Assessing the Impacts of Marine-Hydrokinetic Energy (MHK) Device Noise on Marine Systems by Using Underwater Acoustic Models as Enabling Tools

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Introduction

This chapter describes the use of underwater acoustic models for the evaluation of marine-system noise impacts associated with the installation and operation of marine-hydrokinetic energy (MHK) devices, particularly in coastal oceans. Selection guidance is provided for the current inventory of propagation and noise models. Where available, case studies are examined to illustrate the use of acoustic models for the assessment of MHK device impacts on marine mammals and fish.

Background

Over the past several decades, the soundscape of the marine environment has responded to changes in both natural and anthropogenic influences. A soundscape is a combination of sounds that form, or arises from, a vast environment. The study of a soundscape is sometimes referred to as acoustic ecology. Soundscape refers to both the natural acoustic environment (consisting of natural sounds, including animal vocalizations, the sounds of weather, and other natural elements), and anthropogenic sounds (created by humans), including sounds of mechanical origin associated with the use of industrial technology. The disruption of the natural acoustic environment results in noise pollution.

The soundscape baseline is defined by ambient noise, which is the prevailing, background of sound at a particular location in the ocean at a given time of the year. For acoustic-signal processing, it is the background of noise, typical of the time,

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location and depth against which an acoustic signal must be detected. Natural noise sources include surface weather (wind and rain noise). Anthropogenic activity can include naval-sonar systems, seismic-exploration activity, merchant shipping, fishing vessels, marine-hydrokinetic energy devices, and wind-farm development. Even noise from low-flying coastal aircraft can couple into the water column and add to the background noise field.

Organization of Chapter

Building upon the brief background presented in section "Introduction," section "Evolving Trends and Challenges" addresses evolving trends and challenges. Section "Noise Sources" discusses noise sources, emphasizing marine kinetic energy activity such as tidal turbines and wave-energy devices. Section "Mitigation and Monitoring" reviews mitigation and monitoring. Section "Underwater Acoustic Modeling Techniques as Enabling Tools" reviews the utility of underwater acoustic modeling techniques as enabling tools. Section "Summary" summarizes the notable advances in underwater acoustic modeling that support analyses of noise effects on physical systems due to the deployment of marine renewable energy devices. References and an appendix containing definitions of abbreviations and acronyms are also included.

Evolving Trends and Challenges

Evolving trends and challenges related to the assessment of the impacts of MHK device noise on marine systems are best set in the context of the coastal environments in which such devices may be deployed. Then, an assessment of the associated biological noise impacts, enabling technologies, and emerging solutions can be examined.

Coastal Environments

Coastal environments are generally characterized by high spatial and temporal variabilities. When coupled with attendant acoustic spectral dependencies of the surface and bottom boundaries, these natural variabilities make coastal regions very complex acoustic environments. Changes in the temperature and salinity of coastal waters affect the refraction of sound in the water column. These refractive properties have a profound impact on the transmission of acoustic energy in a shallow-water waveguide that has an irregular bottom and a statistically varying sea surface. Thus, accurate modeling and prediction of the acoustic environment is essential to understanding the prevailing noise fields in coastal oceans.

Physical processes controlling the hydrography of shelf waters often exhibit strong seasonal variations. Episodic passages of meteorological fronts from continental interiors affect the thermal structure of the adjacent shelf waters through intense air–sea interactions. River outflows create strong salinity gradients along the adjacent coast. Variable bottom topographies and sediment compositions with their attendant spectral dependencies complicate acoustic bottom boundary conditions. At higher latitudes, ice formation complicates acoustic surface boundary conditions near the coast. Waves generated by local winds under fetch-limited conditions, together with swells originating from distant sources, conspire to complicate acoustic surface boundary conditions and also create noisy surf conditions. Marine life, which is often abundant in nutrient-rich coastal regions, can generate or scatter sound.

Biological Noise Impacts

Underwater noise is now classed as pollution in accordance with the European Union's Marine Strategy Framework Directive (Directive 2008/56/EC dated 17 June 2008). Noise from shipping is a major contributor to the ambient-noise levels in the ocean, particularly at low (<300 Hz) frequencies. Copping and O'Toole (2010) noted that the effects of underwater noise from MHK devices on receptors such as marine mammals and fish include physical auditory damage, behavioral changes, avoidance of area, chronic stress, altered acoustic sensitivity, and mortality.

