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UNDERSTANDING THE IMPACT OF SONARS ON THE MARINE ENVIRONMENT

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1. INTRODUCTION

The role of underwater sound as a potential stressor in the marine environment is now widely recognised [1] and the designers of sonars find themselves increasingly constrained by environmental legislation which requires them to consider the possible harmful effects of high power sound transmissions on marine life (e.g. fish and marine mammals) and on human beings. This paper describes a formal process of environmental impact assessment being developed by the Defence Evaluation and Research Agency (DERA) in support of the procurement of military sonars. The process is generic (no mention will be made of specific sonar types) and applicable at all stages, from research and development, through procurement and into operational use.

Traditionally, sonar design engineers have been more concerned about the impact of the environment on their sonars than about the impact of the sonars on the environment. Although plankton, fish and sea mammals are all factors that would need to be taken into account when quantifying the performance of an operational sonar (e.g. scattering layers and volume reverberation, biological sounds and false targets), the impact of sound energy on marine organisms and the likelihood of any possible harmful effects is not something that would have normally concerned the sonar engineer in the past. However, new environmental legislation means that these factors can no longer be ignored. Three developments in particular are important. These are (a) the awareness that *sound energy constitutes a form of pollution*, (b) the emergence in environmental legislation of the *precautionary principle* and (c) the obligation within legal rights frameworks of a *duty of care*. The latter is particularly important as it puts the onus on the polluter to prove that their particular action will not have an adverse environmental effect.

To meet MoD environmental strategy requirements [2], DERA has developed an Environmental Auditing Process Model (EAPM) which embodies the above principles and which applies scientific and technical reasoning in a tiered management process, the outcome of which would be to ensure that design of a sonar (including its operational use) can, where practicable, be made compliant with the needs of environmental legislation. The main purpose of this paper will be to consider the complex scientific and technical issues surrounding environmental impact assessment for sonar systems and in particular the reliability of the `cause and effect' modelling which is implicit in the environmental auditing process. Sonars may produce both energy and substance pollution (e.g. explosives may release toxic compounds) which, potentially at least, could have an adverse effect on marine life. But how are environmental impact criteria defined?

How certain is the evidence? Toxic effects are relatively easy to test for and to quantify. Sound energy on the other hand is pervasive and it is difficult to determine its effect on a large marine animal swimming freely in the ocean. Consideration of the hearing sensitivity of fish, for example, leads to the notion of safe exposure level and probability of avoidance. But how representative are the experiments on which these criteria are based? How can we assess the reliability of the overall environmental impact assessment process given the uncertainties in the individual processes, e.g. poor or inadequate knowledge of sound propagation characteristics (including non-linear effects associated with impulsive sound sources), uncertainty in environmental conditions, natural variability and the cumulative effects of repeated exposure to sound energy transmissions? There have been few coincident measurements of sound intensity in the ocean at the ranges at which a particular species exhibits avoidance behaviour and many studies make simplifying assumptions regarding acoustic propagation, e.g. spherical spreading out to unrealistically long ranges. These and other issues will be reviewed with example calculations to illustrate particular aspects of the environmental assessment process which is being developed by the authors.

2. AN ENVIRONMENTAL AUDITING PROCESS MODEL (EAPM) FOR ASSESSING THE POTENTIAL IMPACT OF SONARS

2.1 Environmental Auditing Process Model (EAPM)

Formal assessment of the potential impact of a sonar on the marine environment requires that we have some process or methodology for determining what those impacts are and - importantly - for recording any actions or decisions regarding the use of the sonar. This should apply at all stages in the acquisition of a new system, from research and development, through feasibility studies and trials into procurement and even into operational use of the equipment. Having a means of recording actions and decisions could be useful in the event that the assessment is challenged by an external authority or results in a legal dispute. Equally as important as assessing impacts, is the means of devising an effective monitoring strategy to accompany trials and operational use of a sonar so as to mitigate risk and reduce the likelihood of harmful effects. In response to MoD requirements [2] and European as well as international environmental protection policy directives, DERA has developed a tiered Environmental Auditing Process Model (EAPM).

2.1.1 A Phased Approach to Assessing Environmental Impacts. The EAPM, which is shown schematically in Figure 1, is currently undergoing evaluation by environmental policy and maritime law experts to ensure its compliance with civil and military needs. The environmental auditing process can be broken down into three stages which in turn scope, assess and state the nature of a potentially harmful impact along with any proposed actions to mitigate risks. The output from each of these stages is a formal document *viz.* from tier 1, an Environmental Scoping Study (ESS); from tier 2, an Environmental Assessment (EA) and from tier 3, an Environmental Statement (ES). The latter may appear in the public domain and is an important statement on the extent of consultation and discussion with external groups, a process from which military authorities are not necessarily immune.

