as well as the displacement of the field in range and depth.
- Field-shifted values can be computed for deterministic sensitivities (based on a specific environmental perturbation) or for stochastic sensitivities (based on Monte Carlo sampling of environmental uncertainty).

54 ‘few’ will vary depending on the application. Note that a +3 dB difference represents twice the acoustic intensity, a -3 dB difference represents ½ the acoustic intensity.
An example of this technique is shown in Figure 4-1 below.

- The rows in this figure, starting from the top, show sensitivity calculations for a 0.5, 1.0 and 2.0-m water-depth perturbation respectively in a downward refracting water column, 131-m deep. The model calculations were performed at 100 Hz.
- The columns, starting from the left, show the simple fixed-point rms sensitivity (i.e., no shift between the perturbed and unperturbed fields), the spatial field-shifted rms sensitivity, the corresponding range shifts and the corresponding depth shifts, respectively.

It is clear by comparing column 1 with column 2 that, at 100 Hz, most of the changes to the acoustic field, caused by the water depth perturbation, occur as simple shifts in space with almost no change in acoustic loss i.e., the figure shows that the rms error has been greatly reduced in column 2 (shifted field comparison) relative to column 1 (unshifted field comparison). These conclusions are further supported by the individual shift data shown in columns 3 and 4 which indicate that range shifting is the dominant mechanism affecting differences between perturbed and unperturbed fields.

In contrast, the same study completed at 1200 Hz (not shown here) found that field shifting was much less effective in decreasing the rms error because the field exhibits a more complex structure at higher frequencies and correlations values are much lower.

![Deterministic sensitivity results](image)

*Figure 4-1 Deterministic sensitivity results Rows 1-3 show increasing depth perturbation Columns 1-4 show fixed-point sensitivities, field-shifted sensitivities, range shifts and depth shifts.*

[185]
4.1.1.2 Benchmarks
Benchmarks furnish one option for assessing the quality of numerical computation schemes.

Benchmarks can be exact closed-form analytic solutions to specific problems or they can be numerical models deemed 'correct' by the research community because they capture all the physics of the problem.

In the case of range independence, exact closed-form solutions are available for scenarios like Lloyd's mirror and ideal channel propagation. In the case of range dependence, however, there are almost no closed-form analytic solutions available for even the simplest range-dependent environments (the lone exception is an analytic solution for an ideal wedge with pressure release boundaries).

Some useful steps in a general validation procedure for range-dependent acoustic models are:

i. Comparison with analytic reference solution benchmarks for range-independent environments
ii. Check of energy conservation and reciprocity in the solution
iii. Inter-model comparison
iv. Comparison with numerical benchmark solutions for range-dependent environments 55

The model that has achieved benchmark status by virtue of its complete treatment of the physics is the stepwise-coupled Normal Mode model COUPLE (see the COUPLE questionnaire in Appendix B).

COUPLE has been used for comparison with computationally efficient numerical codes to assess their accuracy in the context of realistic, range dependent ocean channels. The collection of papers in the pages following (Jensen & Ferla, Numerical solutions of range-dependent benchmark problems in ocean acoustics, 1990) in volume 87(4) of the Journal of the Acoustical Society of America display agreement with COUPLE by a ray model, a Normal Mode model, several PE models and a finite-difference numerical method. [18]

OASES is considered to be a benchmark model for seismo-acoustic propagation. Also, for some special problems, RAM has been accepted as a benchmark.

4.1.1.3 Model-to-Model Comparisons
We often find that when the developer chooses to display a model-to-model comparison in a paper, the agreement is usually excellent, but in workshops devoted to a specific problem, the comparisons can be more varied.

A good example of the model-to-model comparisons made at the 2008 ONR Reverberation Modelling Workshop (Perkins [186]) is shown in Figure 4-2. In this figure, the results for Problem V of the Workshop are compared between 13 different models.

55 Problems have been posed for range dependence benchmarks by the Acoustical Society of America (ASA). See [18]. These include a wedge shaped waveguide with three different bottom descriptions and the plane-parallel waveguide with a range dependent sound speed profile at two frequencies.
Figure 4-2 Reverberation levels versus time for workshop problem number five (1000 Hz). The plot shows two families of curves, each corresponding to a different treatment of the reflection loss at the bottom boundary [186].

Table 4-1 summarizes the model-to-model comparisons for some of the propagation models. In these cases, good agreement is generally obtained when both models are used within their regions of validity and when both are given the same form of the input, particularly the bottom characteristics and the functional form used for sound speed profile sampling.

<table>
<thead>
<tr>
<th>Propagation models</th>
<th>Other models or exact solutions used for comparison</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>BELLHOP</td>
<td>KRAKEN, SCOOTER at 10 kHz, 800 m depth (Porter, The Bellhop manual and user's guide, preliminary draft, 2011) [187]</td>
<td>Tested sound speed profile resolution requirements by subsampling XBT's.</td>
</tr>
<tr>
<td></td>
<td>KRAKEN, SCOOTER at 50 Hz, 5000 m depth (Porter &amp; Lui, 1994) [188]</td>
<td>Excellent agreement.</td>
</tr>
<tr>
<td></td>
<td>RAM at 250 Hz, 300 m depth (Porter, Environmental Slicer users guide) [189]</td>
<td>Excellent agreement.</td>
</tr>
<tr>
<td>GRAB</td>
<td>Exact solution at 250 Hz, 100 m perfectly reflecting channel (Brooke G., 2007) [74]</td>
<td>Excellent agreement.</td>
</tr>
<tr>
<td>Propagation models</td>
<td>Other models or exact solutions used for comparison</td>
<td>Remarks</td>
</tr>
<tr>
<td>-------------------</td>
<td>--------------------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>GRAB</td>
<td>ASA benchmark wedge problem (^{56}), at 25 Hz, 200 m depths.</td>
<td>Reasonably good agreement, given that Ray theory is not well suited for this low frequency, shallow water, bathymetric mode-stripping problem.</td>
</tr>
<tr>
<td></td>
<td>FEPE, OASES at 1 kHz, 150 m depths (Keenan &amp; Weinberg, 2001) (^{190})</td>
<td>Phase agreement is excellent.</td>
</tr>
<tr>
<td></td>
<td>OASES in SWAM'99 test cases 25 - 1000 Hz, 100m depths (Keenan &amp; Weinberg, 2001) (^{57})</td>
<td>Was unable to match the interference pattern shown by OASES at low frequency, however it did predict reasonable mean energy levels.</td>
</tr>
<tr>
<td>COUPLE</td>
<td>None listed.</td>
<td>Recognized benchmark for range dependence from the ASA benchmark wedge problem.(^{51})</td>
</tr>
<tr>
<td>C-SNAP</td>
<td>RAM in SWAM'99(^{19}) at 25-1000 Hz (Nielsen &amp; Jensen, 2001) (^{191})</td>
<td>Consistent except in cases where the continuous spectrum was an important contributor in very shallow water.</td>
</tr>
<tr>
<td>FMM</td>
<td>None listed.</td>
<td>A disadvantage of eikonal-based methods, especially in 3D, is that the accuracy is generally not as good as can be obtained with a properly converged iterative ray-tracing method. However, it is sufficient for many applications of 3D tomographic imaging problems.</td>
</tr>
<tr>
<td>INSIGHT</td>
<td>Other reverberation models (Ainslie, Harrison, &amp; Burns, Reverberation modeling with INSIGHT, 1994) (^{89})</td>
<td>Good agreement is found for some features, but not others. Potential sources of disagreement are many (scattering strengths, boundary losses, treatment of multiply-scattered paths, conversion from time to range etc.).</td>
</tr>
<tr>
<td></td>
<td>KRAKEN, SAFARI, SNAP at 1-10 kHz, 100-4000 m depth (Packman, Harrison, &amp; Ainslie, 1996) (^{192})</td>
<td>Incoherent loss in excellent agreement for wide range of environments.</td>
</tr>
<tr>
<td></td>
<td>SUPERSNAP, PAREQ, IFD for bottom interactions and Lloyds mirror (Ainslie &amp; Harrison, 1990) (^{193})</td>
<td>Demonstrates the high-fidelity numerical models are missing steep angle returns.</td>
</tr>
<tr>
<td></td>
<td>KRAKEN (coupled mode version, and ASA benchmark wedge problem(^{13}) at 25 Hz and 250 Hz, 100 m depth.</td>
<td>Coupled model performs quite well, even for cruder stair steps than should be used and the adiabatic model agrees very well except under duress where a crucial mode disappears.</td>
</tr>
</tbody>
</table>

\(^{56}\) (Jensen & Ferla, Numerical solutions of range-dependent benchmark problems in ocean acoustics, 1990) \(^{18}\)

\(^{57}\) SWAM'99 refers to the Shallow Water Acoustic Modelling 1999 Workshop on the topic of benchmarking shallow water range-dependent propagation modeling. See (Tolstoy, Smith, & Maltsev, The SWAM'99 Workshop - an overview, 2001) \(^{50}\)
<table>
<thead>
<tr>
<th>Propagation models</th>
<th>Other models or exact solutions used for comparison</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>adiabatic version)</td>
<td>RAM, ORCA, SAFARI in SWAM’99(^9) at 25 Hz, 100 m depth (Tolstoy, 2001)[194]</td>
<td>For the purposes of Matched Field Processing, particularly the tomographic geoacoustic inversion, it is likely that the simple adiabatic Normal Mode KRAKEN model is sufficient. accurate under most circumstances (low frequency MFP applications on a vertical array in shallow water), i.e., unless there is a loss or gain of a critical mode.</td>
</tr>
<tr>
<td>MMPE</td>
<td>BELLHOP at 10 kHz, 50 m depth (Llor &amp; Malumbres, 2012)[195]</td>
<td>In network simulations, MMPE deemed not as accurate as BELLHOP. Analytic solutions and Benchmark wedge (Smith, Validating range-dependent, full-field models of the acoustic vector field in shallow water environments, 2008)[196]</td>
</tr>
<tr>
<td>MOCASSIN</td>
<td>Split-step PE at 100-110 Hz (frequency averaging) in deep water (Schneider, 1994)[197]</td>
<td>Surface reverberation predictions show reasonable agreement. Monostatic bottom reverberation from the face of a seamount with frequency averaging shows good results in predicting the overall level.</td>
</tr>
<tr>
<td>NUCLEUS</td>
<td>The currently used sound propagation spreading), therefore no assessment of the model is fairly simple (spherical or cylindrical accuracy has been attempted (see questionnaire).</td>
<td></td>
</tr>
<tr>
<td>OASES</td>
<td>Finite Element PE (FEPES), Boundary element model (BEM), Virtual source approach (VISA) (Schmidt &amp; Baggeroer, 1994)[198]</td>
<td>The solutions compare extremely well with elastic-PE solutions for weak contrast problems and with full boundary integral approaches for several canonical elastic benchmark problems.</td>
</tr>
<tr>
<td>ORCA</td>
<td>SAFARI (OASES) at 50 Hz, 200 m depth overlying elastic sediment (Westwood, Tindle, &amp; Chapman, 1996)[11]</td>
<td>Excellent agreement.</td>
</tr>
<tr>
<td></td>
<td>KRACKENC from 10 Hz to 1 kHz, 460 m depth overlying elastic sediment (Westwood, Tindle, &amp; Chapman, 1996)[11]</td>
<td>Showed the speed advantage of ORCA, particularly at frequencies above 100 Hz.</td>
</tr>
<tr>
<td></td>
<td>SWAM’99(^9) at 25 Hz, 100 m depth. (Knobles, Stotts, Koch, &amp; Udagawa, 2001)[199]</td>
<td>Chosen by workshop organizers to produce local eigenfunctions and eigenvalues for internal wave problem.</td>
</tr>
<tr>
<td></td>
<td>SAFARI, split-step Padé PE at 100 Hz, 240 m depth (Bucker waveguide with bi-linear sound speed profile) (Brooke &amp; Thomson, 2000)</td>
<td>Agreement, particularly in phasing is excellent.</td>
</tr>
<tr>
<td></td>
<td>COUPLE in ASA benchmark wedge problem(^9), at 25 Hz, 200 m depth (Brooke &amp; Thomson, 2000)[200]</td>
<td>Excellent agreement.</td>
</tr>
<tr>
<td>Propagation models</td>
<td>Other models or exact solutions used for comparison</td>
<td>Remarks</td>
</tr>
<tr>
<td>--------------------</td>
<td>----------------------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>POPP/PROLOS</td>
<td>Reverberation modeling workshop in 2006 and 2008 (Ellis, 2008), (Perkins, 2009) [201, 186]</td>
<td>Agreement with the other models is excellent for both smooth and rough bottoms.</td>
</tr>
<tr>
<td>PROSIM</td>
<td>C-SNAP, RAM in SWAM’99(3) at 25 Hz, 100 m depth (Nielsen &amp; Jensen, 2001) [191]</td>
<td>The adiabatic nature of range dependence in PROSIM caused deviations in levels at certain depths and ranges, but there was a consistency in the arrival structure of the received time series between the coupled-mode and adiabatic model. The difficulties in applying the adiabatic model were not general, as the success of predictions depended on the specific underwater environment. It is believed that the adiabatic model is sufficiently accurate for practical applications in the majority of range-dependent environments, as the lack of environmental information is often the limiting factor in the prediction performance.</td>
</tr>
<tr>
<td>RAM</td>
<td>None listed.</td>
<td>Frequently used as a benchmark model for testing other model approaches.</td>
</tr>
<tr>
<td>SPADES</td>
<td>None listed.</td>
<td>SPADES is a model with lots of versatility but moderate fidelity. It requires significant user attention on input parameters to get higher fidelity.</td>
</tr>
<tr>
<td>TRACEO</td>
<td>KRAKEN, BELLHOP at 50 Hz, deep water, Munk profile (Rodriguez, 2011, [243])</td>
<td>Good agreement.</td>
</tr>
<tr>
<td></td>
<td>JEPE, REV3D, XRAY at 25.6 kHz (Ey &amp; Rodriguez, 2012) [244]</td>
<td>Good agreement.</td>
</tr>
<tr>
<td>WAVEQ3D</td>
<td>Analytic solutions for ray paths in three deep water tests (Reilly &amp; Potty, submitted 2012) [202]</td>
<td>Cycle range differences ~ 0.05%.</td>
</tr>
<tr>
<td></td>
<td>Analytic solutions for travel time and arrival angles for Lloyd’s mirror on a spherical earth which produces unexpected caustics from the focusing of the concave surface of the earth (Reilly &amp; Potty, submitted 2012) [202]</td>
<td>Most errors were very slight and were attributed to the choice of angle and time sampling for WaveQ3D.</td>
</tr>
<tr>
<td></td>
<td>Analytic solution for TL for Lloyd’s mirror at 2 kHz (Reilly &amp; Potty, submitted 2012) [202].</td>
<td>Some errors, &lt; 1 dB, were found at the very short ranges up to 2 km and these were attributed to surface reflection inaccuracies.</td>
</tr>
<tr>
<td></td>
<td>GRAB, FFP, 2 kHz. (Reilly &amp; Potty, submitted 2012) [202]</td>
<td>Found similar eigenray accuracy and predict similar results with GRAB except in the shadow zone where WAVEQ3D has a more gradual roll-off.</td>
</tr>
</tbody>
</table>
Model-to-model comparisons were also made at the PE Workshops. In (PE Workshop II, 1993, [245]), seven test cases were defined:

