Selection of 180 dB as the Upper Reference Point in the Risk Continuum for SURTASS LFA Sonar Signals

Marine mammals rely on hearing for a wide variety of critical functions. Exposure to sounds that permanently affect their hearing ability poses significant problems for the survival and reproduction of these animals. Many human activities generate loud underwater sounds, and there is an urgent need for methods of estimating potential risk. The quest for a quantitative assessment of risk potential is complicated by scarce data in two areas:

- Data regarding underwater hearing capabilities of marine mammals are rare and limited to a few of the smaller species that make convenient subjects in captivity.

- Hearing loss due to sound exposure is well studied in humans and other terrestrial animals, but data for marine animals are sparse.

These data gaps have prompted the use of various models and extrapolations, in order to provide a rational basis for the assessment of risk potential.

1.0 Hearing Sensitivity

Assessment of potential risk to a particular species must often begin with an estimate of the range of frequencies at which the animal hearing is most sensitive, and the associated thresholds. The range of sounds produced by a species is generally associated with ranges of good hearing sensitivity, but many species exhibit good hearing sensitivity well outside the frequency range of sounds they produce. Closely related species of similar body size, vocalization range and ecological habitat are often presumed to have similar hearing. Anatomical models of inner ear function have been used to extend the scope of limited audiometric data (Ketten, 1992, 1994, 1997, 1998). Ketten determined that the resonant properties of the basilar membrane provide clues to the probable range of animal hearing.

1.1 Critical Ratio

Alternatively, a general model that estimates lower bounds for hearing sensitivity can be sought. This approach assumes that the ambient noise of the environment, combined with general characteristics of vertebrate hearing, create a limit to best hearing sensitivity (Ellison, 1997). A variety of vertebrate studies have demonstrated that a pure tone can be heard against a background of white noise only when the power level of that tone is greater than the adjacent broadband power level of the noise.

This "critical ratio" is usually measured in decibels (dB re 1 Hz) and is defined by Richardson et al. (1995) as the "difference [ratio] between sound power level for a barely audible tone and the spectrum level of background noise at nearby frequencies." It is *closely* related to the "critical band," defined by Richardson et al. (1995) as the "frequency band within which background noise has strong effects on detection of a sound signal at a particular frequency." Or stated another way, measurement of the ability of the ear to act as a narrowband filter.

Critical ratios (CRs) have been measured for a variety of vertebrates. At best hearing, CR values range from 16 to 20 dB. The beluga, or white whale, is the marine mammal whose CRs have been measured underwater across the widest frequency range: 40 Hz to 115 kHz (Johnson et al., 1989). Below 2 kHz, CRs of the beluga were relatively constant, on the order of 16 to 18 dB, closely resembling those of humans in air (Hawkins and Stevens, 1950; Beranek, 1954). A variety of fish species including goldfish, marine catfish, African mouthbreeder, and pinfish also have measured CRs in the low frequency (LF) band on the order of 16 to 20 dB (Fay, 1974; Tavolga, 1974, 1982).

If 16 dB is taken as a general low-end value for the CR, then a conservative lower bound for hearing thresholds can be developed from the lowest natural ambient noise spectrum levels plus 16 dB. For marine vertebrates, this model suggests best hearing thresholds ranging from about 60 dB re 1 uPa at 100 Hz to about 40 dB re 1 uPa at 10 kHz. Figure 1 provides a graphical representation of this relationship.

2.0 Hearing Loss in Humans

Estimating the received level at which hearing loss may occur requires extrapolation. For example, long term-hearing loss in humans is accelerated by chronic daily 8-hour workplace exposure (over time scales on the order of tens of years) to sounds at levels of 85 dB(A) (in air) or greater (Ward, 1997: 1503; also see Guide for Conservation of Hearing in Noise, American Academy of Ophthalmology and Otolaryngology, 1969). The sound power reference unit dB(A) is the frequency-weighted response matching the human hearing threshold; 0 dB(A) being the nominal threshold of best hearing in young healthy humans. Free-field human threshold measurements for binaural hearing in our best hearing range from 400 to 8000 Hz and vary between –10 to + 10 dB re 20 μPa (Beranek, 1954: Fig 13.6).