Taking each of these stages in turn, the ESS is largely a qualitative process the aim of which is to determine whether there is likely to be an environmental impact. The ESS may conclude that

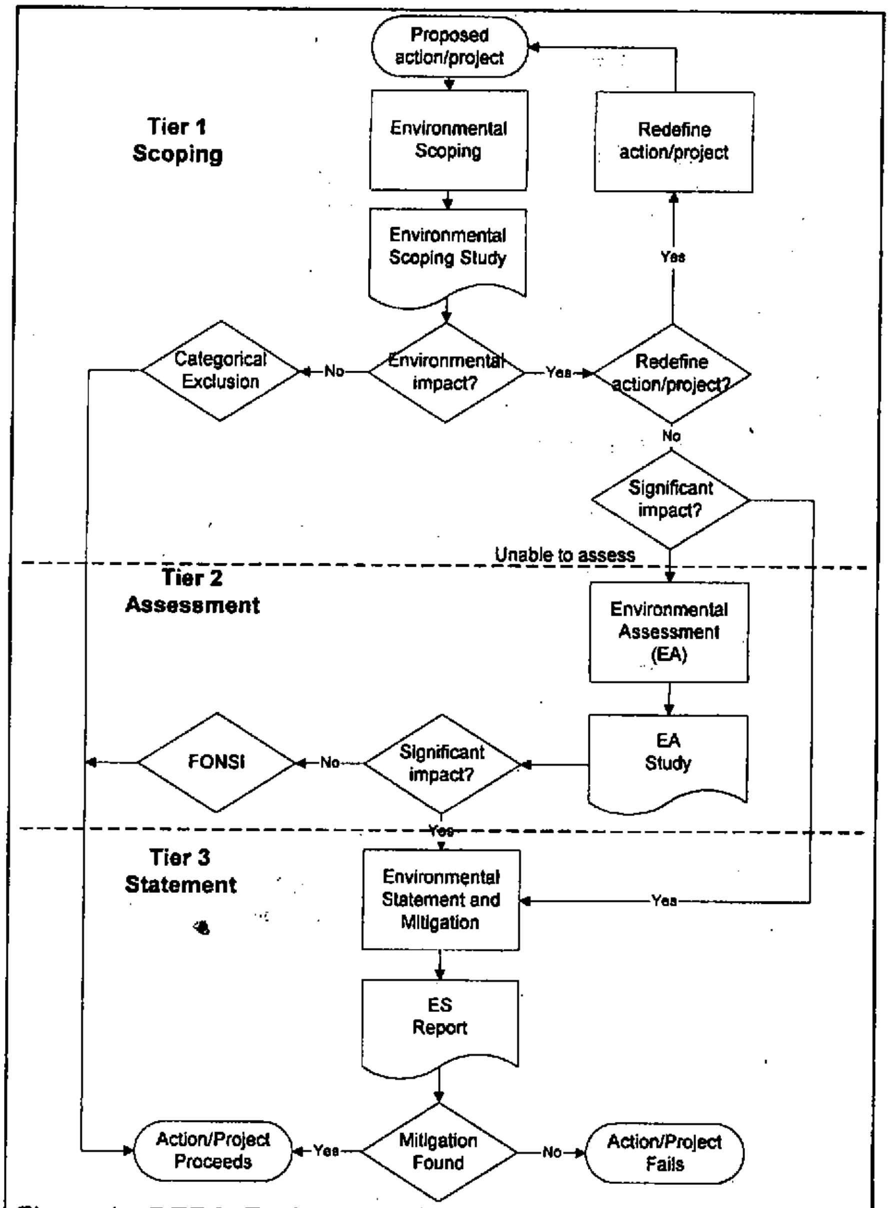

Figure 1 DERA Environmental Auditing Process Model (EAPM) which has been developed to support procurement of future sonars.

there is none, in which case a Categorical Exclusion (CE) would be issued. Alternatively, it may be decided that there is an impact but by redefining the project or action this can be reduced. If this is not possible, the EAPM asks the question, is the impact significant? If the answer is 'yes' the process skips tier 2 and proceeds directly to tier 3, the ES. If it is not obvious that there is an impact or we are unable to decide on the basis of current evidence, the EAPM proceeds to tier 2, where a full environmental assessment would be undertaken. This may eventually find that there is no significant impact (FONSI) in which case the action or project may proceed. Throughout the EAPM, the assessment is with respect to the knowledge available at the time; if there is insufficient knowledge or if more research is required to determine the nature of impacts, then the process should proceed to the next stage.

2.1.2 An Environmental Impact Matrix. The output from the ESS is recorded in the form of an environmental Impact Matrix (IM). This is based on procedures devised by the UK Department of the Environment (DOE) for risk assessment and management in support of environmental protection. For a full assessment, the range of environmental factors that would need to be considered would include socio-economic aspects as well as the physical and biological impacts of the project (e.g. impact on business, leisure and tourism, plus interference with other research programmes). In this paper we shall be concerned principally with the impacts on marine life and human beings. The approach adopted by DERA is an environmental receptor based approach - i.e. it focuses on the impact on the receptor at whatever range and under whatever conditions may be sufficient to cause a 'significant' environmental impact. The question of significance is dealt with later.