1. Lloyd's Mirror – wide angle propagation
2. Conservation of energy in range-dependent propagation
3. Range dependent shear wave propagation
4. Backscatter from a waveguide discontinuity
5. Propagation in constantly changing environment
6. Underwater acoustic model predictions versus measured field data
7. Long range propagation in a leaky surface duct.

The test cases were tackled by 18 PE models (both basic research models and application-operational models) and two Normal Mode models; using COUPLE as the reference solution. The Workshop organizers felt that all the models demonstrated very good agreement. The conclusion of the Workshop was:

“The present PE models can be used to accurately simulate underwater acoustic fields in a highly complex ocean environment (e.g. highly range-dependent propagation over shear-supporting ocean bottoms, including backscatter.” [245]

They further found that the ‘research models’ were able to produce results that were benchmark accurate, fulfilling the requirement of research models that are used to identify, isolate and understand the physical mechanisms involved in propagation and scattering, whereas the ‘operational models’ have the need for computational speed and portability, which requires trade-offs between accuracy and speed. The Workshop conclusions also state:

“The workshop results indicate that some of the operational PE models can be very accurate when not constrained by operational parameters.” [245]

### 4.1.1.4 Model-to-Data Comparisons

Model-to-data comparisons are less frequently published. In Table 4-2 we present those models that have provided these comparisons.
## Table 4-2 Model-to-data comparisons for some propagation models

<table>
<thead>
<tr>
<th>Propagation model</th>
<th>Data used for comparison</th>
<th>Remarks/ Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>BELLHOP</td>
<td>Signal fluctuations due to a rough sea surface. These data were modeled by Monte Carlo techniques on an altimeter file of surface realizations using the JONSWAP surface spectrum. The frequency is 1-18 kHz. The standard deviation of arrival time (a) and arrival angle (b) versus wind speed is shown at right, for the first surface reflected path. Good results are obtained at lower wind speeds. (Heitsenrether &amp; Badiey, 2004) [204]</td>
<td><img src="image.png" alt="Graph" /> Good results are obtained at lower wind speeds. (Heitsenrether &amp; Badiey, 2004) [204]</td>
</tr>
<tr>
<td></td>
<td>Channel impulse response for an LFM Chirp (8-16 kHz). Broadband signals were modeled using SALT arrival tables. Measured data is an average over 40 chirps spanning 10 sec. (Hursky, Porter, Siderius, &amp; McDonald, 2004) [107]</td>
<td><img src="image.png" alt="Graph" /> Graphs are shown in Figure 2-15 in this report (Section 2). Figures display measured (upper) and modeled (lower) channel impulse response as a function of range.</td>
</tr>
<tr>
<td></td>
<td>Data showing measured correlation time series using the Hydra array near San Diego in 100m water is compared to modeled correlograms. (Porter,</td>
<td>Very good results</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Propagation model</th>
<th>Data used for comparison</th>
<th>Remarks/ Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hursky, Tiemann, &amp; Stevenson, 2001 [205]</td>
<td>Data from whale sightings are used in a model-based localization technique in California. (Tiemann, Porter, &amp; Hildebrand, [246])</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Localization of whales in Hawaii demonstrated using time-difference of arrivals from model-based simulations. (Tiemann, Porter, &amp; Frazer, [247])</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Localization of whales at the Pacific Missile Range Facility and San Clemente Island are demonstrated using model generated ambiguity surfaces. (Tiemann, Porter, &amp; Hildebrand, [248])</td>
<td></td>
</tr>
<tr>
<td>CASS/GRAB</td>
<td>Received reverberation levels in torpedo test run data. [Personal Communication]</td>
<td>Successful matching at high frequencies over a variety of range-dependent bottom types.</td>
</tr>
<tr>
<td>C-SNAP</td>
<td>Average $TL$ and $TL$ fluctuations from a range independent site. The frequency range was 50-140 Hz and the water depth was 20-60 m. (Duarte, 1994) [206]</td>
<td>Most successful of the several models tested, but less accurate in sites where no geoacoustic data existed and geoacoustic input was extrapolated.</td>
</tr>
<tr>
<td></td>
<td>$TL$ measured over 18 hours at 250, 450, and 750 Hz at fixed range of 2 and 4 km.</td>
<td>See Figure 4-5, blue line (C-SNAP) vs red line(data)</td>
</tr>
<tr>
<td>INSPIRE</td>
<td>Wide array of measurements of impact piling noise. (Nedwell, Barham, &amp; Mason, [90])</td>
<td>Agreement within 1 to 2 dB</td>
</tr>
<tr>
<td>KRAKEN</td>
<td>Received levels from airgun sources to tagged sperm whales. (DeRuiter S., Tyack, Lin, Newhall, Lynch, &amp; Miller, 2006) [141]</td>
<td>Kraken was used to supply the modal structure for the comparisons</td>
</tr>
<tr>
<td>MMPE</td>
<td>$TL$ in two extremely shallow water environments. The frequency was 250 Hz to 20 kHz over a range of 100 m. Environmental inputs were averaged over a 6-month</td>
<td>MMPE output $TL$ was averaged over depth. In the frequency range 1-16 kHz, average deviation between model and data was within 5 dB.</td>
</tr>
<tr>
<td>Propagation model</td>
<td>Data used for comparison</td>
<td>Remarks/Results</td>
</tr>
<tr>
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</tr>
<tr>
<td>MOCASSIN</td>
<td>Baltic Acoustics on Rocky Outcrops (BAROC) experiment measuring TL. (Pihl, Abrahamsson, Ivansson, &amp; Schon, 2011) [209]</td>
<td>TL levels between model and measurement were found to be consistent. MOCASSIN was used as a forward model for the inversion of bottom data in this experiment.</td>
</tr>
<tr>
<td>ORCA</td>
<td>Source tracking in a shallow water, low shear speed site at 45 and 72 Hz. (Yeremy, Ozard, Chapman, &amp; Wilmut, 1996) [210]</td>
<td>ORCA was used to supply modal information. The modal structure was then post-processed. Results were very encouraging and high MFP correlations were obtained, despite the incomplete environmental knowledge of the geoaoustic bottom profile.</td>
</tr>
<tr>
<td>POPP/PROLOS</td>
<td>Shallow water Mediterranean reverberation, 631 Hz, with bottom properties based on core samples. (Ellis, A shallow water normal-mode reverberation model, 1995) [212]</td>
<td>ORCA generated a synthetic time signal to compare with the data. The agreement was deemed quite good with many interference features being common to both model and measurement.</td>
</tr>
<tr>
<td>Propagation model</td>
<td>Data used for comparison</td>
<td>Remarks/ Results</td>
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<tr>
<td></td>
<td>Monostatic towed array reverberation data (top) gathered on the Malta Plateau at 1750 Hz. Model comparisons (bottom) are made in an Nx2D configuration, with adiabatic range dependence, a uniform half-space bottom and a downward refracting profile. (Ellis &amp; Preston, 2011) [213]</td>
<td></td>
</tr>
<tr>
<td>QUONOPS</td>
<td>Comparison between the noise predicted by QUONOPS and the <em>in situ</em> measurement made in the vicinity of the south-going route of the Ushant separation scheme. Work done in partnership with SHOM, ENSTA Bretagne and Quiet-Oceans. [Personal Communication]</td>
<td></td>
</tr>
<tr>
<td>Propagation model</td>
<td>Data used for comparison</td>
<td>Remarks/ Results</td>
</tr>
<tr>
<td>-------------------</td>
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<td>------------------</td>
</tr>
<tr>
<td>RAM</td>
<td>In-house laboratory experiments of a scale model of an elastic ocean bottom constructed from a PVC slab.</td>
<td><strong>Remarks/ Results</strong></td>
</tr>
<tr>
<td></td>
<td>Transmission loss data (solid line) from (a) 125 kHz, (b) 200 kHz and (c) 275 kHz with a sloping placement of the PVC bottom. Calculations (dashed line) are made from the elastic version of RAM. A fluid version of RAM was also tested against these data but it failed to match the data levels by 10’s of dBs, proving the importance of accounting for the shear properties of the bottom.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>It must be noted that adjustments to the geometric positions of the source, receiver and slab in the model inputs were required to best account for tank geometry variations and initial errors of on average 10%. (Collis, Seigmann, Collins, Simpson, &amp; Soukup, 2007) [214]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Airgun source recorded on tagged sperm whales. (DeRuiter S., Tyack, Lin, Newhall, Lynch, &amp; Miller, 2006) [141]</td>
<td>RAM was exercised across the frequency band of the airgun and post-processed with Fourier transforms to model multipath arrivals recorded on the whales.</td>
</tr>
<tr>
<td>Propagation model</td>
<td>Data used for comparison</td>
<td>Remarks/ Results</td>
</tr>
<tr>
<td>-------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>TRACEO</td>
<td>In-house laboratory experiments of a scale model of an elastic ocean bottom constructed from a PVC slab. (The same data as displayed in the RAM entry)</td>
<td>Transmission loss data (solid line) from (a) 125 kHz, (b) 200 kHz and (c) 275 kHz with a sloping placement of the PVC bottom. Calculations (dashed line) are made from TRACEO, which has the capability to handle an elastic bottom. In comparison with the RAM results, TRACEO is only slightly less accurate. Note that for this upslope case corresponding to an ( h/\lambda ) ratio as small as three at the shallow end of the bottom, the Gaussian Ray method still yields good results. (Rodriguez, Collis, Simpson, Ey, Schneiderwind, &amp; Felisberto, 2012) [215]</td>
</tr>
<tr>
<td>WKBZ</td>
<td>Transmission loss data from the Philippine Sea at 109, 300, 640, and 860 Hz. (Zhang, Results coincide well, when using the adiabatic range dependence.</td>
<td></td>
</tr>
</tbody>
</table>
### Section 4 - Critical Assessment of Acoustic Models for E&P Industry

<table>
<thead>
<tr>
<th>Propagation model</th>
<th>Data used for comparison</th>
<th>Remarks/ Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>He, Liu, &amp; Akulichev, 1995)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Transmission loss data from a North Pacific channel. (Zhang &amp; He, 1995) [203]</td>
<td>The comparison showed that both the arrival times and amplitudes calculated from the WKBZ model are well consistent with those from a conventional normal code, but the computation speed of the WKBZ code is faster by over a factor of 100.</td>
</tr>
<tr>
<td></td>
<td>Broadband matched field localization in the East China Sea. (Zhang, Li, Yan, Peng, &amp; Li, 2002) [112]</td>
<td>The model used for the matched field was based on WKBZ.</td>
</tr>
<tr>
<td>WOSS</td>
<td>At-sea experiments of acoustic modem performance. Metrics include throughput efficiency, end-to-end latency and number of data attempts. (Petrioli, Petroccia, &amp; Potter, 2011) [216]</td>
<td>Comparisons validate not only the relative performance of different classes of MAC protocols but also the validity of the simulation process itself. The conclusion was “that simulations can be used to accurately predict real-life performance at sea, provided care is taken to capture all the important acoustic propagation physics and the physical attributes of the hardware used in the experiment.”</td>
</tr>
</tbody>
</table>

#### 4.1.2 Sensitivity to Inputs

Acoustic sound waves propagating in the real ocean are very dependent upon and sensitive to the environment. The degree of the sensitivity depends on where the energy is in the waveguide. The wave’s energy is injected into the ocean at the source depth and directed by the sound speed profile and the location of the boundaries.

