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An Underwater Acoustics Group Conference held at Loughborough University
23 - 24 July 2001

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Proceedings of the Institute of Acoustics 2nd Symposium on Underwater Bio-Sonar and Bioacoustic Systems, 23 -24 July 2001, Burleigh Court International Conference Centre, Loughborough University, LE11 3TD, UK.

Edited by

A.D.Goodson

Underwater Acoustics Group
Department of Electronic & Electrical Engineering
Loughborough University
LE11 3TU
UK.

P.Dobbins

BAE SYSTEMS
Underwater Systems
PO Box 5,
Filton,
Bristol
BS34 7QW
UK

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Institute of Acoustics
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Herts
AL1 3BN
UK

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FORWARD

In December 1997 the first Institute of Acoustics symposium on *Underwater Bio-Sonar and Bioacoustic Systems* brought together underwater bio-acousticians and sonar engineers from around the world to look at a variety of acoustic topics relating to marine mammal sonar systems, the process of environmental impact assessment and the development of specialised tools. This 2nd Symposium continues this theme and the call for papers was extended to encourage contributions relating to other species including fish.

Post 1997 the impact of man-made acoustic signals on the marine environment has remained a sensitive and emotive issue, as exampled by the Bahamas 'beaked whale incident'. Although the US investigations into this incident have yet to be made public the limited information available to date suggests that there may be some unexpected factors that will need to be considered when the environmental impact of marine acoustic systems are being assessed in the future. Our first invited speaker, Dr Bob Gisiner, is well placed to discuss the difficulties that different agencies experience when studying environmental impacts and marine mammals and he has been instrumental in developing research programmes in this area.

Understanding biological sound production mechanisms provides an insight into the way animals exploit their acoustic environment. We require more detailed knowledge of hearing sensitivity In order to understand how animals may react to the presence of man-made noise and it remains a broad criticism that, to date, the audiograms of very few marine organisms are published. Without such basic information any prediction of acoustic impact must be flawed. Studies of natural biological sonar systems continue to show that nature's signal processing concepts are highly developed and some demonstrate that deceptively simple acoustic signals can be used to interrogate the environment in ways that would severely test any conventional electronic system. Our understanding of how such biological systems operate continues to improve but it is clear that there remains much to be understood before man-made 'bio-mimetic' systems will be able to compete on equal terms. Our second invited speaker Dr Ted Cranford has made major contributions to our understanding of odontocete echolocation sound generation mechanisms and his presentation, based on very recent work, promises to rewrite some of the conventional interpretations.

To improve our knowledge of how biological acoustic systems function in the wild requires innovative approaches to data capture systems. While access to captive animals permits accurate measurements of biological system performance it is also essential to study natural behaviour in the wild. Continued advances in microelectronics, especially in ultra low power circuitry, mass memory cost and processing power, driven in part by the mobile telephone industry, are encouraging the development of sophisticated data capture systems. These benefits are already appearing with the advent of long-life 'pop-up' recording buoys, new satellite tracking tags etc.

Recent improvements in signal analysis and classification methods permit a detailed understanding of animal behaviour to be made in conditions where acoustic observations are the primary data source. Computer modelling methods help to provide explanations where the alternative invasive study techniques are inappropriate. The papers in this volume address a number of these topics and provide an insight into the current state of bioacoustic research and illustrate that innovative hardware and software techniques are now available to researchers in the field.

The conveners particularly wish to thank all the contributors for providing such a wide range of interesting and innovative material and especially acknowledge the help given to them by the referees while preparing this volume. Special thanks are also due to Dr Chris Richards for setting up the web server and writing the scripts to automate the abstract and manuscript submissions.

Dave Goodson

Underwater Acoustics Group - Department of Electronic and Electrical Engineering, Loughborough University, LE11 3TU, UK

Peter Dobbins

BAE Systems, Underwater Systems, PO Box 5 Filton, Bristol, BS34 7QW, UK

CONTENTS

THE ENVIRONMENTAL IMPACT OF UNDERWATER SOUND

A. D. Heathershaw [1], P. D. Ward [1], A. M. David [1]

[1] Defence Evaluation & Research Agency (DERA), Southampton Oceanography Centre, Southampton SO14 3ZH. *a.heathershaw@soc.soton.ac.uk*

1. ABSTRACT

The growing problem of "noise pollution" in the marine environment is discussed and techniques are described for assessing the potentially adverse effects of underwater sound on marine life. The sensitivity of hearing in fish, marine mammals and man is briefly reviewed, together with sources of noise, the nature and type of acoustic impact and the requirement for mitigation measures to reduce environmental risks. A method for assessing acoustic impacts is described that brings together, the frequency, intensity and time domain aspects of the problem and the paper concludes by suggesting areas for future research to improve the understanding and management of acoustic impacts in the marine environment.

