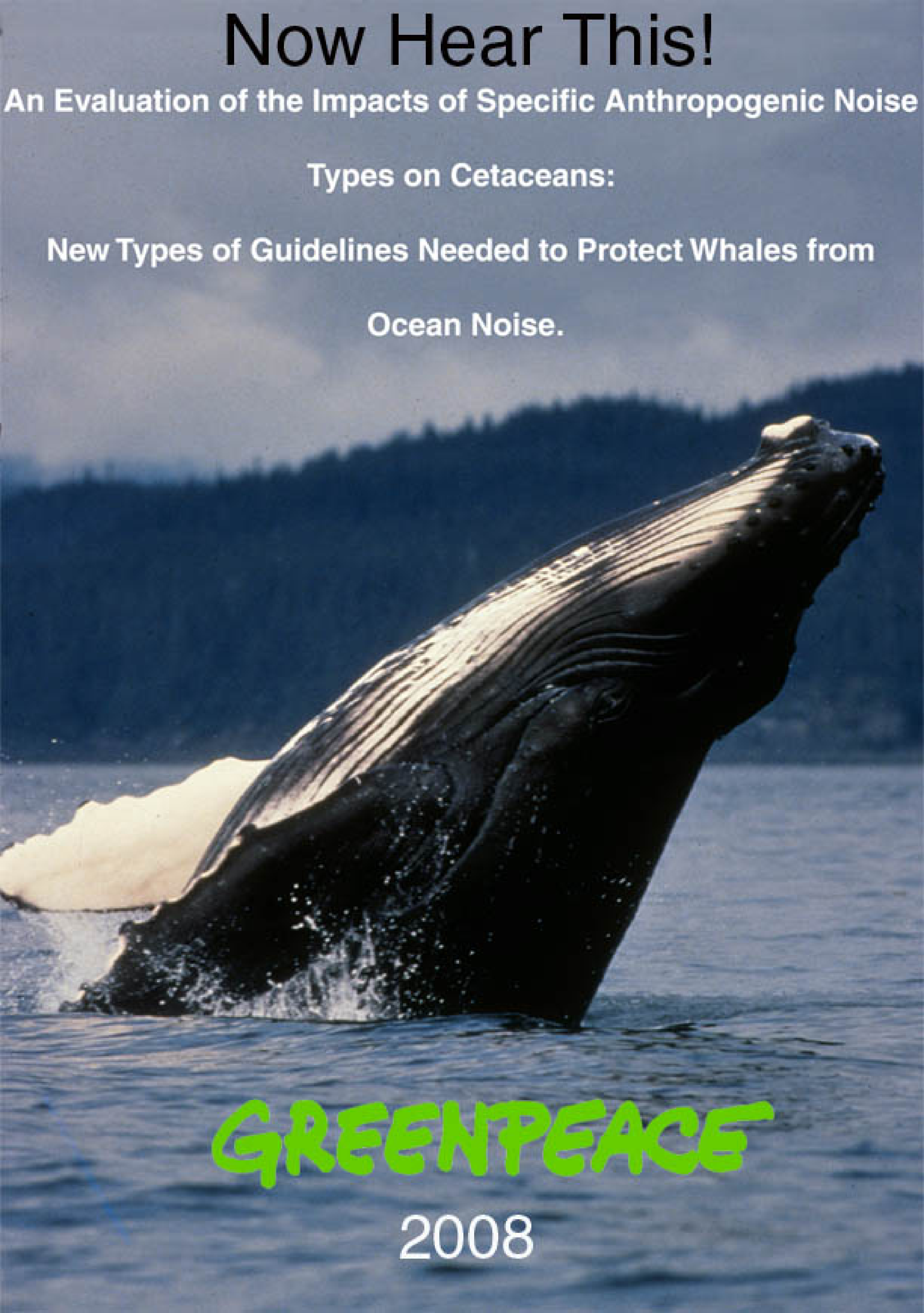
Now Hear This!