Completion of the IM for the purposes of an ESS would need to consider both substance and energy pollution. At this stage of the environmental auditing process, the precise nature of the sound source might not be known. For example the operating characteristics of the sonar (e.g. its frequency, source level, waveform, pulse length and duty cycle) may still be the subject of research. It might, however, be possible to estimate the source level from information regarding the expected detection range of the sonar, the environments in which it is required to operate and the nature of the targets it is expected to detect.

In the DERA EAPM, the impacts are categorised into five groups. These are:

(a) PEI Positive Environmental Impact - Action/Project has (or will have) a positive or beneficial impact on an environmental receptor.
(b) NEI Negative Environmental Impact - Action/Project has (or will have) a negative or harmful impact on an environmental receptor.
(c) NI No Impact - Action/Project has (or will have) no impact on this environmental receptor.
(d) NA Not Applicable.
(e) UA Unable to Assess - Unable to assess if the Project/Action has (or will have) an environmental impact based on the evidence available.

Initial scoping of the impact of a sonar might also be by reference to previous assessments for other or similar sonar devices or activities releasing acoustic energy into the environment (e.g. shock testing). A number of these are currently in the public domain including the USA Acoustic Thermometry of Ocean Climate (ATOC) Project [3]; the US Navy's SEAWOLF submarine programme [4] and the US Navy's Surveillance Towed Array System (SURTASS) [5].

2.2 Environmental Scoping Criteria
Broadly speaking and following environmental auditing processes elsewhere, the DERA model considers the environmental consequences of a sonar in terms of its effects on (a) the physical environment, (b) the biological environment and (c) the socio-economic environment (including man). Other impacts may be assessed including those due to hazardous waste and toxic materials. This would be important if explosives were being used as a possible source of acoustic energy. Of relevance to this paper, we will be particularly concerned with the potential impact of sound on the biological environment including fish and sea mammals. Following OECD [6]

guidelines, the range of factors (or questions) that would need to be addressed might include; the expected intensity of the impact, its scale and duration, the likelihood of any cumulative and/or irreversible effects; the extent to which the effects are politically controversial; infringement of laws, conventions, regulations or directives; social and economic implications including consideration of alternatives which may avoid environmental damage (see tier 1 of EAPM, Figure 1).

2.3 Significance of Impact

A key issue in any environmental auditing process, be it in the early stages of the environmental scoping study, during the actual assessment or even preparation of an environmental impact statement, is the question of what constitutes a significant adverse environmental impact? In the USA where environmental legislation is more prescriptive than that in Europe, a project or action is considered to have an adverse effect on biological resources if it...`Substantially affects a rare or endangered species of animal or plant or the habitat of the species; Interferes substantially with the movement of any resident or migratory fish or wildlife species; or substantially diminishes habitat for fish, wildlife or plants` [3].

A complete audit of the likely environmental consequences of the use of a sonar device in the ocean would need to consider each of these issues in turn, taking into account known species distributions and the available scientific evidence concerning acoustic impacts. These are discussed later but in the case of a new sonar, if it can reasonably be anticipated that use of the device will result in direct auditory injury or a permanent shift in the threshold of hearing of any individual of a rare or endangered species or any significant population of another species, then it should be considered as having a significant impact. Temporary threshold shifts, behavioural and masking (see later) would be considered significant if they resulted in any of the effects above.

3. THE ENVIRONMENTS

3.1 Physical, Biological and Socio-economic Environments

As a precursor to determining the likely impact of a future sonar device, it is necessary to examine the environment in which it may operate from the point of view of what is there already - to provide a baseline for future assessments. Knowing the state of the environment prior to an impact and also the effect of the environment itself on that impact, is an important step in performing an environmental assessment. A proper description of the environment is important in two respects; first, the environment itself constitutes or contains the environmental receptors on which a project or action may potentially impact and second, it is necessary to be able to describe and understand the role of that environment in determining the scale, intensity and significance of the impact on an environmental receptor within it.

Following practice elsewhere [3] and as noted previously (see 2.2), it is usual to consider three categories of environment (pre- and post- impact), namely physical, biological and socio-economic. This range of environments contains all of the environmental receptors and factors described previously and is sufficiently broad to enable discussion of the full range of potential impacts. Here we are concerned with the physical and biological environments. However, for completeness we briefly assess the type of data and information that would be required in performing a full EA and in preparing an ES.