Enabling Technologies and Emerging Solutions

Underwater acoustic models are viewed as enabling tools for evaluating marine-system impacts arising from noise associated with the installation and operation of marine renewable (hydrokinetic) energy devices. Broadly defined, modeling is a method for organizing knowledge accumulated through observation or deduced from underlying principles. Modeling applications fall into two basic categories: prognostic and diagnostic. Prognostic applications include prediction and forecasting functions for which future oceanic conditions or acoustic sensor performance must be anticipated, such as selection of sites for future MHK device installations. Diagnostic applications include system-design and analysis functions typically encountered in engineering trade-off studies involving the interpretation of sparse measurements of sounds produced by marine-energy converters.

Farcas et al. (2016) emphasized that the underwater acoustic models that are presently used in environmental impact assessments (EIAs) consider only the sound-pressure component of sound, which is the means by which marine mammals hear; however, the primary mechanism by which fish and invertebrate species detect sound is through the particle-motion component of sound.

For the period 1996–2015, Finneran (2015) reviewed progress in the methods employed by research groups conducting marine-mammal temporary threshold shift (TTS) experiments. (TTS refers to a temporary increase in the threshold of hearing; i.e., the minimum intensity needed to hear a sound at a specific frequency, but which returns to its pre-exposure level over time.) Specifically, he summarized the relationships between the experimental conditions, the noise-exposure parameters, and the observed TTS. An attempt was made to synthesize the major findings across experiments to provide the current state of knowledge for the effects of noise on marine-mammal hearing. The most critical gaps involved the manner in which exposure frequency affects the resulting patterns of TTS growth and recovery. TTS growth curves at various frequencies are needed for representative species so that effective weighting functions can be developed to predict the onset of TTS and establish upper safe limits to prevent permanent threshold shift (PTS) for various noise frequencies. The noise sources of greatest concern, such as military sonar systems and seismic air guns, involve acute exposures to high-intensity, intermittent sounds; however, significant questions remain regarding the rate of TTS growth and recovery after exposure to intermittent noise and the effects of single and multiple impulses. At present, data are insufficient to construct generalized models for recovery or to determine the time necessary to treat subsequent exposures as independent events. More information is needed about the relationship between auditory evoked potentials and behavioral measures of TTS for various stimuli. Finally, data on noise-induced threshold shifts in marine mammals are available for only a few species, and for only few individuals within these species. Questions still remain about the most appropriate methods for extrapolation to other species.

Noise Sources

To form a more complete portrait of the prevailing noise fields composing the soundscape, this section describes the background noise fields arising from natural as well as anthropogenic noise sources. The noise fields associated with MHK devices, as well as wind-farm noise, are also described.

Natural Background Noise

As summarized in Table 1, the background of natural noise comprises seismo-acoustic noise, bioacoustic noise, wind and rain noise, surf noise, and (where appropriate) Arctic ambient noise.

Table 1 Summary of natural background noise sources

Noise source	Comments
Seismo-acoustic noise	Seismo-acoustics refers to low-frequency (<3 Hz) noise signals originating in Earth's interior and the oceans (Orcutt 1988)
Bioacoustic noise	Marine bioacoustic signal sources are typically transient in nature and exhibit diverse temporal, spatial, and spectral distributions. The main contributors to bioacoustic signals include certain shellfish, fish, and marine mammals. Of the marine mammals, whales are the most notable contributors (see Etter 2013)
Wind and rain noise	Ambient noise correlates well with wind speed in the frequency band 500 Hz–25 kHz, but correlates poorly with significant wave height. The poor correlation with wave height can be attributed to the disproportionate effect of swell on the frequency of breaking waves, which are considered the primary source of wind-dependent noise in the ocean (Felizardo and Melville 1995). The underwater noise spectrum generated by rain has a unique spectral shape that is distinguishable from other noise sources by a broad peak at about 15 kHz; moreover, the relationship between spectral level and rate of rainfall is quantifiable (Scrimger et al. 1987)
Surf noise	Ambient noise in the surf zone in the frequency range 120 Hz–5 kHz is dominated by breaking waves (Bass and Hay 1997)
Arctic ambient noise	Although it is unlikely that large-scale MHK devices would initially be deployed in Arctic regions, they may be used to power autonomous sensor systems and, consequently, it is useful to note that the noise environment under, or near, the Arctic ice is different from that of any other ocean area. Shipping noise is extremely low due to the lack of surface traffic. The ice cover itself affects the ambient-noise field significantly: It can decouple the water from the effects of the wind and produce ambient-noise conditions that are much quieter than a corresponding sea-state zero in the open ocean. The ice itself may produce noises as wind, waves, and thermal effects act on it (see Etter 2013)