For example, if there is a downward refracting profile then we might expect sensitivity to bottom properties but if the profile is upward refracting, the surface interaction becomes important. Why does sensitivity matter?

> It matters because small fluctuations in the environmental properties can have a major impact on the direction and strength of the wave, provided the changing parameters occur spatially where there is a lot of acoustic energy propagating.

> A high fidelity propagation model that represents the physics well will automatically show the same sensitivities, meaning that small changes in the inputs can dramatically change the predictions from the model. This high sensitivity is not a failure of the acoustic model; it is a fact of propagation in the real ocean.

Unfortunately, over the vastness of the ocean with the lack of timely and detailed environmental descriptions, the models cannot hope to reproduce the field, as it exists. That is why the admonishment is always made by the model developer to provide a well-characterized data set. He knows that a slight shift in the geometry or sound speed profile can cause major shifts in the locations of the coherent structures of the sound field predicted by his model. (See for example the discussion about field shifting for better accuracy estimates around Figure 4.1 in section 4.1.1.1.)
In the real world, all sounds have bandwidth. As such, range averaging (4.1.3.2) may be used to accommodate local fluctuations in SSP and bottom topography. What can't be compensated for are regions with wholly unknown bottom loss factors and wholly discontinuous water mass changes seen as an acoustic front, e.g. working an area with duct to the north and CZ to the south; in the same area basin, it would be imperative to obtain a new SSP survey right after a major storm.

A method must be found to account for all the potential uncertainties in the environment to which sound propagation is highly sensitive, or equivalently the uncertainties in the input parameters to which the acoustic model is highly sensitive.

The conclusion of most researchers is that for practical prediction purposes in real ocean environments using high fidelity models, some kind of statistical approach is necessary to counteract the high sensitivity in the face of the unknown.

In the next sub-sections we present some specific examples of propagation and/or model sensitivity.

### 4.1.2.1 Sensitivity to Sound Speed fluctuations

#### 4.1.2.1.1 Sensitivity Example 1

The first example of sensitivity to sound speed comes from a famous discovery made by the early researchers who were doing ship-to-ship echo ranging in the years shortly before World War II. The sailors obtained good echoes in the morning, but after lunch the signals mysteriously went away. This mystery was called the 'afternoon effect' (Urick R. J., 1983) [217].

When it became clear that the signals actually were weaker in the afternoon, the cause was discovered.

- In the morning, the surface temperature was cooler than that in waters below and a surface duct was formed with upward refraction that channeled the sound from ship to ship.
- In the afternoon, the surface warmed with the sun and the surface duct disappeared, replaced by downward refraction.
- These slight thermal gradients, hitherto unsuspected, were responsible for refracting the sound deep into the depths of the sea.

Figure 4-3 displays an example of the 'afternoon effect'. The sound speed profile (SSP) used for this example is shown in the top left figure. In the top right figure, the transmission loss is plotted as a function of range and depth over a rough bottom using the black profile, which features a surface duct. The sound trapped by the upward refraction within the surface duct between 0 and 30 m depth is evident. By warming the surface temperature just 1.5°C, the sound speed increases to the red line near the surface of the top left figure, which now causes only downward refraction.

The bottom figure is a plot of the absolute $TL$ differences between predictions using the black SSP and those with the red changes to the SSP at the surface, that is, the differences between having and losing
the surface duct. It shows the resulting large changes in transmission loss (up to 30 dB or more) that occur throughout the ocean, not just in the upper surface region, due to the loss of the surface duct.

This dramatic change in propagation from the warming of the surface is the ‘afternoon effect’ but even without the loss of the surface duct, small changes in the surface temperature can cause large changes throughout the water column.

**Figure 4.3 Demonstration of the ‘afternoon effect’**

Top left: SSP (black) with surface duct in first 30m. A 1.5°C difference in the surface temperature (shown in red) removes the surface duct. Top right: TL versus range and depth using the black SSP with the surface duct. Bottom: Absolute value of TL (dB) differences with and without the surface duct. These differences occur not only within the duct area but scattered throughout the water column.
4.1.2.1.2 Sensitivity Example 2

In a second example, below (Masui & Pecknold, 2008) [218], transmission loss measurements were made along the continental shelf of the coast of New Jersey as part of the Shallow Water Acoustics 2006 (SWo6) experiment. The experimental area was characterized carefully to examine the sensitivity of the propagation to fluctuations and uncertainty in the environment.

Figure 4-4 (top) shows the sound speed profiles taken over the course of one day at 30-minute intervals, with the receiver depths noted along the margin. The greatest change in the profiles occurs in the downward refraction region between 10 m and 30 m depth. While the sub-surface waveguide does not disappear, it does change its axis depth around the depths of the receivers. Furthermore, these changes are not linearly related to the time of measurement.

Figure 4-4 (bottom) shows transmission loss variability over 7.5 minutes for one set of measurements of 224 Hz and 400 Hz tones denoted by the color of the symbol at three depths (22.1 m, 34.8 m and 51.7 m) denoted by the type of the symbol. The vertical axis indicates measured transmission loss between a fixed source and a fixed receiver 31 km distant, upslope from the receiver array. Source and receivers were omnidirectional. The source depth was 49 m, in 54 m of water. The aim of this portion of the experiment was to make measurements of acoustic propagation over an extended time period with fixed source and receiver positions, while the environment was fluctuating. This particular figure shows one of a number of similar sets of data; the report describes the statistics of the measured transmission loss in more detail, both for this set of transmissions and for a different set of transmissions over a different propagation path. This variability, caused by the fluctuating sound speed profile, is up to 10 to 15 dB depending on the receiver depth and frequency.

Jensen (1988) [109] shows an interesting comparison of transmission loss at multiple frequencies vs. range, as compared to normal mode models, with model-data agreement at similar ranges (20-30 km) to within about ±8-10 dB (Figure 7 of Jensen). It should be noted that Jensen also averaged data over 1/3-octave bands to attempt to reduce or eliminate variability, which is what Figure 4-4 is attempting to illustrate. The figure does not include a model-data comparison, nor does it include results over multiple ranges (some of the results from the SWo6 trial using the same receiver, although different sources, with model-data transmission loss comparisons can be found in other papers, including Pecknold et al. (2008) [219]). Instead, it provides an illustration of the observation, pointed out by the reviewer, that there can be a high ping-to-ping variability over a short period of time even in a fixed experimental setup. The Canadian Defence report [218] (and Pecknold et al, [219]) calculate the bounds of propagation variability that should be observed based on the environmental variability, in this case primarily the envelope of expected changes in the sound speed profile, along with how those changes affect boundary interactions. This is done to determine to what extent the ping-to-ping variability can be constrained given the existing knowledge of the environment, as well as whether better environmental information can actually improve propagation modeling.
Figure 4-4 Left: sound speed profiles measured with XSVs for August 1, 2006. Right: TL variability over 7.5 minutes for one set of measurements of 224 Hz and 400 Hz tones. [218]
4.1.2.1.3 Sensitivity Example 3

In a third example of sensitivity to sound speed, experiments were conducted at the Centre for Maritime Research and Experimentation (CMRE), an executive body of NATO’s Science and Technology Organization (STO), to use measured data for matched-field inversions to estimate seabed properties [225].

These experiments showed that signals were decorrelated in less than an hour or at ranges beyond a few kilometers due to sound speed fluctuations. Beyond a few kilometers, in the frequency range from 250 – 750 Hz, the variability destroyed coherent processing and the possibility to predict acoustic propagation.

Figure 4.5 displays the losses versus depth at a fixed range measured and predicted over an 18 hour span. In each figure, the gray and black shaded areas are the modeled and experimental standard deviation of the losses, respectively, over 18 hours. The fluctuating sound speed profile has introduced a large variation in the losses, on the order of ±5-10 dB.

![Figure 4.5 Transmission losses plotted versus depth](image)

The top row is for a 2.055 km fixed position while the bottom row is for a 10.4 km fixed position. The columns show frequencies of 250 Hz, 450 Hz and 750 Hz. In each figure, the gray and black shaded areas are the modeled and experimental standard deviation of the losses, respectively, over 18 hours. The acoustic model C-SNAP (blue) and mean of the experimental data (red) were averaged over a 10 Hz band. [225].
### 4.1.2.1.4 Sensitivity Example 4

In a fourth example using a numerical simulation [123], the finding of a large scintillation index\(^{58}\) is demonstrated using a full-wave model at 500 Hz in 200 m water. These are Monte Carlo numerical studies of intensity fluctuations in a realistic shallow water environment including internal wave fluctuations and bottom roughness.

In this simulation, the sound speed is expressed as a deterministic sound speed plus a random, time space-varying component to replicate the statistical nature of the small-scale oceanic variability. The bathymetry was assumed to be flat at 200 m depth with a random component simulated using a power-law spectrum, having an rms vertical displacement of 5 m and a horizontal correlation length of 1000 m. This type of depth variation would be representative of a randomly rough bottom rather than a range dependent bathymetry. Results of this study show that the sound intensity at distant receivers (up to 100 km) scintillates dramatically. The intensity variance increases rapidly with propagation range and is significantly greater than unity at ranges beyond about 10 km. The distribution of the intensity was found to be lognormal, so that large deviations from the mean are common.

### 4.1.2.1.5 Sensitivity Example 5

A last example involves studies of the derivative of BELLHOP’s equation for intensity with respect to a random addition to the sound speed in section 2.1.3.2 Uncertainty Modeling. The variance of the intensity is related to the derivative multiplied by the variance of the randomness in the speed. The closed form equation for the derivative is found to be proportional to the inverse of the sine of the propagation angle.

This means that at the depth where the ray turns due to refraction, the derivative becomes very large because the angle is near zero, making the variance very large. Ducts, which contain many rays oscillating rapidly between the duct boundaries, will provide a lot of these very large derivative values near the ray turning points and the variance there will be very sensitive to small fluctuations in the speed. Even outside the duct, fairly small changes in the depths of the minima and maxima result in changes of the intensity for different receiver depths.

### 4.1.2.2 Sensitivity to Attenuation

In Figure 4-6 the test case 6 with measured data in the PE Workshop II \([245]\) representative comparisons in TL are shown at 15 Hz (\(\lambda = 100\) m) for two of six PE models, (IFDPE and PAREQ) using water column attenuations of 0.12 dB/\(\lambda\) and 0.012 dB/\(\lambda\) for the upper row and lower row respectively.

This change raised the predictions by over 10 dB, bringing them more in line with the measured data. It is interesting to note that, at first, none of the models could match the original data given for the test case. The conclusion of the workshop was that either there was an error in the data or an error in the listed environmental data, or indeed, when the data were reprocessed, an error was found. Quoting from the workshop proceedings:

---

\(^{58}\) The scintillation index (SI) is defined as the second moment of the intensity, the intensity variance, normalized by the square of the mean intensity.
“Test case 6 illustrates a recent trend in ocean data-model comparisons.

The PE models have become so accurate that a poor comparison between model prediction and experimental data led to the questioning of the accuracy of the data. A decade ago, when the first PE Workshop was held, no model’s prediction would have been seriously believed if it disagreed with the data.”

4.1.2.3 Sensitivity to Range Dependence Sampling

An example of the sensitivity to the choice of interpolation of range dependence sampling comes from a numerical simulation that was conducted for propagation through a cold water eddy [220] using a Parabolic Equation solution.

