



Acoustics 2008

Geelong, Victoria, Australia 24 to 26 November 2008

Acoustics and Sustainability:

How should acoustics adapt to meet future demands?

Environmental Impact Assessment of Underwater Sound: Progress and Pitfalls

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ABSTRACT

Until very recently, underwater acoustics has been the exclusive domain of marine animals, researchers, the military, and a few companies that make their living from building sonar and related equipment. However, new Government regulations aimed at reducing detrimental impacts on marine animals have greatly broadened interest in this field by placing limits on underwater sound levels produced as a by-product of human activities of considerable commercial importance - particularly offshore seismic exploration and pile-driving. As a consequence, many acoustic consulting companies are finding themselves involved in this field for the first time. This paper looks at some of the issues involved in modelling and measuring sound levels in the underwater environment and in translating these levels into some sort of estimate of likely environmental impacts. There is a lot more to it than simply exchanging your microphone for a hydrophone!

INTRODUCTION

The study of acoustics in air has a long history for the simple reason that it is the medium humans have evolved in, and the vast majority of our experience of sound relates to this medium. Not surprisingly therefore, environmental noise regulations have focussed on the impact of airborne sound on people, taking into account the peculiarities of the human hearings system.

Most people's first-hand experience of sound underwater is limited to what they can hear when swimming or diving which, because of the extreme inefficiency of the human hearing system in that environment, is very little. As a result, public concern about the environmental impacts of man-made underwater sound has lagged well behind concerns about airborne sound.

The situation has recently changed due to a growing public awareness of the heavy use many marine animals make of sound for communication, and some well-publicised whale stranding coincident with US Navy sonar operations.

This increasing awareness is reflected in the Australian Government's Environmental Protection and Biodiversity Conservation Act (1999) (EPBC 1999). Amongst other things, the Act makes it an offence to carry out any action that could have a "significant impact" on the Commonwealth marine area, which extends from the outer limit of State waters (nominally 3 nautical miles from the coast) to the 200 nautical mile limit of Australia's Economic Exclusion Zone. The Act also provides specific protection for a number of protected and migratory marine species, including cetaceans (whales) and sea turtles. Guidelines published along with the

Act specifically include man-made underwater noise as a factor that needs to be considered when establishing whether a particular activity will have a "significant impact".

This new regulatory framework has resulted in an increasing requirement for environmental impact assessments for marine related activities to include a consideration of the underwater sound levels that are likely to be produced, and their potential impact on marine animals. Therefore, acoustic and environmental consultants, who have previously carried out similar assessments of the potential impact of airborne sound on humans, are suddenly finding they need to know something about underwater acoustics and marine animal responses to sound.

Although the physics of sound propagation is the same in water as it is in air, the characteristics of the media, the geometries of interest, and the variety of species of concern, make many of the assumptions that apply to airborne acoustics invalid in the underwater environment. There are thus many traps for the unwary when trying to apply airborne acoustics knowledge to the marine environment. While collecting underwater sounds appears easy enough in theory - place a hydrophone in the water with appropriate electronics and collect recordings - it is not so easy in practice and routinely collecting high quality, calibrated sea noise recordings free of artefacts is as much an art as science.

This paper provides a brief introduction to underwater acoustics as applied to environmental impact prediction and is aimed particularly at acousticians who are new to, or considering entering the field. The issues involved are too complex to be thoroughly dealt with in a paper of this length, so what

follows aims primarily to point out the complexities and highlight potential pitfalls of working in this area.

DIFFERENCES IN CONVENTIONS

The first thing to remember when moving into underwater acoustics is that humans don't live underwater, and therefore the characteristics of human hearing are irrelevant. So throw away any frequency weighting schemes such as dBA - you are now interested in animals that produce and receive sound over a frequency range from less than 20 Hz (great whales) to several hundred kilohertz (dolphin sonar and snapping shrimp). There are workers in marine animal noise impact assessment who try to apply weightings suitable for different marine animal groups, but this largely confuses the issues as there are no standards and what is good for animal A may be disastrous for animal B.

You can also throw away your 20 μ Pa reference pressure, which was chosen because it was thought to be the quietest sound a human could hear. In underwater acoustics the reference pressure is the (slightly) more logical value of 1 μ Pa. Remember that the definition of sound pressure level is:

$$SPL = 20 \log_{10} \left(\frac{p_{rms}}{p_{ref}} \right) \quad (1)$$

where p_{rms} is the measured root mean square sound pressure, and p_{ref} is the applicable reference pressure (20 μ Pa for air, 1 μ Pa for water). Plugging in the numbers you find that, for the **same sound pressure** (p_{rms}) the change in p_{ref} results in a **SPL that is 26 dB higher in water than in air**. Note, however, that this is not the whole story: as discussed below the difference in dB levels is much greater when comparing sounds of the same intensity.