KEY WORDS: environment; impact; underwater; noise; marine mammal; mitigation

2. INTRODUCTION

Underwater sound is used by man for many purposes; for research to probe the ocean's interior and to understand its physical and biological processes; for mapping to describe seabed sediments and sedimentary structures; and for navigation, communication and telemetry. Military uses may include submarine detection systems or sonars. Sound is also a by-product of many of man's activities. These may include shipping; construction, oil and gas exploration, drilling, cable and pipeline laying activities, dredging for marine aggregates and, of growing concern, the recreational use of the marine environment (power boats, jet skis etc). Not all of these uses of underwater sound are necessarily harmful and acoustic devices may in fact be used to protect marine life, e.g. by reducing by-catch of dolphins in fishing nets. However, concern about the possible adverse effects of underwater sound on rare or endangered species of marine mammal has drawn attention to the growing problem of underwater noise pollution.

As a result, acoustic engineers, sonar operators or indeed anyone involved in any activity with the potential to cause acoustic disturbance, will find that they are increasingly likely to have to account for the effect that their particular sonar design or acoustic activity may have on marine life and other human beings in the marine environment. A precautionary approach is often called for although it is doubtful that the "precautionary principle" in its strictest sense could ever be applied across the full range of man's underwater noise-making activities [1]. Notwithstanding, environmental law places a "duty of care" on users of the environment to protect the environment and to avoid harm to marine life. In the absence of guidelines, what constitutes a permissible level of disturbance is often left to individuals to decide, based on their interpretation of the scientific evidence and their judgement about the risk of likely adverse effect. What is needed is a firm body of scientific evidence about the effects of underwater sound on marine life and well established procedures for assessing acoustic impacts. Given the difficulty of studying marine mammal behaviour in response to sound, the rate at which scientific knowledge accrues is likely to be slow. But this should not deter us from putting in place procedures that take such knowledge as there is and which apply this in a precautionary approach to assessing risks and determining mitigation measures. This latter aspect is the subject of this paper.

Following a brief overview of the subject of underwater noise pollution, we discuss the types of measure that may be taken to quantify and manage the risks associated with the use of underwater sound. The subject embraces a wide range of discipline extending from the basic physics of sound propagation, through fish and mammalian audiology and psycho-acoustics and into such areas as environmental impact assessment and risk analysis. The issues are not all clear cut. There are large areas of ignorance concerning the effects of underwater sound on animal behaviour. And yet, as with many other areas of discretionary decision making, the role of scientific evidence turns out to be crucial in determining the balance between risk and benefit.

3. SOURCES OF NOISE IN THE MARINE ENVIRONMENT

The oceans are a noisy place, being filled with a broad spectrum of both natural and man-made sounds. A few of these noise sources are listed in Table 1. Wenz's [2] original 1962 diagram still provides a useful summary of the range of processes contributing to ambient noise in a frequency range from 1 Hz to 100 kHz. Biological sounds are present across virtually the whole of this range from about 10 Hz upwards. Table 1 shows that, within this range, some animals are themselves powerful sources of sound.

Noise Source	Maximum Source Level	Remarks
Undersea earthquake	272 dB	Magnitude 4.0 on Richter scale (energy integrated over 50 Hz bandwidth
Seafloor volcano eruption	255+ dB	Massive steam explosions
Airgun array (seismic)	255 dB	Compressed air discharged into piston assembly
Lightning strike on sea surface	250 dB	Random events during storm at sea
Seismic exploration devices	212-230 dB	Includes vibroseis, sparker, gas sleeve, exploder, water gun and boomer seismic profiling methods
Fin whale	200 dB (avg. 155-186)	Vocalizations: Pulses, moans
Container ship	198 dB	Length 274 m, speed 23 knts
ATOC sound source	195 dB	Depth 980 m, average duty cycle 2-8%
Humpback whale	192 dB (avg. 175-190)	Fluke and flipper slaps
Supertanker	190 dB	Length 340 m, speed 20 knts
Bowhead whale	189 dB (avg. 152-185)	Vocalisations; songs
Blue whale	188 dB (avg. 145-172)	Vocalisations; low frequency moans
Right whale	187 dB (avg. 172-185)	Vocalisations; impulsive signal
Gray whale	185 dB (avg. 185)	Vocalisations; moans
Offshore drilling rig	185 dB	Motor vessel *Kulluk*; oil/gas exploration
Offshore dredger	185 dB	Motor vessel *Aquarius*
Open ocean ambient noise	74-100 dB (71-97 dB in deep sound channel)	Estimates for offshore central California, sea state 3-5; expected to be higher (≥*120 dB)* when vessels present

Table 1: Natural and man-made noise comparisons [3]. Note: Except where stated, all the above are nominal total broadband power levels in the 20-1000 Hz band. These are the levels that would be measured by a single hydrophone (reference 1 μPa) in the water.