UNDERSTANDING THE IMPACT

3.1.1 The Physical Environment. This would need to include a rigorous assessment of the general physical characteristics of the areas or regions in which the sonar was likely to be operated including bathymetry, coastlines, locations of territorial waters limits, exclusive economic zones (EEZs), locations of fishing grounds, fish spawning areas, sensitive environmental habitats, marine sanctuaries, fish and whale migration pathways and other features comprising the air/land/water domain. The general and local meteorology would also be required for each area to describe seasonal and climatic effects and the role of atmospheric forcing on the physical oceanography, water column properties and biological processes, including information on precipitation, wind speed etc. (as input to background and ambient noise calculations). Also needed would be the physical oceanography for regions to include quantitative and descriptive information on ocean circulation, coastal currents, tides, surface and internal waves, turbulence for estimation of ambient noise conditions and the effects of variability in acoustic propagation. Water column characteristics would be needed for properties that have the potential to affect sound propagation either directly or indirectly, or which may have an influence on the distribution of environmental receptors (e.g. dissolved oxygen levels and distribution of fish, zooplankton). This would include in particular the variations of temperature and salinity with depth (as these affect sound speed) and known ambient noise levels. It would also be necessary to know general geology, seabed characteristics and sediment properties, which in conjunction with the bathymetry would be important in determining acoustic propagation losses and received sound pressure levels (SPL).

3.1.2 The Biological Environment. This would need to describe the distribution and occurrence of potentially impacted species (flora and fauna), including threatened and endangered species and the locations of breeding grounds and migration pathways. In most cases, where underwater acoustic systems are concerned, these will be marine environmental species (e.g. fish, sea mammals), extending possibly to seabirds and marine flora. It is beyond the scope of this paper to consider all of these issues in detail. However, it is likely that the following categories of environmental receptor would need to be considered in the design of a future military sonar system. Where information on a particular species was missing or inadequate this would be reflected in an increased need for mitigation and monitoring to reduce risk. Following the experience with ATOC [3] and SURTASS [5], biological environmental categories might include marine mammals (mysticetes, odontocetes and pinnipeds, fissipeds), e.g. baleen whales, toothed whales, seals and sea otters; sea turtles; fish (demersal and pelagic); invertebrates including benthic fauna, demersal epifauna and pelagic invertebrates; plankton including phytoplankton, zooplankton and ichthyoplankton; seabirds; threatened, endangered and protected species; marine sanctuaries and sensitive underwater habitats.

3.1.3 The Socio-economic Environment (including Man). This would need to consider the potential socio-economic impacts of a sonar and would need to embrace all aspects of the use of the environment by man for social, business or leisure purposes. Topics in this category might include commercial fisheries, mariculture, shipping, mineral and hydrocarbon exploration, cultural and historical areas, recreational and tourist activities, research and education and even other military usage of the environment. Particularly important (although not the subject of this paper) would be the potential direct (i.e. physiological, behavioural) impacts on man (swimmers, divers) as well as any indirect impacts resulting from the proposed action.

4. LIKELY ENVIRONMENTAL CONSEQUENCES

4.1 Nature of the Impact

The potential impact of sound energy on marine animals (and humans) depends upon three factors; (a) the intensity of the sound at various subsurface locations; (b) the location of marine animals in relation to those locations and (c) the sensitivity of animals to the sounds to which they could be exposed. Current active sonar designs (which involve the use of impulsive as well as electromechanically actuated devices) span a range of frequencies that overlap with the hearing sensitivity ranges of fish and sea mammals. There have been exhaustive reviews of this subject (e.g. [1]) but in summary, the assessment of potential impacts would need to consider (a) death or injury, (b) direct damage to hearing receptors, (c) permanent and temporary shifts in hearing thresholds, (d) behavioural disruption and habituation, and (e) masking.

The majority of sonars are not expected to impact directly on the physical environment although those employing impulsive devices (e.g. explosives) could, in exceptional circumstance, destroy the habitat (e.g. cratering in seabed sediments, destruction of coral reef). The effects on the economic and social environment (the latter to include human beings) have been assessed elsewhere [3] in terms of the direct consequences on commercial fisheries, tourism and increased economic activity from research and development, plus production of sonar devices. Of particular concern with some sonars [4] has been the potential impact of low frequency sound on human beings leading to; (a) temporary changes in hearing sensitivity and threshold shifts; (b) resonances in air containing cavities including the heart, lungs and respiratory passages; (c) harmful effects on mechanoreceptor cell functions and (d) acoustic annoyance.

4.2 Expected Intensity of the Impact

This is concerned with the (acoustic) energy input to the water and will depend critically on the precise operating characteristics of the sonar. This information is usually classified. However, some idea can be obtained from information already in the public domain and in particular that for ATOC and SURTASS [3,5].

ATOC is a US civilian ocean-acoustic experiment using long range (3000 -10000 km) acoustic transmissions to measure climate change in the ocean. ATOC will employ a 195 dB sound source transmitting a 260 Watt digitally coded signal with a centre frequency of 75 Hz and a bandwidth of approximately 35 Hz from 57.5 Hz - 92.5 Hz. This range of frequencies is considerably lower than many active military sonar systems but still overlaps with the hearing sensitivity ranges of fish and some sea mammals.