Anthropogenic Background Noise

As summarized in Table 2, the three principal sources of anthropogenic noise of interest include seismic sources, shipping traffic, and environmental phenomena of human origin that contribute to the background noise levels. Additional sources of anthropogenic noise may derive from a new generation of multistatic naval sonar systems.

MHK Device and Wind-Farm Noise

This section addresses available observations of the noise fields associated with the installation and operation of MHK devices and wind farms in the context of marine renewable energy (MRE). A discussion of wind-farm noise is included because there is a relative abundance of acoustic data collected on the installation and

Table 2 Summary of anthropogenic background noise sources

Noise source	Comments
Seismic sources	Marine seismic surveys are used to assess the location of hydrocarbon resources, including gas and oil. Acoustic models have been used to estimate marine-mammal sound-exposure levels generated in geophysical surveys by multi-beam echo sounders, side-scan sonar systems, subbottom profilers, and seismic boomers (Zykov 2013)
Shipping traffic	Noise from distant shipping generally occupies the frequency band 20–500 Hz (Carey and Evans 2011). A comparison of time-series measurements of ocean ambient noise over two periods (1963–1965 and 1994–2001) revealed that noise levels from the latter period exceeded those of the earlier period by about 10 dB in the frequency ranges of 20–80 Hz and 200–300 Hz, and by about 3 dB at 100 Hz. The observed increase was attributed to increase in shipping (Andrew et al. 2002). Ambient-noise measurements collected at the same site but separated by an interval of nearly 40 years (1964–1966 and 2003–2004) revealed an average noise increase of 2.5–3 dB per decade in the frequency band 30–50 Hz (McDonald et al. 2006, 2008)
Environmental phenomena	Climate change also affects the ocean soundscape. The emission of carbon into the atmosphere through the effects of fossil-fuel combustion and industrial processes increases atmospheric concentrations of carbon dioxide (CO_2). Ocean acidification, which occurs when CO_2 in the atmosphere reacts with water to create carbonic acid (H_2CO_3), is increasing. The attenuation of low-frequency sound in the sea is pH-dependent; specifically, the higher the pH, the greater the attenuation. Thus, as the ocean becomes more acidic (lower pH) due to increasing CO_2 emissions, the attenuation will diminish and low-frequency sounds will propagate farther, effectively making the ocean noisier (see Etter 2013)

operation of such devices; these data may have direct application to the estimation of MHK device noise fields.

Deployment of MHK devices is still in the early stages, and a substantial database is not yet available regarding the impacts of MHK noise on the environment. Only a limited understanding of the environmental impacts has been achieved to date because few of these projects are presently operational. Therefore, it is important to note that much of the following discussion describes results that precede recent published work on the characterization of sound generated by operational MHK devices.

The topic of uncertainty is included here to raise awareness of inherent limitations in the fidelity of model outputs.

Tidal Turbines

Lloyd et al. (2011) modeled underwater noise sources associated with horizontal-axis tidal turbines and their potential impact on shallow-water marine environments. The requirement for device-noise prediction as part of environmental impact assessment was considered in light of the limited amount of measurement data available. Noise sources included self-noise, interaction noise, and hydroelastic noise. In future studies, machinery (generator) noise and cavitation noise also need to be considered. The dominant flow-generated noise sources were modeled using empirical techniques. The predicted sound-pressure level due to inflow turbulence for a typical horizontal-axis tidal turbine was estimated to generate 1/3-octave-bandwidth pressure levels of 119 dB re 1 μPa at 20 m from the turbine at individual frequencies. This preliminary estimate revealed that this noise source alone would not be expected to cause either a PTS or TTS in typical marine animals of the North Sea including cod, harbor seal, and harbor porpoise.