Physical processes such as turbulence associated with tidal currents are a significant source of ambient noise up to about 100 Hz, while above this, from 100 Hz to approximately 10 kHz, surface process such as bubbles and spray from breaking waves and precipitation, contribute a variable proportion of the spectrum of background noise that is governed by weather and climate. Below about 100 Hz the effects of earthquakes and underwater explosions are an intermittent but powerful source of sound.

In addition to these natural sources, man has added a steadily increasing level of underwater noise from industrial, scientific and military use of the marine environment. Ross [4] estimated an increase in shipping noise of 10 dB between 1950 and 1975, and forecast a further 5 dB increase by the end of the twentieth century. More recently, it has been shown [5] that shipping is the dominant source of low frequency noise in the Pacific. However, there will be many local variations on this, particularly in shelf seas and coastal waters. Here, concentrations of other types of industrial activity and man's increasing recreational use of the ocean are likely to present serious threats to conservation initiatives (e.g. protection of sensitive habitats) and it is these pressure points or 'hot spots' that perhaps require the most immediate attention.

Perversely, scientific research itself may cause disturbance; acoustic devices are now widely used by oceanographers for studying physical and biological processes and yet may have the potential to harm the environment and arouse public concern. Perhaps the best known case of this is the Acoustic Thermometry for Ocean Climate (ATOC) experiment [6]. Although designed to study the effects of global warming and climate change, the ATOC proposal caused alarm amongst animal welfare groups and led to the publication of an Environmental Impact Statement (EIS) [3]. As a result, ATOC acoustic transmission protocols have been modified in such a way as minimise harm to marine mammals. Also in the USA, experiments undertaken in support of the procurement of the US Navy's Surveillance Towed Array Sonar System (SURTASS) [7] have been required to publish EISs and to prepare mitigation in order to ensure that the experiments that are designed to study the behaviour of animals in response to sonar transmissions (so called "replay experiments") do not themselves result in undue harm. Between them, these two projects have probably done more to stimulate research on the effects of sound on marine mammals than any other projects anywhere else in the world [8, 9].

In regard to purposeful sound transmission, a wide range of acoustic devices and sonars is in use throughout the environment for a variety of purposes. Information concerning military sonars is of necessity limited but what is known about these and other devices is summarised in Table 2.

Sonar type	**Frequency** (kHz)	**Duration** (ms)	**Source level** (dB re 1 μPa at 1 m)
Depth sounders	12+		180+
Bottom profilers	0.4 – 30	0.1-160	200-230
Side scan	50 – 500	0.01-0.1	220-230
Navigation (transponders)	7 – 60	3-40	180-200
Military			
Search and surveillance	2 – 57	4-1000	230+
Mine and obstacle avoidance	25 – 500	1-30	220+
Weapon mounted	15 – 200		200+
Underwater telephone	5-11	Continuous	180-200

Table 2: Typical source levels and operating frequencies for man-made sounds

Some of these source levels may appear high but it should be remembered that it is the received Sound Pressure Level (SPL) at the location of an environmental receptor that is important in determining an impact. To properly evaluate this, it is necessary to consider the effects of the environment in attenuating sound. This is possible using underwater propagation loss models [10]. In turn these enable the variation of SPL with depth, bearing and range from an acoustic source to be determined with considerable accuracy.

With regard to sound energy that is generated as a by-product of other of man's activities in the marine environment (e.g. drilling, piling, construction, dredging), this is distributed over a wide range of frequencies and intensity levels according to distance from the source and environmental conditions. For a review of this subject area, readers are referred to an excellent summary elsewhere [11]. (See also Table 1).