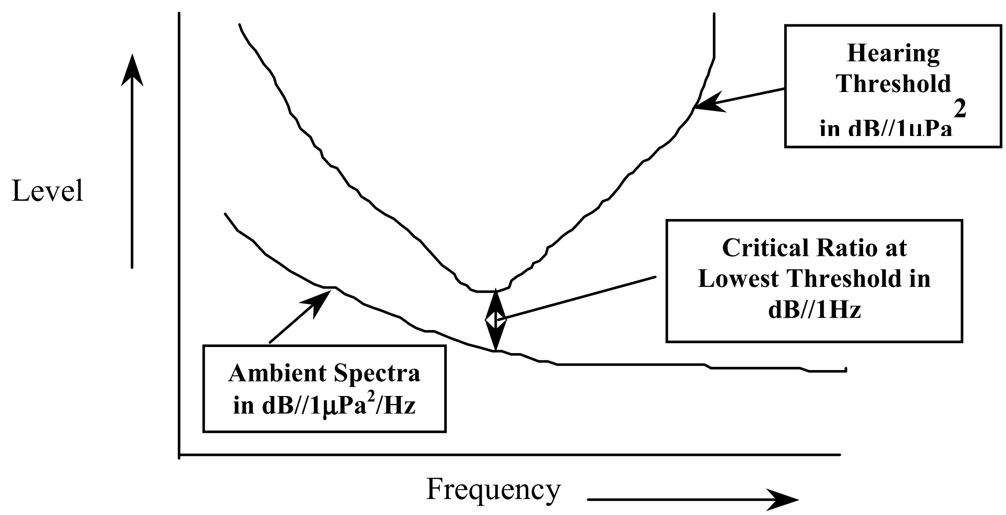
For a single exposure to sounds, Ward (1997) has derived a relationship of maximum safe level vs. exposure duration. Thus, levels higher than this may be viewed as potentially harmful. Simple temporary threshold shifts are not included in this damage category. The relationship provided by Ward scales on a 10log(duration) basis. Typical values (above a nominal best hearing threshold of 0 dB re 20 μPa) are (Ward, 1997, Figure 3):

- 144 dB for 1 sec;
- 126 dB at 1 minute;
- 112 dB at 20 minutes; and
- 100 dB at 8 hours.

If viewed as levels above best hearing threshold, these values can be used to extrapolate and thus infer one-time received level thresholds for single safe exposure for other species, given their hearing thresholds.

Figure 1. Relationship Between Low Ambient Spectra, Critical Ratio, and Best Hearing Threshold in Hearing Animals

Hypothesis: Best Hearing Threshold =Lowest Natural Ambient Spectra in Habitat + Critical Ratio



3.0 Selection of 180 dB Upper Reference Point

In terms of biological risk, it is important to note that individuals will vary in their pre-exposure hearing sensitivity, in their responses to loud sounds, and in the severity of the consequent biological effects. No two individuals can be expected to react to SURTASS LFA sonar exposure in the same way. The risk continuum presented in the SURTASS LFA EIS estimates that 95 percent of the marine mammals exposed to a single ping in water of 180 dB re 1 uPa could suffer a risk of significant change in a biologically important behavior. In this sense this level is comparable to Ward's (1997) acceptable one-time exposure limit described above for humans.

In order to extrapolate the above results to the marine mammals that are most tuned to the LF frequency band, an estimate must be made of their best hearing threshold. In the SURTASS LFA sonar transmission band, low natural ambient spectrum level (no shipping noise and zero sea state) is estimated to be about 44 dB re 1 $\mu Pa^2/Hz$. Assuming a low-end critical ratio value of 16 dB/Hz, the algorithm described above for best hearing sensitivity (in the 100 to 500 Hz band) predicts hearing thresholds of 60 dB.

If the "dynamic range" between hearing thresholds and problematic exposure levels is the same as for humans, this suggests that hearing loss in marine animals would be accelerated by continuous long-term exposure (100 percent duty cycle such as propeller noise) to sound levels 85 dB greater (Ward, 1997, p. 1501) or 145 dB re 1 μPa. Potential single-ping maximum safe level criteria would arise from exposures greater than:

- 1 second at 204 dB;
- 1 minute at 186 dB;
- 20 minutes at 172 dB; or
- 8 continuous hours of sound at 160 dB.

A single LFA ping is on the order of 1 minute in duration. Because the above limits are based on extrapolations from maximum safe levels, the single-ping 180 dB risk criterion is conservative. These conclusions are further supported by the studies described below.

3.1 Fish Studies

Hastings et al. (1996) studied the effects of intense sound stimulation on the ear and lateral line of the oscar fish (*Astronotus ocellatus*). They found that there was some damage to the sensory hair cells of two of the otolith organs, the lagena and utricle, when the fish were exposed to continuous underwater sound at 300 Hz and 180 dB for one hour. The interpretation of these results was that continuous exposure to a pure tone, high intensity sound on the order of one hour has the potential to damage the ear of fish.

Other studies also suggest that intense sound may result in limited damage to the sensory hair cells in the ears of fish. Cox et al. (1986a, b; 1987) exposed goldfish (*Carassius auratus*), a fish with specialized and sensitive hearing, to pure tones at 250 and 500 Hz at 204 and 197 dB, respectively, at durations of approximately 2 hours, and found some indication of hair cell damage. Enger (1981) determined that some ciliary bundles (the sensory part of the hair cell) of the inner ear of the cod (*Gadus morhua*) were destroyed when exposed to sounds at several frequencies from 50 to 400 Hz at 180 dB for 1-5 hours. Since the physiology of inner ear hair cells is considered to be similar among vertebrates, and exposure to 180 dB in water is expected to have the same effect on the inner ears of fish and marine mammals, the single-ping 180-dB criterion for LFA can be considered relatively conservative.

