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REVIEW OF UNDERWATER ACOUSTIC PROPAGATION MODELS

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Review of underwater acoustic propagation models

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Summary

In September 2013, the European Commission commissioned a project entitled *Impacts of Noise and use of Propagation Models to Predict the Recipient Side of Noise* (project number 1109.05/659011/SER/C.2), under a Framework Service Contract (ENV.D2/FRA/2012/0025) with the subject ‘Emerging pressures, human activities and measures in the marine environment (including marine litter), led by Cefas. The project consortium members include Cefas, NPL, TNO, OASIS and JNCC (later in an advisory role).

This report is the deliverable of Task 4, ‘*Compile existing information on underwater sound propagation models*’, of the above project, its aim being ‘*to critically review existing relevant literature and results from research projects and make an inventory of existing models with pros/cons and gaps, and especially the reliability and information needs required for applying these models, with assumptions and limitation explicitly mentioned’*.

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1 Background to ocean acoustic propagation modelling

Ocean acoustic propagation models have been widely used for several decades, to support a broad range of applications including anti-submarine warfare [Bucker, 1976], global scale underwater sound propagation [Heaney et al., 1991; Collins et al., 1995] characterisation of acoustic communications channels [Simons et al., 2001], passive acoustic monitoring of marine biota [e.g. Potter et al., 1994; Stafford et al., 1998; McDonald et al., 1999; Thode et al., 2004; Helble et al., 2013], ocean acoustic tomography [Munk and Wunsch, 1979; Cornuelle et al., 1989; Worcester et al., 1999]), ambient noise forecasting [Wenz, 1962; Heitmeyer, 2006; Merchant et al., 2012] and other oceanographic applications [Harrison 1989; Buckingham, 1992; Jensen et al., 1997]. Since the first underwater sound experiment, conducted by Colladon and Sturm in 1826 on Lake Geneva, it has been known that sound travels extremely well underwater [Lichte, 1919]. With the advent of large-scale submarine warfare during the Second World War and the subsequent Cold War, there was intense effort to understand and predict the propagation of sound in the ocean, accruing a wealth of knowledge about underwater sound propagation, and its environmental dependencies [Ainslie, 2010]. Relatively recent advances in a number of scientific disciplines have provided further confidence in the ability to predict the acoustic field for a given source, and much of the progress is founded on advancements in:

- Computational acoustics – which provided a solution to the wave equation permitting the computation of the acoustic field for a given environment;
- Bathymetric remote sensing – which provided input water depth for small and large scale problems;
- Oceanographic dynamics and modelling –the complexity of the temperature and salinity field (that drive sound speed) has been characterised and observational and modelling methods have helped quantify these fields;
- Computer hardware speed – much of the capabilities of modern ocean acoustic modelling has benefited from the rapid increase in computer processing speed (i.e. CPU) and memory access efficiency (i.e. RAM).

The outputs of an acoustic propagation model may be used to establish the time-series at a single receiver, the range/depth slice of received level (established from the propagation loss), or a geographically based plan-view of the ensonification area from a particular source.

The reduction in the level of the acoustic field between a source and a receiver position, i.e. the propagation loss, is generally stated as the difference between the source level and the sound pressure level at a receiver position, expressed in decibels (dB) relative to 1 m. This reduction will occur due to the spreading laws, although there will also be a number of environmental factors that may affect the propagation of the acoustic wave and therefore the propagation loss over a given distance, including:

- The volume characteristics
    - Water sound speed profile (driven mainly by temperature, hydrostatic pressure and salinity)
    - Water attenuation profile
    - Volume scattering characteristics
- The surface boundary

    - Surface roughness
    - Bubbles
    - Doppler shift resulting from ocean wave motion
- The seafloor/seabed boundary
    - Parameterisation of the sediment via reflection coefficient or geo-acoustic parameters
    - The bathymetry
    - The seafloor and sub-seafloor roughness

The influence of these factors will be dependent on the geographic location and their influence may be frequency dependent. These dependencies are further discussed in Section 2 below.

2 Ocean acoustic propagation models

2.1 Introduction

Ocean acoustic propagation models usually solve the wave equation (or Helmholtz equation), further described in Section 2.2. This is generally done for a given frequency, and broadband signals, for example, a pulse, may have to be modelled using a time-domain model. Alternatively a solution is calculated for each frequency or frequency band across the required frequency range, with the use of a suitable inverse transform. It is also worth noting that not every propagation model will consider all of the environmental factors listed in Section 0, which may influence the propagating wave.

In general, propagation modelling solutions can be divided into three large classes based upon i) the frequency characteristics of the source; ii) the environmental dependence of the propagation region; and iii) the water depth. Models within class ii) are generally categorised as *range independent* (the environmental parameters are kept fixed with range), and *range dependent* (environmental input parameters, such as water depth and sound speed, are allowed to vary with distance from the source), the latter being the preferred choice when the bathymetry or water column conditions change along the propagation path.

Given a particular frequency band and environment, the choice of a suitable propagation model can be made. There are a wide variety of models available, some of which are available for download free of charge, but these complex models require some expertise to run successfully. The available propagation models are commonly categorised based on their underlying method into the following groups [Jensen et al., 2011; Etter, 2013], which captures the most commonly used methods:

- Ray tracing
- Normal mode
- Parabolic equation
- Wavenumber integration
- Energy flux
- Finite Difference, Finite Element models

There are other methods such as the image method [Brekhovskikh, 1980] and the multipath extension [Weinberg, 1975], which are not considered here.

Note that although it is possible to model vector field quantities such as sound particle velocity, in practice this is rarely done, and most modelling is used to predict the transmission of sound energy or sound pressure.

One further parameter that influences model choice is computational cost (or model efficiency). There can be orders of magnitude differences in the required computational time for different models and a decision is required between higher fidelity/accuracy and the computational time. It should be noted that for given propagation conditions, there will be a number of modelling solutions which may provide the appropriate accuracy, and computation time may be a distinguishing factor.

2.2 Solutions to the wave equation

Underwater sound field can be described by the Helmholtz equation:

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

where the solution $\emptyset(\boldsymbol{r}, f)$ is a function of position vector $\boldsymbol{r}$ and frequency f. The solution can be found if source and boundary condition are known.

There are a number of solutions of the wave equation depending on the methods applied to the equation. An introduction to the physics and implementation of each solution is provided in Jensen et al., [1997]. These solutions to the wave equation can generally be categorised into six propagation modelling methods each of which is outlined here, with their potential advantages and limitations, and also introduced are the qualifications to understand suitability of each model. A list of the available models is also provided in a summary book by Etter [2013].