Li and alişal (2010) presented a preliminary study of four principal characteristics of tidal-current turbines: power output, torque, induced velocity, and acoustic emission. Numerical models were developed to predict these characteristics for tidal-current turbines. It was proposed that these same models could also be used to develop standards for tidal-current turbines. The resulting hydrodynamic noise intensity (acoustic emission) was evaluated at three locations downstream from the subject turbine. The frequencies corresponding to the first peak (main noise frequency) at the three locations were all around 4 Hz. Successively smaller amplitude peaks were also observed at 18 Hz and at 31 Hz.

Wave-Energy Devices

Austin et al. (2009) provided wave-energy developers in Oregon with fundamental information about the principles, methods, and equipment involved in conducting environmental noise assessments related to the permitting of such projects. In the absence of any documented ambient-noise measurements for the near-shore environment off the Oregon coast, characterizations of the environmental components that contribute to the overall ambient-noise field were provided instead. The marine operations noise model (MONM) computed transmission losses for arbitrary three-dimensional, range-varying acoustic environments using a parabolic-equation (PE) solution to the acoustic wave equation. The modeling took into account a number of environmental parameters including bathymetry, sound-speed profile in the water column, and geoacoustic properties of the seafloor.

Ikpekha et al. (2014) developed a computer model that simulated low-frequency (<1000 Hz) acoustic signals produced by a wave-energy device in coastal environments. They analyzed these signals with the aid of marine-mammal audiograms of the harbor seal. This enabled them to estimate the levels of acoustic noise experienced by marine mammals due to the presence of ocean-deployed devices. Propagation of the underwater acoustic signals was modeled using the finite-element (FE) method with appropriate boundary conditions at the sea surface and the seafloor. Based on an audiogram of the harbor seal, it was deduced that animals at least 51 m distant from the sound source would not be affected.

Wind-Farm Noise

A wind farm, which is a group of wind turbines in the same location used for production of electric power, may be located offshore. The installation of ocean wind farms requires medium water depths (<30 m) and construction logistics such as access to specialized vessels to install the turbines. Economic wind generators require wind speeds of 16 km/h or greater (Etter 2013).

One of the most significant activities during MHK device and wind-farm construction is foundation installation, during which dredging, rock laying, and pile driving may be undertaken Activities include scour protection, cable protection, and modifying non-ideal bathymetry. Other construction activities include cable laying, turbine and turbine-tower installation, and ancillary structure installation (such as offshore transformers). Additional noise sources include industrial traffic associated with transporting workers, materials, and hydrokinetic energy devices to offshore sites (Etter 2013).

Uncertainty

Uncertainty has been defined as a quantitative measure of our lack of complete knowledge of the sound-speed field and boundary conditions constituting the waveguide information necessary for simulation of the acoustic field (Finette 2005). This uncertainty is distinct from any errors related to numerical solution of the wave equation. Existing simulation methods typically solve a deterministic wave equation separately over many realizations, and the resulting set of pressure fields is then used to estimate statistical moments of the field. Proper sampling may involve the computation of thousands of realizations to ensure convergence of the statistics.

A study of the impacts of uncertainty in the modeling of anthropogenic noise impacts suggested a precautionary approach to regulation (Lawson 2009): Due to the complex patterns of sound propagation encountered in diverse shelf regions, some marine mammals may not necessarily encounter the average sound-exposure conditions predicted for any given impact scenario.

In practice, noise modeling efforts in support of EIAs are often carried out using simplistic underwater acoustic models, with limited environmental data, and with little or no field measurements to ground-truth the model predictions. In some cases, practitioners have developed proprietary models, the inner workings of which are not disclosed to regulators. This presents regulatory decision-makers with considerable uncertainty regarding the prediction of possible impacts; moreover, this uncertainty is often not apparent. In an effort to better inform regulators, stakeholders, and developers of the factors that may lead to uncertainty in noise assessments, Farcas et al. (2016) provided concrete examples of how different modeling procedures can affect predictions. Raising awareness of these issues can help promote best practice in noise-impact assessments and enable better-informed EIA processes for noise-generating developments. To further explore this aspect, Farcas et al. (2016) used measurements of impact pile-driving noise that were made simultaneously at two locations in the Cromarty Firth, Scotland. Different acoustic models were then used to calculate the source level of pile-driving noise. This exercise served to illustrate that, although there is considerable uncertainty about the relationship between noise levels and impacts on aquatic species, the science underlying noise modeling appears to be well understood. Farcas et al. (2016) further observed that underwater acoustic models that are currently applied in EIAs consider only the sound-pressure component of sound, which is the means by which marine mammals hear; however, the primary mechanism by which fish and marine invertebrate species detect sound is through the particle-motion component of sound.