Because of the potential for confusion brought about by the different reference unit, the convention in underwater acoustics is to **always explicitly state the reference unit for any quantity expressed in dB**. For example a source level would be stated as 190 dB re 1 μ Pa @ 1m, but never as just 190 dB. Similarly a noise spectral level would be stated as 76 dB re 1 μ Pa²/Hz, or equivalently as 76 dB re 1 μ Pa²/Hz, but never as just 76 dB. Doing this is a little long-winded but removes any possibility of ambiguity. The only exception to this rule is where the quantity involved is itself is a dimensionless ratio. For example, transmission loss, which is defined by:

$$TL = 20 \log_{10} \left(\frac{p(1)}{p(r)} \right) \quad (2)$$

is just given in dB.

Here $p(r)$ is the pressure a distance r metres from the source and $p(1)$ is the pressure at a distance of 1 m from the source.

ACOUSTIC PROPERTIES OF AIR AND WATER

Density and sound speed

The fundamental acoustic properties of air and seawater are compared in Table 1.

The sound speed in seawater is about 4.4 times greater than that in air, which of course means that the acoustic wavelength at any given frequency will also be a factor of 4.4 greater in seawater than in air. One implication of this is that wave effects such as waveguide cut-off and diffraction are important at higher frequencies than you might expect.

Table 1. Comparison of acoustic properties of air and seawater

Medium	Density (kg.m ⁻³)	Sound speed (m.s ⁻¹)	Characteristic impedance (Rayls)
Air	1.1	340	374
Seawater	1024	1500	1.5 x 10 ⁶

However, it is the fact that water has a characteristic impedance a factor of more than 4000 times that of air that accounts for the most significant differences between the two media:

- For the same **intensity**, $I = \frac{p^2}{\rho c}$, the **SPL in water is 62 dB higher in water than in air**. (This accounts for both the increase in the characteristic impedance, ρc , and the change in reference pressure from 20 μ Pa to 1 μ Pa.)
- The characteristic impedance of the seabed is usually not much different from that of seawater, so there is significant penetration of sound into the seabed, and conversely the seabed properties (to considerable depth) have a significant effect on acoustic propagation in the water column.
- There is strong coupling between underwater sound and structural vibrations. This has implications for transducer design and for predicting scattering from underwater objects.
- Transducers designed for use in air (including our ears) are totally unsuitable for use underwater. Because our ears are extremely inefficient in water we don't hear much apart from our own breathing when we go swimming. We therefore tend to think the ocean is a quiet place - however the reverse is actually true.

Ambient Noise

Figure 1 provides a good summary of the main sources of noise in the ocean. In the open ocean there is a fairly continuous background noise level that is usually dominated by traffic noise (distant shipping) or distant biological sources at frequencies below 100 Hz and by so-called "wind dependent" noise at higher frequencies. Wind dependent noise is produced by the oscillation of air bubbles entrained by breaking surface waves and can vary by more than 20 dB depending on wind speed. Traffic noise depends on the density of shipping in the area and the prevailing acoustic propagation conditions, which together result in the regional dependencies shown in the plot. Note that these curves specifically exclude nearby ships and boats, which can produce noise levels well in excess of the levels plotted here.

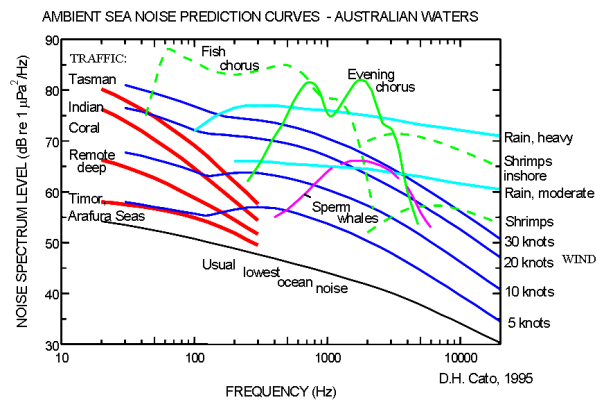


Figure 1. Ambient sea noise prediction curves for Australian waters (Cato, 1995).

As shown in Figure 1, this continuous background noise can be substantially exceeded by a number of other sources such as rain, marine animal choruses (often regular fish choruses occur and in some instances multiple whales produced so much noise they can be considered as choruses), and individual marine mammals. There is also a shrimp known as a "snapping shrimp" that produces high amplitude, broadband acoustic pulses with a frequency spectrum that extends up to several hundred kilohertz. These animals are ubiquitous in waters less than about 60 m deep and latitudes less than about 40°, (Cato, 1977), although they may also be found in smaller numbers outside these limits. The combined effect of many thousands of individuals results in snapping shrimp being the main source of ambient noise in coastal waters at frequencies above a few kilohertz.