SURTASS is a US military low frequency active sonar (LFAS) design. The source consists of a vertical line array (VLA) with 18 transducers in a depth range 60-180 m below the sea surface. The broadband source level is variable and selectable to achieve a desired received level at a given location. The source frequency is adjustable between 100-500 Hz with available bandwidth per signal of up to 100 Hz. A variety of signal types is transmitted including continuous wave (CW) and hyperbolic frequency modulated sweeps. The length of any continuous sound transmission is <50 s with various inter-sound transmission intervals such that the total duration of a sound transmission sequence is 100 s. The precise details of the SURTASS source levels are not known but of relevance to this paper, the experiments that are being conducted to study the impact of LFAS transmissions are designed to ensure that the received SPLs for an individual species do not exceed 160 dB re. 1μPa. Furthermore, 'soft start' procedures are being used to reduce the likelihood of a marine mammal being exposed to a level $\geq$ 180 dB re. 1μPa if it were very close (i.e. <100 m) to the SURTASS source. LFAS trials in the USA (to devise monitoring strategies) have established those sound pressure levels which have progressively more effect on marine mammals. These correspond to (a) a 'field of awareness' criteria at 120 dB re. 1μPa, (b) a 'field of modified behaviour' at 140 dB re. 1μPa and (c) a 'field of potential impact' at 160 dB re. 1μPa.

An assessment of any sonar which is based on the 'precautionary principle' suggests that the 'safe working range' or 'stand off distance' should be that range at which the received sound pressure level is reduced at least, to the lowest of these levels, giving a field of awareness criteria, taking into account the actual acoustic propagation conditions. For fish, Hastings [7] has proposed a 'safe' exposure level of 150 dB re. 1μPa for low frequency (<2 kHz) pure tone bursts. In the case of divers, previous DERA research suggests that received SPLs should not exceed 145 dB re. 1μPa, applying these criteria. These intensity criteria will be used later in examining acoustic propagation conditions.

4.3 Likely scale of the impact

This relates to the geographical area or volume extent of an impact plus the range and diversity of potential environmental receptors. New low frequency active sonars are being designed that will give detection ranges of several tens of kilometres and sound pressure levels that are still above the threshold of hearing for fish and mammals at distances well beyond this. These sonars are therefore capable, potentially at least, of influencing marine life over a significant volume of the ocean, particularly in view of the fact that the sonars move through the environment. The scale of the impact of a sonar should also be judged from the range and diversity of the environmental receptors upon which it may potentially influence. Particular account should be taken of the involvement of one species in the food chain of another (for example an impact on a fish species could have a detrimental effect on seabirds). As noted above, previous environmental assessments have had to consider potential direct and indirect effects plus cumulative effects on marine mammals, including whales, porpoise, dolphins and seals; other marine species including sea turtles, fish, invertebrates, plankton, seabirds; threatened or endangered species; marine sanctuaries and special biological resource areas.

4.4 Duration of Impact

The duration of any negative environmental impact which may be attributed to a sonar, ranges from the relatively short term effects associated with periods of operational use to latent and possibly longer term behavioural responses which may impact on breeding, on predator-prey relations and on fish and whale migration. In some cases the impact may be so severe as to cause death or injury. Linked to the operational use of the sonar and in particular its duty cycle, temporary or permanent threshold shifts may occur in the hearing sensitivity of some marine animals. The intensity of the sonar and the frequency with which it is used will also determine the extent to which some marine species may 'habituate'. Habituation has been described [3] as '...the development of reduced response when there is repeated or continuous exposure to a stimulus and when the stimulus is not accompanied by anything that the animal "perceives" as threatening'. Animals are more likely to habituate to a sound with steady characteristics, than to a highly variable sound. Habituation is potentially harmful if it causes the animal to become unaware of a hazard or results in the animal being unable to detect vocalisations from its own or prey species.

4.5 Cumulative and Irreversible Effects

Within the context of US environmental legislation [3] cumulative impacts are defined as '..those resulting from the incremental effects of the proposed action when added to other past, present and reasonably foreseeable future actions, regardless of which agency or person undertakes them. Cumulative impacts can result from individually minor, but collectively significant, actions taking place over time.` It is unlikely that all of these effects could be addressed during an environmental scoping study because of the need for precise information on the operating characteristics of a sonar. It is more likely that they would be addressed at stage 2 of the EAPM as details of the prospective sonar emerge from the design team.

5. ENVIRONMENTAL MODELLING

5.1 Cause and Effect Modelling

The EAPM discussed previously involves as many as 3 separate 'models' in a process of 'cause and effect' modelling. These are illustrated in Figure 2 and include the modelling of the sonar signal, its propagation through the environment and its subsequent impact upon a receptor within that environment (e.g. fish, mammal, human being). The accuracy of these models and the data that are input to them will in large measure determine the overall level of confidence in the findings of the EA and establish the need for any subsequent monitoring to mitigate risks (i.e. the less certain we are, the more we need to monitor). The model of the sonar itself may be the least of our worries and it should be possible to accurately determine the energy and frequency content of the acoustic signal from the sonar design parameters (e.g. power, directional characteristics). Of more concern will be the environmental models and the modelling of acoustic impacts. In the following section we pay particular attention to the acoustic modelling component of the EAPM in Figure 1.