An Evaluation of the Impacts of Specific Anthropogenic Noise Types on Cetaceans:

New Types of Guidelines Needed to Protect Whales from Ocean Noise.



GREENPEACE

2008

An evaluation of the impacts of specific anthropogenic noise types on cetaceans:

New types of guidelines needed to protect whales from ocean noise

by Michael Stocker for Greenpeace

Executive Summary

It is well established that certain anthropogenic noises have a severe effect on whales. Many sounds that humans introduce into the sea today are without precedent in the evolutionary history of marine mammals and other ocean life. Seismic testing associated with oil and gas exploration, military SONAR, and other industrial sources of ocean noise have injured or killed dolphins and whales in many instances. Additionally, behavioral impacts can also be severe, with animals interrupting feeding, nursing, or reproductive activity to flee from disruptive or painful sounds. There is also evidence that whales may be subject to "masking," where some types of noises interfere with their ability to communicate with each other. As the military and industrial producers of these sounds are required by law in some countries to prevent impacts to marine mammals, there has been considerable debate and litigation in response to this continuing problem.

Various mitigation schemes have been proposed, but they have not proven effective in eliminating harm to whales. Despite a wealth of information demonstrating the need to address multiple characteristics of sound, such as form, frequency, and periodicity, mitigation levels have thus far focused only on signal amplitude, or volume. Many of the studies have also been focused on physiological thresholds such as "threshold shift" using sinusoidal-derived signals which may not accurately reflect the types of anthropogenic noises to which whales are exposed.[1,2] Mitigation levels based on these thresholds and signal types are often higher than known behavioral thresholds. It is clear from the literature that marine mammals avoid certain types of signals at significantly lower amplitudes than naturally occurring signals or other types, frequencies and forms of anthropogenic signals.

This paper presents data on signal-specific biological responses of cetaceans and calls for incorporation of signal types as well as decibel levels when establishing noise exposure criteria for whales. Given the existing evidence that cetaceans are adversely impacted by a range of noises far below current mitigation levels, a more precautionary approach is needed.

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New types of guidelines needed to protect whales from ocean noise

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1.0 Overview

The increase in human population density over the last 50 – 75 years has caused unexpected environmental impacts throughout the globe. The ocean, once believed to be so expansive as to be immune from the small scales of human enterprise is now a looming conservation concern. It is no longer enough to just manage commercial fisheries in terms of catch quotas and harvest practices; the very habitat of these fisheries needs to be conserved under the rubric of "eco-system management." Considerations of predator/prey relationships, food stock viability, coastal wetlands management, toxic pollutants, bycatch, habitat protection, and global warming all play into contemporary fisheries management concerns.

This recent framing arose rapidly following the collapse of the long standing view that the ocean was both an unlimited food source and a bottomless dumping ground, which had resulted in unrestricted or poorly regulated ocean practices.[3] As fisheries catch levels increased and the effects of accumulated ocean dumping and runoff grew more visible, it became rapidly clear that the ocean was more vulnerable to human activities than was once thought. Problems with sustainable yields became apparent as the various commercial fisheries ceased being economically viable due to low catch rates.[4] But other eco-system problems such as the impacts of ocean plastic refuse on zooplankton,[5] mercury concentrations in animal tissues[6] and depletion of coastal wetlands[7] came as more of a surprise because these elements of the ecosystem became evident only through broader examination of the interdependence of commercial fisheries and the habitat that supported them.

One of the more recent surprises is the impact that human generated noise has on marine ecosystems.[8] Despite decades of ship-shock trials, naval training exercises with explosives and even ocean-based atomic bomb tests, significant public concern with the potential environmental impacts of anthropogenic noise did not arise until the introduction of the Acoustic Thermography of Ocean Climate (ATOC) program (originally proposed in the early 1990's).[9] Leading up to ATOC, the Heard Island Feasibility Test (HIFT) was done without public scrutiny, and the researchers did not notice any adverse impacts on marine mammals.[10]

Neither of these programs seemed to have an immediate catastrophic impact on marine mammals, but the question was raised as to whether the increase in the ocean noise floor as a consequence of ATOC and other introduced noises might have a long-term deleterious effect on ocean habitat. Nonetheless, the ways that anthropogenic noises affected ocean habitat were not deeply studied or understood, so human acoustical engagement in the sea continued to increase – with nominal consideration for the biological impacts that these engagements might have.