Absorption

There is a general tendency for the ambient noise in the ocean to decrease with increasing frequency, which is partly as consequence of the increase of sound absorption with frequency shown in Figure 2. This progressively reduces the range at which noise sources make a significant contribution to the received signal as frequency increases.

Acoustic absorption in air and seawater are compared in Table 1. In both cases absorption increases with increasing frequency, but at all frequencies the absorption in seawater is much lower than it is in air. This is one reason why acoustic signals can propagate over much longer distances in water than in air.

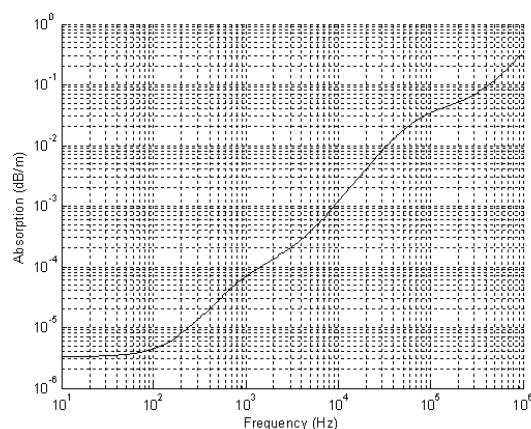


Figure 2. Attenuation of sound due to absorption in seawater as a function of frequency. Calculated using the Thorpe attenuation formula (Urlick, 1983)

Table 2 A comparison between acoustic absorption in seawater and dry air. Air data is from CRC (1984), seawater data was calculated using Thorpe attenuation formula (Urlick, 1983).

Frequency (Hz)	Absorption in dry air (dB/km)	Absorption in seawater (dB/km)
10	0.15	0.0033
100	1.2	0.0045
1000	1.5	0.069
10,000	60	1.2

Sound speed profiles and refraction

The speed of sound in the ocean increases with increasing values of temperature, salinity and pressure (depth). At low and mid latitudes the ocean is heated at the top by incident sunlight and interaction with the atmosphere, which suppresses convection within the water column and results in temperature profiles similar to that shown in Figure 3. Surface wave action results in an upper mixed layer with fairly uniform properties, below which there is a rapid drop in temperature with increasing depth in a region known as the thermocline. Eventually the temperature becomes nearly constant in the deep isothermal layer.

Over the typical range of oceanic values, the sound speed dependence on temperature is much stronger than its dependence on the other variables so, above the deep isothermal layer the sound speed profile tends to have a similar shape to the temperature profile. At deeper depths the pressure effect dominates and the sound speed increases with increasing depth. The resulting sound speed minimum, at a depth of about 1000 m in the open ocean (equator side of the polar convergence zones), gives rise to the so-called SOFAR channel, or deep sound channel, which has a profound effect on sound propagation in the deep ocean.

Figure 4 shows the path of a number of sound rays emanating from a source at a depth of 1000 m, at the axis of a notional deep sound channel. Where the sound speed decreases with depth, the rays bend downwards, whereas a sound speed that increases with depth results in rays that bend upwards. The net result is that the sound no longer spreads vertically, resulting in a substantial reduction in attenuation due to spreading. The existence of the deep sound channel, together with the very small absorption at low frequencies makes it possible for sound to propagate many thousands of kilometres in deep water.

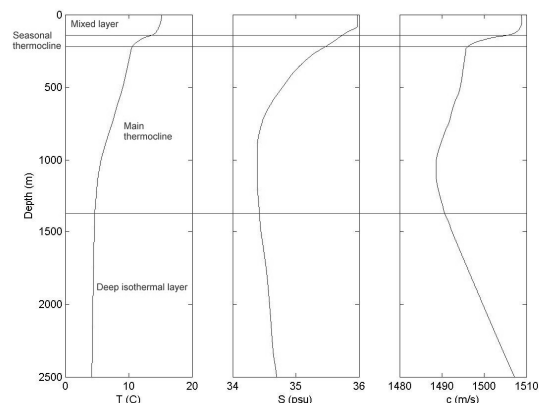


Figure 3. Notional mid-latitude oceanic temperature (left), salinity (middle) and sound speed (right) profiles.