Mitigation and Monitoring

In the present context, mitigation refers to the administrative, procedural, legal, and technical aspects of reducing or eliminating sources of noise that might be potentially harmful to marine life, especially marine mammals. Monitoring indicates connections between identified environmental impacts, measurement indicators, detection limits, and the thresholds that will signal the need for corrective action. This section is divided into three parts: (1) mitigation measures and monitoring; (2) passive acoustic technologies; and (3) underwater acoustic networks.

Mitigation Measures and Monitoring

The Committee on Potential Impacts of Ambient Noise in the Ocean on Marine Mammals was charged by the Ocean Studies Board of the U.S. National Research Council to assess the state of our knowledge of underwater noise and recommend research areas to assist in determining whether noise in the ocean adversely affects marine mammals (National Research Council 2003). One of the findings of this committee was that models describing ocean noise are better developed than those describing marine-mammal distribution, hearing, and behavior. The biggest challenge lies in integrating the two types of models. The National Research Council (2005) further examined what constitutes biologically significant in the context of level B harassment as used in the latest amendments to the U.S. Marine Mammal Protection Act (MMPA). The MMPA separates harassment into two levels. Level A harassment is defined as "any act of pursuit, torment, or annoyance which has the potential to injure a marine mammal or marine mammal stock in the wild." Level B harassment is defined as "any act of pursuit, torment, or annoyance which has the potential to disturb a marine mammal or marine mammal stock in the wild by causing disruption of behavioral patterns, including, but not limited to, migration, breathing, nursing, breeding, feeding, or sheltering." Enacted in 1972, the MMPA was the first legislation that called for an ecosystem approach to natural-resource management and conservation; it specifically prohibited the *take* (i.e., hunting, killing, capture, and/or harassment) of marine mammals.

Todd et al. (2015) described noise-reduction methods and associated acoustic-mitigation devices. Noise-reduction methods included acoustic-isolating materials and bubble curtains (or screens) that reduced initial sound output or reduced sound intensity along a propagation path. Acoustic-mitigation devices included acoustic-harassment devices (or pingers) that encouraged animals to move away from high-risk operational areas.

Ramp-up (or soft-start) procedures employ a gradual increase in the source level in order to mitigate the effects of sonar transmissions on marine mammals. Von Benda-Beckmann et al. (2014) investigated the effectiveness of ramp-up procedures in reducing the area within which changes in hearing thresholds in marine mammals can occur. The effectiveness of the ramp-up procedure depended strongly on the assumed response threshold of the marine mammals and differed with ramp-up duration.

Passive Acoustic Technologies

Fixed autonomous passive acoustic arrays can sample continuously for prolonged periods of time in all weather conditions, thereby allowing for assessments of seasonal changes in both the distribution and acoustic behavior of individual animals without the disturbance of survey vessels or aircraft. Autonomous underwater vehicles and gliders can serve as adjuncts to ship-based hydrographic casts, towed sensors, and satellite-based sensors. Underwater acoustic networking is the enabling technology for these applications.

Underwater Acoustic Networks

To collect data about noise emitted from MHK devices, it may be necessary to deploy seafloor-mounted and autonomous-drifting hydrophones to monitor noise levels before, during, and after testing of wave-energy and tide-energy conversion devices.

A model of the ocean medium between acoustic sources and receivers is called a *channel model*, and it may be digital or analog. In an oceanic channel, characteristics of the acoustic signals change as they travel from transmitters to receivers. These characteristics depend upon the acoustic frequency, the distances between sources and receivers, the paths taken by the signals, and the prevailing ocean environment in the vicinity of the paths. Properties of received signals can be derived from those of the transmitted signals using *channel models* (Etter 2013).