4. THE SENSITIVITY OF HEARING IN FISH, HUMAN BEINGS AND MARINE MAMMALS – A GENERIC THRESHOLD OF HEARING CURVE

The potential for underwater sound to impact on marine life and human beings is easily illustrated by comparing the frequency of a sound source with the range of hearing of aquatic animals and man underwater. This is shown in Figure 1, which indicates the threshold of hearing for fish, man and marine mammals as a function of frequency and illustrates the characteristic 'U'-shaped curve or 'audiogram' that is a feature of the hearing of all species. Also included in Figure 1 is a Generic Threshold Value (GTV) curve that has been developed by the authors and which gives the threshold of hearing of the most sensitive species at all frequencies. Inspection of the audiograms reveals that these may be grouped in three overlapping bands: (a) low frequencies (10 Hz to 300 Hz), where fish are most sensitive, (b) mid-frequencies (300 Hz to 1500 Hz), where humans are most sensitive and (c) higher frequencies (1500 Hz to 100 kHz), where toothed whales are most sensitive. Above 100 kHz, the sensitivity of marine mammals falls off very rapidly and other species are not sensitive at all to sound at these frequencies.

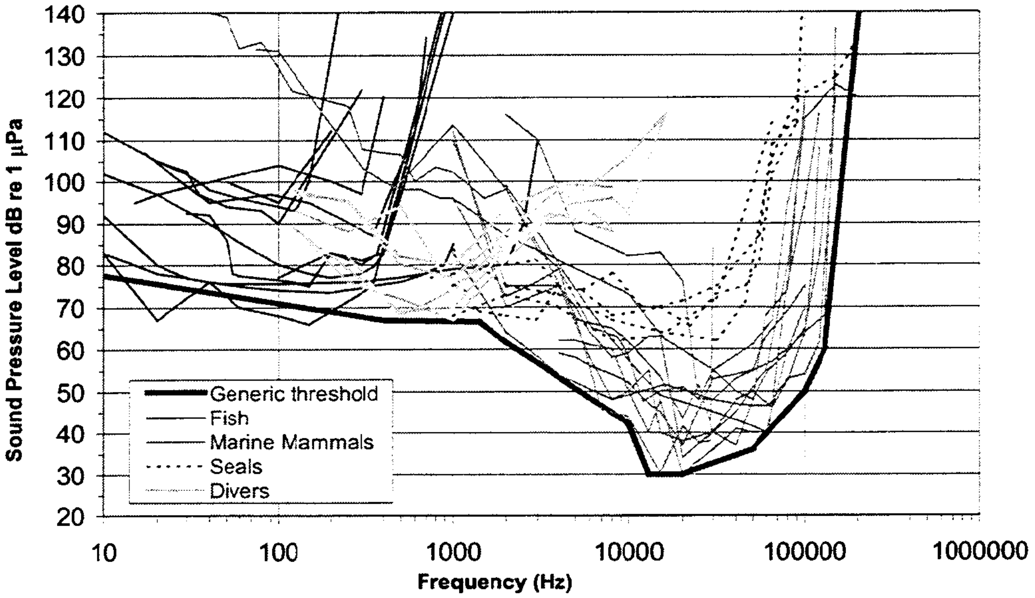

Figure 1: Threshold of hearing for assorted species of fish, human divers and marine mammals along with the Generic Threshold curve

From Figure 1, the following general deductions are possible. First, the potential for impacts is possible across a wide range of frequencies, and therefore species, from which it follows that broadband sounds (e.g. airguns, explosives) may be of greater concern than narrow band sounds or tonals. Second, those frequencies that are likely to be optimum for man are also likely to be optimum for marine animals (e.g. they can be exploited to propagate sound over long ranges or used to achieve high spatial resolution). However, while Figure 1 draws attention to the importance of sound intensity and frequency, it overlooks the importance of the temporal domain in evaluating impacts, i.e. the length of time that an animal may be exposed to a sound. While it is true that a sufficiently intense sound may cause instantaneous hearing loss, as with humans it is the measure of exposure to persistent noise that is needed in assessing the true extent of acoustic impacts. These matters are dealt with in later sections. This does not diminish the importance of the audiogram in understanding the effects of noise pollution and it should be noted that for a significant number of animals, including many rare and endangered species, even this rudimentary information is lacking [11, 12]. Comprehensive reviews of hearing in fish, marine mammals and human beings are given elsewhere [11]-[15].

5. THE IMPACT OF SOUND ON MARINE LIFE

The effects of high levels of underwater sound on fish and marine mammals may generally be categorised as physiological or behavioural [11]. In extreme cases, physiological effects may involve mortality, although in the majority of reported cases this appears to be by indirect means, e.g. trampling of young pinnipeds during stampedes following sudden noise disturbance [11]. Less severe reactions may involve permanent or temporary damage to body tissue and organs resulting in internal injuries to, amongst others, air sacs and lungs. Within this category falls hearing damage which may be permanent or recoverable over a period of time ranging from minutes days or weeks.