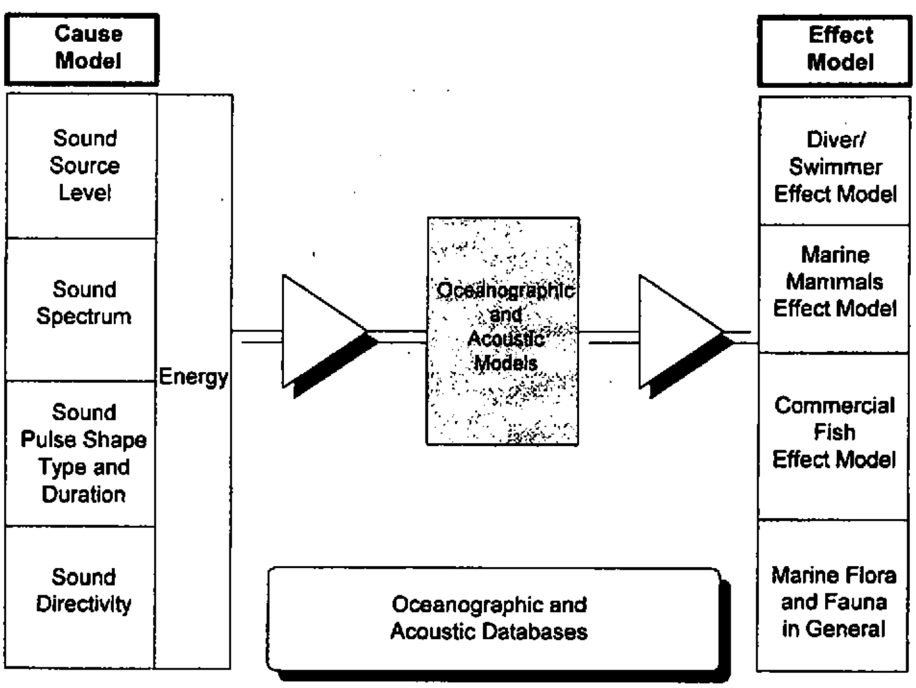

Figure 2 Schematic diagram to illustrate various components (models, databases) required in 'cause and effect' modelling studies.

5.1.1 Acoustic Modelling. The range of acoustic models which may be brought to bear on an environmental impact assessment is quite considerable and each may have its place at different stages in the environmental auditing process shown in Figure 1. Richardson [1] provides a useful review of sound propagation and acoustic models in the context of marine mammals and noise while more detailed and specialised treatments of this subject can be found in Etter [8] and Jensen et al [9]. Models may range from simple analytical expressions (e.g. spreading laws) to sophisticated computer codes describing surface and boundary losses, volume attenuation, scattering, reverberation and refraction through the water column and within sediments. It is important however, to recognise the limitations of these models and to use them accordingly.

For example, simple spreading laws and an assumption regarding frequency dependent attenuation and scattering could be used to estimate the range or distance at which the sound pressure level corresponding to a particular sound source has fallen below some predetermined threshold (e.g. the 120 dB re. 1μPa `field of awareness criteria` given above). At low frequencies it may be possible to neglect attenuation and scattering and to consider spreading losses only. For example, the longest range (R_{max}) in metres at which a sonar might affect fish could be estimated from the expression

$$R_{max} = 10^{((SL - T)/20)} \qquad (1)$$

where SL is the source level, T is the threshold SPL of the particular effect and might in this case be set to 150 dB re. 1μPa, the Hastings [7] 'safe' exposure level for fish for low frequencies (<2 kHz). Alternatively, for sea mammals, a 120 dB re. 1μPa threshold SPL might be used. In this case, the SPL decay is given by spherical spreading. In very shallow water or ducts, cylindrical spreading might apply. In general, the received SPL may decay as N log R where R is the range and N might have values of 10, 15, 20, 25, 35 and 40 according to the relation of the source depth and acoustic wavelength (λ) to water depth (H). In addition then to cylindrical spreading (N=10) in very shallow water (or ducts), and spherical spreading (N=20) in deep water, N=15 might apply at intermediate depths ($H/\lambda > 5$) and N=25, 35 and 40 correspond to deep or shallow water situations where the sound source and/or receiver are within ¼ λ of the surface. As noted previously, to these terms would need to be added any frequency dependent attenuation and diffraction effects [1, 8].

To model accurately sound propagation requires models that are site specific and which describe exactly the conditions in a particular area. This would require all of the environmental data at 3.1.1 to be assembled to describe precise water depths (bathymetry), temperature and (possibly) geoacoustic properties. Dependent upon frequency and the precise operating characteristics of the sonar, models may include range-dependent ray theory treatments and full wave equation models, or range-independent normal mode and fast field models. Etter [8] provides a useful review of the available models.