2.2.1 Ray method

Ray method – brief description:

Following the analogy of optics, the wave equation can be solved in the high-frequency limit by integrating Snell's law and the associated eikonal equation. This ray tracing solution is highly intuitive because the sound paths can be traced and show the path of each ray. Ray tracing is very efficient (fast). Once the rays are computed, the acoustic field levels are calculated by summing the rays near the receiver. The rays are often extended in size by using the Gaussian beam approximation. Ray interaction with the seafloor is achieved using a reflection coefficient without penetration into the seafloor. Ray theory is limited in accuracy at low frequencies (typically below around 200 Hz) where diffraction is significant and where seabed penetration occurs. The ray theory approach performs poorly when there are surface ducts and other sound speed fields with discontinuities and rough surfaces. Ray theory handles arbitrary range-dependent environments, is best in deep water and is suitable at higher frequencies.

The ray method of the wave equation is a high frequency approximation solution [Officer, 1958; Boyles 1984; Brekhovskikh and Lysanov, 1982; Tolstoy et al., 1966], assuming the following form:

$$p = Ae^{j\varphi} \qquad [2]$$

where A is the amplitude and φ is the phase, both of which are functions of distance between the source and the receiver. This solution generates two separate equations when applied to the wave equation.

In practice, the amplitude of an acoustic field varies very slowly in comparison with the phase, especially at high frequency. The first solution can be simplified by ignoring the term of the second derivative of the amplitude with respect to distance, resulting in the eikonal equation, a non-linear partial differential equation. The eikonal equation can be solved numerically to produce a ray trace when the initial launch angle and sound speed profile are given. The second solution, called the transport equation, is used to determine the amplitude.

Ray-tracing models are only limited in capability as a consequence of the approximation leading to the eikonal equation since no other approximations appear in the ray-theoretic development. The physical implications of this approximation are that the curvature of a ray over a wavelength must be small; the fractional change in sound speed must be small over a wavelength; and the fractional change in A must be small over a wavelength.

Ray-tracing models are fast to compute, providing a pictorial representation, in the form of ray diagrams, of the field in the channel. This is useful for integrating and understanding the results. Further advantages of ray tracing are that: (i) the directionality of the source and receiver can be fairly easily accommodated, by introducing appropriate launch and arrival-angle weighting factors; and (ii) rays can be traced through range-dependent sound speed profiles and over complicated bathymetry. Conversely, the computations must be performed at all distances to the receiver. While only a few rays are required to determine the sound field at a distant receiver in deep oceans, many rays are needed in shallow water. Perhaps the most pertinent disadvantage, however, is that wave effects such as diffraction and caustics cannot easily be handled adequately by ray tracing, which limits the usefulness of this approach for the investigation of seafloor interactions and for low frequency propagation:

- *Wave diffraction allows sound to spread into the shadow zone near the boundary region of the zone, whereas ray tracing predicts no sound in the shadow zone, resulting in a very sharp contrast each side of the boundary region;*
- *At a caustic the amplitudes become singularities due to converging rays resulting in a high pressure region.*

Modified ray methods have been developed to overcome these problems for example by Keller [1962], White and Pederson [1981], and Tindle [2002].

Beam tracing [Porter and Bucker, 1987; Bucker, 1994; Weinberg and Keenan, 1996] is a variant of ray tracing. It uses the same rays as in ray tracing, but applies a beam width associated with each ray to determine the amplitude of the pressure. It overcomes the shadow zone and at caustics problems associated with the ray tracing method.

Available ray tracing programs consider only the wave field in water column, perhaps for historical reasons, as the method was intended for underwater applications. However, the effect of the seabed is taken into account through the consideration of the reflection coefficient at the interface of the water and the seabed. The surface loss caused by scattering of rough surface and air bubbles near the surface can also be included.

2.2.1.1 Example of a ray/beam tracing propagation model: Bellhop [Porter, 2011]

BELLHOP is a beam tracing model for predicting acoustic pressure fields in ocean environments. Several types of beams are implemented including Gaussian and hat-shaped beams, with both geometric and physics-based spreading laws. BELLHOP can produce a variety of useful outputs including propagation loss, eigenrays which are the rays that connect the source and receivers, arrivals, and received time-series. It allows for range-dependence in the top and bottom boundaries (altimetry and bathymetry), as well as in the sound speed profile. Additional input files allow the specification of directional sources as well as geo-acoustic properties for the bounding media. Top and bottom reflection coefficients may also be provided.

2.2.2 Normal mode method

Normal mode method – brief description:

A full-field solution to the wave equation involves using separation of variables to solve the local vertical part of the wave equation and then apply various solutions to the horizontal component. The vertical wave equation solutions are standard normal modes, or eigenvalues. The modes are then summed up in varying fashion, depending upon the horizontal propagation, at the source and receiver to generate the full acoustic field. These modes encompass the solution to the wave equation including sound speed and density discontinuities and sound field in the seabed. The horizontal component of the solution can be (i) carried out trivially for range-independent environments, (ii) solved easily using adiabatic mode theory [Tindle and Zhang, 1997] for mildly range-dependent environments, and (iii) solved explicitly using coupled mode [Collins 1993a; Preisig and Duda, 1997; Holland 2010; Heaney et al., 2012] or parabolic equation models for complex range-dependent environments. Normal mode solutions are best suited to mildly range-dependent environments and at lower frequencies as the number of modes goes up linearly with frequency. They are used extensively in both shallow and deep water.

The normal mode method was introduced into the field of underwater acoustics by Pekeris [Pekeris, 1948]. The solution for a cylindrical coordinate system can be written as:

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

where $\Phi_m(r)$ is a function of distance r and $\Phi_m(z)$ is a function of depth z. The mth term in the equation represents the contribution of the mth mode.

A propagating mode is formed in a underwater channel with parallel sea surface and seabed where two plane waves travel at two opposite grazing angles, one up-going and one down-going due to reflection from the sea surface and seafloor as shown in Figure 1.

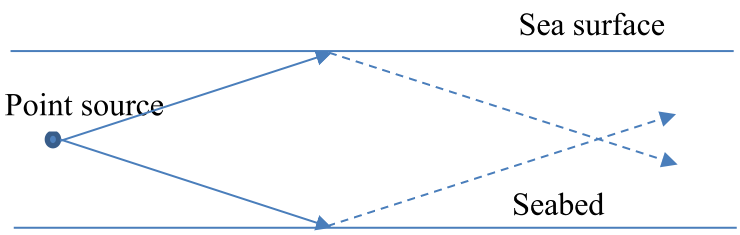

Figure 1. Schematic of two wave paths, travelling from a point source, with opposite grazing angles that have undergone reflection in an underwater channel.