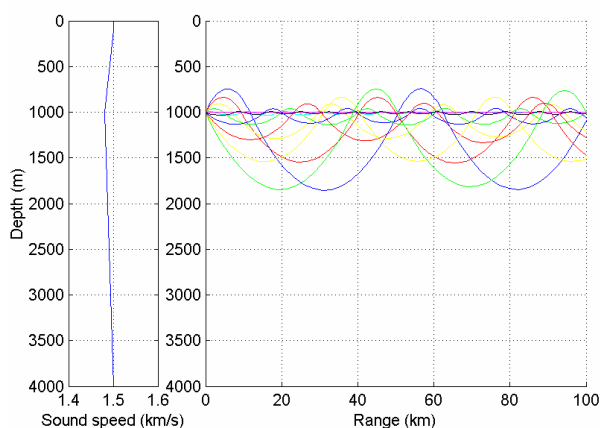


Figure 4. Deep sound channel propagation for a source at a depth of 1000 m.

Note that the situation is quite different in polar regions due to a net cooling of the top of the ocean. This results in a temperature profile and hence sound speed profile that increases with depth, only upward refraction occurs, and there is no deep sound channel. There is still a reduction in spreading, but this time in a surface duct which is formed by the combination of upward refraction and reflection from the sea surface.

Although refraction is extremely important for controlling long-range propagation it becomes less important as the range reduces, and is usually insignificant at ranges less than a few kilometres.

Interaction of sound with the seabed and sea surface

The large difference in characteristic impedance between water and air makes a smooth sea surface an almost perfect reflector of sound, however because it is an acoustically 'soft' interface (from the perspective of sound in the water), the incident waveform is inverted: a positive pressure becomes a negative pressure and vice-versa. However, the sea surface is hardly ever smooth, so in practice some losses occur due to scattering. How significant this is depends on several factors, including the acoustic wavelength, the wavelength of the surface waves, and the grazing angle at which the sound strikes the surface. Scattering increases as the acoustic wavelength reduces, the surface wavelength increases, and/or the grazing angle increases.

The large difference in acoustic impedance between air and water also means that anything underwater that contains air will be a strong reflector and/or scatterer of sound. One particularly important example is air bubbles, which due to resonance effects can have a much bigger effect on sound propagation than a rigid sphere of the same size.

Interaction of sound with the seabed is much more complicated. Figure 5 shows the waves produced in the water column by a point source above a uniform fluid seabed with a sound speed higher than the sound speed in the water. Three signals arrive at the receiver: the first is a so-called Head wave which propagates along the interface between the seabed and the water column at the seabed sound speed, the second is the direct wave, and the third is the geometrically reflected wave.

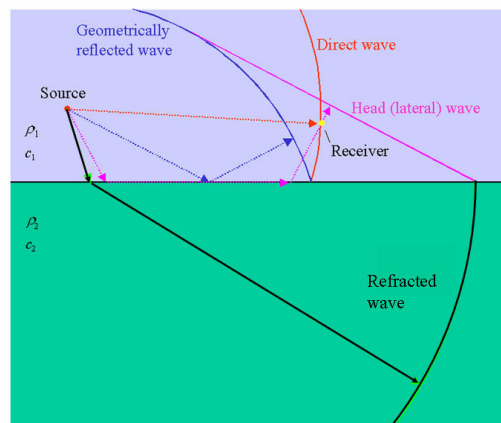


Figure 5. Interaction of sound from a point source with a fluid seabed.

Head waves can be clearly seen in the sequence of recorded airgun signals shown in Figure 6. Due to the higher seabed sound speed they precede the waterborne signal by a longer interval as the range increases.

Unconsolidated sediments in the upper parts of the seabed are water saturated and often well approximated as a fluid. However, consolidated sedimentary rock such as limestone is often encountered at or close to the top of the seabed, especially around the southern two-thirds of the Australian continental shelf where seabeds typically consist of a limestone substrate covered by a thin (< 2m) layer of sand.

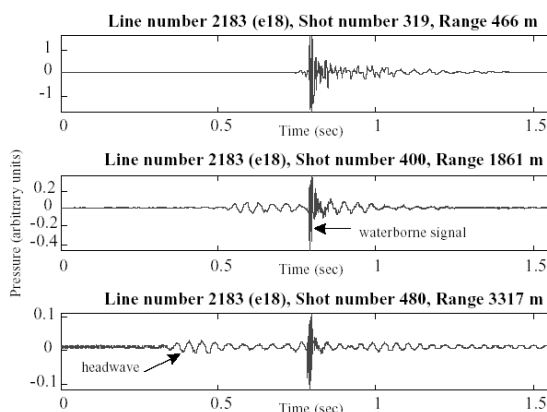


Figure 6. Signals received from a single airgun at three different ranges in 20m of water in Exmouth Gulf, Western Australia.