A coarsely sampled set of sound speed profiles was tested (sampled every 60 km samples in a 250 km wide Gulf Stream cold water ring). The continuously changing sound speed gradients in the eddy were replaced by a series of discrete increments in the model. When the range intervals between samples were large, use of these discrete increments led to a very poor approximation of the continuously changing value. This numerical experiment suggested that profiles must be input every 2 to 3 km to adequately sample the horizontal gradients in a changing environment such as a Gulf Stream ring. Quoting [220]:
"It is shown that an error of 18 dB is observed arising from a choice of inappropriate range intervals at which new profiles are input. Errors of this magnitude can lead to a highly inaccurate assessment of the acoustic impact of range-dependent anomalies. This example demonstrates the importance of providing proper input to these acoustic models and supports the conclusion that interpolation routines should be made standard features of range-dependent simulation techniques."

4.1.3 High Fidelity versus Low Fidelity

High fidelity models are those that correctly produce the coherent acoustic field in time and space. With this definition, almost all of the models listed in this report (except the energy flux models) are capable of high fidelity. These models provide the detailed phase relationship of the acoustic field, but for practical purposes, the details are often too confusing because they present deeply modulated spatial interference patterns.

For example, in Figure 4-7 the SAFARI model (now called OASES) is exercised for a North Atlantic winter profile [221] at 150 Hz in 3600 m water in which there was a 500 m surface duct.

- The left hand figure shows a single TL curve from SAFARI at 150 Hz.
- The right hand figure shows the frequency-averaged curve over a 1% bandwidth about 150 Hz, using 129 SAFARI runs.

Adding the acoustic power from adjacent frequencies in a broadband signal gives a blurred and smoothed representation of the field at the center frequency. In the case shown here, the frequency-averaged result was entirely equivalent to the 1% range averaged result.

![Figure 4-7 SAFARI transmission loss versus range Left: Single run at 150 Hz. Right: Average of 129 runs in a 1% bandwidth about 150 Hz. [221]](image)

Spatial fluctuations in transmission loss caused by interference patterns are the hallmark of high-fidelity models (see for example, the TL plots in the RAM entry in Table 4-2).

Spatial interference patterns are important for detailed analysis of a particular feature in academic studies, but they are not the best representation for system performance prediction or exposure prediction purposes, particularly if the properties of the environment such as the sound speed profile or receiver depth are not accurately known, since differences in these parameters cause the acoustic field to shift in space. For these purposes, lower fidelity may be a better choice.
Section 4 - Critical Assessment of Acoustic Models for E&P Industry

4.1.3.1 Incoherent Summation
Some models are capable of providing an incoherent result. Those models that split the acoustic energy into rays or modes achieve this. Then, in the summation of terms, the intensity can be formed by the sum of magnitude squares of pressures, removing the phase interference patterns.

- In the case of Ray theory, this produces a reasonably smoothed version of the coherent summation if a few rays do not dominate the propagated field.

- In the case of incoherent summation in mode theory, all range-produced phase relationships between the modes are lost, resulting in just a smooth cylindrical decay with range. This is unfortunate because the major structures of the sound field are lost along with the ‘noise’.

- The Normal Mode model WKBZ separates the modes that are entirely waterborne from those that interact with the bottom. The contributions of the two types of modes to the field are different.

- The characteristics of long range propagation, especially the fields in convergence zones, are mainly determined by the waveguide modes, while the fields in the deep shadow zones are mainly contributed by the bottom reflection ones.

- Since there are a great number of bottom reflection modes, the interference periods of which are much shorter, the field of bottom reflection modes is suitable for smoothly averaging. Then the whole intensity is expressed as a sum of the coherently summed intensity from the waveguide plus the sum of smoothly averaged intensity from the bottom reflection modes.

4.1.3.2 Range and Frequency Averaging
The result of applying frequency averaging is shown above in Figure 4-7, where the authors state that the 1% bandwidth average was entirely equivalent to a 1% range average [221]. In practice, in Naval tactical decision aides (PCIMAT for example), the transmission loss is always range averaged to provide a smoothed prediction of signal excess. The developers of MOCASSIN recommend that the $TL$ be smoothed by splines.

A useful relationship for performing frequency averaging using range substitution is demonstrated by Siderius and Porter [71] and is valid for range dependent environments. By this technique, a broadband result can be constructed by a single transmission loss calculation at the band's center frequency, by shifting the range with the ratio $ffc$ prior to addition.

The conclusion of this discussion is that for practical prediction purposes in real ocean environments with broadband sources, the output from a high fidelity model needs to be smoothed by range and/or frequency averaging to provide useful measures of the acoustic field. Furthermore, for meaningful predictions of the sound exposure level (SEL) in mammal exposure software, an estimate of the mean expected field and its variance is more important than a rapidly spatially varying prediction.

4.2 Identification of Best-Suited E&P Models
In this section, we discuss the attributes that are required for E&P modeling for marine animal exposure. We then discuss those models that may provide these attributes.
4.2.1 Most Important Attributes for E&P Modeling

The particular needs for the modeling of the marine environments where E&P developments may occur are predominately related to frequency, source characterization, spatial coverage and metrics of exposure. The following paragraphs provide an explanation of each.

4.2.1.1 Frequency Ranges

The range of frequencies required to model all the sources of sound produced by E&P activities is very broad and has been arbitrarily divided into four bands, listed below. No one model can be employed with confidence in all bands, either because of physics limitations or run time considerations.

Below, we list the theoretical approaches most applicable to these frequency ranges. Not surprisingly, the water depth-to-wavelength ratio \((h/\lambda)\) or equivalently, the water depth-frequency product divided by the sound speed \((f\cdot h/c)\) is the quantity that is used to determine applicability for Ray theory, and runtime and/or memory requirements are the quantities used to determine applicability for Normal Mode, PE and Wavenumber Transforms.

1. Very low frequency, VLF, \((f = 10 \text{ to } 100 \text{ Hz}); \text{ wavelengths } (\lambda = 150 \text{ m} – 15 \text{ m})\)
   - The theoretical approaches most applicable to this frequency band are Normal Mode, Wavenumber Transform, and PE (the speed of calculation depends on water depth). At these low frequencies, all of these techniques need detailed sediment layering information because the sound penetrates deeply into the sediments.
   - Ray theory is typically not considered valid if the water depths are less than 1500m – 150m for 10 Hz and 100 Hz respectively, and if used, it requires a detailed bottom reflection coefficient that includes shear and sub-bottom reflections.
   - The models OASES (formerly SAFARI) or BOUNCE (available on www.oalib.hlsresearch.com) can supply these reflection coefficients. However, a common Ray theory approximation neglects the beam displacement for rays emerging from the bottom. Therefore the head wave from the sediment (important at low frequencies over clay bottoms) is not included.

2. Low frequency, LF, \((f = 100 \text{ Hz} \text{ to } 1 \text{ kHz}); \text{ wavelengths } (\lambda = 15 \text{ m} – 1.5 \text{ m})\)
   - The model classes suitable to this frequency range are PE and Normal Mode. Knowledge of the upper layers of the sediment is important.
   - Ray theory is applicable if water depths exceed 150 m – 15 m for 100 Hz and 1 kHz respectively, with a detailed bottom reflection coefficient that includes shear (below 200 Hz) and layer reflections, although the absence of the head wave from rays emerging from slow speed sediment is still a problem.

3. Mid-frequency, MF, \((f = 1-10 \text{ kHz}); \text{ wavelengths } (\lambda = 1.5 \text{ m} – 0.15 \text{ m})\)
   - The theoretical approach most applicable to this frequency range is Ray theory.
   - In shallow water, some PE codes and some Normal Mode codes can be employed, although runtime and memory requirements may be a limitation.
   - In this band, the surface interaction becomes important, and a sophisticated surface reflection coefficient that includes the effect of entrained surface bubbles is needed.

4. High frequency, HF, \((f > 10 \text{ kHz}); \text{ wavelengths } (\lambda < 0.15 \text{ m})\)
   - The only viable model class at these high frequencies is Ray theory. For these small wavelengths, all the environmental inputs will be very coarsely sampled, so any modeled phase coherence is automatically suspect and interpretations based upon this output should be approached with extreme caution.
The use of incoherent phase summations should be employed. In the case where incoherent output is not available, averaging techniques employed in conjunction with the acoustic field predictions typically lead to results that are more easily interpreted.

These four frequency ranges and recommendations are summarized in Table 4-3.

**Table 4-3 Frequency ranges and model classes most appropriate for use for selected E&P activity**

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>Model Class</th>
<th>Region of Applicability</th>
<th>Relevant Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLF</td>
<td>Normal Modes</td>
<td>Shallow water</td>
<td>Air gun arrays, explosives, drilling</td>
</tr>
<tr>
<td></td>
<td>Wavenumber Transform</td>
<td>Near field and detailed sediment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PE</td>
<td>Deep water or complicated bathymetry</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LF</td>
<td>Normal Modes</td>
<td>Shallow water</td>
<td>Pile driving, construction and maintenance ships, air guns, explosives</td>
</tr>
<tr>
<td></td>
<td>PE</td>
<td>Long range, deep water</td>
<td></td>
</tr>
<tr>
<td>MF</td>
<td>Rays</td>
<td>Everywhere except very shallow water or thick soft sediments</td>
<td>Sparkers, boomers, chirps, ship noise</td>
</tr>
<tr>
<td></td>
<td>Normal Modes</td>
<td>Shallow water 1-2 kHz</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PE</td>
<td>Complicated bathymetry, long range 1-2 kHz</td>
<td></td>
</tr>
<tr>
<td>HF</td>
<td>Rays</td>
<td>Everywhere</td>
<td>Echo sounder</td>
</tr>
</tbody>
</table>
4.2.1.2 Source characterization

<table>
<thead>
<tr>
<th>1. Horizontal and vertical beam patterns and/or spatial description of array elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Figure 2-3 displays a typical beam pattern 2D representation from a set of four arrays and Table 2-7 presents the beam pattern capabilities of the models in this survey. In general, vertical beam patterns are easy to apply in Ray theory and Mode theory because the field is partitioned by arrival angle.</td>
</tr>
<tr>
<td>• For PE, vertical directionality is more complicated to apply because this theory assumes that energy propagates primarily in the horizontal direction, which is valid in the far field where energy is trapped with low grazing angles.</td>
</tr>
<tr>
<td>• For PE, vertical beam patterns can be handled by transforming the standard starting field from coordinate space to wavenumber space, then filtering with the beam pattern, then inverse transforming back to the spatial coordinate to obtain a new starting field.</td>
</tr>
<tr>
<td>• Horizontal beam patterns can be applied to those models with bearing coverage by simply varying the source level in azimuth.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2. Broad band spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>• True time-domain broadband modeling using Fourier synthesis requires calculations at hundreds of discrete frequencies and is very computationally intensive.</td>
</tr>
<tr>
<td>• Most broadband models use center-frequency of 1/3-octave bands to produce energy-based received levels suitable for impulsive noise sources.</td>
</tr>
<tr>
<td>• Table 2-4 describes the broadband capabilities of the models in this survey.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3. Time series generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Sources that generate a shock wave exhibit a series of pulses in time, first from the shock, then from the oscillation of the bubble formed by the shock.</td>
</tr>
<tr>
<td>• Measures of this type of source include peak-to-peak duration, primary-to-bubble duration and bubble period, and the metric is often defined in terms of the duration of 90% of the energy.</td>
</tr>
<tr>
<td>• The output required from an acoustic propagation model is the channel impulse response, which is then convolved with the source in post-processing.</td>
</tr>
<tr>
<td>• Listed in Table 2-5 are the propagation and application models in this survey that can provide the quantities necessary to readily produce a time series output.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>4. Multiple arrays forming a composite sound field</th>
</tr>
</thead>
<tbody>
<tr>
<td>• The predictions of the sound field from multiple independent sources will require post-processing in all the models in this survey.</td>
</tr>
</tbody>
</table>
4.2.1.3 Spatial capability

### 1. Near field capability
- Table 2-7 lists the near field capability of the models in this survey. We note that the definition of near field will depend on the source characterization because airgun arrays have spatial extent as opposed to single airgun acting like a point source.
- Near field can be described as ranges less than the source aperture dimension-wavelength ratio, or in the case of point sources, at ranges less than one-quarter wavelength.
- Typically, ray models are applicable. PE models may be used if higher order terms in their expansions are used. The discrete modes computed by many Normal Mode codes are not suitable for near field predictions because with pulsed sources, the sound has not propagated sufficiently in depth to establish standing wave patterns.
- Normal Mode codes that compute the continuous spectrum (also called leaky modes) can be used for near field calculations. Also, Wavenumber Transform models can operate in the near field.

