Technical Support Information to the CMS Family Guidelines on Environmental Impact Assessments for Marine Noise-generating Activities

Module D.

Exposure Levels

The full CMS Family Guidelines on Environmental Impact Assessments for Marine Noise-generating Activities and the stand-alone modules are online at:

cms.int/guidelines/cms-family-guidelines-EIAs-marine-noise

D. Exposure Levels

Silvia Frey
OceanCare

D.1. Impact of Exposure Levels and Exposure Duration

One of the first comprehensive definitions of exposure criteria for noise impact on marine mammals considering two types of impacts, namely auditory injury and behavioural disturbances by three sound types (single pulse, multiple pulse and nonpulse) has been published by Southall *et al* (2007). Just recently, the National Oceanic and Atmospheric Administration (NOAA) compiled and synthesized best available science to guide the assessment of effects of anthropogenic noise on marine mammals (NOAA, 2016). Both guidance documents consider cetaceans and pinnipeds assigned to five functional hearing groups (i.e. low-frequency cetaceans, mid-frequency cetaceans, high-frequency cetaceans, pinniped in water, pinnipeds in air and low-frequency cetaceans, mid-frequency cetaceans, high-frequency cetaceans, phocid pinnipeds underwater, otariid pinnipeds underwater respectively). The assignment to functional hearing groups was based on functional hearing characteristics of the species (e.g. frequency range of hearing, auditory morphology) and with reference to Southall *et al* as well the medium in which the amphibious living pinnipeds were exposed to sound. The developed noise exposure criteria do not address polar bears, sirenians, and sea otters due to the absence of necessary data in these species. To account for different hearing bandwidths and thus differences in impacts of identical noise exposure frequency-weighting functions were developed for each functional hearing group and considered in the formulation of the noise exposure criteria. Southall *et al* and NOAA applied dual criteria for noise exposure using peak sound pressure level (SPL) and sound exposure level (SEL) in each of the considered functional hearing groups in order to account for all relevant acoustic features such as sound level, sound energy, and exposure duration that influence the impacts of noise on marine mammals.

The onset of a permanent threshold shift (PTS-onset) has been considered as the onset of auditory injury (Southall *et al* 2007, NOAA 2016, Finneran 2015). PTS-onset estimates are applied in order to formulate dual noise exposure levels. The PTS-onset thresholds were estimated from measured TTS-onset thresholds (=threshold where temporary change in auditory sensitivity occurs without tissue damage) in very few mid-frequency odontocetes (i.e. bottlenose dolphin and beluga) and pinnipeds (i.e. California sea lion, northern elephant seal, and harbour seal) and extrapolated to other marine mammals due to the scarcity of available TTS data. It has been noted, that this extrapolation from mid-frequency cetaceans and the subsequent formulation of exposure criteria may be delicate in particular for high-frequency cetaceans due to their generally lower hearing threshold as compared to other cetaceans. The growth rates of TTS were estimated based on data in terrestrial and marine mammals exposed to increasing noise levels. Noise exposure levels for single pulse, multipulse and nonpulse sounds were expressed for SPL and SEL whereby the latter has been frequency weighted to compensate for the differential frequency sensitivity in each functional marine mammal hearing group as described above. No noise exposure criteria were developed by Southall *et al* (2007) or NOAA (2016) for the occurrence of non-auditory injuries (e.g. altered immune response, energy reserves, reproductive efforts due to stress, tissue injury by gas and fat emboli), due to a lack of conclusive scientific data to formulate quantitative criteria for any other than auditory injuries caused by noise.

Additionally to auditory injuries Southall *et al* (2007) presented also explicit sound exposure levels for noise impacts on behaviour resulting in significant biological responses (e.g. altered survival, growth, reproduction) for single pulse noise. For the latter it has been assumed that given the nature

(high peak and short duration) of a single pulse behavioural disturbance may result from transient effects on hearing (i.e. TTS). Therefore, TTS values for SPL and SEL were proposed as noise exposure levels. In contrast, for multiple and nonpulse sounds it has been taken into account that behavioural reactions to sounds are highly context-dependent (e.g. activity animals are engaged at the time of noise exposure, habituation to sound) and depending also among others on environmental conditions and physiological characteristics such as age and sex. Thus noise impact on behaviour is less predictable and quantifiable than effects of noise on hearing. Moreover, adverse behavioural effects are expected to occur below noise exposure levels causing temporary loss of hearing sensitivity. Therefore, a descriptive method has been developed by the authors to assess the severity of behavioural responses to multipulse and nonpulse sound. A quantitative scoring paradigm has been developed by Southall *et al* (2007) which numerically ranks (scores) the severity of behavioural responses. Noise exposure levels have been identified in a scoring analysis based on a thorough review of empirical studies on behavioural responses of marine mammals to noise. Reviewed cases with adequate information on measured noise levels and behavioural effects were then considered in a severity scoring table with the two dimensions, severity score and received SPL.