Whilst, there are an infinite number of modes in an ocean channel, only a limited number of these modes can travel a long distance from a source. These are propagating modes with low amplitude attenuation and will depend on frequency, water depth, sound speed and density of the water and the seabed, and attenuation in the water and the seabed. The modes that do not propagate are leaky modes [Tindle et al., 1976; Boyles, 1984; Ainslie et al., 1998] or evanescent modes [Jensen et al., 2011]. These are modes, which have a grazing angle greater than the critical angle, or decay rapidly with distance from the water/seabed interface, resulting from the elastic properties of the seabed. Most normal mode models treat the underwater acoustic channel as a water column on top of a sediment layer that is over laid on a semi-infinite solid substrate. The sediment layer may support shear wave, with a very low shear wave sound speed.

The main challenge for the normal mode solution is to find all contributing modes from the depth dependent part of Eq. (3). The two general approaches are either to search only propagating modes or to search the propagating and some of the leaky modes (and evanescent modes if they exist). The primary advantage of searching for only the propagating modes is a simpler program and higher speed of execution. However, this approach can only be applied in the far field. The normal mode models that include the leaky modes (and evanescent modes) are better closer to the source in terms of accuracy, but they are relatively slow, due to the time consuming search for the additional modes.

The normal mode method is applicable to range independent problems where environmental parameters are constant with distance, and the method has been extended to deal with range dependent problem using adiabatic mode theory [Nagl et al., 1978], or the coupled mode method [Evans, 1983]. In this case, the propagating channel is divided into horizontal sections of discrete length with distance from the source, where the environmental parameters are constant within each section. Normal mode solutions are obtained for each of the sections, and coupling coefficients are derived based on continuity of the solutions at the interfaces of each section.

The full coupled mode method can deal with large variation of environmental parameters, where both forward and backward propagations are accounted for. However, the method is very numerically intensive [Jensen and Ferla, 1990]. An adiabatic mode method can be applied when the environmental parameters vary slowly so that a mode can adapt to the change without any energy exchange to other modes, hence the ‘adiabatic mode’ name. It is much more efficient using the adiabatic solution than the full coupled mode when both are applicable. In practice, there are many cases where some modes are coupled into other types of forward propagating modes. One example is a wave travelling upward in a penetrable wedge with a small slope where a propagating mode that is far away from the apex of the wedge gradually approaches the cut-off depth where the water depth is no longer able to support the mode. The grazing angle of the mode at the cut-off depth exceeds the critical angle and therefore becomes a leaky mode. The mode eventually propagates completely into the sediment with no back propagation due to the gradual change of water depth. The solution to this kind of problem is a one way coupled mode method, which is implemented in some normal mode propagation models [Porter, 1991; Ferla et al., 1993]. The execution speed of this method is naturally slower than the adiabatic mode, but much faster than full coupled mode methods.

Unlike the ray solution, the normal mode method allows the sound field to be calculated anywhere between the source and the receiver. The normal mode method is most suited to a channel where the number of modes is small, i.e. relatively shallow water channels with low frequency signals. It becomes difficult to find all the contributing modes at high frequencies in a deep water channel since the differences in the vertical wave number of different modes become increasingly small with an increasing water depth to wave length ratio.

2.2.2.1 *Examples of normal mode propagation models: Kraken [Porter, 1991] and C-SNAP [Ferla, et al., 1993]*

Kraken and C-SNAP are normal mode models using a coupled-mode and an adiabatic normal mode solution, respectively, which find only the propagating modes in water column. The attenuation of the propagating media and the surface roughness are included using the perturbation method [Porter, 2001]. There is also a complex version of Kraken, KrakenC, which is capable of finding the leaky modes, although, the computation time is several times longer. These example models cannot solve the field inside elastic layers (seabed) since they use an equivalent reflection coefficient at the interface to account for the effect of the layers.

The predicted propagation losses by Kraken, KrakenC and C-SNAP can be expected to be comparable at distances that only the lowest propagating modes can reach. The predicted propagation loss using KrakenC can differ from that using Kraken and C-SNAP at distances where the contribution from leaky modes requires consideration, i.e. closer to the source. All three models can be applied to range dependent problems (i.e. range dependent bathymetry and sound speed), and are also able to deal with stratified layers which support shear waves. Kraken and KrakenC, are both incorporated into AcTUP [Duncan and Maggi, 2006].

Note: *AcTUP is a MATLAB based program which includes a number of propagation models, Kraken, KrakenC, Bellhop, RamGeo, RamsGeo and Scooter, and runs through a graphical user interface. However, it should be noted when using AcTUP that it limits some of the functions available for some of the models; for example, Kraken and KrakenC cannot be used for range dependent problems.*

2.2.3 Wave number integration

Wave number integration method – brief description:

The wave equation can be solved exactly at close range using the numerical approach of spectral wavenumber integration. Such solutions are often called Fast-Field Programs (FFP). For range-independent environments they compute the exact field and are often used as benchmark solutions. The method has been extended to range-dependent environments, but this extension is not publically available, and is thus less widely used.

The wave number integration method, also known as Fast Field Program (FFP), solves the wave equation using the Green's function [DiNapoli and Deavenport, 1980; Kutschale, 1973; Schmidt, 1984; Schmidt and Jensen, 1984; Schmidt and Jensen, 1985] as a function of depth in a stratified media, where the physical properties vary only with depth. The integration is then performed over the wave number range using Fast Fourier Transformation. An approximation made with the wave number integration method is to use the asymptotic form of Hankel function, limiting to methods accuracy when the distance is less than a wavelength.

The wavenumber integration method is an exact solution, in contrast to the normal mode method, since it includes the contributions from not only the propagating modes, but also from the leaky and evanescent modes. This makes the method particularly useful in cases where the evanescent waves are important. The method can also be extended to treat range-dependent problems [Goh and Schmidt, 1996].

2.2.3.1 *Example of a wave number integration propagation model: OASES [Schmidt, 2004] and Scooter [Porter, 2007]*

OASES [Schmidt, 2004] and its predecessor, SAFARI [Schmidt, 1987], are widely considered to be *de facto* standards for propagation loss prediction, especially in range-independent channels due to the wavenumber integration solution being an exact solution even with an elastic seabed. These two wave number integration implementations inherently handle compressional, shear and interface [Tamir and Bertoni, 1971; Rauch, 1980] waves at all distances, as well as representing the modes accurately everywhere, including through cut-off. The range independent version of OASES is freely available.