In 1996 the US Navy began a process of public scoping meetings to develop an Environmental Impact Statement on the global application of Low Frequency Active Sonar, submitting a Draft Overseas Environmental Impact Statement (SURTASS LFA DOEIS/EIS) by July 1999.[11] Perhaps it was a matter of timing, or the global scope of the project, but this document caught the attention of the American public who came out in huge numbers to object to the program.[12] Public alarm with SURTASS and related programs was increased by the March 2000 mass stranding event of beaked whales in the Bahamas as a consequence of U.S. Naval exercises.[13] The Bahamas event provided the most compelling evidence to date that Active Sonar has the potential to be ototoxic to whales. The event also illuminated the distinct differences between the effects of Low Frequency Sonar being proposed in the SURTASS LFA program, and the new tactical Mid Frequency sonars responsible for the beaked whale mass stranding.

In the SURTASS LFA program, the mitigation level was set at a Received Level (RL) of 180dB (re:1 Pa).[14,15] Meanwhile, the received levels in the Bahamas stranding were either “well below 180 dB” [16] or between 160 dB and 180dB[17] – in any event, generally below the SURTASS LFA mitigation level of 180dB.

This disparity between mitigation levels and biological response levels to different signal types is but one indication that marine mammals respond to many characteristics of anthropogenic noise. Received level is but one characteristic, and is less strongly correlated to behavioral response than other factors. Nonetheless recommended mitigation levels often tend to hinge on exposure levels alone, without regard to other signal characteristics.[18]

This paper will examine various types of anthropogenic noises framed by how the noises evoke biological responses in various marine mammals or how the noises might interfere with biologically significant communication channels. Based on this examination, the paper makes recommendations for better crafting mitigation criteria to match biological responses based on the characteristics of the specific noise.

2.0 Biological Responses

For purposes of this examination, “biological responses” are grouped into four categories based on how readily observable the response is. There will necessarily be overlaps in these categories, as well as ambiguity in observable responses in any of the categories. These ambiguities are a product of many aspects of the observation including time frame and duration of the observation; natural or captive settings; habituation to the stimulus; learned responses from prior situations or signals that influence exposure in the observation setting;[19] assumptions by the observer; other complexities of the observation settings, and the simple fact that the subjects are animals, not input devices.

Subject to these caveats, the biological response categories for the purpose of this paper are: Synergistic effects; Masking of biologically significant sounds; Phonotaxis – such as startle and avoidance responses and other cognitive effects of harassment; and ototoxic responses including temporary threshold shift and permanent tissue damage.

2.1 Synergistic Effects

Synergistic effects of anthropogenic noise exposure are the most difficult biological impact to observe or measure. This is aggravated by the fact that there are few known baselines from a time when wild animals were not subjected to anthropogenic noise. Synergistic effects, by definition, are not clearly defined, but include everything from the compromise of the individual organism as a product of synergistic external stressors, to population declines due to habitat compromise or displacements (and the consequent synergistic effects on the individual organisms). This later synergistic condition has been observed when animals abandon an area subject to noise, repopulating it after the noise source is removed. [20] In this case the area in question was Guerrero Negro Lagoon in Baja California, abandoned by gray whales during the operation of salt works in the lagoon and repopulated after the salt works were shut down.

