THE DB_{HT}, A METHODOLOGY FOR ASSESSING THE BEHAVIOURAL EFFECTS OF UNDERWATER NOISE.

J. R. Nedwell, D. M. Howell.

Subacoustech Ltd, Chase Mill, Winchester Road, Bishop's Waltham, Hampshire SO32 1AH United Kingdom. subacoustech@subacoustech.com

1. INTRODUCTION.

With increasing exploitation and exploration of the coastal and deep sea, attention is increasingly being paid to the environmental effects that may result from the consequent man-made underwater noise. While the hazards associated with, for instance, the dispersal of toxic materials are now well understood, the understanding of the effects which may be associated with noise is in its infancy, despite its status as a significant underwater environmental issue. This results primarily from the lack of an objective scale which may be used to relate the observation of environmental effects to recorded levels of noise. The dB_{ht} scale discussed herein provides this necessary methodology, and may be used as the basis of a standard for interpreting the effects of underwater noise.

There are three categories of the effects of noise, which comprise

- Primary effects, where noise leads to immediate or delayed death,
- Secondary effects, where sub-lethal injury such as swimbladder rupture or deafness leads to increased mortality, and
- Tertiary or behavioural effects, where the noise alters the behaviour of the species, for instance causing avoidance of an area.

1.1 Non-auditory effects.

The primary effects of noise, typically caused by underwater blast, may be obvious, for instance when it causes floating dead fish. The symptoms of secondary effects may also be readily observed by dissection and observation of exposed individuals, which has facilitated the development of criteria for levels at which primary or secondary effects will occur. These effects only occur at high levels of sound, for instance typically within a few tens or hundreds of metres from underwater blast, and hence effect relatively small areas and numbers of individuals.

1.2 Auditory effects.

The auditory effects of sound comprise noise induced deafness and the tertiary or behavioural effects of underwater noise. Both of these are poorly understood, yet behavioural effects may have an influence over great ranges, often of kilometres or tens of kilometres, and hence on much larger numbers of individuals. High noise levels have been cited as having the potential to impede communication amongst groups of animals, drive them away from feeding or breeding grounds, cause strandings, or to deflect them from migration routes.

2. THE NEED FOR A PERCEPTION SCALE.

The behavioural effects of underwater noise are poorly understood. This partly results from the lack of a significant body of simultaneous measurements of noise level and environmental effect from which such understanding could be drawn. This in turn rests on the lack of a suitable scale for measuring noise, in a way that might be related to its environmental effects.

The work of Engas [1], for instance, is well accepted as demonstrating significant environmental effects caused by a seismic survey, but is compromised because no measurements were made of the level of sound from the survey. The effects of the survey were in this case related to an assumed level of sound from the source and an assumed rate of loss of sound with range; there is in addition no consideration of how the sound should be measured, with an implicit assumption that unweighted peak pressure levels are sufficient to evaluate the sound in terms of its potential for behavioural effects. This assumption is consequently often encountered in regulatory matters. For instance a simple limit such as 160 dB re 1 μPa is often specified as a limit for man made noise underwater, without consideration of the differing sensitivities and hearing ranges of species.

For instance, the loudest terrestrial animal call is the echolocation click of a bat; yet humans do not avoid such a sound, or find it deafening, because they are insensitive to the frequencies that bats transmit. A high level of such sound may therefore be tolerated by a human without any effect. Similar considerations pertain to marine mammals with hearing predominantly in the 10 kHz to 100 kHz frequency range, for whom an airgun with a sound spectrum peaking in the low hundreds of Hertz may be largely infrasonic. Similarly for fish, many of which hear only below a few hundred Hertz, a sonar system operating at a few kiloHertz may be ultrasonic.

These comments serve to underline the importance of measuring and objectively assessing sound on a scale that incorporates the ability of a species to perceive the sound, and hence to be influenced by it.

3. PERCEPTION SCALES.

We define the perception of sound as being its level above the hearing threshold of an animal, and which is consequently a measure of its ability to excite the hearing process of the animal. A perception scale for noise therefore incorporates the hearing sensitivity and frequency range of a species. Perception may differ from loudness, which we define as the subjective assessment of its level, and hence its ability to cause an effect. In general, we would suggest that the loudness sound is well correlated with its perceived level, and hence that a perception scale allows objective decisions about a species' subjective reaction to sound to be made, such as whether noise is likely to be inaudible or unbearably loud for that species.