While there is some evidence concerning physiological effects, in particular the association between sound exposure and reduction in hearing sensitivity in fish, marine mammals and man, relatively little is known regarding the behavioural effects of sound on marine life, although as recent evidence shows, it may be biologically significant [16]. Behavioural impacts affect the general actions of an animal. These are often hard to quantify and the results and conclusions from a number of studies may even be contradictory. For instance, several studies have been carried out on the response of baleen whales to man-made sounds. The results show that sometimes the whales change their vocalisations or else move away from the noise, yet on other occasions there is no change in behaviour, even at high exposure levels [17, 18, 19]. Also in this category are long term responses and effects such as displacement from feeding or breeding grounds, impact on energy balance and sound-induced stress resulting in physiological damage through increased stimulation of the adrenal cortex and hormonal complexes in cetaceans [1].

The effect of sound on a biological receptor (e.g. fish, cetacean or human being) at a particular frequency and for a particular duration, can only be evaluated by considering the intensity of the sound at the position of the receptor. As noted previously this requires knowledge of the SPL at the location of the receptor. Dependent upon the Source Level (SL) associated with an underwater acoustic device or activity, the receptor's distance from the source and the propagation conditions, the SPL may be sufficient to cause permanent damage. Criteria are required which enable "safe" working distances or stand-off ranges to be determined for an acoustic source. These distances or ranges may be used to: (a) calculate a zone or volume of influence around an underwater acoustic device, within which it would not be safe for an animal or human being to remain and within which monitoring should be undertaken, and (b) estimate suitable closest points of approach to fixed areas such as marine mammal sanctuaries, special areas of conservation, fish spawning grounds, dive sites, etc.

This paper concentrates on the links between SPL and physiological effects that determine the stand-off ranges to be used in deriving mitigation measures for underwater sound sources and sonars in particular. While this may seem less than precautionary given the concern being shown about behavioural effects, the authors required a method that was capable of being used in situations where the species in an area might not be known exactly and which could also be applied to multiple sound sources and sound sources having widely differing characteristics. The approach that has been adopted, therefore, considers the conditions likely to lead to Temporary and Permanent Threshold Shifts (TTS and PTS respectively) in the hearing of marine mammals and man, for which there is a wider body of scientific evidence.

6. EVALUATING IMPACTS AND DEVELOPING MITIGATION MEASURES

In order to assess the severity of an acoustic impact, it is necessary to consider not only the frequency and intensity of the sound but also the length of time to which an environmental receptor has been exposed [11, 20]. The following sections describe how the frequency and time domain aspects of the problem can be brought together with sound intensity and propagation characteristics to arrive at scientifically supportable criteria for assessing the effects of a sound source on fish, marine mammals and human beings.

The approach adopted in this paper is based upon the concept of the Damage Risk Criterion (DRC). Application of the DRC involves establishing a relationship between the level of sound likely to lead to temporary or permanent hearing damage, and the length of time (i.e. duration) required for this to happen. This is termed the sound dosage. Intuitively, we might expect there to be an inverse relationship between SPL and exposure, if TTS or PTS is to be avoided. The limited data for PTS, and slightly more extensive data for TTS (Figure 3) confirm this and indicate that the human in-air DRC forms a good basis for assessing these effects on humans and other species in the marine environment. The application of human DRC to hearing in fish and sea mammals may seem contentious but is not without some scientific justification given the basic similarities in audiological response and inner-ear transduction mechanisms in the various species [11]. Furthermore, with the immediate needs of assessing acoustic impacts in mind, it is probably the best that can be done given the paucity of scientific data [21].

The DRC vary from country to country, according to the statistically estimated level of risk of hearing damage. In the UK [22], a 3 dB increase in DRC is employed for every halving of the length of time for which a human is exposed to sound. This leads to the concept of sound exposure dosage being used to prevent humans being exposed to harmful levels of sound. Designed primarily to reduce the risk of hearing damage in the work place, total exposure is normalised to 8 hours. This gives the daily personal noise exposure of an individual ($L_{EP,d}$), in dB, as

$$L_{EP,d} = 10\log_{10}\left\{\frac{1}{T_0}\int_0^{T_e}\left[\frac{p_A(t)}{p_0}\right]^2 dt\right\} \qquad (1)$$

where T_e = the duration of the person's personal exposure to sound, T_0 = 8 hr (28800 s), p_0 = 20 µPa (reference in air) and p_A = the time-varying A-weighted instantaneous sound pressure [20].