### 2. Range dependence
- All of the environmental properties of the ocean are dynamic in time or space. As one moves away from the source, weather and wave action will change the upper layers of the sound speed profile.
- The depth of the bottom (bathymetry) changes as the sediments change, often with patches of sediment ponds, rocky outcrops, and slopes toward shore. For the best characterization of the environment, the range dependence of the sound speed, bathymetry, sediment properties (for low frequency) and surface conditions (for high frequency) are required.
- Table 2-6 describes the sampling techniques of the range dependent models in this survey. We note that for many of the models, the range dependence is limited to bathymetry. Some models can also use horizontally varying sound speeds and sediments.
- Only a few accommodate changing surface conditions.

### 3. Bottom characterization
- The characterization of the bottom is an important component of acoustic modeling in all frequency regimes.
- In the VLF and LF frequency bands, the sound penetrates deeply into the sediment. Knowledge of the sub-bottom composition and its elastic properties are therefore important.
- Table 2-7 and Table 2-8 list the capabilities of the models in this survey to perform sub-bottom propagation and to include the effects of elastic sediments in the generation of shear waves.
- The classes of Normal Mode, Parabolic Equation, and Wavenumber Integration model sediment penetration while Ray Theory does not.
- In the MF and HF frequency bands, the sound has little minimal penetration, however the surficial character of the sediment is more important.
- Rough surface scattering from shells and rocks may be an important contributor to the losses.

### 4. Azimuthal coverage
- Table 2-6 presents the inherent area coverage of the propagation models. The application models cover the area of interest using Nx2D techniques, which means they compute N azimuthal directions with independent propagation radially outward along each bearing.
- An azimuthally varying source level easily accommodates a horizontal beam pattern.
- In Table 2-14 which lists future plans, we find that many of the evolving models of today are working to include the mathematics to compute a true 3D capability. However, the azimuthal coupling, that is, energy passed out of plane from one azimuth to the next by sloping bottoms and canyon walls, is very low, so the Nx2D approach is reasonable (and much faster) in all but the most extreme cases.
5. Active capability

- In some cases, active echolocation techniques may be employed to determine the presence of marine animals. For these applications, the acoustic models must be able to compute the reverberation generated by the source and two-way propagation from source to animal and back.
- Since reverberation is measured in time, the models for its prediction must be able to separate the acoustic field in time. Reverberation models are not included in this survey, however we can identify the classes of propagation model that lend themselves to the computation of reverberation.
- These classes include Ray Theory, Mode Theory, and Wavenumber Transform.
- The Parabolic Equation class is not traditionally used for any backscattering or reverberation calculations.

### 4.2.1.4 Metrics

The most common measures of the acoustic field that are provided by acoustic propagation models are the sound pressure level and the transmission loss which are required to solve the sonar equation for military applications. However, in the evaluation of marine mammal noise exposure to impulsive sounds, other metrics have been defined.

1. **SEL, CSEL**

   - The most commonly used metrics are the sound exposure level (SEL) and cumulative sound exposure level (CSEL). These may be weighted by a frequency function designed to specifically include the hearing range of an animal (M-weighting).
   - Rigorous calculation of these metrics require the received time series or the sound pressure by frequency over the length of the pulse.
   - Most of the marine exposure application models listed in Table 2-12 can compute these metrics by post processing the output from multiple runs of their core propagation models.

   - When questioned about the SEL calculation, several developers described their techniques. We found that some exposure modelers use a simple definition of $\text{SPL}_{\text{RMS}}$ by just relying on using the source level expressed as an RMS quantity.
   - Others use a more rigorous definition by forming the channel impulse response and convolving it with the source waveform.
   - In addition, the duration can be defined over different times, ranging from hours, days, months, even a year for some applications.
   - There seems to be no consensus on how to form these metrics and whether they are really the most appropriate ones to use.

2. **Other hearing related metrics for threshold shifts, masking, and behavior**

   - There are many other exposure metrics listed in Southall et al. [144] that may be vital to a better understanding of exposure. Since the core propagation models do not supply any of them, the marine exposure application models must compute these metrics by post processing.

3. **Particle velocity**

   - Vector particle velocity is output by only one model in this survey, TRACEO, using directional pressure derivative estimates.
   - Scalar particle velocity in the direction of the pressure wave is simply a scale factor and can be computed from the pressure output of most of the models.
   - Models that can supply this include BELLHOP, KRAKEN, MMPE, OASES, and ORCA. The particle velocity is used for some estimates of threshold shifts, so the vector directions may not be needed.
4.2.2 Evaluation of Model Capabilities for E&P Modeling

In Table 4-4, the various acoustic requirements for E&P modeling that were identified in section 4.2.1 are listed in the columns and the propagation models (suitable to be core models) surveyed in this report are listed in the rows.

A broad-brush approach is used to identify the attributes that the models have with regard to the requirements. The following indicators are used in Table 4-4:

- [●] A solid circle indicates the model will satisfy the requirement,
- [O] An open circle indicates the model has a limited or partial ability to satisfy the requirement, and
- [   ] A blank box indicates the model does not satisfy the requirement.

In some cases, a requirement (such as broadband output) could simply be produced by post-processing, that is, by designing an algorithm that makes repeated calls to the core model at different frequencies, and then combine the outputs. However, in this table, we have only given the ’●= yes’ to models that will do all that internally. Any requirement that needs post-processing to be achieved (no matter how easy that may be) is given a blank box.
Table 4.4 Evaluation table for propagation models that meet the needs of E&P modeling (refer to Appendix B for individual model details)

<table>
<thead>
<tr>
<th>Model</th>
<th>Availability</th>
<th>High frequency or deep water h&gt;10λ</th>
<th>Low frequency or shallow water h&lt;10λ</th>
<th>Source beampatterns</th>
<th>Broadband output</th>
<th>Time series</th>
<th>Near field</th>
<th>Range dependence</th>
<th>Range prediction</th>
<th>Particle velocity</th>
<th>Elastic sediments</th>
<th>Sub-bottom propagation</th>
<th>Active prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>BELLHOP</td>
<td>● ●</td>
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<td>Parabolic Equation</td>
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<td>Normal Modes</td>
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<td>C-SNAP</td>
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<tr>
<td>KRAKEN</td>
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<td>ORCA</td>
<td>● ○ ●</td>
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4.2.3 Specific Recommendations for E&P Modeling

The following section presents the opinions of the authors (listed in Appendix F). Judgments are based on the responses to the questionnaires and on personal experience. While all the models in our survey may be able to handle many of these topics, we are concentrating on those we feel are perhaps the best suited. It is a judgment call.

The following recommendations are for core models suitable for use in exposure application models.
4.2.3.1 Water Depths and Frequency Range

A combination of the topics of water depth and frequency range is necessary to provide recommendations with the least caveats.

4.2.3.1.1 Deep Water or High Frequency, \( h/\lambda > 20 \)

**BELLHOP MODEL**

BELLHOP was the first choice for all depth/frequency combinations for which the depth-to-wavelength ratio exceeds 20 \( (h/\lambda > 20) \). Substantiations:

- Gaussian Beam theory is efficient and accurate.
- BELLHOP easily accommodates source beam patterns and easily computes the spatial and temporal spreading of the field.
- The code is freely available to the public. As of this writing, the creator of BELLHOP, Dr. Michael Porter, is still actively involved in the further development of the model and is available for consultation.

Note that 5 of the 11 listed exposure application models Table 2-12 use BELLHOP. While CASS/GRAB is used by several of the exposure models, because the U.S. Navy controls it, it is not available to the general public. In addition, the technique in CASS/GRAB for vertical angle interpolation and eigenray generation of ray bundles requires a very fine ray angle sampling, in many cases 0.01° or less. This requires a much longer run time as compared to Gaussian beam models. For these reasons, BELLHOP is a recommended model.

**TRACEO & WAVEQ3D**

The second and third choices are the newly released models TRACEO (2011) and WAVEQ3D (2012).

- These two models use a variant of the GRAB style Gaussian beams and they are both freely available.
- Specific features of these are that TRACEO can compute the components of particle velocity and WAVEQ3D is a 3D model in the Under Sea Modeling Library (USML).
- However the relative youth of these models may mean that all the bugs are not worked out yet.

**MOCASSIN**

The fourth choice is MOCASSIN,

- This is an older model (1970's – and it is unclear of it availability).
- Estimates the intensity given the assumption of stochastic variability in sound speed, water depth and bottom loss.
- This technique attempts to mitigate uncertainty by lowering the fidelity of the model.
- An executable of this model is commercially available, but the source code is not.
4.2.3.1.2 Shallow Water or Low Frequency, \( h/\lambda < 20 \)

**ORCA**

ORCA was selected as the first choice for all depth/frequency combinations for which the depth-to-wavelength ratio is less than 20 (\( h/\lambda < 20 \)). Substantiations:

- Normal Mode models are best suited to shallow water cases where complex layered sediments are found and the range dependence is very slight (meaning small slopes). Our preference is toward this mode model because it is using Airy functions for the eigenfunctions as opposed to purely numerical solutions, which means that derivatives used for broadband and uncertainty are also analytic functions. We feel these analytic models provide clear intuitive explanations of near fields, shadow zones, sediment penetration, and temporal spreading using the mode group velocity.
- The ORCA model features efficient broadband operation using analytical expressions for eigenvalue derivatives and can output the frequency sampled transfer function, which is used to produce the channel impulse response.
- It can operate at very low frequencies (VLF) in complex elastic sediments and in the near field of the source.
- It outputs modal group velocities for measuring time spreading and displacements and it outputs stresses for computing particle velocity and motion.
- One of its particular attributes is that it can perform Monte Carlo repetitions using up to 25 input parameters from the sediment and the water column to provide statistics on propagation uncertainty.
- It has been designed to be easy to run for those who are unfamiliar with Normal Mode theory and it is freely available to the public. As of this writing, ORCA’s developer, Dr. Evan Westwood, is still actively involved in its development and is available for consultation.

ORCA’s drawbacks are that it does not include range dependence and it approximates the source beam pattern with a Gaussian function and a tilt angle. Post-processing could be applied to the ORCA output to provide range dependence (adiabatic dependence is particularly easy to obtain).

**KRAKEN**

A close-second choice is KRAKEN.

- This model is slower and requires more expertise to run, but it provides most of the same output of the ORCA model. In the event that range dependence is important then KRAKEN is our first choice.

**RAM**

RAM is a very popular model for some applications that involve the creation of new or modified versions for academic purposes. It has all the inherent limitations of PE models: no angle or time separation of the field, difficulty applying beam patterns, not good for complex sediment penetration, requiring shorter range steps than Normal Modes, not efficient for broadband, and not easily useful for active calculations.

Both KRAKEN and RAM include range dependence, but neither provides propagation uncertainty statistics.

**OASES**
The OASES model, with its many alternate codes for specific problems (see its questionnaire in Appendix B), appears to satisfy all the requirements. However, this model is a research-oriented model and its runtime is very long. Each of its alternate codes is designed to handle one specific problem, so there is not one single algorithm that can handle all problems. OASES requires considerable expertise to correctly run and for these reasons, the authors are not recommending its use for exposure modeling.

4.2.3.2 Range Dependence

Any of the ray models, BELLHOP, TRACEO or WAVEQ3D and either KRAKEN or RAM, (recommended to cover the water depths and frequency ranges listed in section 4.2), are suited for including range dependence.

The ray models are constructed to accommodate range dependence anywhere in the environment, that is, in the bathymetry, sound speed, surface conditions and bottom properties. The Parabolic Equation model RAM handles range dependent bathymetry, sound speed and bottom properties. While the Normal Mode model KRAKEN is very good in shallow water layered environments at low and mid frequencies, its adiabatic range dependence applies only for small slopes and its more general coupled mode range dependence requires a lot of run time; therefore this model is not as efficient as RAM. As a rule of thumb at low frequencies, the faster of these two models is KRAKEN run adiabatically. The more accurate model is KRAKEN using the coupled mode approach. When the slopes are not small and wanting a faster result, RAM is the best choice.

4.2.3.3 Near Field versus Far Field

Both of the models, BELLHOP and ORCA, (recommended to cover the water depths, and frequency ranges listed (in section 4.2), are also the well suited for performing near field as well as far field calculations. The Ray approach can operate in the near field by defining wide-angle coverage. The Normal Mode approach can be valid at very short ranges using the calculation of leaky modes.

4.2.3.4 Source Characterizations

BELLHOP can model either a point source or a line source. ORCA models only a point source. Most of the core models in this survey also operate using a point source representation. The spatial aspects of the sound radiated from a distributed array are accounted for by multiplying the angular components of the acoustic field by the source beam pattern such as those shown in Figure 2-3. This is the equivalent of looking in the far field of an array of sources. This is best accomplished using a technique, which is capable of separating the field, by vertical angle, meaning Ray theory and Normal Mode theory. The Parabolic Equation technique is not suited for angular decomposition without a lot of post-processing. The integration of multiple sources to estimate a composite sound field is not available in any of the core models. Consequently post-processing in the exposure model must do this.