3.1 The dB(A), or human perception scale.

We are familiar with the effects of noise on ourselves. The human ear is most sensitive to sound at frequencies of the order of 1 to 4 kHz, and hence these frequencies are of greatest importance in determining the physical and psychological effects of sound for humans. At lower or higher frequencies the ear is much less sensitive, and humans are hence more tolerant of these frequencies. To reflect the importance of this effect a scale of sound (the dB(A)) has been developed which allows for human frequency dependent hearing. In effect, rather than measuring the absolute level of noise, the dB(A) may be considered to measure its level *above the hearing threshold of a human.* A given sound has therefore to be of much higher level at high and low frequencies, than at peak hearing frequencies, to give the same dB(A) level.

The dB(A) measure of sound has been found to be well related to not only the behavioural effects of sound on humans, but also auditory injury. It greatly simplifies the judgement of the effects of sound on humans by allowing simple criteria such as "sound at 120 dB(A) is unbearably loud". The simplifying nature of such a scale should be noted; in this example there is no need to specify the nature of the source, for instance, as to whether it is from a machine tool or hifi system, or even of high or low frequency. The approach has also been extended to underwater human exposure to sound (where hearing ability differs greatly from that in air), yielding the dB(UW), which has allowed the effects of noise on submerged human divers to be estimated [2], [3].

3.2 The dB_{ht} (species) or generalised perception scale.

A generalisation of this approach was originally proposed as a result of concerns over the effects of noise from seismic exploration on the environment [4]. It incorporates the hearing ability of an animal into the scale to provide a generic perception scale which simplifies and improves estimates of the effects of noise on marine species, and allows biologically significant features of noise to be identified,

The measure of a species' ability to perceive sound is the audiogram. The hearing sensitivity of a species at various frequencies is represented by an audiogram such as those shown in figure 1, which presents the lowest level of sound, or threshold, at which a species can hear, as a function of frequency. It is usually determined by measuring behaviourally or electrophysiologically the threshold of hearing of the species. Audiograms have been determined experimentally for about 70 species of marine mammals and fish [5], although this is a small fraction of the number of species that are of conservational or commercial interest.