In contrast to former sound exposure assessment attempts Southall *et al* (2007) and NOAA (2016) account for differences in functional hearing bandwidth between marine mammal groups through the developed frequency-weighting functions. Thus, this approach allows to assess the effects of intense sounds on marine mammals under the consideration of existing differences in auditory capabilities across species and groups respectively. Furthermore, as compared to the widely used RMS sound pressure Southall *et al* (2007) and NOAA (2016) propose dual criteria sound metrics (SPL and SEL) to assess the impact of noise on marine mammals, accounting not only for sound pressure but also for sound energy, duration and high-energy transients.

All these aspects are certainly major accomplishment as compared to earlier attempts to assess noise effects on marine mammals. However, it has also to be noted that due to the absence of data noise exposure criteria had to be based on extrapolations and assumptions and therefore, as Southall *et al* (2007) and Finneran (2015) pointed out, caution is needed regarding the direct application of the criteria presented and that it is expected that criteria would change as better data basis becomes available.

D.2. Species Vulnerabilities

The best documented vulnerabilities to noise in marine mammals in terms of number of studies and species involved are certainly behavioural responses to noise. Only a few studies considering a few species exist regarding noise impacts on hearing and hearing sensitivity and physiology in marine mammals and therefore the respective knowledge on specific vulnerabilities of noise is rather scarce.

Auditory effects resulting from intense noise exposure comprise temporary threshold shift (TTS) and permanent threshold shift (PTS) in hearing sensitivity. For marine mammals TTS measurements exist for only a few species and individuals whereas for PTS no such data exist (Southall *et al* 2007, Finneran 2015). Furthermore, noise may cause auditory masking, the reduction in audibility of biological important signals, as has been shown for pinniped species in air and water (Southall *et al* 2000, 2003) and in killer whales (Foote *et al* 2004) for example.

Physiological stress reactions induced by noise may occur in cetaceans as has been shown for few odontocete species where altered neuro-endocrine and cardiovascular functions occurred after high level noise exposure (Romano *et al* 2004, Thomas *et al* 1990c). Furthermore, regarding noise-related physiological effects it has to be noted that scientific evidence indicates that in particular beaked whales experience physiological trauma after military sonar exposure (Jepson *et al* 2003, Fernandez *et al* 2004, 2005) due to in vivo nitrogen gas bubble formation.

The magnitude of the effects of noise on behaviour may differ from biological insignificant to significant (= potential to affect vital rates such as foraging, reproduction, or survival). Noise-induced behaviour response may not only vary between individuals but also intra-individually and depends on a great variety of contextual (e.g. biological activity animals are engaged in such as feeding, mating), physiological (e.g. fitness, age, sex), sensory (e.g. hearing sensitivity), psychological (e.g. motivation, previous history with the sound) environmental (e.g. season, habitat type, sound transmission characteristics) and operational (e.g. sound type, sound source is moving / stationary, sound level, duration of exposure) variables

(Wartzok *et al* 2004).

Observable behavioural responses to noise include orientation reaction, change in vocal behaviour or respiration rates, changes in locomotion (speed, direction, dive profile), changes in group composition (aggregation, separation), aggressive behaviour related to noise exposure and/or towards conspecifics, cessation of reproductive behaviour, feeding or social interaction, startle response, separation of females and offspring, anti-predator response, avoidance of sound source, attraction by sound source, panic, flight, stampede, stranding, long term avoidance of area, habituation, sensitization, and tolerance (Richardson *et al* 1995, Gordon *et al* 2004, Nowacek *et al* 2007, Wartzok *et al* 2004).

Studies have shown that in mysticetes the reaction to the same received level of noise depends on the activity in which whales are engaged in at the time of exposure. For migrating bowhead whales strong avoidance behaviour to seismic air gun noise has been observed at received levels of noise around 120 dB re 1 µPa while engaged in migration. In contrast, strong behavioural disturbance in other mysticetes such as gray and humpback whales as well as feeding bowhead whales has been observed at higher received levels around 150-160 dB re 1 µPa (Richardson *et al* 1985, 1999, Malme *et al* 1983, 1984, Ljungblad *et al* 1988, Todd *et al* 1996, McCauley *et al* 1998, Miller *et al* 2005). Furthermore, in different dolphin species reactions to boat noise varied from avoidance, ignorance and attraction dependant on the activity state during exposure (Richardson *et al* 1995).

Noise-induced vocal modulation may include cessation of vocalization as observed in right whales (Watkins 1986), sperm whales and pilot whales (Watkins and Schevill 1975, Bowles *et al* 1994) for example. Furthermore, vocal response may include changes in output frequency and sound level as well as in signal duration (Au *et al* 1985, Miller *et al* 2000, Biassoni *et al* 2000).