59 While some Ray models simply ask for the source level and beam pattern to be input, CASS/GRAB contains code for creating the source beam pattern by specifying the dimensions of the array of sources, however the authors cannot recommend this model for E&P modeling because it is not available to the general public. The Gaussian Ray model SPADES can compute $\frac{\sin(x)}{x}$, shaded $\frac{\sin(x)}{x}$ and horizontal line array beam patterns, however the status of this model's availability is unknown.
4.2.3.5 Bottom Characterizations
In the frequency bands where bottom penetration and sub-bottom propagation is important, both Normal Mode model, ORCA and KRAKEN are capable of correctly representing the sediment. At higher frequencies where the bottom may be represented as a surficial reflecting interface, any of the recommended Ray models, BELLHOP, TRACEO or WAVEQ3D are appropriate.

4.2.3.6 Scattered and Bottom-Propagated Paths
Seismic exploration signals produced by airgun arrays are designed to penetrate deeply into the sediment and have the main lobe of their beampatterns concentrated at a very steep angle downward. The towed arrays that record the returning signals are very near the source arrays. This strong fathometer type return could be converted to shallower angles and coupled into the ducts in the water column by the mechanism of scattering from the surface and from the bottom (Figure 4-8, paths B and C), in which case some outward propagation to more distant regions downrange could occur.

![Figure 4-8 Conversion of high-angle incident source energy to bottom-propagated and boundary scattered energy (shown paths only illustrate some of the many possibilities)](image)

In our view, in the absence of significant scattering mechanisms, it is less likely that acoustic energy propagating at such steep downward angles will introduce significant horizontal propagation within the seabed that can re-emerge into the water column any appreciable distance from the source (path A). However, this question merits further investigation in order to place upper bounds on any increase in exposure levels due to this effect. One caveat is that when the source beam pattern shows significant sidelobes sound can be injected into the water column ducts, but this is separate from the seabed path.

Accounting for true “scattering” processes (and hence the part of the energy that is converted from steep angles to shallow angles as a result of scattering) is a very difficult problem, probably attainable to some approximation for each model, but difficult nonetheless. Most models treat the problem from a perturbation standpoint whereby the rough interface introduces loss (as a function of angle say) but do not account for conversion between angles (a complicated multi-scattering process). The two exceptions are COUPLE (which does represent approximately the multi-scattering or mode-conversion process) and the range-dependent version of OASES which also accounts for inter-wave transference of energy (using techniques similar to COUPLE).
4.3 Gaps in Propagation Modeling
The following are the authors’ opinions on the perceived gaps in the core propagation models.

4.3.1 Outputs Designed to Feed Exposure Models
The usual output from core propagation models is the acoustic pressure. This is readily converted to transmission loss, however, as we have seen in Section 4.2, Metrics, this is not considered the most useful measure for computing exposures or assessing potential damage to marine life.

There appears to be a knowledge gap between the core model developers and the exposure application developers concerning the most useful outputs. It would be very useful to have definitive agreement among the scientific community as to which outputs are important for exposure modeling and this would give the needed direction to core model developers to tailor their mathematics appropriately.

4.3.2 Calculation of Statistics of Data Based Inputs
In order to estimate the variability statistics of the environment from data based inputs, intra-database sampling techniques need to be developed. These techniques may include broadly sampling the database geographically or temporally to determine the range of values provided and to extract a measure of variability. Or, given study, a ‘universal’ variation may be identified that could be applied to all accessed values to provide a worst case.

For example, the sea surface temperature can be expected to vary over a predetermined range in a given season. Since the exposure estimates are assumed to apply for weeks or months of activity in E&P, the expected excursions of the sound speed profile is just as important as its exact value. Similarly, the expected variation of the $TL$ is just as important as its exact value.

While it remains true that the environmental models that transform the raw environmental data into model-friendly inputs (such as bottom loss tables or sound speed profiles) are mostly empirical and therefore accompanied by their own uncertainty, it is the opinion of the authors that these models can still be used to transform the variability of the raw environmental data into the variability of propagation model inputs which is required for computing statistical characterizations of the $TL$.

4.3.3 Calculation of the Statistics of $TL$
In the above sections, the sensitivity of the acoustic field to the environment was demonstrated. We assert that a high fidelity propagation model will automatically show the same sensitivities, meaning that small changes in the inputs can dramatically change the predictions from the model.

This high sensitivity is not a failure of the acoustic model; it is a fact of propagation in the real ocean.

The gap in propagation model development that is identified with this survey is the lack of the calculation of the statistics of the intensity field given an underlying variability and uncertainty in the environmental inputs. This gap could be addressed with existing models by performing Monte Carlo iterations using
randomly chosen input parameters that represent the expected variations of the environmental uncertainty, e.g. the input error bar size.

Alternative approaches described in Section 2, involve determining the statistics of the field with analytic solutions that can run concurrently with the core calculation and therefore may be more efficient than Monte Carlo simulations. The relative advantages of using an analytic intensity derivative versus numerical Monte Carlo iterations need to be evaluated.

4.3.4 Effective Interfaces for Inexperienced Users
This topic addresses the traditional difficulty with programming in Fortran, the language of most of the core propagation models, in which a graphical user interface (GUI) is not available. Command line interfaces and structured input files are the norm for the running of core models. This limitation immediately restricts the model usage to an experienced user who has studied the User’s Guide carefully. In addition, most of the core models require the user to ensure convergence for internal settings such as step sizes or wavenumber limits that often must experiment with inputs. The inexperienced user would benefit from an effective user interface and automatic defaults for program settings.

4.3.5 Interpolation of SSP in Range
The proper technique for interpolating between range dependent changes in the sound speed profile is a topic that needs to be investigated. The technique must ensure that the proper oceanography is maintained between adjacent SSP’s. The oceanographic mechanisms that change the SSP include density and temperature inversions, internal wave passage and surface interactions. These oceanographic mechanisms cause ducts to move up and down, compress, expand, or vanish altogether. The interpolation techniques used by the models are shown in Table 2-6.

A simple linear interpolation between two adjacent SSP’s with ducts at different depths will cause a double duct to be formed across the interpolation space, which is clearly not how the profiles should change. A stair-step change between two profiles is also not displaying proper oceanography. We note that CASS/GRAB has developed a triangular interpolation to follow the axis of the duct as it shifts, and BELLHOP and TRACEO are using more complicated bilinear schemes. The efficacy of these interpolation techniques needs to be studied.

4.3.6 Translate Statistics of Boundary Roughness through TL into Exposure Models
There is a lack of understanding of how to translate the statistics of the boundaries into and through a propagation loss model and into an exposure model. For this gap, we define boundary roughness to mean the small range perturbations in depth of the surface boundary, the bottom boundary and the sound speed layers, which cause scattering of the sound. The perceived need is for a good physics based energy scattering model. Boundary roughness is currently being included in some form in some of the core propagation models: C-SNAP, KRAKEN, MMPE, MOCASSIN, OASES, PECAN and POPP/PROLOS. The efficacy of these treatments needs to be examined so that the statistics of the roughness can be properly reflected in exposure models.
4.3.7 Complete Bottom Treatment
There is a need for a more complete bottom treatment, particularly at low frequencies. Techniques such as a volumetric-centric model that include the complexity of sediment deposition and distribution need to be investigated.

4.3.8 Intelligent Sampling Intervals
Most propagation models do not critically examine the bathymetry or SSP sampling intervals of the input environment. The physics of sound propagation dictates that small scale fluctuations (less than $\lambda/2$) in the properties of the waveguide are not going to be felt. However, most core models do not examine the inputs to determine if the ‘noise’ could be eliminated. The exception is MOCASSIN which imposes a filter on the SSP to eliminate small ducts. All the other models utilize every input point, leading to a very inefficient calculation. The elimination of noise from small scale fluctuations by using frequency-dictated intelligent sampling intervals would result in an improvement in the efficiency of model predictions.

4.3.9 Ambient Noise Treatment
Ambient noise is often treated as a simple decibel level number when in reality it possesses directionality, a detailed spectrum from its many causes including wind, shipping and fish, and a temporal variation based on time-of-day differences in fish locations. The more deliberate and specific modeling of noise should involve using a propagation model. The advantages of this improvement in determining ambient noise for exposure modeling need to be investigated.

4.3.10 Currents
The effects of currents on the sound field were mentioned as a potential knowledge gap, however it was thought to be of minor importance.

4.3.11 Ice Cover
There is a need for more complete models of inhomogeneous ice cover including models for young and multi-year ice and the differences in scattering they cause. Methods for ingesting these ice representations into core propagation models are missing. Research on the best boundary conditions for representing ice cover would be useful.

4.3.12 Physics-Based Boundary Interaction
This gap addresses the fact that most of the propagation models do not have real physics based boundary interactions at the interfaces between the surface, bottom and internal sound speed layers representing currents and internal wave structures. Many core models do not include roughness effects. Fortunately for exposure modeling, this gap may not be too significant because propagation models with even higher fidelity are not really needed.

4.3.13 Physics-Based Scattering Model
There is a need for physics based scattering model for reverberation estimations that includes the roughness spectrum of the scattering interface.
4.4 Gaps in Physical Databases

The following are the authors’ opinions on the perceived gaps in the physical databases.

4.4.1 Ambient Noise Databases

Ambient noise databases are very scarce and the *in situ* databases appear to be all region-specific. There are no long term (greater than a decade) systematically collected data sets for any frequency band. More information is needed on surface ship noise spectra which should include frequency content, pressure time series, duration, repetition rate, directionality, etc., particularly within the frequency range of marine mammal echolocation (1 to 100 kHz). In regions with high source concentrations, physical environmental data, including local winds and wind-wave noise spectra, are needed to permit more accurate modeling of the relative contribution of anthropogenic noise and natural noise sources. The distribution and characteristics of marine mammal sounds should also be considered as a part of ambient noise.

4.4.2 Sediment Composition Below the Surficial Layer

Overall, the availability and accessibility of geoacoustic databases is very poor. In highly variable littoral waters the coarseness of the spatial and temporal sampling results in the necessity for averaging. Such averaging can erase some of the acoustically important environmental features. All geoacoustic data found in databases with any significant area coverage are derived from other *in situ* measurements, such as from physical sampling techniques (such as cores and grabs), which are analyzed for geophysical properties, or from seabed acoustic reflection measurements. These measured properties, or acoustic responses, are then used as inputs to numerical empirical or theoretical physical models, which yield estimates of the geoacoustic parameters. Thus, no direct evidence of sediment composition below the surficial layer is available.

4.4.3 Correlation Lengths of Data

Spatial and temporal correlation lengths of environmental data are scarce. Such correlations would provide the modeler with the ability to more intelligently interpolate between database entries.

4.4.4 Open Access to Geo-acoustics Databases

The largest geoacoustic databases are those controlled by the U.S. Navy, which are classified for military applications only. The vast resources required to create and populate a geoacoustic database (primarily at-sea measurement programs) are not likely to be supplied by any sources other than the military, therefore the need is to persuade the government that these databases should have open access. This, however, is highly unlikely.

4.4.5 Ice Databases

With commercial shipping being so vital, and with high-latitude coverage by satellites being so complete, there are few, if any, data gaps for sea ice location. Sea ice thickness is also now being measured. However, for acoustic modeling, the under ice topography is the quantity of interest. There is a need for knowledge of ice keel direction and depth, both specifically and statistically.
4.4.6 **In situ Measurement Databases for Geo-acoustic Data**

Geoacoustic data are collected by physical sampling techniques (such as cores and grabs) which are analyzed for geophysical properties, or from seabed acoustic reflection measurements. These measured properties, or acoustic responses, are then used as inputs to numerical empirical or theoretical physical models, which yield estimates of the geoacoustic parameters. In the resulting database, there is no associated understanding of the precise conditions (frequency, method, etc.) under which these data were collected to ensure relevance to the present case being modeled. There is a need to measure directly the properties of the sediments for comparison with the geo-acoustic data based values and to document the range of validity of the measurements.

4.4.7 **Wind and Surface Wave in situ Data**

Of all the input parameters to acoustic models, the sea surface description exhibits the highest variability in both space and time, owing to the vagaries of the local meteorological conditions. All wave data should be considered ‘historical’ and therefore quite stale as the sea state can change within a matter of hours. For Lloyd’s Mirror coherence and for surface duct propagation, the state of the surface is paramount. Because exposure modeling occurs days, weeks or months before the E&P activity commences, the most useful measures of the surface interaction can only be supplied by statistical representations. Therefore the need exists to obtain wind and surface wave in situ data for the generation of appropriate statistical measures and for the examination of the means by which these measures can be properly used by the acoustic models.