2.2.4 Parabolic Equation method

Parabolic equation method – brief description:

Almost all acoustic modelling involves the computation of the field propagation from a source to a distant receiver. In this problem the propagation is one-way. Separating the wave equation into incoming and outgoing solutions leads to the Parabolic Equation. Neglecting incoming (back-scattered energy), the acoustic field can be computed using a marching algorithm referred to as the Parabolic Equation (PE) model. There are two classes of PE models available – the split-step Fast Fourier Transform solution developed by Tappert [1977] and the Padé expansion solution developed by Collins [1993b]. The PE is an efficient marching solution that is suitable for range-dependent environments, discontinuous sound speed profiles and is commonly used in shallow and deep water. The PE computational requirements increase with frequency squared (or $f \cdot \log(f)$ for the Fourier PE) and therefore the PE is generally used at frequencies less than 1 kHz. The split-step Fast Fourier Transform approach does not handle density discontinuities easily and therefore it is not the model of choice in shallow water.

The parabolic equation solution is derived from Eq. (1) with an approximation that only the out-going wave is considered. The propagation problem becomes an initial boundary condition problem where the propagated sound field can be calculated from the source location, where the field value is known, by marching out the solution step-by-step to the required distance.

The original version of the parabolic equation, adapted from applications in optics and geophysics, was introduced into ocean acoustics by Hardin and Tappert [1973]. A detailed description on the development of the method is available in two comprehensive reviews by Lee and Pierce [1995] and Lee et al., [2000]. Parabolic equation models have acquired popularity amongst the ocean-acoustics community not least because they have been made widely available, but also because they calculate the field over the entire water column with no additional effort and can handle range-dependent environments, over a range of water depths. In addition, elastic boundary conditions can also be included, however, this may introduce some computational constraints. Some of the PE models can also handle sound propagation with ray angles up to 90^{o}. However, the use of PE models are generally limited to lower frequencies due to the increase in computation effort at higher frequencies.

There are two common approaches to the parabolic equation models, the split-step Fast Fourier Transform approach developed by Tappert [1977] and the split-step Padé expansion approach developed by Michael Collins [1993b].

Other solutions to the parabolic equation include the Implicit Finite Difference (IFD) scheme [Lee and Botseas, 1982] which is considered more accurate for shallow water compared with the split-step Fast Fourier Transform [Kewley et al., 1983].

2.2.4.1 Example of a parabolic equation propagation model: RAM [Collins, 1993c]

RAM (Range-dependent Acoustic Modelling) is a parabolic equation code that uses the split-step Padé algorithm to achieve high efficiency and the ability to model propagation at large angles from the horizontal. There is a trade-off between the angular range and the speed of computation that is governed by the number of terms the user specifies for the Padé approximation – the more terms, the wider the angle, but the longer the run time. RAM is capable of modelling low frequency propagation in fully range dependent environments. There are a number of modified versions of RAM, such as PEREGRINE, RAMSurf with faster execution time, not all of which are freely available. Implementations of RAM are also incorporated into AcTUP [Duncan and Maggi, 2006]; these are RAMGeo for a fluid seabed and RAMSGeo for an elastic seabed.

2.2.5 Energy flux method

Energy flux method – brief description:

A hybrid solution first developed by Weston [Weston 1959; 1968], between rays and modes is the energy flux model, based upon the Hamiltonian action [Holland, 2010]. Analytic solutions exist for simple environments (iso-velocity water, flat bottom) and extensions to depth dependent sound speeds and range dependence have been made [Harrison, 2012]. These flux-based solutions are extremely fast, handle diffraction but are not used to compute the coherent acoustic field and often neglect high spatial frequency interference. For accuracy and speed they lie somewhere between ray theory and mode theory, as the solution suggests.

Weston [1980] provided a set of equations based on the energy flux method and mode characteristics to predict propagation loss in iso-velocity underwater channels with an arbitrary seafloor profile. This approach divides the channel into four regions depending on the sound propagation mode; spherical spreading in the immediate vicinity of the source, followed by cylindrical spreading, then mode stripping and finally single mode. The propagation loss at close distance, up to the cylindrical spreading region, is subject to only spreading loss, with additional loss due to seafloor reflection loss in the mode stripping region where higher modes are attenuated more quickly as they have larger grazing angles with respect to the seafloor. The fourth region is the single mode region where all but the lowest mode have decayed away. A detailed description of the propagation losses in each of the regions is given in A Table in Appendix A.

Comparisons between the Weston energy flux model other complex models, indicate that the model can produce very good propagation loss predictions [Sertlek and Ainslie 2013; 2014].

2.2.6 Finite difference / finite element

Finite difference / finite element method – brief description:

A common, computational physics approach to solving 3D problems, is to grid the entire environment, and solve the wave equation for space and time. These Finite Difference (FD) and Finite Element (FE) models are rarely used in ocean acoustics. The computational expense of gridding each, sub-wavelength spaced, grid-point for the scale of most ocean acoustic problems is prohibitive. These solutions are generally applied to scattering or very near source propagation. They have been applied to pile-driving excitation problems and the seismic generation of low frequency modes in the oceans sound speed minimum channel.

3 Considerations for propagation modelling

3.1 Water depth and uniformity of the propagation environment (range dependence/range independence)

Ocean environments can often be classified as shallow water or deep water. The primary driver in this selection process is not the water depth, but the importance of the sound interaction with the seafloor. Specifically if the seafloor interaction is small or can be neglected, the propagation conditions are considered as deep water. For basin scale open ocean propagation, for example, the presence of a SOFAR (SOund Fixing and RAnging) channel (a deep sound channel), may result in most of the energy arriving at a distant receiver having been refracted away from the sea-surface and from the seafloor. Such efficient propagation is then largely a function of range-dependent variations in the sound speed, and is less dependent on the seabed characteristics. In contrast, shallow water propagation will generally be dominated by boundary interactions (seafloor, sea surface) and often the geo-acoustic parameters of the seafloor will be the primary environmental parameter that affects the acoustic propagation.

In most ocean environments, particularly over large distances, the bathymetry and the sound speed field can be expected to vary with distance. Such environments will require a range dependent model.