Determining the synergistic effects of noise on health is not as clear cut. While markers for stress such as cortisol levels in the blood or plasma catecholamine in urine are cues to the fact that an animal is subject to short or intermediate term health effects,[21] tracking the effects of temporary but periodic noise exposures in the long term is highly challenging and often inconclusive, particularly in wild populations. Similarly, determining the synergistic effects of chronic, persistent or increasing noise, (such as the increase in ambient noise levels in the sea due to shipping noise) is difficult because there are few opportunities to study established control populations in an ocean increasingly saturated with shipping noise. This may be changing through “common sense” mitigations such as relocating shipping lanes away from sensitive resident marine mammal areas. Efforts akin to this may provide some much needed data on the effects of shipping noise and the recovery of resident populations.[22]

As a consequence of the inconclusive nature of synergistic effects of noise on animal welfare, mitigation policy may often fall under the rubrics of “common sense” or “how would you like it if…” qualified by what is known about the subject species’ hearing and vocalization ranges.

2.2 Masking

Masking concerns about introduced noise are framed either in terms of interference with animal communication signals, or interference with other biologically important signals such as the important sounds of habitat dimensions, sources of danger, or the sounds of predators or prey. In a captive setting, a beluga whale modified its vocalizations to accommodate natural noise source masking, [23] so there is likely some latitude to adapt to variable noise levels in the sea by other species as well. In this case the beluga shifted its vocalization frequency out of the range of dominant ambient noise.

For high frequency echolocation and social vocalizations of odontocetes, this may be a common adaptation, but in the low frequency, long distance vocalizations of mysticetes, changing the frequency of the communication channel is less of an option.[24]

A starting point in the evaluation of masking effects involves establishing the ranges of biologically important sounds of the subject animals – from vocalizations, communication channels, and passive acoustical evaluation of their environment.[25] This information may be used as a "base sheet" to overlay "received levels" of anthropogenic noise to determine where the respective ranges overlap in frequency and amplitude. The effectiveness of this strategy is based on the assumption that the subject animals segregate useful biological sounds through frequency and amplitude discrimination only.

2.3 Phonotaxis – behavioral responses to introduced noise

Phonotaxis is a response to an introduced noise that can be noticed by observing behavioral changes in the subject animal as a consequence of the noise. Behavioral changes can include aversion/avoidance, attraction, or modification of ongoing behaviors. Any of these behaviors represent a potential risk to the extent and the degree of the particular response. In the simplest terms, any of these behaviors expend an animal's "natural response energy budget" as a consequence of an "unnatural" stimulus. There is a biological cost when an animal needs to modify its behavior or divert from its natural course of travel to avoid noise.[26]

Behavioral responses are accompanied by changes in metabolic functions, such as respiratory and heart rates, and other metabolic stress responses. The threshold for any behavioral response is not necessarily predictable; threshold of ototaxis correlates to activity. A group of whales resting quietly would seem more likely to be disturbed by human activity than whales that are actively engaged in feeding or interacting in social activities.[27] The behaviors stimulated by a particular noise may also not be predictable: a noise that an individual animal avoids in one instance may attract another individual in another. This accounts for the variability in net-predator sea lion responses to Acoustic Harassment Devices (AHD) that are effective only until the sea lions habituate to them, at which point they become "dinner bells" for them.[28]

2.4 Ototoxic and "Acousti-toxic" Effects

It is not surprising that marine mammals are vulnerable to ear damage due to explosive blasts,[29] though it was initially surprising that modern tactical sonars were powerful enough to cause the deaths of whales.[30] As powerful as they are, the manner in which intense sounds cause tissue damage is still not entirely known. There is evidence that powerful low frequency signals can resonate cavities within the bodies of the animals. There is also evidence that physical damage can be caused by the animal's reaction to the noise – regardless of frequency.[31] The existence of both of these possibilities points to a need to evaluate auditory thresholds as well as the mechanical effects of high energy noise on the marine mammal body.

The most dramatic evidence of ototoxic and acoustic-toxic effects has come in the form of multi-species stranding incidents or other unusual mass-avoidance behavior. These have been most often associated with naval mid-frequency sonars.[32] But premature hearing loss in marine mammals caused by chronic or occasional exposure to loud sounds such as seismic airgun surveys [33] or just high levels of anthropogenic ambient noise [34] may also result in the same outcome – premature mortality.