Underwater Acoustic Modeling Techniques as Enabling Tools

This section summarizes the modeling techniques that can be employed to predict and assess the acoustic impacts of MHK device installation and operation, with particular emphasis on propagation and noise models.

Propagation Models

As sound propagates through the ocean, the effects of spreading and attenuation diminish its intensity. Spreading loss includes spherical and cylindrical spreading losses in addition to focusing effects. Attenuation loss includes losses due to absorption, leakage out of ducts, scattering, and diffraction. Propagation losses increase with increasing frequency due largely to the effects of absorption. Sound propagation is also affected by the conditions of the surface and bottom boundaries of the ocean as well as by the vertical and horizontal distribution of sound speed within the ocean volume. Sound-speed gradients introduce refractive effects that may focus or defocus the propagating acoustic energy.

Formulations of acoustic propagation models generally begin with the three-dimensional, time-dependent wave equation. For most applications, a simplified linear, hyperbolic, second-order, time-dependent partial differential equation is used:

$$\nabla^2 \Phi = \frac{1}{c^2}\frac{\partial^2 \Phi}{\partial t^2} \tag{1}$$

where $\nabla^2 = (\partial^2/\partial x^2) + (\partial^2/\partial y^2) + (\partial^2/\partial z^2)$ is the Laplacian operator, Φ is the potential function, c is the speed of sound, and t is the time.

Subsequent simplifications incorporate a harmonic (single-frequency, continuous-wave) solution in order to obtain the time-independent Helmholtz equation. Specifically, a harmonic solution is assumed for the potential function Φ:

$$\Phi = \phi\ e^{-i\omega t} \tag{2}$$

where ϕ is the time-independent potential function, ω is the source frequency ($2\pi f$), and f is the acoustic frequency. Then the wave Eq. (1) reduces to the Helmholtz equation:

$$\nabla^2 \phi + k^2 \phi = 0 \tag{3}$$

where $k = (\omega/c) = (2\pi/\lambda)$ is the wavenumber and λ is the wavelength. Equation (3) is referred to as the time-independent (or frequency-domain) wave equation; in cylindrical coordinates, it is commonly referred to as the elliptic-reduced wave equation

Propagation models of potential interest to MHK acoustic assessments can be reduced to three techniques (Etter 2013): **ray-theoretical models** calculate propagation loss on the basis of ray tracing; **normal-mode solutions** are derived from an integral representation of the elliptic-reduced wave equation; and **parabolic approximation approaches** replace the elliptic-reduced wave equation with a PE.

Each of these three techniques has a unique domain of applicability that can be defined in terms of acoustic frequency and environmental complexity (for more details, refer to Etter 2013). These domains are determined by the assumptions invoked in deriving each solution from the wave equation. **Ray-theoretical models** invoke the geometrical acoustics approximation, which effectively limits the ray-theoretical approach to the high-frequency domain: $f > 10\ c/H$, where f is the frequency, H is the duct depth, and c is the speed of sound. **Normal-mode solutions** compute eigenvalues (or characteristic values) that represent the discrete set of values for which solutions of the normal-mode functions exist; the number of modes increases with increasing frequency, which makes this approach more viable at lower frequencies. **Parabolic approximation approaches** can be numerically solved using marching solutions when the initial field is known; although this approach is also more viable at lower frequencies, the computational advantage lies in the fact that a parabolic-differential equation can be marched in the range dimension, whereas the normal-mode approach must be numerically solved in the entire range-depth region simultaneously.

A further division can be made according to range-independent (1D—depth-dependence only) or range-dependent environmental specifications, where environmental range-dependence can be 2D (depth and range) or 3D (depth, range, and azimuth). Hybrid formulations obtained by combining two or more different techniques are often developed to improve domain robustness.

The Ocean Acoustics Library (OALIB) (http://oalib.hlsresearch.com) (last accessed August 24, 2016) provides access to selected stand-alone propagation models of potential interest to MHK acoustic assessments. This access is provided directly to downloadable software or indirectly by reference to other authoritative Web sites. Candidate models derived from the OALIB are summarized in Table 3. A more extensive list of underwater acoustic propagation models is presented by Etter (2013).