4.5 **Gaps in Exposure Modeling**

The following are the authors’ opinions on the perceived gaps in the exposure application models.

4.5.1 **Core Model Selection Criteria**

There is a clear need for robust, automated selection criteria for determining which model to choose for any given environment and source frequency band. These criteria must evaluate the bathymetry to determine if it is truly range dependent, requiring a range-dependent model, or if it is just rough, requiring a model with interface roughness loss terms. These criteria should examine the sound speed profile to see whether it can be filtered to eliminate small ducts that would add nothing but 'noise' to a calculation and slow the models down. In the case of multiple profiles, these criteria should determine if the various profiles are sufficiently unique to require a range dependent model. These criteria also need to determine the bearing selections to properly sample an area with changing bathymetry or sound speed for NxD calculations for area coverage.

4.5.2 **Use of Probability in Exposure Metrics**

There is an urgent need for the inclusion of the probability of transmission loss in the definition of SEL and other exposure measures. New enhanced exposure metrics will need to be defined. It must be determined whether a knowledge of the probability distribution function (pdf) of the TL is required to enable the computation of higher order moments such as skew and kurtosis, or whether just knowledge of the variance of the TL is sufficient for characterizing the uncertainty in the exposure metrics. The utilization of the error bars is essentially a signal-processing question whose answers will shape the regulatory decisions.
4.5.3 Standardization of Metrics
In the course of this survey, several exposure model developers were questioned about their techniques for performing the SEL calculation. We found that some exposure modelers use a simple definition of $SPL_{RMS}$ by just relying on using the source level expressed as an RMS quantity. Others use a more rigorous definition by forming the channel impulse response and convolving it with the source waveform. In addition, the duration can be defined over different times, ranging from hours, days, months, even a year for some applications. There seems to be no consensus on how to form these metrics and whether they are really the most appropriate ones to use. There is a significant gap in the understanding of the best metrics to use and how to obtain them from the output of the propagation models.

4.5.4 Soundscape Modeling
Soundscape present an overall picture of the noise surrounding an E&P activity. They should be generated before the activity starts to provide a baseline understanding of the ambient sound field which can help to realistically place the animals within the region, as for example, a loud ambient level may have caused many animals to avoid the region even before the E&P activity began. This requires obtaining good ambient noise predictions from the environmental noise (wind, rain) and distant shipping noise as well as any other ongoing E&P activity nearby.

4.5.5 Target Strength of Mammals
One of the E&P techniques for damage mitigation is to use active echolocation to survey the volume of the ocean for the current locations of marine mammal. This requires an active acoustic model capable of computing the two-way transmission losses and the anticipated reverberation from the active emissions. A very important component of this calculation is a model of the target strength of the various species. The target strength model must include both level and directionality as a function of the frequency being employed for the search. Parvin et al. provided a critical review (2007) of marine mammal target strength research up to that time for mysticetes and odontocetes, including a summary of the difficulties in obtaining measurements of this parameter [242]. For a range of mammal species found in United Kingdom waters they propose a series of TS values over 4 decades of frequency.
Section 5 - Potential Areas for Further Development

Prepared for Joint Oil & Gas Industry Programme (JIP) on Sound and Marine Life

Solicitation Number: JIP 08-08

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Section 5

5 POTENTIAL AREAS FOR FURTHER DEVELOPMENT

5.1 Ways to Improve Propagation Models

This survey has shown that the currently existing high-fidelity model solutions for the acoustic field are very accurate and well established efficient algorithms that are readily available.

Nevertheless, propagation modeling remains a very complex and difficult mathematical problem space to solve.

Because the results of the exposure modeling will be used to define an environmental impact for the weeks or months of E&P activity, relying on a deterministic model output given just one scenario characterization will be misleading and most likely completely inaccurate. It has been presented herein that the statistics of the environmental uncertainty must be carried through the propagation calculations to allow the statistics of the transmission loss to be estimated. These statistics should be included in any output from the propagation model, including broadband spectra, channel impulse responses and pulse time series. The propagation of the uncertainty will also require the development of statistical characterizations of the environmental inputs.

Some noted gaps in the propagation models are in the areas of ice cover, Doppler shifts and the effects of stratified water currents. High-fidelity physics based scattering models and boundary interaction models are also lacking. A more comprehensive bottom treatment would be a good addition to many of the propagation models.

In the end, the use of a propagation model in isolation has little value. The modeling system needs to be part of a much bigger decision loop – the inputs and outputs of the models can and will significantly impact the outputs and outcomes. Hence, the recommended improvements needed to propagation modeling are:

i. Creating more intuitive user interfaces. Propagation modeling is a very complex and difficult field to understand, many propagation models are used at a low level and have cumbersome and lack graphical user interfaces (i.e. from the command line directly or via coded scripts);

ii. Creation of standards that facilitate data flow between a wide variety of source models, propagation models and exposure models;

iii. Tailoring the outputs to better compute exposure metrics; better metrics for decision making are needed;

iv. Improving range-dependent interpolations schemes of oceanographic & hydrographic input data; and

v. Devising methods to calculate the degree of model sensitivity to environmental input data uncertainty.

The following recommendation for future development efforts by the E&P Industry is submitted.
5.2 Recommendations on New Model and Database Development

Section 4 described the gaps in propagation modeling, listed the gaps in physical databases and described the gaps in exposure modeling that this survey has uncovered. Addressing these gaps may require new model development, new methods of populating databases and enhancement of existing models.

Table 5-1 & 5-2, below, list the recommended development items, in three development areas (e.g. exposure models, core propagation models, physical parameter databases), based on the identified gaps, and our ranked prioritization of these development items, respectively. Each development item was scored against five categories, namely:

1. **Feasibility**. A measure of the difficulty of task execution, based on the existence of theoretical approaches or experimental abilities. I.e. does industry have the capability to execute this development?

2. **Cost**. The amount of dollars needed to execute this development task based on the availability of existing data or theory.

3. **Timing**. The time it would likely take to execute this task. This can be assessed as duration or level of effort.

4. **Ease of Validation**. The availability of convenient theoretical or model predictions to validate the development task.

5. **Perception of need**. The assessed understanding of how important this research is to the perceived required solution. I.e. is the level of importance high versus the current capability of the industry.

The following is a short description of each of the development areas based on the survey gaps.

*Table 5-1 Development Item and descriptions, ranked according to the score in Table 5-2.*

<table>
<thead>
<tr>
<th>Development Item</th>
<th>Description</th>
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<tbody>
<tr>
<td>1. Core model selection criteria</td>
<td>Define ways to choose the best model for specific environments, frequency bands, input data knowledge and sampling coverage.</td>
</tr>
<tr>
<td>2. Outputs to feed exposure models</td>
<td>Produce outputs from propagation models that specifically relate to the calculation of exposure metrics. Broadband sources should provide results in some form of band, e.g. stepped 1/3-octave, range averaging, etc.</td>
</tr>
<tr>
<td>3. Use of probability in exposure metrics</td>
<td>Develop methods to include in exposure metrics the probability of transmission loss caused by the uncertainty in the environment. SSP, bathymetry resolution and bottom loss are of primary importance.</td>
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<tr>
<td>Development Item</td>
<td>Description</td>
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<tr>
<td>4. Statistics of databased inputs</td>
<td>Determine the best method for developing the statistics of databased parameters. For example, different techniques might include performing temporal and/or spatial averaging of database entries, and employing a generic expected variation.</td>
</tr>
<tr>
<td>5. Statistics of transmission loss</td>
<td>Develop methods for computing the statistics of transmission loss given the underlying statistical nature of the inputs. Include these statistics in the predicted pulse shape and time spread of impulsive signals.</td>
</tr>
<tr>
<td>6. Effective interfaces for inexperienced users</td>
<td>Provide practical default values for esoteric input parameters in high-fidelity propagation models.</td>
</tr>
<tr>
<td>7. Ambient soundscape modeling</td>
<td>Improve the description of ambient noise by including directionality, temporal variations, and consistent metrics (e.g. band levels)</td>
</tr>
<tr>
<td>8. Ambient noise databases</td>
<td>Improve ambient noise databases by including ship noise spectra and wind and wave noise spectra.</td>
</tr>
<tr>
<td>9. Standardization of exposure metrics</td>
<td>Standardize and define the best metrics to use for exposure that will encompass temporal, spectral and spatial exposures.</td>
</tr>
<tr>
<td>10. Interpolation of SSP in range</td>
<td>Provide guidance for the best mathematical method to interpolate the sound speed profile between two measurements to retain oceanographic realism.</td>
</tr>
<tr>
<td>11. Translate statistics of roughness into exposure models</td>
<td>Include the statistics of the roughness of boundaries in exposure models so that the changes in the exposure field can be more precisely defined.</td>
</tr>
<tr>
<td>12. Complete bottom treatment</td>
<td>Expand the ability of acoustic models to handle more complex bottom descriptions (e.g. including shear, occluded matter, fine layering, gas hydrates, etc.), particularly for low frequency modeling.</td>
</tr>
<tr>
<td>13. Intelligent sampling intervals</td>
<td>Provide methods to obtain the best choices for sampling intervals for bathymetry and SSP to make the model calculations efficient and eliminate unnecessary oversampling. Particular attention needs to be given to the region inside a 10 km radius where most non-lethal injurious impacts (Level A Harassment) may occur.</td>
</tr>
<tr>
<td>14. Sediment composition below the surficial layer</td>
<td>Develop methods for obtaining sediment composition below the surficial layer for improved modeling of low frequency sediment penetration.</td>
</tr>
<tr>
<td>15. Correlation lengths of data</td>
<td>Develop methods to determine the spatial and temporal correlation lengths of input parameters such as sound speed, surface roughness and bottom properties in order to better interpolate between database entries displaced in time and space.</td>
</tr>
<tr>
<td>16. Open access to geoacoustic databases</td>
<td>Pursue the opening of U.S. Navy controlled databases to unclassified users. The authors recognize this is extremely unlikely.</td>
</tr>
<tr>
<td>17. Ambient noise treatment</td>
<td>Increase the knowledge base of ambient noise as produced by surface ships, wind and wave spectra, and other pre-existing anthropogenic activities.</td>
</tr>
<tr>
<td>Development Item</td>
<td>Description</td>
</tr>
<tr>
<td>------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>18. Ice databases</td>
<td>Determine the best way to portray ice cover in databases, particularly sea ice locations, keel location and direction.</td>
</tr>
<tr>
<td>19. Currents</td>
<td>Examine the effect of currents on the propagation of sound in shallow water.</td>
</tr>
<tr>
<td>20. In situ measurement databases for geoacoustic data</td>
<td>Compare directly the measured geoacoustic properties with the database values</td>
</tr>
<tr>
<td>21. Ice cover</td>
<td>Provide methods for incorporating ice descriptions into propagation models as boundary conditions.</td>
</tr>
<tr>
<td>22. Wind and surface wave in situ data</td>
<td>Obtain data for the generation of statistical measures for sea surface variability to be used as input in acoustic models.</td>
</tr>
<tr>
<td>23. Physics based boundary interaction</td>
<td>Develop physics based models for boundary interfaces which may contain currents and internal waves causing roughness.</td>
</tr>
<tr>
<td>24. Physics based scattering model</td>
<td>Develop physics based models for reverberation estimates that include roughness of the scattering interface.</td>
</tr>
</tbody>
</table>

The numerical values of these categories were summed as a final score showing a ranking of the development item priority, as shown in Table 5-2. The development area is shown in the leftmost column.
Table 5-2 Ranked Development Area recommendations for new model or database development