Noise-induced behaviour depends on the characteristics of the area where animals are during exposure and/or of prior history with that sound. In belugas for example a series of strong responses to ship noise such as flight, abandonment of pod structure and vocal modifications, changes in surfacing, diving and respiration patterns has been observed at relatively low received sound levels of 94-105 dB re 1 µPa in a partially confined area but the animals returned after some days while ship noise was higher than before (LGL and Greeneridge 1986, Finley *et al* 1990).

The distance of a noise source or its movement pattern influences the nature of behavioural responses. For instance, in sperm whales, changes in respiration and surfacing rates has been observed in the vicinity of ships (Gordon *et al* 1992) and dependant on whether a ship is moving or not different reactions of bowhead whales and other cetaceans have been observed (Richardson *et al* 1995, Wartzok *et al*, 2004)

D.2.1. Species not listed on the CMS Appendices that should also be considered during assessments

- Deep-diving cetaceans, in particular beaked whales need special consideration regarding noise exposure levels due to the risk for tissue trauma due to gas and fat emboli under certain noise conditions.
- Due to their lower overall hearing thresholds, high-frequency hearing cetaceans (true porpoises, river dolphins, *Pontoporia blainvillei, Kogia breviceps, Kogia sima, cephalorhynchids*) may need additional consideration as their sensitivity to absolute levels of noise exposure may be higher than other cetacean hearing groups.
- Southall *et al* pointed out that due to a lack of data they could not formulate noise exposure levels for polar bears, sea otters, and sirenians. Certainly a point which needs consideration when dealing with areas where these marine mammal taxa occur.

References

Au WWL Carder DA, Penner RH and Scronce BL. 1985, 'Demonstration of adaptation in beluga whale echolocation signals, J Acoust Soc Am. 77:726-730.

Biassoni N Miller P J and Tyack PL. 2000, 'Preliminary results of the effects of SURTASS-LFA sonar on singing humpback whales (Technical Report #2000-06)', Woods Hole, MA: Woods Hole Oceanographic Institute, 23 pp.

Bowles AE Smultea M Würsig B DeMaster DP and Palka D. 1994, 'Relative abundance and behavior of marine mammals exposed to transmissions from the Heard Island Feasibility Test', J Acoust Soc Am. 96:2469-2484.

Fernández A Arbelo M Deaville R Patterson IAP Castro P Baker JR *et al* 2004, 'Pathology: Whales, sonar and decompression sickness (reply)', [Brief Communications], Nature, 428(6984), U1-2.

Fernández A Edwards JF Rodríguez F Espinosa de los Monteros,A Herráez,P Castro P *et al* 2005, 'Gas and fat embolic syndrome involving a mass stranding of beaked whales (Family Ziphiidae) exposed to anthropogenic sonar signals', Veterinary Pathology, 42, 446-457.

Finley KJ Miller GW Davis RA and Greene CR Jr. 1990, 'Reactions of belugas, *Delphinapterus leucas*,

and narwhals, Monodon monoceros, to ice-breaking ships in the Canadian high arctic', Canadian Bulletin of Fisheries and Aquatic Sciences, 224, 97-117.

Finneran JJ. 2015, 'Noise-induced hearing loss in marine mammals: A review of temporary threshold shift studies from 1996 to 2015', The Journal of the Acoustical Society of America, 138 (3), 1702-1726.

Finneran JJ. 2015. Auditory weighting functions and TTS/PTS exposure functions for 39 cetaceans and marine carnivores. July 2015. San Diego: SSC Pacific.

Foote AD Osborne RW and Hoelzel AR. 2004, 'Whale-call response to masking boat noise', Nature, 428, 910.

Gordon J Leaper R Hartley FG and Chappell O. 1992, 'Effects of whale-watching vessels on the surface and underwater acoustic behaviour of sperm whales off Kaikoura, New Zealand', In Science and research series (p. 64). Wellington: New Zealand Department of Conservation.

Gordon J Gillespie D Potter J Frantzis A Simmonds MP Swift R *et al* 2004, 'A review of the effects of seismic surveys on marine mammals', Marine Technology Society Journal, 37, 16-34.

Jepson PD Arbelo M Deaville R Patterson IAP Castro P Baker JR *et al* 2003, 'Gas-bubble lesions in stranded cetaceans', Nature, 425, 575-576.

LGL Ltd. and Greeneridge Sciences 1986, 'Reactions of beluga whales and narwhals to ship traffic and icebreaking along ice edges in the eastern Canadian High Arctic: 1982-1984', In Environmental studies, 37. Ottawa, ON, Canada: Indian and Northern Affairs Canada. 301 pp.

Ljungblad DK Würsig B Swartz SL and Keene JM. 1988, 'Observations on the behavioral responses of bowhead whales (*Balaena mysticetus*) to active geophysical vessels in the Alaskan Beaufort Sea', Arctic, 41, 183-194.