If exposure constitutes discrete pulses of sound rather than a continuous time-varying signal, then the integral may be replaced by a summation of the individual exposure events. Applying these arguments to other species in water, the equivalent intensity is given by

$$\left[\frac{p_X(t)}{p_0}\right]^2 = 10^{\frac{SPL-GTV}{10}} \qquad (2)$$

where SPL = the instantaneous sound pressure level with units of dB re 1 µPa, GTV = the sensitivity of hearing of the most sensitive species at the frequency of interest (same reference pressure as SPL), p_0 = reference pressure for p_X and p_X = the time-varying instantaneous sound pressure weighted to the hearing of the most sensitive species.

Equation (1) may, therefore, be rewritten as

$$L_{EP,d} = 10\log_{10}\left\{\frac{1}{28800}\sum_{t=0}^{t=24hr} 10^{\frac{SPL-GTV}{10}}\,\delta t\right\} \quad (3)$$

where: *SPL - GTV* is the hearing threshold exceedance of each received pulse in dB and δt is the length of each single pulse (s).

Here, the duration of an individual animal's exposure to sound (T_e) has been taken as t = 24 hrs in a parallel with the human hearing case. The exposure must be summed for every 24-hr period. It is the 24-hr period for which exposure is potentially the greatest that will determine the stand-off range. In many cases, the application of these ideas will be complicated by the fact that the sound source is moving and that fish and sea mammals are at various times passing in and out of the insonified region of water (see later).

Because of the logarithmic nature of (3), a brief exposure at high SPL contributes to a receptor's daily dosage significantly more than continual exposure at much lower SPL. A daily dosage of 75 dB above threshold could, for example, be made up of 8 hr of exposure at 75 dB above threshold of hearing or by a single 8 s pulse at 110 dB above threshold. Equally, ten 8 s pulses at 100 dB above threshold would give the same total exposure.

A note of explanation is perhaps required here regarding the significance of the 8 hr period in (1). The body of scientific evidence concerning hearing damage has been gathered by study of the hearing of humans in air. These data have been used to formulate guidance, regulations and law concerning noise exposure for humans in the workplace. Hearing may be harmed by high intensity sound of short duration or by lower intensity sound but over a longer duration. Also, the ear (in humans, fish and sea mammals) does not recover immediately but sound at a later time may add to the impact of a previous noise. In order to take these various effects into consideration the total integrated A-weighted energy per day is taken. Where the total duration of sound is greater than 8 hrs, then the energy within an 8 hr period is taken. These 24 and 8 hr periods may seem somewhat arbitrary although it should be noted that they correspond to measured effects and that they are based on a typical human being's working life. As no better data are available, these figures have been applied to mammals in the marine environment. What data are available indicate that such an approach is realistic. Few data are available regarding whether the effect of duration of exposure declines after a composite 8 hrs of exposure.

Research on humans [21] suggests that there is a statistically significant risk of TTS from exposure to sound (in air) at levels of 85 dB above threshold for periods in excess of 8 hrs. This 'dosage' is taken as the basis of the method proposed in this paper The DRC is then used to extend the 85 dB figure to shorter durations (i.e. a 3 dB increase in threshold per halving of duration). For mitigation purposes though, we need to know the conditions leading to the onset of TTS and PTS. Examination of the data (Figure 2) suggests equivalent 8 hr dosages of 75 and 95 dB above threshold for the onset of TTS and PTS in fish and human beings. Similarly, the DRC is used to extrapolate these findings to shorter durations. This is illustrated in Figure 2 by the solid trend lines ±10 dB either side of the 85 dB TTS line. Use of the DRC requires us to distinguish between sounds that are 'continuous' and those that are 'intermittent' (but not impulsive), as shown in Figure 2. We also note that the DRC are essentially frequency independent, being the averaged response of large numbers of humans over a wide range of frequencies. Individual experiments show that the onset of TTS and PTS are in fact frequency dependent but that the DRC provides a useful estimate of the lowest values at which TTS or PTS first occur across a range of durations of sound exposure. (Extrapolation from air to water and between dB reference units is possible because SPL-GTV (dB) in (1) is a pure ratio and therefore dimensionless.)