5.1.2 An Example. To illustrate the sensitivity of calculated SPL variations and consequently the range at which sound may impact on fish or mammals, we look at an example from the Malin Shelf west of the UK. In this scenario, the sound source is located in relatively shallow water at the top of the continental slope with water depths increasing from 180 m to 1500 m. As acoustic propagation loss is highly dependent on the variation of sound speed in water with respect to depth and also sediment types, representative summer and winter profiles were chosen as well as a seabed consisting of either high loss or low loss sediments overlying a consolidated rock basement. The seabed parameters are given in Table 1.

To illustrate the variations in received SPL in response to summer and winter variations in the temperature (hence sound speed) profiles, and acoustic bottom loss conditions, we have calculated the SPL's along a 100 km transect extending westward from the shelf break into the deeper water of the Rockall Trough region of the NE Atlantic. In this case SPL = (SL-TL) where SL is the sonar source level and TL the transmission loss. These calculations have been performed using a ray-trace model.

Table 1 Seabed parameters for low loss and high loss sediments

Seabed parameters	High loss	Low loss
Sediment sound speed (m/s)	1470	1650
Sediment density (kg/m^3)	1600	2000
Sediment curvature factor	-0.86	
Sediment gradient	5.0	
Sediment thickness (m)	100 m	
Sediment loss (dB/m/kHz)	0.15	
Basement reflection loss (dB/bounce)	10	
Minimum loss	1 dB	

Ray trace patterns (not shown) illustrate several important differences. In summer, surface heating effects (insolation) produce a very shallow surface duct (mixed layer) with a second layer in deep water lying between 100 m and 600 m depth. A small amount of energy is trapped in a region close to the seabed. In contrast, in the winter, wind mixing and convective cooling at the sea surface result in a deep mixed layer giving ducted propagation down to about 1000 m depth. The trapping of energy in these well defined layers has a profound effect on the received SPL at the range of an environmental receptor (fish or sea mammal). This is illustrated in Figures 3 and 4 and discussed in the following section.

6. DISCUSSION

6.1 Sound Propagation, Acoustic Threshold Criteria and Environmental Conditions

Figure 3 shows the SPL in dB re. 1µPa as a function of source-receiver separation in km at a receiver depth of 70 m for both summer and winter sound speed profiles, a frequency of 300 Hz, a source depth of 70 m and a high loss sediment. The source level (SL) for these calculations was 210 dB. These results show that for the winter conditions, the SPLs are higher than those in the summer (surface duct), with the differences generally increasing with range. The winter conditions produced a series of well defined convergence zones centred at ranges 45 km, 60 km, 73 km, and 87 km with the SPLs about 15 dB higher within the zones. By contrast, the summer conditions show a number of partial shadow zones most notably around ranges of 27 km, 45 km and 87 km where the SPLs decrease by as much as 40 dB in a zone up to 10 km wide. This figure also illustrates comparisons with both spherical (N=20) and cylindrical (N=10) spreading functions. For this location (propagation is from shallow into deep water), spherical spreading approximates the general trend of the calculated SPLs fairly well, although there are significant variations about this level (20-40 dB). Figure 4 provides a similar comparison for low loss bottom sediments which occur in the same area within a short distance of the transect used in Figure 3. The differences between summer and winter conditions are now less extreme and again follow a spherical spreading law assumption reasonably well. In terms of the ranges at which fish or marine mammals might respond to an acoustic stimuli, the

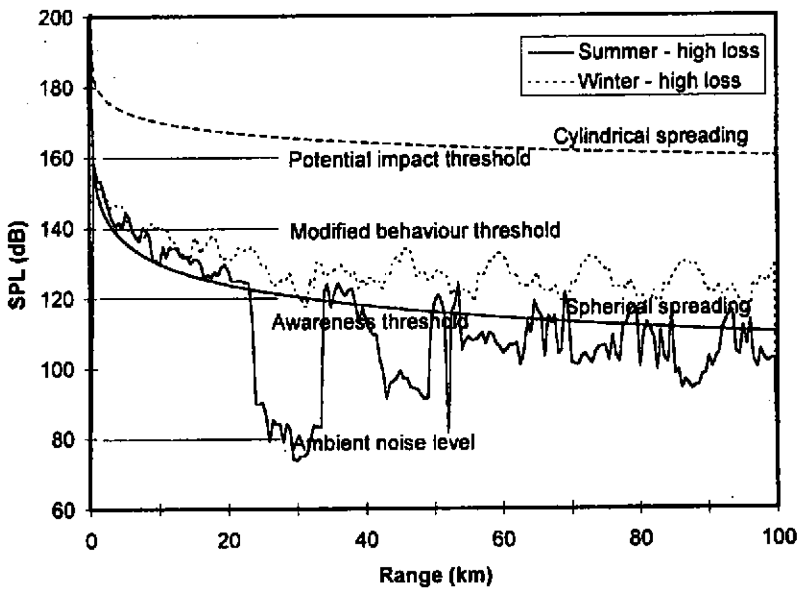

Figure 3 *Comparison of summer and winter conditions in Malin Shelf region west of UK for a high loss sediment. See 6.1 for explanation of figure.*