Some applications, such as work related to acoustic impacts on marine mammals, do not require extremely high-fidelity model outputs. Transmission losses averaged over depth, for example, are often adequate. An approach referred to as *energy-flux* (Weston 1971, 1980a, b) is useful for the rapid calculation of transmission losses where the propagation conditions are dominated by numerous boundary-reflected multipaths, and when only the coarse characteristics of the acoustic field are needed. In specific configurations, especially at long ranges in shallow-water environments, the transmitted field can be viewed as being composed of many paths propagating by successive reflections from the surface and bottom boundaries. Here, the acoustic energy will remain trapped between these two

Table 3 Summary of candidate underwater acoustic propagation models that are accessible on the OALIB Web site (http://oalib.hlsresearch.com). (Acronyms are defined in Appendix A. Also see Etter 2013 for more details regarding these and other propagation models.)

Technique	Candidate models
Ray theory	BELLHOP HARPO TRIMAIN TV-APM
Normal mode	COUPLE KRAKEN MOATL WKBZ
Parabolic approximation	FOR3D PDPE PECan RAM/RAMSURF UMPE

boundaries. Furthermore, if the acoustic frequency is high enough that the field oscillations can be considered to be random, then an average intensity can be calculated using simple algebraic formulas. This concept can be extended to ocean environments where the sound speed is not constant, or where there are slight losses at the boundaries. In such cases, the transmitted field cannot be taken as a volumetric average. Rather, it has to be decomposed into its angular components and the cyclic characteristics of the various beams must be detailed (Lurton 1992, 2002).

Noise Models

Noise is the prevailing, unwanted background of sound at a particular location in the ocean at a particular time. The local noise field is thus characterized by temporal, spatial, and spectral variabilities. The noise generated by both natural and anthropogenic point sources is diminished by the effects of spreading and attenuation, which are quantified by propagation models. Ambient-noise models are applicable over a broad range of frequencies and consider noise originating from surface weather, biologics, shipping, and other commercial activities.

One example of a noise model with potential application to MHK acoustic research is ESME (effects of sound on the marine environment). This is a multidisciplinary research and development effort to explore the interactions between anthropogenic sounds, the acoustic environment, and marine mammals (Shyu and Hillson 2006; Siderius and Porter 2006). The ESME workbench models the entire sound path including the sound sources, the medium (water column and seafloor), and the TTS models of the marine mammals. The goal is to predict impacts of anthropogenic sounds on marine mammals. This entails three elements: accurate estimates of the sound field in the ocean, accurate estimates of the cumulative sound exposure of the marine mammals, and reliable predictions of the incidence of TTS for the species of interest given the estimated cumulative exposure. A more extensive list of underwater acoustic noise models is presented by Etter (2013).

Summary

This chapter describes the use of underwater acoustic models for the evaluation of marine-system noise impacts associated with the installation and operation of MHK devices, particularly in coastal oceans. This review is placed in the context of an underwater soundscape, which is a combination of sounds that characterize, or arise from, an ocean environment. Disruption of the natural acoustic environment results in noise pollution. The field of underwater acoustics enables us to observe and predict the behavior of this soundscape and the response of the natural acoustic environment to noise pollution. Specifically, underwater acoustic models can serve as enabling tools for assessing noise impacts on marine systems through the generation of analytical metrics useful in resource management.

Marine-mammal protection research has focused on simulating anthropogenic sound sources, which derive in part from seismic-exploration activity, merchant shipping traffic, and a new generation of multistatic naval sonar systems. Additional sources derive from MRE resources, including the deployment of wind farms, tidal turbines, and wave-energy devices.

One of the most significant activities during MHK device construction is foundation installation, which may involve dredging, rock laying, and pile driving. Other construction activities could include cable laying, turbine and turbine-tower installation, and ancillary structure installation (such as offshore transformers). Additional noise sources include industrial traffic associated with transporting workers, materials, and hydrokinetic energy devices to offshore sites. Knowing the length of time the marine environment is exposed to an underwater noise source is useful when assessing environmental effects.