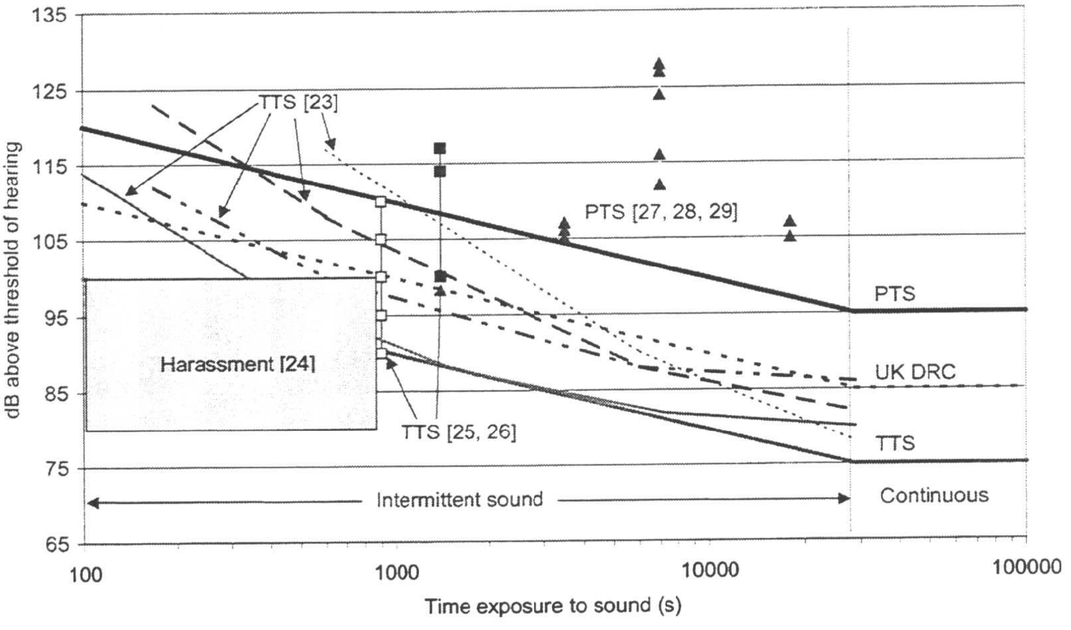

Figure 2: Effects associated with hearing impacts in the time domain

In summary, therefore, human DRC have been used to establish a trend (3 dB increase per halving of exposure duration) with a TTS dosage limit of 85 dB above threshold for 8 hrs exposure. Experimental data have then been used to set ±10 dB limits about this, giving equivalent 8 hr dosage limits for the onset of TTS and PTS of 75 dB and 95 dB above the threshold at the frequency of concern (see Figure 1).

To calculate stand-off ranges for the purposes of mitigation, it is necessary to compute the TTS and PTS dosages given by Equation (3) and Figure 2, and then to estimate the distances at which these effects may occur from a sound source. According to the source level (SL) and sound propagation conditions, this may be accomplished using simple geometrical spreading laws or computer based acoustic propagation models, as noted previously. While there are plenty of models from which to choose [30], it is important that an appropriate modelling technique is used [31] and that conditions are not over-simplified.

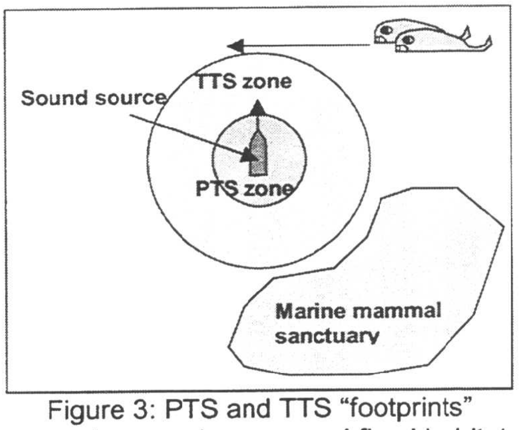

Figure 3: PTS and TTS "footprints" around a sound source and fixed habitat

Figure 3 and Table 3 illustrate the use of these arguments to determine the 'acoustic footprint' or 'zones of influence' associated with a particular acoustic device. These results illustrate the importance of duration or cumulative sound exposure in controlling the overall spatial scale of any adverse acoustic effect, while clearly the choice of impact criteria (e.g. TTS or PTS) will determine the nature of any adverse effect. Figure 3 also illustrates the difficulty of determining acoustic impacts when the sound source and receptor are moving relative to one another.

The stand-off distances given in Table 3 indicate stand-off distances to given impact criteria for associated cumulative exposures to sound of given frequency and received level. Rather than using complex acoustic propagation models, the PTS stand-off distances were generated using a spherical spreading (20 log R) argument with associated absorption as this approach has been found to be particularly applicable for very short ranges. Similarly, for the longer range TTS stand-off distances, a 15 log R argument with absorption was used as this models with reasonable accuracy, the propagation loss expected over many continental shelf environments [11]. In the examples illustrated in Table 3, it will be seen that the stand-off distances increase with increasing duration, frequency and source level. For a source level of 180 dB re 1 μPa at 1 m, (typical of an underwater telephone – see Table 2), the limit of the PTS zone increases from 0.3 m to 1.1 m as the duration increases from 60 s to 600 s at a frequency of 1 kHz. At 4 kHz, there is a similar increase in stand-off to the PTS impact criterion from 1.7 m to 5.4 m. The TTS stand-off distance increases from 5.3 m to 202 m over the same range of durations and frequencies. For a source level of 230 dB re 1 μPa at 1 m (typical of a military sonar – see Table 2), the PTS stand-off distance varies from 110 m at a duration of 60 s and a frequency of 1 kHz to 1.7 km at 600 s exposure duration and 4 kHz. Similarly, the TTS stand-off distance varies from 10 km to 56 km.