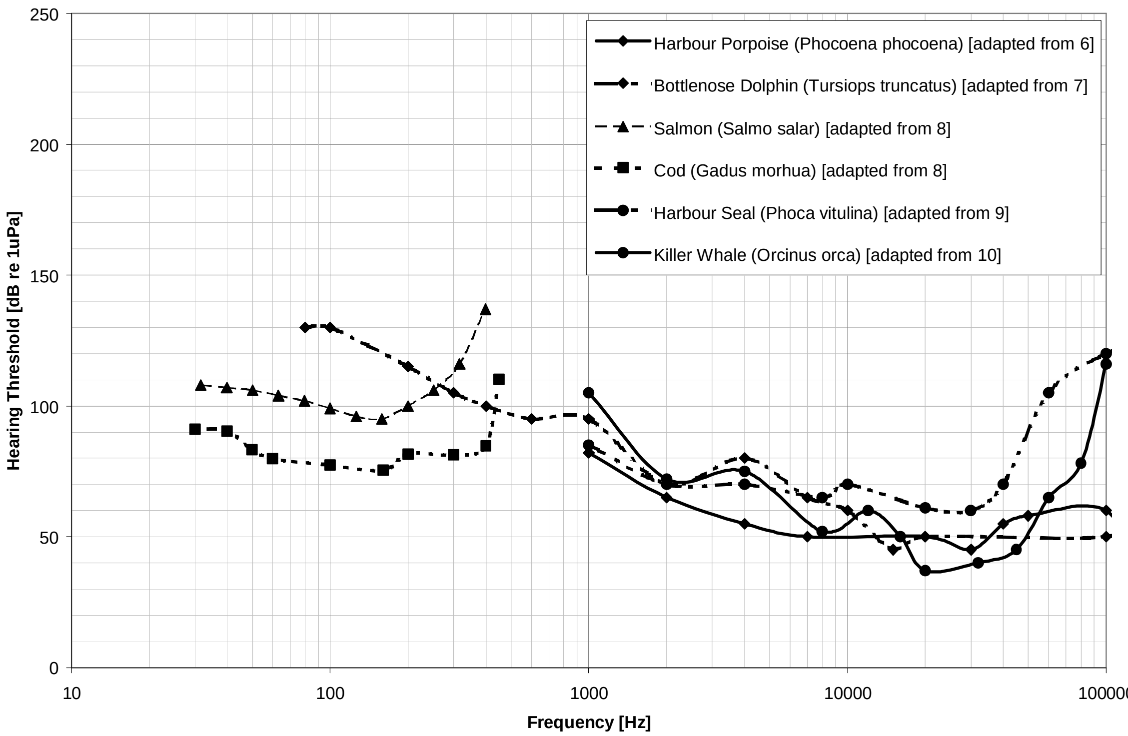

Figure 1. Marine mammal and fish audiograms.

The dB_{ht} (species) is a measure of how much a noise is greater than a species' threshold of hearing; Howell [11] discusses the means by which this quantity may be calculated. The subscript 'ht' relates to the fact that the sound is expressed in deciBels which are referenced to the hearing threshold of the species. The scale is consequently non-dimensional and may be thought of as a dB scale in which the species' hearing threshold is the reference. Because hearing varies from species to species, dB_{ht} values for a given noise source will be species specific and hence generally the specific name must be appended.

Noise measured in dB_{ht}(*species*) levels will usually be much lower than the unweighted levels for the same noise, both because the sound will contain frequency components that the species cannot detect, and also because most marine species have high thresholds of perception of (are relatively insensitive to) sound.

This approach has significant prospective advantages in estimating the behavioural effects of underwater sound. It can be applied equally well to both narrow band noise such as sonar transmissions, and wideband noise such as is caused by seismic airguns. It enables useful quantities such as the *effective* Source Level of a noise source and the *effective* Transmission Loss for it to be determined for a particular species. Finally, it lends itself to measurement schemes which could be used by non-expert users, such as an "underwater species specific sound level meter".

4. UNDERLYING HYPOTHESES.

The dB_{ht}(*species*) scale rests on seven underlying hypotheses, which enable general assessments of the significance of noise to be made. Where detailed assessments are required, the applicability of each hypothesis may need to be individually considered or tested.

Hypothesis 1: Loudness causes avoidance. *An animal exposed to a loud noise may exhibit an avoidance reaction. The behavioural effects of noise are chiefly caused by it being perceived by a species as "unbearably loud", and the species taking an evasive reaction, the strength of which is in proportion to the loudness of the sound.*

The reaction to noise is no different to that which would be taken when any stimulus reaches an unacceptable level, for instance in avoiding heat or bright light.

Hypothesis 2: Loudness related to perception. *Irrespective of the source type, the "loudness" of a sound and hence the effect of a sound on a species will tend to primarily be related to its perception, or level above the hearing threshold of the species.*

This means that two very different sources can be compared for a given species, for instance, if a fish reacts to an airgun at a given point on its dynamic range, it will react to say blast in the same way at the same level.

Hypothesis 3. Limits of dynamic range. *The dynamic range of hearing will be similar for well evolved animals, of perhaps 120 dB.*

The dynamic range of hearing is set by physical constraints, from displacements of molecular dimensions at the lower end to displacements that are large enough to cause damage to hearing processes at the upper end. An animal will evolve to use this dynamic range, but those living in a quiet environment may possess a high sensitivity to sound, associated with a low level at which avoidance will occur, and those in a noisy environment insensitivity to sound, associated with an high level at which avoidance will occur.

Hypothesis 4: Reaction related to position on dynamic range. *The effect of the sound will be mainly related to the amount above threshold, or position ion the dynamic scale, for any species, that is, on its "loudness" for that species.*

This means that the effect of any arbitrary source can be estimated by finding where it lies on the dynamic range. The strength of the reaction will depend where on the dynamic range it is; gentle avoidance of noise by a minority of individuals might start at 70 and an instinctive startle response to sudden noise at 110.

Hypothesis 5. Hearing damage: *Auditory injury caused by noise is simply related to the sound approaching the upper limit of the dynamic range.*

The avoidance of noise is consequently be considered to be simply an evolutionary response that protects hearing.

Hypothesis 6: Evolutionary considerations. *Reactions to noise must have evolved to occur towards the upper end of the species' dynamic range, since if they lay towards the lower end of the range the species would be in a perpetual state of panic or avoidance. Similarly, the lower end of the dynamic range must have evolved to be similar to the level of background noise in which the animal normally lives, in order that maximum use may be made of this available dynamic range.*

The level for a given effect such as avoidance is however likely to be lower in "nervous" species (for instance, the grazers) than in "bold" (predatory) species.