Figure 7 shows the computed plane wave reflection coefficient for limestone seabeds covered by various thicknesses of sand, h . The two extremes are given by the curve for $h = 0$, which corresponds to a uniform limestone seabed, and the curve for $h = \infty$, which corresponds to a sand seabed. In underwater acoustics we are usually dealing with near-horizontal propagation, so it is grazing angles less than 20° that are most important. In this region, contrary to what you might expect, limestone has a much lower reflection coefficient than sand. In the sand case, the sound incident on the seabed at grazing angles less than about 25° undergoes total internal reflection, so a propagating compressional wave doesn't exist in the seabed and there is very little loss. In a limestone seabed, however, there is still no propagating compressional wave, but there is a propagating shear wave which carries energy away from the interface and reduces the reflection coefficient. This effect is particularly strong for limestone seabeds because the shear speed in the limestone is similar to the sound speed in the water.

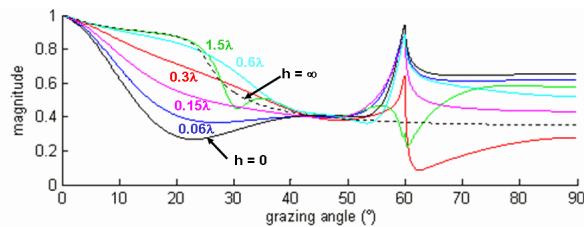


Figure 7. Seabed reflection coefficient vs. grazing angle for limestone seabeds covered by sand layers of various thicknesses. Layer thickness (h) is indicated relative to the wavelength of sound in the sand (λ).

Another point to note from Figure 7 is that the reflection coefficient at low grazing angles is extremely sensitive to the thickness of the sand layer, and even layers with a thickness that is a small fraction of the acoustic wavelength have a noticeable effect.

A consequence of the sensitivity of the reflection coefficient to sand layer thickness is that received levels are also very sensitive to layer thickness. This can be seen in Figure 8, which shows plots of modelled received levels from a seismic airgun array operating in shallow water for four different sand layer thicknesses.

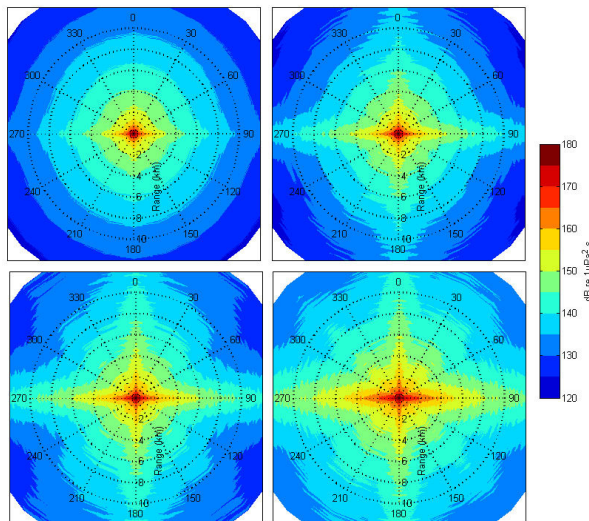


Figure 8. Modelled received levels (dB re $1 \mu\text{Pa}^2.\text{s}$) for a seismic airgun array operating in approximately 60m of water. Maximum received level at any depth is plotted as a function of range and azimuth from the source. Seabed is a sand layer over limestone. Layer thicknesses are: top left, 0 m; top right, 1 m; bottom left, 2 m, and bottom right, 5 m. Range rings are at 2 km intervals.

SOUND LEVEL PREDICTIONS

Environmental impact assessments usually require the prediction of received sound levels. There are two aspects to this:

1. Prediction of the source characteristics including level, spectrum, and directionality, and
2. Computation of the transmission loss, which relates the received level to the source level. Transmission loss is a function of frequency, range, bathymetry, sound speed profile, and seabed properties.

Source characteristics

Source characteristics are best determined by measurement, but this is often not practical - especially for a predictive study. The alternatives are to use an empirical model based

on previous measurements of similar sources, or a physical model based on the principles of operation of the source.

An example of an empirical model is the extrapolation of measurements of thruster cavitation noise from one vessel to another vessel of different size based on the assumption that the radiated acoustic power is a constant proportion of the installed mechanical power. Such an extrapolation has its obvious dangers, but there is some supporting evidence in the very scant literature on the subject Ross (1987).

Estimation of underwater noise levels from in-air acoustic measurements of similar machinery or processes is a much more difficult undertaking because of the necessity to take proper account of the change in radiation efficiency resulting from the much higher acoustic impedance of water, and the consequent stronger coupling between structural vibrations and propagating sound waves. Except for a few very simple cases for which analytic results are known (eg. spheres and cylinders) this requires the full numerical machinery of finite element / boundary element modelling - a substantial task in itself. Ross (1987) provides a very useful discussion of the coupling of structural vibrations to sound waves, but is by no means an easy read.