A review of the methods employed in conducting marine-mammal TTS experiments indicates that (1) existing data are insufficient to construct generalized models for recovery, and (2) existing models cannot determine the time necessary to treat subsequent exposures as independent events. More information is needed about the relationship between auditory evoked potentials and behavioral measures of TTS for various stimuli. Data on noise-induced threshold shifts in marine mammals are available for only a few species, and for only a few individuals within these species. Questions still remain about the most appropriate methods for extrapolation to other species. A study of the impacts of uncertainty in the modeling of anthropogenic impacts suggested a precautionary approach to regulation based on modeling results; specifically, due to the complex patterns of sound propagation encountered in diverse shelf regions, some marine mammals may not necessarily encounter the average sound-exposure conditions predicted for any given impact scenario.

Mitigation refers to the administrative, procedural, legal, and technical aspects of reducing or eliminating sources of noise that might be harmful to marine life, especially marine mammals. Monitoring indicates connections between identified environmental impacts, measurement indicators, detection limits, and the thresholds that will signal the need for corrective action. Noise-reduction methods include

acoustic-isolating materials and bubble curtains (or screens) that reduce initial sound output or reduce sound intensity along a propagation path. Acoustic-mitigation devices include acoustic-harassment devices (or pingers) that encourage animals to move away from high-risk operational areas.

Applied underwater acoustic modeling technologies (specifically, propagation and noise models) have evolved over the past several years in response to new regulatory initiatives that place restrictions on uses of sound in the ocean. The mitigation of marine-mammal endangerment is now an integral consideration in acoustic-system design, installation, and operation. Additional advances have been achieved using energy-flux techniques that can simplify the interpretation of sound-channel models. To assist researchers and practitioners in the proper usage of underwater acoustic models, updated summaries are provided for the existing inventory of propagation and noise models, tailored to potential MHK applications. Additional guidelines are provided to assist users in the selection and utilization of the most appropriate models for any given impact scenario. Where available, case studies are examined to illustrate the use of acoustic models for the assessment of MHK device impacts. It is important to note that many underwater acoustic models currently used in EIAs consider only the sound-pressure component of sound, which is the means by which marine mammals hear; however, the primary mechanism by which fish and invertebrate species detect sound is through the particle-motion component of sound. Consequently, this aspect warrants further development and refinement of the existing model inventory.

Finally, it should be stressed that the deployment of MHK devices is still in the early stages, so a substantial database is not yet available regarding the impacts of MHK noise on the environment. Only a limited understanding of the environmental impacts has been achieved to date because few of these projects are presently operational. This situation creates an opportunity for numerical modelers to generate prognostic indicators of MHK noise impacts to guide resource planners in the selection of sites suitable for MHK installations.

Appendix A—Abbreviations and Acronyms

1D	One-dimensional
2D	Two-dimensional
3D	Three-dimensional
BELLHOP	Gaussian-Beam, Finite-Element, Range-Dependent Propagation Model
CO_2	Carbon dioxide
COUPLE	Coupled Mode Model
dB	Decibel(s)
EIA	Environmental impact assessment
ESME	Effects of sound on the marine environment
FE	Finite element

FOR3D	Finite Difference Methods, Ordinary Differential Equations, and Rational Function Approximations to Solve the LSS 3D Wave Equation
h	Hour(s)
HARPO	Hamiltonian Acoustic Raytracing Program—Ocean
Hz	Hertz (cycles per second)
kHz	Kilohertz
km	Kilometer(s)
KRAKEN	Adiabatic/Coupled Normal Mode Model
LSS	Lee-Saad-Schultz Method
m	Meter(s)
MHK	Marine-hydrokinetic
MMPA	Marine Mammal Protection Act
MOATL	Modal Acoustic Transmission Loss Model
MONM	Marine Operations Noise Model
MRE	Marine renewable energy
OALIB	Ocean Acoustics Library
PDPE	Pseudo-Differential PE
PE	Parabolic equation
PECan	Canadian Parabolic Equation
pH	Scale used to specify the acidity or basicity of an aqueous solution
PTS	Permanent threshold shift
RAM	Range-Dependent Acoustic Model
RAMSURF	RAM Rough Surface
TRIMAIN	Range-Dependent Acoustic Propagation Model Based on Triangular Segmentation of the Range-Depth Plane
TTS	Temporary threshold shift
TV-APM	Time-Variable Acoustic Propagation Model
UMPE	University of Miami PE
WKBZ	Adiabatic Normal Mode Model

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