Hypothesis 7: Cognitive and instinctive reactions. *A reaction to noise can be both instinctive (a species swimming away from a loud sound) and cognitive (a species avoiding a sound because it sounds like a predator). Whereas strong instinctive reactions will be associated with loudness, a strong cognitive reaction may happen at any perceivable level of noise (from 0 dB_{ht} upwards) if the species believes it signifies a threat.*

Man-made noise is most likely to cause instinctive reactions linked to a sensation of loudness, since it is very unlikely that a man made noise will have the characteristics of a predator's noise.

It is not claimed that the dB_{ht}(*Species*) scale is perfect. It is, for instance, known that some types of sound have a slightly greater effect on humans than their level in dB(A) would imply, that is, that the perception of such noise is not the same as its loudness. It is however suggested that measurements made using this scale are likely to be much better related to behavioral effect than for instance simple peak pressure measurements, which embody an assumption that all species have equal hearing sensitivity over a frequency range of indefinite bandwidth.

5. DRILL SHIP NOISE: AN EXAMPLE.

Measurements were taken of the noise radiated during normal operations from the *West Navion* drill ship, while drilling in deep water west of the Hebrides, during May 2001.

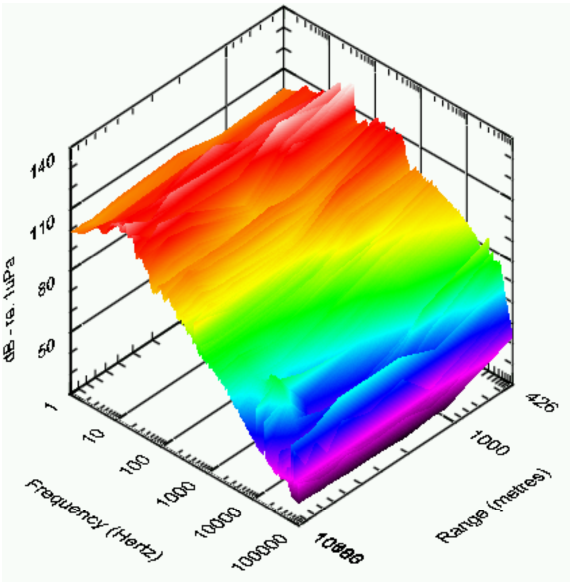

Figure 2. Narrow band power spectral level against range from the West Navion drill ship.

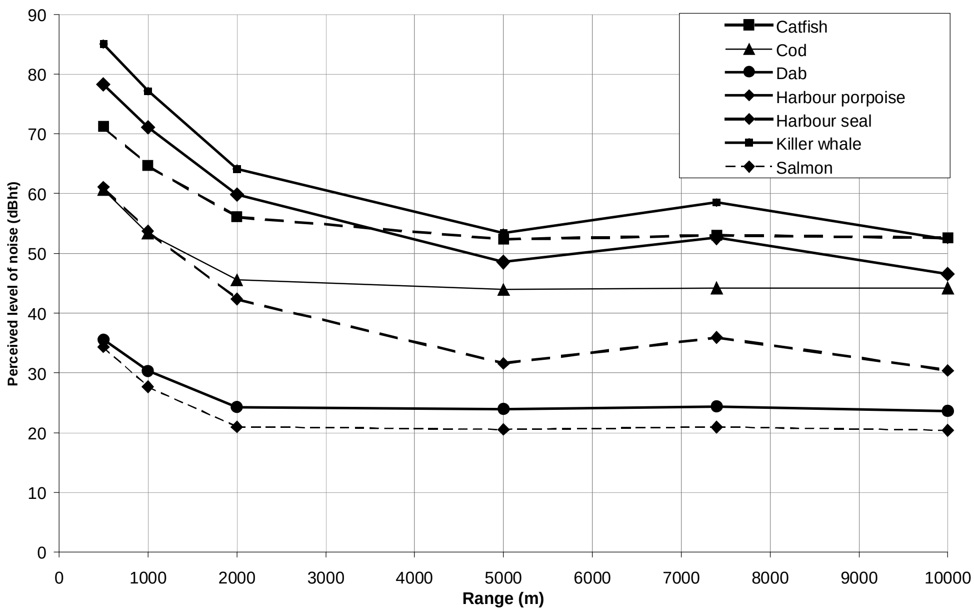

Figure 3. Marine mammal and fish dB_{ht} levels with range from the *West Navion* drill ship.