3.0 Noise Sources and Characteristics

The "natural" ocean is not necessarily a quiet place: weather conditions, waves, turbulence, seismic events, and biological noises are but a few of the contributing factors to ambient noise in ocean ecosystems.[35] Some of these noises can be relatively loud, such as earthquakes, volcanic activity and the breaking up of sea ice. As these sound sources have been integral to the ocean ambient noise levels throughout the evolution of sea life, however, sea animals have presumably adapted to them. Only within the last 100 years or so has human enterprise contributed to the oceanic soundscape – with noise sources that can be equal to or significantly louder than natural sounds. While animals may have the ability to adapt to some of these sounds, adaptation may be a consequence of the introduced sound's similarity to natural sounds.[36] The sound's characteristics may also be within the range of natural sounds that do not interfere with the animal's necessary acoustic cues.[37] But it is clear that biological adaptation to anthropogenic sound is not always possible.

The much quoted "Ross Prediction" alerted us to the fact that ocean ambient noise as a consequence of shipping would increase by 0.4 dB/year from 1950 – 1975 (10dB increase in the 50Hz band) and that low frequency noise in the North Pacific deep sound channel increased 15 dB from 1950 - 1975.[38] Ross was only accounting for shipping noise and did not predict the development of new acoustic technologies or the increase in human uses of the sea in addition to shipping – such as increased dependence on submarine communication for national security, the expansion of seismic survey noise in the search of outer continental shelf oil reserves, or the acoustical consequences of offshore industrial processing. Had he anticipated these additional sources of noise, his predictions would have been more even more alarming.

Anthropogenic noise can be grouped in two categories “intentional” and “incidental” noises. (Partial list in Appendix Table 1 and Table 2, respectively.) These categories help define mitigation strategies, inasmuch as intentional noises might be tailored for reduced biological impact. Incidental noises, on the other hand, can only be mechanically attenuated or timed to occur for least biological impact.

The dominant sources of ocean noise pollution are:

- Military operations, including communication, surveillance, navigation, sonars, transportation, and “ordinance” (explosives).
- Ocean seismic exploration and mapping.
- Commercial cargo vessels including propulsion, hull coupled mechanical noise and navigation sonar.
- Petroleum and minerals extraction, including drilling and mining operations.
- Marine based civil engineering projects such as bridge building and pipelines.
- Offshore industrial processes such as factory boats and Liquefied Natural Gas plants.
- Marine fisheries and aquaculture including processing, trawling, and use of “Acoustic Harassment Devices (AHD’s).

Each of these sources produces an array of noises that compromise various environments in the sea – from ports and harbors, to coastal waters, to the deep sea.

The sounds produced by these sources are not just “noise,” rather they can be qualified by characteristics of amplitude, frequency and bandwidth, form (impulse or burst, fast rise time, sinusoidal, ramped or square wave) and periodicity (single event, pulsed or rhythmic, intermittent, or continuous). These characteristics are all features of how a given noise is used (e.g. for long or short distance communication, surveillance or biological deterrence). Each of these characteristics will also have some bearing on how the sound induces biological responses in various marine mammals.

When crafting mitigation guidelines for anthropogenic noise, the subject noise needs to be evaluated by how it induces the biological responses outlined in Section 2 above in terms of these characteristics.

3.1 Amplitude

Of primary concern in the evaluation of any sound is whether it is loud enough – or has enough amplitude—to detect. Amplitude plays into the detection “threshold” or sensitivity of the receiver. Any receiver – biological or technological – will have a limited dynamic range, defined as the range between the detection threshold and the overload or “saturation” threshold. The favorable operating range for receivers rides comfortably between these extents with enough gain to hear above the noise, and enough “overhead” to handle signal transients. Any noise (unwanted sound) will limit the dynamic range of the receiver by how much it impinges on the receiver’s dynamic range – up to the point where the noise meets or exceeds the overload threshold of the receiver. Technological receivers can often be adjusted at overload to accommodate the saturation point. Biological receivers do not adjust as easily or recover as readily and may become temporarily or permanently damaged at the overload point.