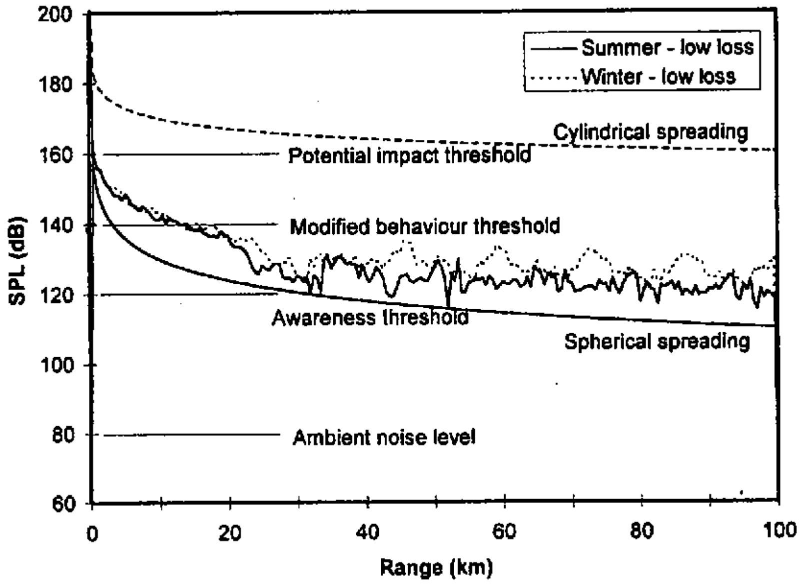

Figure 4 *Comparison of summer and winter conditions in Malin Shelf region west of UK for a low loss sediment. See 6.1 for explanation of figure.*

two sets of results illustrate some striking differences. Assuming T = 120 dB re. 1µPa, the 'field of awareness' threshold criteria, equation (1) would give R_{max} values of about 30 km whereas the computed SPL values for low loss bottom conditions (Figure 4) on the continental slope west of the UK might extend to 60 - 80 km. For a 'modified behaviour threshold' (T = 140 dB re. 1µPa), comparison of Figures 3 and 4 shows that while spherical spreading might do a reasonable job of estimating the range at which this impact occurs on a high loss bottom (i.e. approximately 5 km), it would underestimate the range on a low loss bottom for both summer and winter conditions by as much as a factor of 4 - 5. Therefore, summer and winter conditions on a low loss bottom (Figure 4) would introduce the greatest uncertainly in calculated safe working ranges relative to a simple spherical spreading law assumption. This small selection of results serves to illustrate the differences which may exist between simple spreading laws and the results obtained with more sophisticated acoustic models and realistic environmental data.

Even these results, however, may not be representative of actual conditions in the area at the time say of a trial or exercise involving the sonar. Atmospheric conditions and variability due to oceanographic processes (e.g. internal waves) would need to be taken into account and any uncertainty quantified during the EA undertaken in stage 2 of the model in Figure 1. Doubts about the precise conditions during anticipated sonar operations would need to be reflected in a more effective monitoring strategy and proposed with the Environmental Statement (ES) at stage 3. These findings illustrate the importance of having a detailed knowledge of environmental conditions in reaching a balanced view on the scale and intensity of any potentially harmful acoustic impacts. Uncertainty may exist elsewhere - for example in the hearing sensitivity threshold data for various species of fish or marine mammal - but every effort should be made to improve the confidence in the overall process of 'cause and effect' modelling which is illustrated in Figure 2. How the errors and uncertainties are compounded through the various stages of this process and how they are interpreted in the light of the 'precautionary principle' is not yet clear and is the subject of further research.

6.2 Environmental Auditing Process Model (EAPM)

One of the aims of this paper has been to outline the EAPM which is being developed by DERA to support future sonar research, development and procurement. This has been designed to identify and quantify potentially harmful acoustic impacts on marine life and on human beings. The EAPM is currently being tested and evaluated in the course of a number of major sonar procurements for the UK Ministry of Defence and in forthcoming operational exercises where it will be necessary to complete a formal environmental assessment. An important requirement will be to ensure that the EAPM methodology is robust and that it will meet the MoD environmental strategy requirements and the needs of international environmental protection policy.

7. CONCLUSIONS & RECOMMENDATIONS

This paper concludes that while it is possible to integrate models and databases into an EAPM of the type proposed above, the validity of any assessment regarding potentially harmful impacts on fish, sea mammals or humans will depend crucially on the accuracy and representativeness of the models and the data used in this process. In particular, there is a need for better and more accurate environmental models (physical and biological), more information on naturally occurring and man-made noise in the ocean and significantly more information regarding the reactions of fish and marine mammals to underwater sound.

Finally, advantage should be taken of recent developments in ocean observation and monitoring techniques (e.g. autonomous underwater vehicles, better oceanographic and acoustic sensors, remote sensing from aircraft and satellites) to improve the forecasting of environmental conditions and to provide more effective monitoring strategies to reduce the risk of potentially harmful impacts on sea mammals and on fish and fisheries during sonar operations.

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