<table>
<thead>
<tr>
<th>Development Area and Item</th>
<th>Feasibility</th>
<th>Costs</th>
<th>Timing</th>
<th>Ease of validation</th>
<th>Perception of need</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Ex Core model selection criteria</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>90</td>
</tr>
<tr>
<td>2. M Outputs to feed exposure models</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>85</td>
<td></td>
</tr>
<tr>
<td>3. Ex Use of probability in exposure metrics</td>
<td>5</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>85</td>
<td></td>
</tr>
<tr>
<td>4. M Statistics of databased inputs</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>2</td>
<td>5</td>
<td>80</td>
</tr>
<tr>
<td>5. M Statistics of transmission loss</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>75</td>
</tr>
<tr>
<td>6. M Effective interfaces for inexperienced users</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>60</td>
</tr>
<tr>
<td>7. Ex Ambient soundscape modeling</td>
<td>5</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>56</td>
</tr>
<tr>
<td>8. Pd Ambient noise databases</td>
<td>5</td>
<td>1</td>
<td>2</td>
<td>5</td>
<td>4</td>
<td>52</td>
</tr>
<tr>
<td>9. Ex Standardization of exposure metrics</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>5</td>
<td>50</td>
</tr>
<tr>
<td>10. M Interpolation of SSP in range</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>48</td>
</tr>
<tr>
<td>11. M Translate statistics of roughness into exposure models</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>44</td>
</tr>
<tr>
<td>12. M Complete bottom treatment</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>36</td>
</tr>
<tr>
<td>13. M Intelligent sampling intervals</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>34</td>
</tr>
<tr>
<td>14. Pd Sediment composition below the surficial layer</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>32</td>
</tr>
<tr>
<td>15. Pd Correlation lengths of data</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>30</td>
</tr>
<tr>
<td>16. M Ambient noise treatment</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>29</td>
</tr>
<tr>
<td>17. Pd Open access to geoacoustic databases</td>
<td>1</td>
<td>5</td>
<td>2</td>
<td>5</td>
<td>2</td>
<td>16</td>
</tr>
<tr>
<td>18. Pd Ice databases</td>
<td>4</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>22</td>
</tr>
<tr>
<td>19. M Currents</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>20. Pd In situ measurement databases for geoacoustic data</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>14</td>
</tr>
<tr>
<td>21. M Ice cover</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>14</td>
</tr>
<tr>
<td>22. Pd Wind and surface wave in situ data</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td>23. M Physics based boundary interaction</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>24. M Physics based scattering model</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>8</td>
</tr>
</tbody>
</table>

Our process for determining the numerical values was an iterative one, in which each item was initially scored on its own to achieve objectivity. Then the entire group was reassessed to be sure we all agreed on the rankings. The end result satisfied our goal to be objective and to provide our best recommendations.
Table 5-2 notes on scoring values:

| Feasibility (f) | • 1 = Task assessed as very difficult due to experimental difficulties or lack of political/industrial will 
• 5 = highly feasible – relatively easy to accomplish |
| Cost (c) | • 1 = high cost for experiments or deriving new mathematics 
• 3 = trade studies costs involved along with moderate effort; 
• 5 = low cost, little effort required using analysis of existing data/ ideas |
| Timing (t) | • 1 = Long term effort, no immediate solution or theory available, will require new research 
• 3 = Mid-term effort, development already in progress, reasonable milestones; 
• 5 = Short term effort, techniques already mature, level of effort reduced; |
| Ease of Validation (v) | • 1 = Development effort assessment as difficult to validate due to lack of data. New benchmarks required. 
• 3 = Moderately easy using existing experimental data; 
• 5 = Very easy validation effort using theoretical or model-to-model assessments; |
| Perception of need (p) | • 1 = Assessed as low in industrial/political importance. 
• 5 = Assess as a vital or critical need of the industry; |
| Score | The score is determined as follows: 
• Summation of feasibility, costs, timing and ease of validation, then multiplying this sum by the ranking for perception of need. 
• Score = (f + c + t + v) * p. |

5.2.1 Core Recommendations

The first 9 entries in Table 5-21 (and Table 5-2) contain the topics we feel require the most urgently needed research.

These topics have been grouped into 4 main thrusts.

5.2.1.1 Core Model Selection Criteria (No. 1)

We recommend the acoustics community needs to provide guidance on model selection to correct potential errors from employing models outside their regions of applicability. This leads to a decision making capability, which is necessary to aid the acoustic non-specialist user in understanding the acoustic environment and the potential impacts on marine life. However, it’s not enough to have the right model – but the right model needs to be properly and “effectively” incorporated in the decision making loop, to assess multiple scenarios and to arrive at the best solution.

5.2.1.2 Improved, Statistical, Measures of Sound Exposure (No. 3, 4, 5 & 9)

The marine animal exposure community needs to develop methods that provide a statistical characterization of the sound exposure levels that ensures a more accurate basis for risk assessments. We recommend the establishment of universally accepted metrics for evaluating sound exposure (not just sound exposure level) that also includes the statistics of the propagated field and the character of the sound (e.g. spectral-statistical description). The calculation techniques of these metrics should become officially standardized.
The translation of the uncertainties in environmental data to statistical measures of the propagation model outputs, and hence exposure statistics, is required. To facilitate calculation of the propagation model statistics, it is recommended that measures of the environmental uncertainty be embedded in the databases.

We recommend statistical measures showing a range of exposures rather than a single-value, as the best approach that can be employed in a decision capability.

5.2.1.3 Improved Ambient Noise (No. 7 & 8)
Any signal from any source, after travelling a distance, will be competing against the prevailing and local ambient noise. Recorded ambient noise levels should include directionality, spectra with base set of statistical moments, for improved modeling of the ambient noise fields (soundscape). A concerted effort needs to be driven by industry to collect and build noise repositories. This problem will not go away and it will need to be addressed, if the above two priorities are to be successful.

5.2.1.4 Improved Ease-of-use (No. 2 & 6)
To encapsulate the above 7 priorities, it is recommended that the scientific community and the E&P Industry work in concert to better facilitate the integration of core propagation models with exposure applications, such as through a standardized data interface. Furthermore, these communities should work together, assisting with the creation of user-friendly software applications for users who are non-acoustics experts but are nonetheless involved in the marine exposure assessment. These user interfaces should be intuitive and allow the user to make better informed decisions with a high degree of confidence.

5.3 Recommendations for the Development of a Decision Making Capability
The oil and gas exploration and production (E&P) industry is subject to stringent environmental regulations. Prior to underwater exploration activity that employs acoustic sources directly, or that produces acoustic energy as a by-product, the industry's principals must complete an Environmental Assessment (EA). The EA must contain evidence concerning the potential for E&P acoustic operations to adversely affect marine life. The oil and gas industry must therefore use, and are indeed dependent on obtaining seismic data, and face the need to forecast the impact of E&P on marine life—on its physiology and behavior. The stakes are high for the oil and gas sector, and for marine life, and hence for other important industries that rely on seismic exploration or marine life.

What, precisely, are the key scientific elements in the chain of impact in an E&P exploratory region, going from the relatively high seismo-acoustic energy injected systematically at its source during exploration, to:

i. exposure levels throughout the water column and on the seafloor across the long distances that seismic waves travel in water; and

ii. physiological and behavioral impact on selected species, to impact finally on other important industries?
The solution can be addressed by focusing step by step at points along the chain of impact. Many of the tools required (theory, practice, and modeling) exist for framing and pressing the leading elements in that chain to completion, by focusing on exploration scenarios that may be faced in exploratory regions.

Obtaining the outcomes from the chain of impact requires complete modeling from source to exposure of selected species. These outcomes will in turn set the context and way ahead (relevant metrics, regulatory evaluation, experimental design, and even the motivation and urgency) for understanding the impact expected on species and on the industries that rely on them.

Today, the oil and gas industry must use and are now fully dependent on collecting important seismic data with the need to forecast (model) the impacts of these explorations on marine life, their physiology and behavior. What are the important elements of the data and analysis that will allow regulators to make effective decisions on the explorations and the subsequent impacts on all marine life?

The following subsections provide the Joint Oil & Gas Industry Programme (JIP) on Sound and Marine Life a series of project ideas that can supplement or improve acoustic modeling systems for (E&P) industry and their integration with the decision making capability.

5.3.1 Scope

Using the acoustic model evaluation assessed in this survey, the authors suggest the following project activities:

1. Through past work, further data collection and analysis, and predictive modeling, develop an objective, consistent, and evidence-based approach to forecasting seismic-source exposure levels for selected species due to exploration that may be foreseen E&P exploration regions;

2. Validate the above approach through benchmarking of acoustic models;

3. Apply much the same approach to forecast the exposure of the same species to other noise sources, natural and/or man-made; and

4. Assess the impact of seismic exploration as early in the analysis as possible by relative comparison of the exposures forecast for seismic exploration (for selected scenarios and regions) with the exposures currently faced due to background noise exposure levels from other natural or anthropogenic sources in those regions (each with varying degrees of industry acceptance and apparent marine life tolerance).

Consolidating various energetic noise sources into a common frame of reference this way in effect enlightens, calibrates, and de-mystifies the exposures due to seismic exploration for industries, regulators, and scientists alike. E.g., speculating briefly: Consider whale watching industry concern over impact of seismic exploration 50 km away. Then compare noise exposure levels of seismic exploration relative to propeller noises on whale watching vessels that routinely vector into a location routinely frequented by whales.
5.3.2 Intended Project Activities
A primary component of this project development is to demystify noise from seismic exploration. Sea life faces exposure to noise from many sources. Just how extreme is seismic exploration relative to noise exposure from other sources? A project goal is to assess and interpret marine life noise exposure levels from seismic exploration in terms of noise exposure levels from other currently tolerated natural and human noise sources.

1. Survey existing high energy noise sources not related to seismic exploration in an exploratory region;
2. Assess (model/measure) nominal exposure levels due to selected noise sources (particularly energetic, impulsive, natural, and anthropogenic).
3. Assess (model/measure) exposure levels due to seismic exploration.
4. Develop scale (ranking) of seismic exposure levels relative to other noise sources.
5. Develop noise dosage equivalents for seismic exploration in terms of other noise sources (e.g., seismic exposure levels under scenario \( X \) are equivalent to noise-source \( Y \) under scenario \( Z \)). Repeat for several representative scenarios \( X \).
6. Create tutorial about ocean noise relative rankings and equivalents (workshop)

5.3.3 Methodology
The main purpose of this project is to synthesise the current and emerging data sets and information relating to exposure modeling impacted species, ocean conditions, and seismic source levels, and conduct state of the art acoustic propagation modeling research that would assess main drivers of variability in the scenarios (e.g. geographic range dependencies, seasonal variability and other factors).

1. **Scientific field study & Data collection – Collaborative efforts & support**. A field team will need to engage in sampling the sound environment in relevant areas using long term monitoring devices, including when seismic survey operations are not conducted. The team will use sensors whose systems will be calibrated using hydrophones to measure \( SPL \), while acoustic vector sensors can also be used to measure particle motion. Multiple sensors can be deployed and attempt to collaborate with surveyors to get track data for distance measurement. Calibrated analysis of seismic pulses using existing software tools to provide field data measurements for acoustic modeling verification.

2. **Detection of marine mammals** is typically accomplished through employing visual and sometimes passive acoustic monitoring methods. In addition, project activities will need to monitor existing background sound levels in exploration regions. Instruments will be deployed for long periods paying particular attention to calibration and data validation. The observations will be interpreted through meteorological records and ocean model outputs.

3. **Data Management Plan – from cradle to grave**. A detailed Data Management Plan will ensure project input and output data products are well planned in advance of collection, catalogued
when acquired or created, and that these data products can be easily accessible for use in future JIP projects, and for authorized external users. A data backup and recovery system needs to be put in place, including a plan for any catastrophic data loss. Planning and collection of data sets and results from scientific field studies includes data storage requirements, preprocessing considerations, and criteria for quality control. Very long term storage and retrieval needs to be considered as well as data disaster recovery plans.

4. **Database and Data.** This survey research project also has access to a metadata library of over 200 environmental databases to compare and validate the managed field data from this research. The aim is to ensure that data can be properly archived, accessed and used to compare effectively against modeling results.

5. **Acoustic Modeling & Validation.** This component of the research project is where the genesis of decision making takes place. The types of models that will be used will be commensurate to the environment, the E&P scenario and the type of decisions needed. A project team will employ and compare different propagation modeling systems to assess and validate against the field data: (1) Transform Solutions (Wave No. Integration, Normal Modes, Energy Flux & Multipath Expansion); (2) Ray Solutions (Eigenrays & Beam systems); (3) Marching Solutions (such as Parabolic Equations solutions). With this effort, the team will be able to determine which acoustic modeling system, solution and scenario will best fit the decision making capability.

5.4 **Project Outreach & Workshop(s)**
It became evident during the period of this research project that very little is understood about propagation modeling by a large number of people, the different types and uses of modeling and the source, propagation, and exposure modeling sequence.

It is the strong opinion of the authors that a modeling workshop should be organised involving scientific experts, industry, regulators, government organizations and other relevant stakeholders to help develop the processes needed for operators and regulators to effect proper decisions in the domain space of the E&P Industry and the associated impacts on marine mammals during offshore oil and gas activities.

5.5 **Modeling Handbook**
It is recognised by the authors that this report is very comprehensive and in some areas very involved. In an effort to provide additional information to the E&P Industry, regulators and model users, a condensed version of this report can be created as a "User’s Modeling Handbook". This Handbook could be used to support the project outreach and workshop described in 5.4.
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Section 6 - References

Prepared for Joint Oil & Gas Industry Programme (JIP) on Sound and Marine Life

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Section 6

6 REFERENCES


21. See, e.g., the treatment given in Sections 3.1.5 and 3.1.6 of [3].


6.1 Additional Material Used During Research


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