Range dependence versus range independence:

Model selection may be divided into those solutions that handle range-independent (or mildly range-dependent) propagation environments, and those that support arbitrary range-dependence. For range-independent environments, normal modes, wavenumber integration and analytic energy flux solutions are often used as they support a fast run time. For scenarios where strong range-dependence exists, the more appropriate choice may be the parabolic equation solution and ray theoretical solutions. Coupled mode solutions have accuracy comparable to the parabolic equation solution, but are generally not preferred because of their relative computational cost.

The representation of the seabed, for a given propagation model, can have a significant influence on the outputs of the model. It is not always possible to establish the exact acoustic properties of the seabed, particularly as a function of depth below the seabed and furthermore, any underlying geology may not always be fully characterised or understood. This often requires a compromise when implementing the seabed in a propagation model and not all propagation models treat the seabed in the same way. The choice of propagation model should thus consider the extent to which seafloor conditions might influence the propagating sound.

Additionally, the seabed can be treated as a fluid or a solid medium (i.e. supporting shear wave propagation). For sediments, these are often saturated and so can exhibit viscoelastic properties.

3.2 Frequency range

The frequency band of interest is the primary discriminator between propagation models. For low-frequency sound, the parabolic equation solution and the normal mode solution, represent the most appropriate model choice at lower frequencies. For high frequency computations ray tracing or energy flux models are generally used.

Shallow water - low frequency	Shallow water - high frequency	Deep water - low frequency	Deep water - high frequency
Ray theory (Red)	*Ray theory* (Green)	*Ray theory* (Amber)	*Ray theory* (Green)
Normal mode (Green)	*Normal mode* (Amber)	*Normal mode* (Amber)	*Normal mode* (Red)
Wave number integration (Green)	*Wave number integration* (Green)	*Wave number integration* (Green)	*Wave number integration* (Amber)
Parabolic equation (Green)	*Parabolic equation* (Amber)	*Parabolic equation* (Green)	*Parabolic equation* (Red)
Energy flux (Green)	*Energy flux* (Green)	*Energy flux* (Amber)	*Energy flux* (Amber)

Green – suitable; Amber – suitable with limitations; Red – not suitable or applicable

Another consideration when selecting a propagation model is the bandwidth characteristic of the signal, i.e. narrowband vs. broadband. Normal mode, wavenumber integration and parabolic equation models are computed in the frequency domain. For broadband signals this can become computationally intensive, requiring the calculation of the propagation loss at multiple frequencies. Furthermore, it might be necessary to construct the signal in the time domain by inverse-Fourier-transforming (IFFT) the frequency-domain solution. Whilst this approach is accurate, it can become computationally intensive, requiring modelling of many frequencies, particularly for signals with a wide bandwidth. Ray and energy flux models can be solved with travel time along the ray or bundle computed in-stream, providing a solution of a pressure time-series that is generally computationally less intensive.

> *Note on frequency averaging:*
> *For propagating signals within a defined band, for example within specific third-octave frequency bands, a propagation model may be required that accounts for the range of frequencies within the band. Many models run in the frequency domain, producing propagation loss data for single frequency excitation that exhibit strong amplitude fluctuations due to the coherent interference effects. For a broadband signal, an average of the propagation loss for the entire frequency band is required (this is likely to exhibit much smoother spatial variation than for individual frequencies within the band). This can be achieved by running a model at a number of frequencies within the band and averaging the results, or by performing an equivalent averaging process as a function of distance [Harrison and Harrison, 1995].*

3.3 Three-dimensional modelling

Most propagation models are two-dimensional solutions, calculating the propagation loss along a transect, which does not include horizontal refraction, reflection or diffraction (i.e. each transect modelled is independent of the neighbouring transect). In many cases, such models provide sufficient accuracy and can provide three-dimensional maps by combining, often through interpolation, a number of two-dimensional (distance and depth) transects.

However, in some instances the use of two-dimensional models may not be sufficient to accurately model the sound propagation. A possible example includes a scenario where an island or land mass is situated between the source and receiver. A two-dimensional model will result in a shadow behind the land mass where the modelled transects intersect the land mass. In reality, diffraction will occur causing bending of the sound around the land mass. In such cases, it may be necessary to use a three-dimensional model, which accounts for horizontal diffraction to accurately represent the sound field. Other scenarios where two-dimensional models may not provide sufficient accuracy may be environments characterised by sub-surface obstacles such as sand banks, or where there is a strong up-sloping or down-sloping seabed, such as propagation around continental shelves.

In general, three-dimensional implementations can be computationally intensive, and it may be appropriate to utilise a two-dimensional solution, which will be sufficient in most cases.

4 Input data and factors influencing accuracy

4.1 Representation of the sound source

Most propagation models make simplified assumptions about the nature of the acoustic source, for example, that it behaves as a monopole point source. These simplifying assumptions are often necessary to make the computational problem tractable. However, real acoustic sources are not point sources, but are instead distributed sources of sound, although most will approximate to a point source when observed from a sufficient distance (where all the sound waves appear to diverge from an "acoustic centre"). Thus, for many acoustic sources where predictions are required for a considerable distance away from the source, the simplification of the source representation will be appropriate.

However, it is not always possible to represent a source as monopole point and it is not always common practice to establish such a monopole source level. For example, neither the ANSI/ASA standard for measuring the radiated noise level from a ship [ANSI/ASA S12.64-2009] nor the equivalent ISO Publically Available Specification [ISO PAS 17028, 2012] require that a monopole point source level be calculated. Rather, an 'affected source level' [ANSI/ASA S12.64-2009] or 'radiated noise level' [ISO PAS 17028, 2012] is calculated from the *in situ* measurement data. To establish a monopole source level would require correction for the Lloyd's mirror effect and absorption in the water. For example, in the case of ambient sound mapping based on Automatic Identification System (AIS) information for ships, using an 'affected source level' or 'radiated noise level' parameter would introduce significant errors into the estimated noise levels. Similarly, other distributed sources or arrays cannot easily be represented as a point source. Particular examples include pile driving, where the source extends both out of the water and into the seabed, and seismic airgun arrays, which can be made up of many point sources at some depth below the surface.

> Note on the use of source level:
> Care should be taken when using available or published source level data to ensure it is in the appropriate form, or is the appropriate type of source level for use in the propagation model of choice.