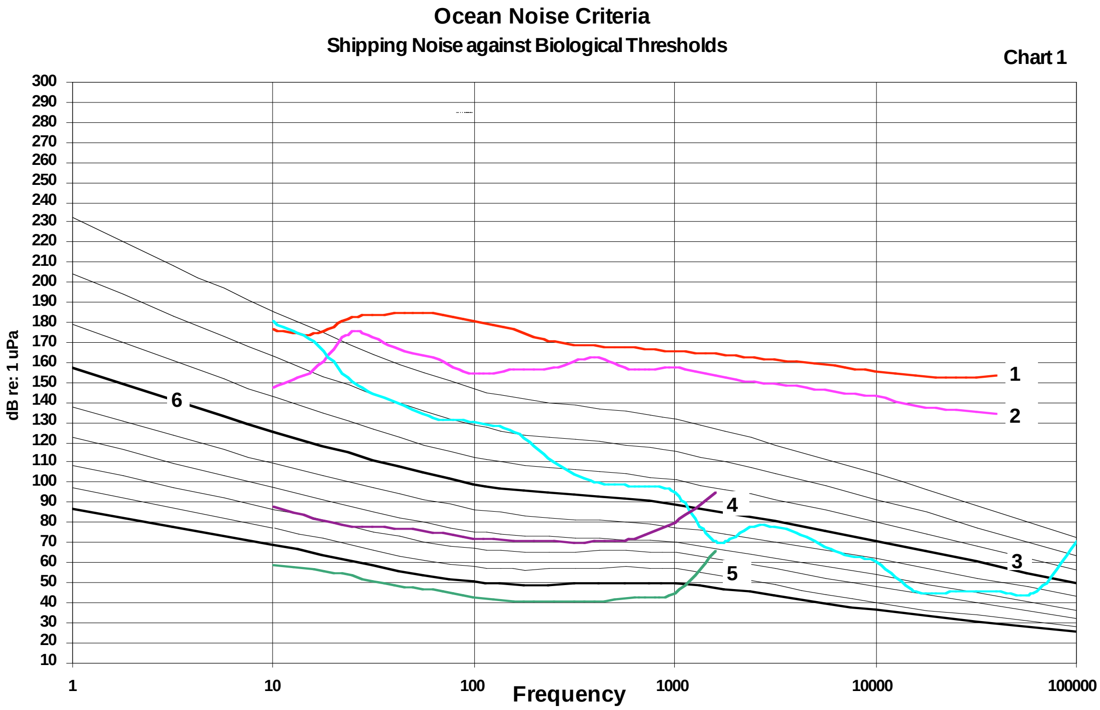
Until the introduction of anthropogenic sounds in the ocean, overload was not a common concern for biological receivers. Thus any noise that approaches or exceeds the amplitude of naturally occurring sounds should be evaluated for mitigation.

3.2 Frequency

An obvious categorization of noise sources after their amplitude is their frequency and band width. Human sound perception priorities typically group sound frequencies into “Infrasonic,” “Sonic,” and “Ultrasonic” categories—describing frequencies that are below human pitch discrimination, within human pitch discrimination range, or above our ability to hear. From the standpoint of animal communication these human oriented categories are arbitrary. Thus, by loose convention, marine mammal communication sounds fall into three general bands established by their biological purposes: low, mid and high frequencies. Low frequencies are typically considered 1kHz and below – corresponding to the long distance vocalizations of Mysticetes. The mid frequency band lies between 1kHz and 10kHz, corresponding to short range social signals of both Mysticetes and Odontocetes. High frequencies begin at around 10kHz and extend up to 200kHz; they are used for short-range echolocation and perhaps communication.