		1000 Hz		4000 Hz	
Cumulative Exposure		60 s	600 s	60 s	600 s
SL=180 dB re 1 μPa at 1 m	PTS	0.3 m	1.1 m	1.7 m	5.4 m
	TTS	5.3 m	25 m	43 m	202 m
SL=230 dB re 1 μPa at 1 m	PTS	110 m	354 m	532 m	1.7 km
	TTS	10 km	37 km	30 km	56 km

Table 3: Stand-off ranges for impact criteria as a function of source level, cumulative exposure and frequency

The dimensions of these zones may be used for the purposes of developing a suitable monitoring strategy (e.g. visual observers plus passive acoustic monitoring techniques) to detect for the presence (say) of cetaceans in advance of a moving acoustic source (e.g. a seismic survey ship). Additionally, the dimensions of these zones may be used as the basis of mitigation measures to protect fixed locations such as designated breeding grounds, marine nature reserves, Special Areas of Conservation (SACs). In this case the distance to the edge of the TTS zone might give the stand-off range and closest point of approach for an activity entailing prolonged exposure to high intensity underwater sound.

The method described by the authors exploits a 'generic audiogram' or threshold of hearing curve (GTV in Figure 1) in an approach that would be regarded as precautionary for a majority of species. That is, it might reasonably be expected to take into account those animals for whose hearing is most acute at the frequency of interest (noting that this might turn out to be humans). In the event that it is known which animals are present in an area, the mitigation may be designed around an individual animal's audiogram, leading, possibly, to some relaxation of the more stringent measures arising from the use of the generic approach. The important point is that the method proposed by the authors has the flexibility to take either approach.

Mitigation measures are required to reduce environmental risk to manageable levels. For sound sources that are controllable such as ocean research sonars, it may be possible to limit exposure by reducing source levels or stopping emissions altogether if monitoring activities indicate the presence of e.g. whales or dolphins. The stand-off ranges to any given impact criterion indicate the extent of the areas over which monitoring should take place. This paper has also demonstrated the importance of sound exposure duration in controlling the spatial extent of potentially adverse effects. So in situations where it is not possible to reduce the source level, acoustic emissions should be 'managed' by controlling duration and using the exposure arguments described above. To be truly effective, however, mitigation should begin well in advance of any activity and include "water space" management techniques to identify sensitive areas or habitats. To that end, every effort should be made to ensure that sound emission activities with the potential to cause harm or disturbance in the marine environment are kept well away from sensitive areas.

The principal aim of the work described in this paper has been the development of mitigation measures that are applicable to a range of environments and underwater sound sources and yet which offer a reasonably precautionary approach to assessing the likely adverse effects of underwater sound on marine life and human beings. A methodology has been proposed that should be capable of extension and refinement with the results of research undertaken elsewhere.

7. CONCLUSIONS

For the purposes of assessing the adverse environmental effects that may be associated with purposeful underwater sound transmissions or other sources of anthropogenic noise (where the levels are unknown), and on the basis of the available scientific evidence, it is concluded that a reasonable approach might be based upon:

(a) the use of a generic threshold curve to alleviate species dependency and deal with frequency dependency;

(b) the use of a suitable Damage Risk Criterion (DRC) to deal with intensity and duration aspects of underwater sound transmissions;

(c) the use of stand-off distances to delineate areas or exclusion zones, in which sound sources should not be used, along with cordons around the sound source where monitoring and mitigation strategies should be applied.

8. RECOMMENDATIONS

Although a great deal of progress has been made towards understanding the effects of noise on marine life, there are still gaps in the available knowledge. To highlight a few: the audiology of baleen whales has yet to be determined, conclusions from behavioural studies are often contradictory and resonance effects on body organs may be important [32]. In addition, the long-term impact of noise remains largely unknown. Work is needed on all of these topics. Additionally more research is required to establish the efficacy of visual and acoustic monitoring strategies that are being put in place to support marine mammal mitigation measures. Only when these and many other issues have been fully addressed can it be said that man is being truly precautionary in the use of sound underwater.

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