Figure 2 illustrates a typical result, which shows the dominance at short ranges of the noise source. In this case the spectrum of the sound measured at 50 metres depth is presented as a function of the range from the drill ship. The drill ship could be approximated as a broadband noise source in the range 100 Hz to 400 Hz, having a Source Level of about 195 dB re 1 μPa and a Transmission Loss modelled as 23 log R, where R is the range in metres.

Figure 3 illustrates the measured levels from the drill ship, but in this instance as dB_{ht}(*species*) levels. The levels are plotted for seven species of fish and marine as a function of the range from the drill ship.

It may be seen that the general form of the levels is fairly similar from species to species. Near to the source, at ranges of 500 metres to 2 kilometres, all of the dB_{ht}(*species*) levels show an increase, indicating that for all species there is a contribution to their perceived noise field from the drill ship noise. As the range increases the level settles down to a relatively constant value; this is the level of background noise in the perception scale of the species and it is reasonable to assume that there is little possibility of any environmental effect. This conclusion alone is a valuable conclusion of dB_{ht}(*Species*) analysis. It is also of interest to note that due to their sensitivity to the high frequency sound radiated from the drilling rig, the perceived levels for marine mammals are in general much higher than is the case for the fish species.

6. SUMMARY.

In summary, the dB_{ht}(*species*) scale incorporates the ability of a species to perceive noise, and hence to be influenced by it, and offers a means of objectively measuring noise, assessing its potential for behavioural effects, and identifying features of the noise that are of environmental significance.

REFERENCES.

[1] Engas, R, Lokkeborg, S and Soldal, A V. Effects of seismic shooting on catch availability of cod and haddock. Institute of Marine Research, Norway, Fisken og Havet, 9, 117pp.

[2] Nedwell, J R, Al-Masri, M and Martin, A. Underwater hearing thresholds and proposed noise exposure limits. Advances in underwater technology, ocean science and offshore engineering, Subtech '93, V 31. Kluwer Academic Publishers, PO Box 17, 3300 AA Dordrecht, The Netherlands

[3] Parvin S J and Nedwell J R. Underwater sound perception and the development of an underwater noise weighting scale. Journal of the Society for Underwater Technology V21 N1 1995.

[4] Nedwell, J R and Turnpenny A W H. The use of a generic weighted frequency scale in estimating environmental effect. Proceedings of the Workshop on Seismics and Marine Mammals, 23rd-25th June 1998, London. UK.

[5] Nedwell J R, Edwards B, Turnpenny A W H and Gordon J. Fish and Marine Mammal Audiograms: A summary of available information. Subacoustech Report to the DTI No 534 R 0213 June 2004. Subacoustech Ltd, Chase Mill, Winchester Road, Bishop's Waltham, Hampshire SO32 1AH United Kingdom.

[6] Andersen, S., Auditory sensitivity of the harbour porpoise Phocoena phocoena., Invest. Cetacea, vol. 2, pp. 255-259, 1970.

[7] Johnson, C., Sound detection thresholds in marine mammals., 1967, in: W.N. Tavolga (ed), Marine bio-acoustics, vol. 2. Pergamon, Oxford, UK.

[8] Hawkins, A.D., Myrberg, A. A. (jnr), Hearing and sound communication under water, 1983, In: Bioacoustics: a comparative approach. B. Lewis (ed.), pp. 347-405. Academic Press, New York.

[9] Møhl, B., Auditory sensitivity of the common seal in air and water., J. Aud. Res., vol. 8, no. 1, pp. 27-38, 1968.

[10] Szymanski, M.D., Bain, D.E., Kiehl, K, Pennington, S., Wong, S. & Henry, K.R. , Killer whale (Orcinus orca) hearing: Auditory brainstorm response and behavioral audiograms., J. Acous. Soc. Am., vol. 106, no. 2, pp. 1134-1141, 1999.

[11] Howell, D., Nedwell, J., A species specific sound level meter: calculating underwater noise levels above a species' hearing threshold., Proceedings of the Symposium on Underwater Biosonar Systems and Bioacoustics, Loughborough, Sep.2004. [In preparation]