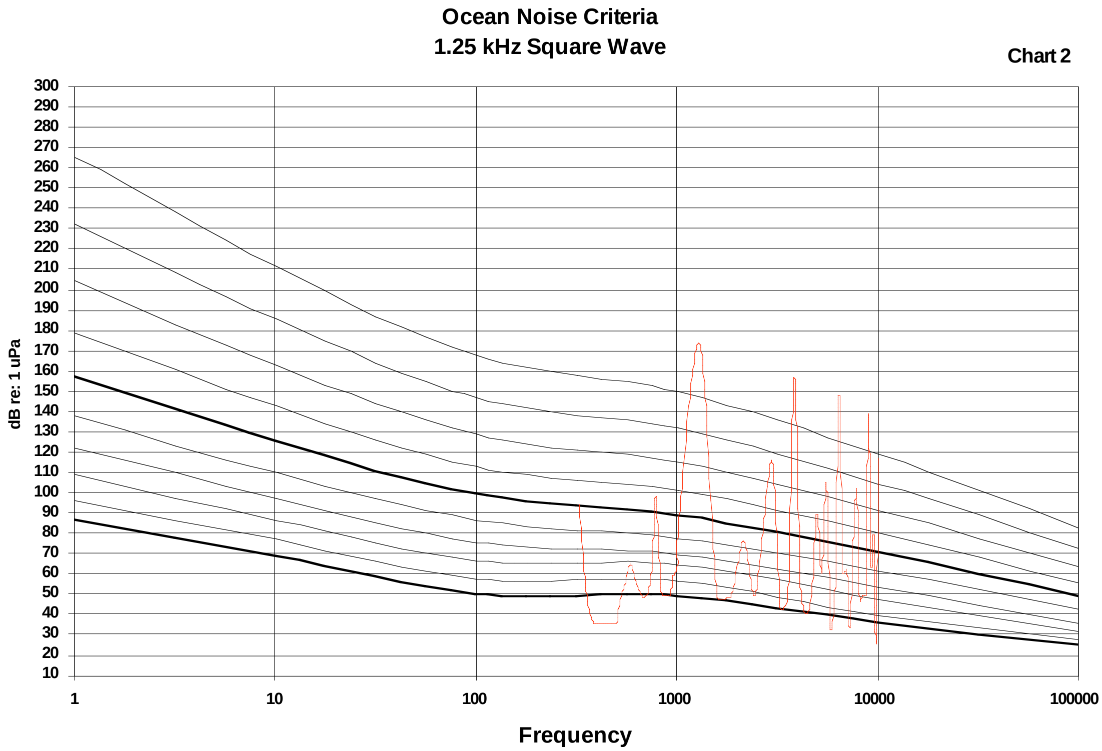
Receivers by necessity are limited in the frequencies and width of their “pass band.” The pass band is the frequency range of signals that a receiver can “hear.” Signals below or above the pass band frequencies are “rejected” or not heard. A limited pass band allows for the required information to be processed without interference from noise outside of the pass band. Technological receivers often have finely tuned pass-bands tailored to their specific purpose. With the exception of a few anurans and arthropods,[39] biological pass-bands are typically fairly wide, admitting signals for multiple purposes, from communication, to hunting or foraging, to surveillance. Mammalian hearing is prioritized (perhaps uniquely)[40] to frequency by way of their cochlea. It is not uncommon for mammals to have a 7 – 9 octave pass-band.[41, 42] This wide pass-band allows for diverse use of sound perception but also exposes them to a broader range of noise interference.