4.2 Environmental data availability and its accuracy

Underwater sound propagation is influenced by the local propagation environment, which may vary spatially and temporally. As such the accuracy of a propagation model output relies on representative environmental input data to the model. As discussed in the previous sections, environmental variables such as *bathymetry*, *seabed properties* and *sound speed profile*, for example, all influence the propagating sound and changes in these parameters may lead to considerable differences in the characteristics of the propagated sound. Other more specific model input parameters, such as wind speed, used as a proxy input when surface scattering requires consideration, for example, may also represent a source of uncertainty, and should be considered carefully.

In this section, consideration is given to model input data for bathymetry, sound speed and acoustical seabed characterisation, highlighting some of the most common sources of uncertainty. In addition, the sources of some commonly used, publically accessible environmental data are provided.

4.2.1 Bathymetry

Bathymetry is particularly important for shallower water propagation. It is not just the water depth, which influences the propagation, but also the shape of the seabed. Near continental shelves or in regional seas, the sloping seabed can have a significant influence on the propagating sound.

Very high-resolution bathymetric survey data may be available in some cases, generally in relation to a particular local site, with specific stakeholder interest. Global bathymetry data, or bathymetry data from another source, may then be used for the adjacent areas, outside the spatial extent of the site-specific survey data. Such global bathymetric data may be obtained from the General Bathymetric Chart of the Oceans (GEBCO, http://www.gebco.net/), and is available at a resolution of 30 seconds, or lower.

Whilst higher resolution bathymetry data may provide a fine scale representation capable of capturing small scale seabed features, such as sand waves and ripples, which can influence the propagating sound, these seabed features are dynamic and might be expected to change with time.

Besides the resolution and accuracy of the bathymetry data, the accuracy of the modelled outputs, may also be influenced by the vertical datum. This can typically be based on the mean sea level or the lowest astronomical tide. Whilst this parameter is usually less important in deep water, it can have a significant effect on the assumed water depth in shallow coastal regions, with considerable tidal changes.

Subsequently, tidal variation can be another factor that may require consideration, especially in shallow coastal regions, where tidal variation may correspond to a substantial ratio of the water depth. It is worth noting that tidal variation can be very localised.

4.2.2 Seabed properties

The acoustic properties of the seabed are an important parameter in acoustic propagation modelling in shallow water. In general, they will determine how much sound is reflected from the seabed and how much sound, re-enters the water column after transmission through the seabed. A stratified seabed can, for example, result in bending of the sound waves, and a hard seabed layer, such as rock, can reflect the sound. Both can result in sound energy being retransmitted into the water column.

It is often possible to build the acoustic properties of the sediment (as a half-space, for example), and in some cases the stratification of the seabed, into an acoustic propagation model. However, the accuracy of this is often limited by the availability of the actual data at a sufficient spatial scale and with the necessary resolution such that the data are representative of the actual environment. It can also be challenging, or in some cases not possible, to build the necessary variations with distance into a range dependent acoustic propagation model.

Seabed core data can often provide information of the underlying geology, although the specific characteristic might be localised and it might not be correct to extrapolate this across a broader region.

Seabed survey data may be used to provide information about the upper sediment layer, such as that provided by EMODnet/EUSeaMap (http://jncc.defra.gov.uk/page-5040). However, this sediment information has to be converted into acoustic properties for the seabed and sufficient information is not always available to correlate with published acoustics properties of various sediment types [e.g. Hamilton and Bachman, 1982; Hamilton, 1980; and 1985; Lurton, 2003; Ainslie, 2010].

4.2.3 Sound speed profile

The sound speed profile can have a significant influence on how the sound propagates, especially in deep water. The sound speed profile is dictated by changes in the water temperature, pressure and salinity, with depth. Where there is variation in the sound speed with depth, bending and trapping of the sound can occur, which in some cases can lead to the sound travelling substantially further due to reduced spreading and less interaction with the seafloor and sea surface (sound is trapped in the SOFAR channel, for example).

In shallow water, although the sound speed profile may influence propagation through bending of the sound, the bathymetry and sediment acoustic properties generally constitute the more influential propagation parameters.

The sound speed profile may be measured *in situ,* and may also be obtained from global data sets, such as the data available from the World Ocean Atlas (WOA) database (http://www.nodc.noaa.gov/OC5/indprod.html), providing information about the geographic and seasonally variability.

4.2.4 Sea surface

The rough sea surface, and associated wind-generated bubbles, is usually characterised by means of a wind speed (at a height of 10 m). The conversion, and the resulting effects on propagation, are the subject of ongoing research [Hall 1989; Keiffer et al., 1995; Novarini et al., 1998; Norton and Novarini, 2002; Ainslie, 2005].

4.2.5 Model input data uncertainty

Given that environmental input data are generally limited, and some might be critical to the performance of the acoustic propagation model, it is important to understand the influence that the accuracy of the environmental data has on the outputs of the model, i.e. the uncertainty in the modelled output as a function of the uncertainty associated with the input data. In general, the influence of the uncertainty in the environmental input data on the propagation efficiency may be assessed through sensitivity analysis, where the value of a parameter is varied, with other variables fixed for control. The same approach may be employed to assess the effect of data resolution on the modelled output.

5 Specific considerations for sound mapping

As discussed in previous sections, propagation models compute the propagation loss, which is often used to generate a sound map (i.e. a visual representation of the acoustic field around the source). This relies on the acoustic source information being available in a suitable form for use as an input to the model (this is most often in the form of a monopole source level).

In some cases sound maps might be required which represent multiple sources, for example, shipping sound maps or operational wind farm maps. In this case, the contributions in space may require summation, either coherently or incoherently, to represent the resulting sound field.

The production of a sound map will often specifically require sound propagation over large distances (often tens of kilometres, and sometimes hundreds or even thousands of kilometres), where substantial variations in the propagation environment can be expected (see Section 4.2). This will inherently place demands on the model such as range dependence, and, for a broadband signal, frequency dependence. It will generally also require the model to be computationally efficient particularly if propagation across large spatial scales is considered.

When producing a sound map, consideration needs to be given to the process of gridding the data in terms of spatial resolution. This may be influenced by the resolution in the available bathymetric data. A decision must be made as to whether the model produces data resolved in terms of water depth (such that the acoustic field variation with depth may be calculated), or whether the average of the sound energy with depth is calculated (as produced by an energy flux approach). The former requires considerably more intensive computation. In the azimuthal direction (the plane of the water surface), the grid is typically Cartesian with data calculated for each node in the grid. A grid based on radial transects will suffer decreasing spatial resolution with increasing distance from the source. Propagation over large areas may therefore require higher radial resolutions and interpolation, and it is important that any interpolation undertaken as part of the mapping is acknowledged and clearly described.