In some situations the physics of the sound source are straightforward enough that a fairly accurate physical model can be constructed. An example is the Centre for Marine Science and Technology's (CMST's) airgun array model, which allows the azimuth dependent source spectrum of a seismic sound source comprising any configuration of airguns to be computed. The CMST airgun model was used to compute the sound field in Figure 8. (An airgun is a device that produces sound by suddenly releasing compressed air into the water. Seismic sources typically consist of horizontal planar arrays of 20 to 40 airguns of different sizes.) Note, however, that even for this physics based model, the non-ideal nature of a real airgun makes it necessary to calibrate against an example waveform provided by the seismic contractor in order to ensure that the absolute source levels are correct.

Propagation modelling

As previously discussed, sound propagation in the ocean is far from being a simple process, so it should not come as a surprise that simple formulae for computing transmission loss, such as the oft quoted spherical spreading and cylindrical spreading laws are often highly misleading.

Fortunately, there is no need to resort to these simple formulae because a number of numerical transmission loss models that do take proper account of all the relevant factors are freely available (see OALib 2008). However, these models are by no means trivial to use and although there are now reasonably user friendly front-ends available (e.g. AcTUP 2006) it is very easy to obtain totally erroneous results if you don't understand the requirements, limitations and underlying assumptions of the models. Providing an adequate background to underwater acoustic propagation modelling is well outside the scope of this paper, but here is a brief description of the most common types of models and their applications.

Direct solution of the acoustic wave equation through finite difference or finite element methods is impractical for most problems in underwater acoustics, so a number of alternative methods have evolved, each based on different simplifying assumptions.

Type 1. Wavenumber integration (fast-field) models. When used correctly, these models produce highly accurate results at all ranges, in range-independent situations (i.e.

where the water depth, sound speed profile and seabed properties are independent of range). However their computational requirements become prohibitive at long range and/or high frequency. Examples include SCOOTER and OASES.

Type 2. Normal mode models. The normal mode method provides a very efficient way of computing the field at long range, but is not accurate at short range. How short is short depends on water depth, seabed properties and whether the model uses real or complex arithmetic. The latter improves short range performance and the ability of the model to deal with seabeds that support shear, but reliable complex mode-finders are notoriously difficult to implement. Although normal mode models are fundamentally range-independent, it is relatively straightforward to apply them to range-dependent situations using either the adiabatic or coupled mode method (Jensen 2000), although with a loss of computational efficiency. Examples include KRAKEN, KRAKENC, and ORCA.

Type 3. Parabolic Equation (PE) method. PE models are based on a so-called "paraxial" approximation to the wave equation that is valid for acoustic energy travelling close to the horizontal. Advanced numerical techniques implemented in newer models have allowed the maximum angle to the horizontal to be traded-off against computational efficiency, making PE models applicable to a wide range of problems. The PE method can also be applied to range-dependent situations in a straightforward way, and has become popular for these applications. However, there are still some significant issues with regard to their application to seabeds that include both high and low shear speed layers. Examples include RAM, RAMS, RAMGeo, and MMPE.

Type 4. Ray and beam models. The above models all include wave effects such as diffraction and are therefore accurate at all frequencies. However, their computational requirements increase with frequency, and at some stage it becomes necessary to switch over to models that ignore or approximate wave effects. The chief of these are ray models, which use Snell's Law of refraction to trace the path of rays (normals to the acoustic wavefronts) through the water column. The acoustic field is then computed by looking at how the spacing between adjacent rays varies with range and depth. Simple ray models produce a number of unphysical results, such as infinite sound levels at caustics, so various attempts have been made to improve on them. One of the more popular is the Gaussian beam model, which treats each ray as the centre of a beam of sound with a Gaussian intensity profile. BELLHOP is a publicly available ray / beam model that can deal with range-dependent bathymetry and (in its latest version) sound speed.

Of course, these models are only as good as your knowledge of the relevant environmental parameters. This isn't usually a major limitation in deep water, where climatological oceanographic databases are adequate for many purposes, but in shallow water uncertain knowledge of seabed properties is often a major limiting factor.

MEASUREMENT OF UNDERWATER SOUND

Accurate measurement of underwater sound levels requires careful attention to a number of factors. Some are common to any acoustic measurements, but there are some that are peculiar to working at sea.

One of the main issues with underwater sound measurement is flow-noise. This is caused by the turbulent pressure fluctuations that occur whenever there is a flow of water over the hydrophone. It is similar to wind noise in air acoustics but

unfortunately more difficult to eliminate due to the lack of an underwater equivalent to the windshield commonly fitted to microphones. Flow-noise results in high intensity, low frequency noise that can seriously interfere with signals of interest.