Goldfish in this frequency band have excellent underwater hearing with thresholds in the 60 dB re 1 μPa range (Offut, 1968). Following the extrapolation based on Ward's (1997) one-time exposure criteria and using a lumped average exposure time of 2 hours and a threshold of 60 dB, the safe limit would be predicted to be 166 dB. Thus, the damage appears to have been caused by levels 14 dB and higher above an extrapolated single continuous two-hour ping guidance criteria. Further extrapolation in time would indicate that, for the goldfish, a single 1-minute exposure level on the order of 186 dB would have been safe and 200 dB or more would have been required to cause damage equivalent to that of the hours-long exposure period. On this basis, a 1-minute duration criterion for LFA of 180 dB is conservative.

3.2 Marine Mammal Studies

A panel of nine experts in the fields of marine biology and acoustics sponsored by California's High Energy Seismic Source (HESS) Team convened at Pepperdine University in June 1997. The consensus of the combined experts was that they were apprehensive about the effects of received levels greater than 180 dB re 1 μPa (rms), and this should be identified as a safety zone for marine mammals in general.

Temporary threshold shifts (TTS) of varying degrees occur naturally in the environment of all animals, including humans. Although not necessarily harmful on a limited basis, an organism could miss important signals until its normal hearing sensitivity is restored. Also, TTS serves as an indicator that *more* extensive exposure or significantly louder levels may cause permanent hearing loss. Two recent measurements of TTS in marine mammals are discussed below along with the relationship of these measurements to the selection of 180 dB as the LFA single exposure limit value for risk assessment.

Schlundt et al. (2000)

Schlundt et al. (2000) documented temporary shifts in underwater hearing thresholds in trained bottlenose dolphins (*Tursiops truncatus*) and white whales (*Delphinapterus leucas*) after exposure to intense one-second duration tones at 400 Hz, and 3, 10, 20, and 75 kHz. Of primary importance to this deliberation are the LF-band tones at 400 Hz. At this frequency, the researchers were unable to induce TTS in any animal at levels up to 193 dB re 1 μPa, which was the maximum level achievable with the equipment being used.

This experiment also provides an additional verification point for the extrapolation of the human data set for hearing effects at best hearing. For both species tested, their best hearing threshold is broadly set at about 40 to 45 dB in the 20 to 75 kHz range. In this band, TTS was reported for levels (varying significantly between individuals) from 182 to 193 dB. Applying the extrapolated one-time safe levels above threshold for one-second duration from Ward (1997), the result (144 dB above threshold) is 184 to 189 dB, providing further validation for the extrapolation technique.

Kastak et al. (1999)

Kastak et al. (1999) documented TTS in three species of pinnipeds exposed to varying levels of octave band noise (OBN) for periods on the order of 20 minutes. OBN center frequencies from 100 to 2000 Hz were used in these tests, and the results presented in the paper pooled the data from each exposure frequency. The results indicate onset of TTS at mean values of 137, 150, and 148 dB re 1 μPa for the harbor seal, sea lion and elephant seal, respectively, for 20- to 22-minute exposures of OBN. Because of the pooling effect, these data also have variations around the mean on the order of -5 to +10 dB. As described in the account of the test, these levels can be considered to represent the lower level for onset of TTS.

In humans, ordinary TTS (i.e., effects lasting longer than 2 minutes) from narrow-band (octave band or less) sound occurs only at exposure levels in excess of 70 dB above hearing threshold.

Ward (1997) terms this level "equivalent quiet," or EQ. At exposure levels below EQ, no ordinary TTS will result, independent of duration. There is not a strong relationship between TTS and the safety of one-time exposure levels. However, based on Ward's (1997) review it can be seen that in humans the 1-minute one-time safe exposure level of 126 dB is 56 dB above EQ.

If a 10log(t) relationship is used to conservatively estimate how Kastak et al. (1999) TTS received levels for 20-minute exposures relate to the EQ for the animals they tested, the result is 10log(20 [min]/1 [min]) = 13 dB. Then extrapolating from the human experience, the average equivalent single-ping safety limit for a 1-minute duration signal would be 180 dB (137+56-13), 193 dB (150+56-13), and 191 dB (148+56-13), respectively for the three species. Again, this extrapolation substantiates 180 dB as a reasonable choice.

4.0 Conclusions

The present scientific consensus is that serious problems in a marine mammal's hearing capability will not arise at single ping received levels of < 180 dB re 1 uPa. At higher received levels or greatly extended continuous duration one cannot be certain, and the general consensus is that this 180 dB level should be considered as the point above which some potentially serious problems in marine mammals' hearing capability could start to occur. The following is a list of scientific and technical workshops and meetings at which this consensus was developed:

- High Energy Seismic Survey (HESS) Team Workshop, Pepperdine University School of Law, June 12-13, 1997;
- Office of Naval Research Workshop on the Effects of Man-Made Noise on the Marine Environment. Washington, DC, February 9-12, 1998; and
- National Marine Fisheries Service (Office of Protected Resources) Workshop on Acoustic Criteria, Silver Spring, MD, September 9-12, 1998.

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