It should be noted that sound maps will usually comprise of a series of two-dimensional slices through the water column (distance versus depth) at a succession of bearings, rather than be fully three-dimensional. Consequently, such maps can exhibit “shadow zones” where the modelled sound cannot penetrate behind obstacles such as small islands. When modelling over large areas, particularly in regional seas, the interactions with land masses can become more important (see Section 3.3 for more details on three-dimensional modelling).

6 Benchmarking and experimental validation of propagation models

Many of the freely available propagation models developed over the years have been extensively benchmarked. There have also been a number of workshops and special conference sessions based on model comparisons [e.g. Spofford, 1973; Davis et al., 1982; Felsen, 1986; Felsen, 1987; Jensen and Ferla, 1990; Goh et al., 1997].

An example of a benchmarking comparison is provided here using a Pekeris channel [Pekeris, 1984] with a water depth of 35 m, and a sediment seabed. The acoustic properties of the channel are listed in Table 1.

Table 1. Parameters of the propagation environment used for underwater sound propagation modelling benchmark presented in Figure 2 and Figure 3.

Propagation medium	Depth (m)	Compressional sound speed (m/s)	Density (kg/m^3)	Compressional sound wave attenuation (dB/wavelength)
Water	35	1490	1000	0
Fine sand	Infinite	1706	1941	0.9

Propagation losses are predicted over a distance of 20 km with ten different calculations at two frequencies, 160 Hz and 1 kHz, shown in Figure 2 and Figure 3, respectively. The modelled propagation loss indicates complicated propagation at close range, with a number of modes, both, propagating, and leaky, contributing to the acoustic field. Higher modes with large grazing angles are subject to more reflection loss from the seabed, and thus decay more rapidly. The modelled results in Figure 2 and Figure 3 show that the pattern of the propagation loss curve becomes more regular, at greater distances from the source, where a smaller number of low order modes are dominant. The resulting propagation losses from each of the models are in very good agreement with the largest discrepancy occurring at the maximum modelled distance of 20 km (about 1 dB from the results of the OASES model, which is used here as a reference).

Such benchmarking comparisons provide critical information on the model accuracy and possible range of application, identifying limitations of certain models, for particular test cases. Ideally, the modelled data should be compared with experimental data and if agreement within the uncertainties can be achieved then this provides considerable confidence in the model. It should, however, be noted that validation against experimental data ideally requires measured acoustic data with minimal uncertainty, and high confidence in the environmental input parameters for the model. Lack of confidence in environmental data may introduce uncertainty in the input parameters of the model, and the predicted results may not be a representative. Published comparisons of modelled propagation loss with in-situ measurement data, such as work by Dosso and Chapman [1984; 1987], for example, increase confidence in the predictive ability of propagation models.

To overcome the significant challenge of carrying out experimental validations over large distances for a range of scenarios and environmental conditions, it is often more practical to carry out the measurements under laboratory conditions. This allows control over the environmental parameters, such that they can be modelled representatively, and further allows greater control over the experimental setup to achieve good uncertainties. These comparisons provide a good reflection of the physical world in its mathematical description

[Wang, 1989; Ainslie et al., 1993; Wang et al., 1994; Collis et al., 2007; Sturm et al., 2007, Rodrıguez et al., 2012]. To simulate long distance propagation in the laboratory environment, the comparison can be simply scaled with frequency. The main drawback of this approach is that the frequency dependent absorption coefficient cannot be scaled and requires correction.

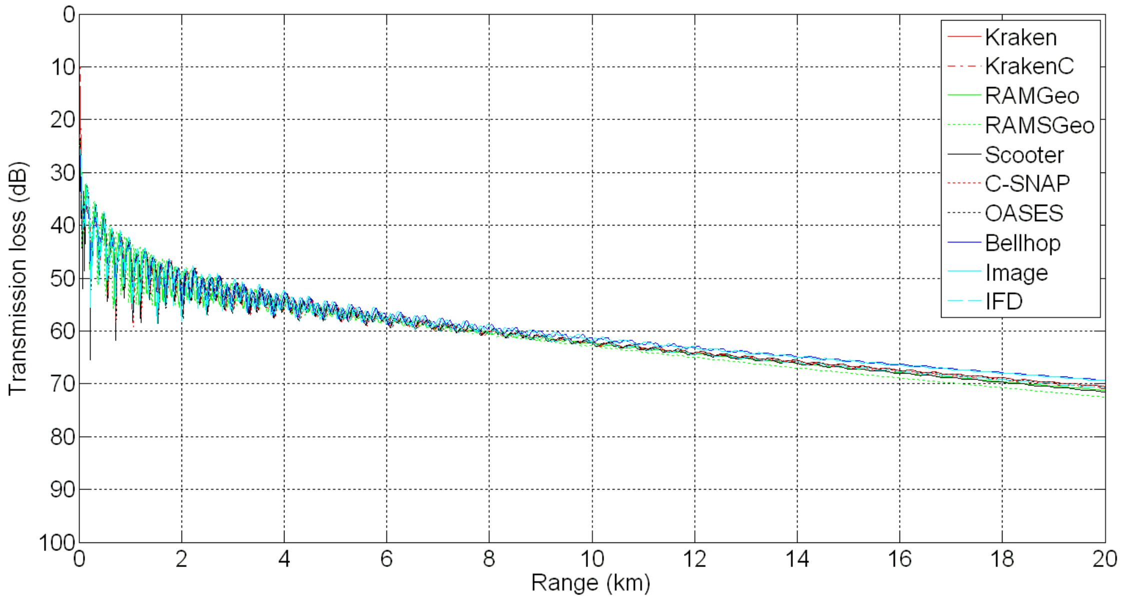

Figure 2: Comparison of modelled propagation loss [dB re 1 m] for a number of commonly used numerical propagation models. Propagation loss is shown as a function of distance for a 160 Hz sound, adopting the model input parameters listed in Table 1.