The most common cause of flow-noise occurs when the hydrophone is suspended directly from a boat or surface float. Vertical motion of the boat or float due to surface waves results in vertical motion of the hydrophone relative to the water at depth, producing flow-noise that oscillates in intensity. In addition, the force of the wind acting on a boat's hull and superstructure will often cause it to move at a speed sufficient to produce substantial continuous flow noise.

The best way of eliminating flow noise is to eliminate any direct mechanical connection to the sea surface by placing the recording system on the seabed. This can be achieved by using an acoustic release for recovery, or by using a U shaped mooring such as shown in Figure 9(a). An acoustic release is the preferred option as it eliminates the need for any surface presence, which minimises wear and tear on the mooring and eliminates the possibility of equipment being stolen (yes it happens at sea as well). Acoustic releases do, however, occasionally fail, so it is prudent to design the mooring so it can be recovered by grapple if necessary. Ideally the hydrophone should be placed on the seabed out of any prevailing current, although it can be suspended from a sub-surface float if required.

Where boat based measurements are necessary then steps need to be taken to decouple the hydrophone from the boat motion. An example of how this can be done is shown in Figure 9(b).

In either case it is necessary to pay careful attention to the mooring / suspension construction to eliminate any potential sources of mechanical noise such as metal on metal contact of shackles, chain etc. If the mooring is to be deployed for more than a few hours it is also necessary to ensure that all shackles are wired and that failure won't occur due to chafing of rope components against anything hard.

Water flow at right-angles to electrical cables and ropes can cause them to vibrate (strumming), and if these vibrations couple to the hydrophone they will be picked up as apparent acoustic signals. This is particularly a problem in locations with significant tidal currents and is another good reason for putting the hydrophone on the seabed where practical. Attaching commercially available fairings to the cables can reduce strumming, although these often cause handling problems. A simpler but less effective solution is to spirally wrap the cable with a thin cord.

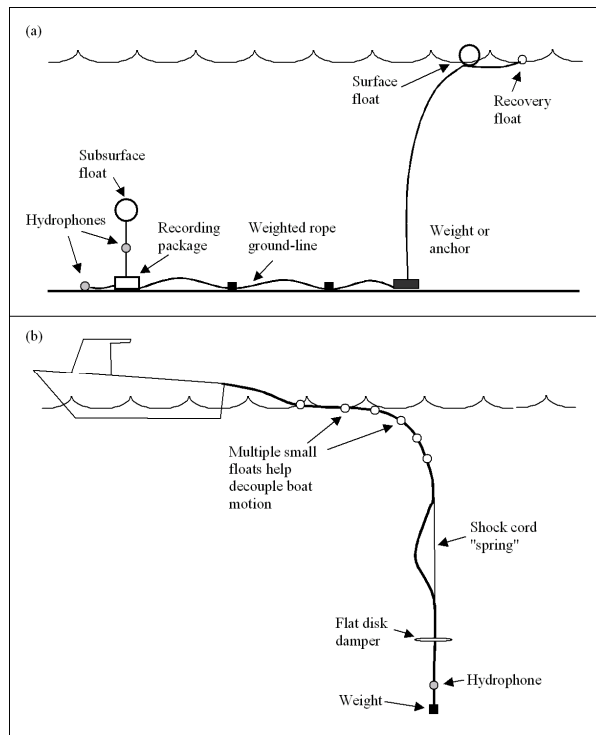


Figure 9. Notional deployment configurations for (a) U-shaped mooring for a sub sea recording package and (b) boat-based recording.

Marine animals can be at any depth in the water column, so unlike in air, there is no 'standard' depth at which to make measurements. The choice of hydrophone depth is therefore usually governed by practical considerations, such as minimising flow noise.

It is usually impractical to make measurements at all depths and ranges of interest, so the main purpose of underwater acoustic measurements is typically to calibrate models that can then be used to predict levels at other locations. Similarly, estimating source characteristics from measured data usually requires propagation modelling in order to remove propagation effects from the measured data.

Acoustic propagation depends strongly on the vertical sound speed profile, so it is important to supplement any acoustic measurement with measurements of the sound speed using a device called a CTD (conductivity-temperature-depth) profiler.

Although it sounds obvious, you also need to carefully plan how you are going to deploy and recover your equipment. Getting the gear off the back deck and into the ocean is the easy bit. It still needs to be functional when it hits the bottom, and keep working for the duration of the deployment. You also have to find it again, and get it back onto the boat in good enough condition that you can recover the data. All of this while you (and your gear) are being thrown around by the motion of the boat and (if you don't go to sea very often), you are taking frequent trips to the rail to empty the contents of your stomach.