Malme CI Miles PR Clark CW Tyack P and Bird JE. 1983, 'Investigations of the potential effects of underwater noise from petroleum industry activities on migrating gray whale behavior (BBN Report No. 5366, NTIS PB86-174174)', Report from Bolt Beranek and Newman Inc. for U.S. Minerals Management Service, Anchorage, AK.

Malme CI Miles PR Clark CW Tyack P and Bird JE. 1984, 'Investigations of the potential effects of underwater noise from petroleum industry activities on migrating gray whale behavior. Phase II: January 1984 migration (BBN Report No. 5586, NTIS PB86-218377)', Report from Bolt Beranek and Newman Inc. for U.S. Minerals Management Service, Anchorage, AK.

McCauley RD Jenner M-N Jenner C McCabe KA and Murdoch J. 1998, 'The response of humpback whales (*Megaptera novaeangliae*) to offshore seismic survey noise: Preliminary results of observations about a working seismic vessel and experimental exposures', Australian Petroleum Production and Exploration Association Journal, 38, 692-707.

Miller PJO Biassoni N Samuels A and Tyack PL. 2000, 'Whale songs lengthen in response to sonar', Nature, 405, 903.

Miller GW Moulton VD Davis RA Holst M Millman P MacGillivray A *et al* 2005, 'Monitoring seismic effects on marine mammals – southeastern Beaufort Sea, 2001-2002', In S. L. Armsworthy, P. J. Cranford, and K. Lee (Eds.), Offshore oil and gas environmental effects monitoring: Approaches and technologies (pp. 511-542). Columbus, OH: Battelle Press.

NOAA. 2016. Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing: Underwater Acoustic Thresholds for Onset of Permanent and Temporary Threshold Shifts. U.S. Dept. of Commerce, NOAA. NOAA Technical Memorandum NMFS-OPR-55, 178 p.

Nowacek DP Thorne LH Johnston DW and Tyack PL. 2007, 'Responses of cetaceans to anthropogenic noise', Mammal Review, 37, 81-115.

Richardson WJ. 1985, 'Behavior, disturbance responses and distribution of bowhead whales (*Balaena mysticetus*) in the eastern Beaufort Sea, 1980-84 (OCS Study MMS 85-0034, NTIS PB87-124376)', Report from LGL Ecological Research Associates, Inc for U.S. Minerals Management Service, Reston, VA. 306 pp.

Richardson WJ Greene CR. Jr Malme CI and Thomson DH. 1995, 'Marine mammals and noise', New York: Academic Press. 576 pp.

Richardson WJ Miller GW and Greene CR. Jr. 1999, 'Displacement of migrating bowhead whales by sounds from seismic surveys in shallow waters of the Beaufort Sea', Journal of the Acoustical Society of America, 106, 2281.

Romano TA Keogh MJ Kelly C Feng P Berk L Schlundt CE *et al* 2004, 'Anthropogenic sound and marine mammal health: Measures of the nervous and immune systems before and after intense sound exposure', Canadian Journal of Fisheries and Aquatic Sciences, 61, 1124-1134.

Southall BL Schusterman RJ and Kastak D. 2000, 'Masking in three pinnipeds: Underwater, low-frequency critical ratios', Journal of the Acoustical Society of America, 108, 1322-1326.

Southall BL Schusterman RJ and Kastak D. 2003, 'Auditory masking in three pinnipeds: Aerial critical ratios and direct critical bandwidth measurements', Journal of the Acoustical Society of America, 114, 16601666.

Southall BL Bowles AE Ellison WT Finneran JJ Gentry RL Greene Jr CR Kastak D Ketten DR Miller JH Nachtigall PE Richardson WJ Thomas JA and Tyack PL. 2007, 'Marine mammal noise-exposure criteria: initial scientific recommendations', Aquatic Mammals, 33 (4), 411-522.

Thomas JA Kastelein RA and Awbrey FT. 1990c, 'Behavior and blood catecholamines of captive belugas during playbacks of noise from an oil drilling platform', Zoo Biology, 9, 393-402.

Todd S Stevick P Lien J Marques F and Ketten D. 1996, 'Behavioral effects of exposure to underwater explosions in humpback whales (*Megaptera novaeangliae*)', Canadian Journal of Zoology, 74, 1661-1672.

Wartzok D Popper AN Gordon J and Merrill J. 2004, 'Factors affecting the responses of marine mammals to acoustic disturbance', Marine Technology Society Journal, 37, 6-15.

Watkins WA. and Schevill WE. 1975, 'Sperm whales (*Physeter catodon*) react to pingers', Deep Sea Research I, 22, 123-129.

Watkins, WA. 1986, 'Whale reactions to human activities in Cape Cod waters', Marine Mammal Science. 2:251-262.