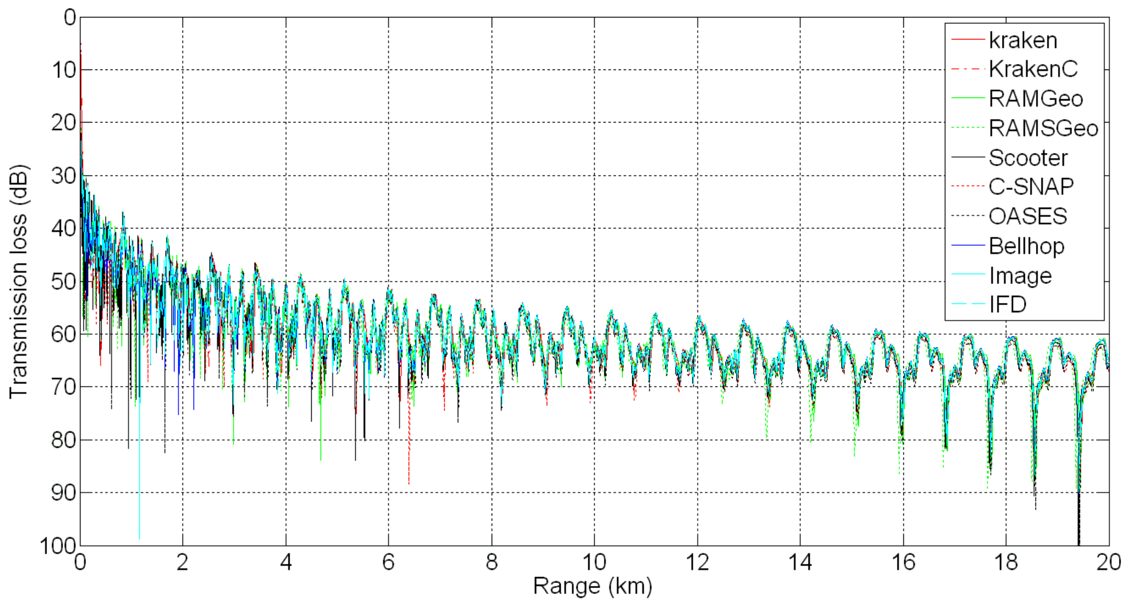

Figure 3: Comparison of modelled propagation loss [dB re 1 m] for a number of commonly used numerical propagation models. Propagation loss is shown as a function of distance for a 1 kHz sound, adopting the model input parameters listed in Table 1.

7 Conclusions

A number of 'off-the-shelf' acoustic propagation modelling solutions have been developed, and are used relatively widely. The solutions, many of which are readily downloadable from different sources, employ particular solutions to the wave equation, all of which have been reviewed here. These solutions each have advantages and disadvantages in relation to their suitable frequency range, water depth, computational requirements and their ability to include range dependent variables, which are summarised in Table 2. Many of these models have been 'benchmarked' and in some cases have been compared with measurement data, for particular environments, providing increased confidence in their ability to be used as a predictive utility. However, the accuracy of the modelled output will be critically dependent upon, not just the model used, but also the input parameters used for the model. For underwater acoustic propagation models, these parameters can be extensive and can include, for example, bathymetry, seabed data, sound speed profile, and sea surface roughness. In general, these variables can be obtained from open sources and provide a reasonable approximation, however, the limitations in applying these input data to acoustic propagation models needs to be understood, particularly in relation to sound maps involving large propagation areas.

Table 2: Inventory of some commonly used, freely available, ocean acoustic propagation modelling implementations, outlining the model suitability, with model source reference also provided.

Method	Model Name	Shallow water		Deep water		Range dependent	Availability	Originator
		LF	HF	LF	HF			
Ray	BELLHOP	NO	YES[¤]	YES[‡¤]	YES[¤]	YES[¤]	http://oalib.hlsresearch.com/Rays/index.html	*M. Porter* Heat, Light, and Sound Research, Inc. La Jolla, CA, USA
Normal mode	Kraken	YES	YES[‡]	YES[‡]	NO	YES	http://oalib.hlsresearch.com/Modes/index.html	*M. Porter* SACLANT Undersea Research Centre, Italy
Wave number integration	SCOOTER	YES	YES	YES	YES[‡]	NO	http://oalib.hlsresearch.com/FFP/index.html	*M. Porter* Heat, Light, and Sound Research, Inc. La Jolla, CA, USA
	OASES	YES	YES	YES	YES[‡]	YES[†]	http://lamss.mit.edu/lamss/pmwiki/pmwiki.php?n=Site.Oases	*H. Schmidt* Massachusetts Institute of Technology, MA, USA
Parabolic equation	RAM	YES	NO	YES	YES[‡]	YES	http://oalib.hlsresearch.com/PE/index.html	*M. Collins* Naval Research Laboratory, Washington, USA
	IFD	YES	NO	YES	YES[‡]	YES	Ocean Acoustic Propagation by finite difference methods, Pergamon Press, Oxford, 1988	*D. Lee and S. T. McDaniel* Naval undersea warfare centre CA, USA
	MMPE	YES	NO	YES	YES[‡]	YES	http://oalib.hlsresearch.com/PE/index.html	*F. Tapper and K. Smith* U.S. Naval Postgraduate School, and Rosenstiel School of Marine and Atmospheric Sciences, USA
	P-CAN	YES	NO	YES	YES[‡]	YES	http://oalib.hlsresearch.com/PE/index.html	*G. Brooke* Defence Research Establishment Atlantic, Canada

‡ Suitable with limitations. † A range dependent version OASES exists, however, it is not freely available.
¤ Requires a suitable, simplified, sound speed profile at any frequency.

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Appendix A Energy flux (Weston) model

Appendix A Table 1: Propagation loss by Weston model

Spherical	$TL = 10\log[R^2]$	R<$H_a/2\theta_c$
Channelling	$TL = 10\log[RH_aH_b/2H_c\theta_c]$	$H_a/2\theta_c$<R<$6.8H_a/\alpha\ \theta_c^2$
Mode stripping	$TL = 10\log\left[RH_aH_b\left(\alpha\int_0^R \frac{dR}{H^3}\right)^{1/2}/5.22\right]$	$6.8H_a/\alpha\ \theta_c^2$<R<$27k^2H_a^3/(2\pi)^2\alpha$
Single mode	$TL = 10\log[RH_a\,H_b/\lambda] + \frac{\lambda^2\alpha}{8}\int_0^R \frac{dR}{H^3}$	R>$27k^2H_a^3/(2\pi)^2\alpha$

where H_a is the depth at source, H_b is the depth at receiver, H_c is the minimum depth along the bathymetry profile. θc is the critical angle given as in Eq. 1, α is the seabed reflection loss gradient (loss per unit angle in dB/rad), k=2π/λ is the wave number and λ is the wave length of the signal. The water depth has to be deep enough to support at least one mode, for example, for the lowest mode: $H\sin\theta_c > \frac{\pi-\rho_{sed}/\rho_w}{2\pi}$, where ρ_w and ρ_{sed} are density of water and sediment.