When analysing recorded data it is important to use units that are appropriate for the task at hand. It is meaningful to quote measurements of continuous noise sources as mean squared pressure (MSP) (dB re $1\mu\text{Pa}^2$ or equivalently dB re $1\mu\text{Pa}$ rms), but unfortunately MSP is often inappropriately applied to impulsive sources such as airguns or pile driving noise. Measurements of impulsive noise should be given as integrated squared pressure, often called sound exposure level, or SEL (dB re $1\mu\text{Pa}^2\cdot\text{s}$). SEL is proportional to the received

acoustic energy, and is much less sensitive than MSP to the often difficult determination of the signal's duration.

PREDICTION OF ENVIRONMENTAL IMPACTS

After one has derived measurements of sound fields around a source in appropriate units, usually to several decimal places, the then difficult task of determining what the potential environmental impacts of this noise are, follows. This is not an easy task, given that we are talking of a myriad of biological entities potentially ranging from plankton to great whales, all with differing hearing capabilities, and often behavioural responses to noise which we are lucky to define within an order of magnitude, let alone several decimal places.

One of the first considerations is the type of noise exposure. Before assessing potential impacts one needs to define if the concern is with impulse or continual noise, stationary versus moving sources, what is the noise duration, repetition rate, frequency content and intensity, and whether cumulative noise doses need to be considered. Once these are defined the literature can then be searched for appropriate effects on the species group concerned, which is usually marine mammals as these are what are primarily covered in legislation. More than often the response of marine animals for the particular scenario of noise exposure and species of concern will not be well defined in the literature so must be extrapolated from available observations and our knowledge of how humans or other animal groups respond to sound.

The full range of potential noise effects range through: 1) lethal effects; 2) sub-lethal effects or pathological damage; 3) changes in behavioural patterns including attraction to some noise types; 4) masking of signals of interest directly or via temporarily changing an animals hearing response; 5) no direct effect at all; or 6) impacts on a critical species (such as prey) affecting a species which may not be directly impacted by the noise. In general terms it is only the use of explosives or nearby pile driving which are known to produce physiologically lethal effects on marine animals, due to the high peak pressures involved and the energy delivered. There are several texts offering methods of determining safe standoff distances for humans and underwater explosives. In the absence of any other data these safe working ranges can be assumed applicable for marine mammals and fish.

Some behavioural effects of underwater noise may translate to lethal impacts, as is now widely believed to have occurred with beaked whales and the nearby operation of certain models of low frequency, high power military sonars. In these instances the cause of death is believed to be a behavioural change triggered by sonar exposure, which ultimately leads to the animal's death either by stranding ashore or some induced pathological cause (the formation of nitrogen bubbles, or the bends is often quoted as occurring). Thus when considering noise impacts the consequence of any behavioural changes need to be considered. This may be at the level of individual animals (i.e. the noise will impact a few individuals only) or be at the population level (i.e. the noise may displace or disrupt a spawning fish school and so disrupt a season's spawning effort), with more serious consequences.

Sub-lethal impacts from excessive noise exposure, particularly on animal hearing systems, have been shown to occur in fishes and marine mammals. The onset of temporary hearing threshold shifts (TTS) has been widely observed in fishes and marine mammals. The required noise level at which TTS occurs in toothed whales is contentious but defined in Southall et al (2007). This level is often used as a maximum desirable noise exposure criteria for marine mammals.

It should be noted here that the units and noise metric are important when defining impacts of impulse noise as the often widely used mean squared pressure units are totally inadequate in defining impulse noise since they require a defined averaging time. Variations in the averaging length used over an impulse will give rise to different measures of the same impulse signal.

The literature on the behavioural impacts of underwater noise is large, sometimes confusing and often severely lacking for many animal groups. The impacts of noise on marine mammals was considered in the mid 1990's by Richardson et al. (1995). Since this publication there have been varying standards of follow up reviews, some further experimentation or observations of noise impacts and numerous interpretations of noise impacts on marine mammals. The most recent effort to summarise data is Southall et al (2007) who present tables of varying responses to defined sound levels for different animal groups, but note that many of their recommended sound levels for a respective impact type and group are not well defined or based on insufficient experimental data. If one is interested in impacts of underwater sound on fishes or marine fauna other than marine mammals then the literature base of actual experimental data is small.

CONCLUSIONS

If, having taken the trouble to read this paper, you have both an improved understanding of the complexities of underwater acoustics, and a better appreciation of the potential pitfalls of working in this field, then it has served its purpose.

Assessing the environmental impact of man-made underwater sound is currently an uncomfortable mix of well understood, but difficult to apply physics, and poorly understood and highly uncertain behavioural biology. Progress is being made, but setting appropriate standards and guidelines is going to be a long, slow process.

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