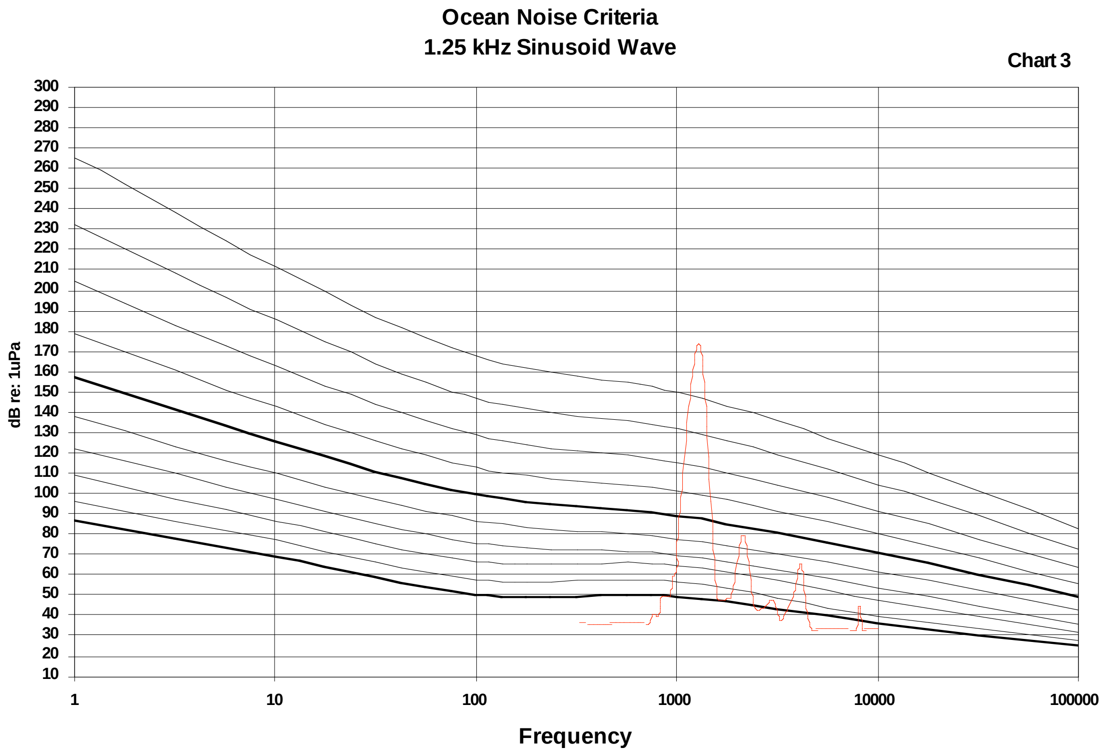
In the simplest terms, the potential for biological response occurs when the frequency of introduced signal is above the auditory threshold of the subject animal’s perceptual band (see Chart 1). The extent of the biological response will be somewhat dependent on how far the signal sits above this threshold – from the animal “noticing” or being aware of the signal, to the signal masking biologically important sounds, to the signal interfering with or distracting the animal’s ‘normal’ behavior, to the signal damaging the animal’s hearing system or tissues (as in Sections 2 above). The two ship spectrograms in Chart 1 illustrate broad band continuous noise sources against the auditory thresholds of bottlenose dolphin *Tursiops truncatus*[43] and the humpback whale *Megaptera novaeangliae*[44] (model derived). The chart has a logrhythmic display of frequency along the “x” axis, and signal amplitude on decibels (re:1 Pascal) on the “y” axis. For level reference, the chart also includes contoured level indicator lines across the entire chart spectrum. (These contour lines are derived from ocean ambient noise levels found in G.M. Wentz[45] which refer to natural ambient noise levels as a consequence of weather conditions.) The chart illustrates that both ship noises have the potential to invoke any of these biological responses.[46]



[1] MV Overseas Harriett 176m boat at 140 rpm. [2] MV Overseas Harriett at 86 rpm. [3] *Tursiops truncatus* from CS Johnson "Sound detection thresholds of marine mammals" 1967 Marine Bio-acoustics v.2 Pergamon [4] Humpback whale estimated upper threshold from "Houser, D.S. et.al. "A bandpass filter-bank model of auditory sensitivity in the humpback whale." 2001 Aquatic Mammals 27:82-91. [5] ibid. Lower threshold. [6] Reference lines on this chart are derived from Wenz, G.M. "Acoustic ambient noise in the ocean: Spectra and sources. 1962 JASA v.34. Upper and lower bold lines are lower and higher natural ambient levels. Lighter lines are extrapolated from this data.

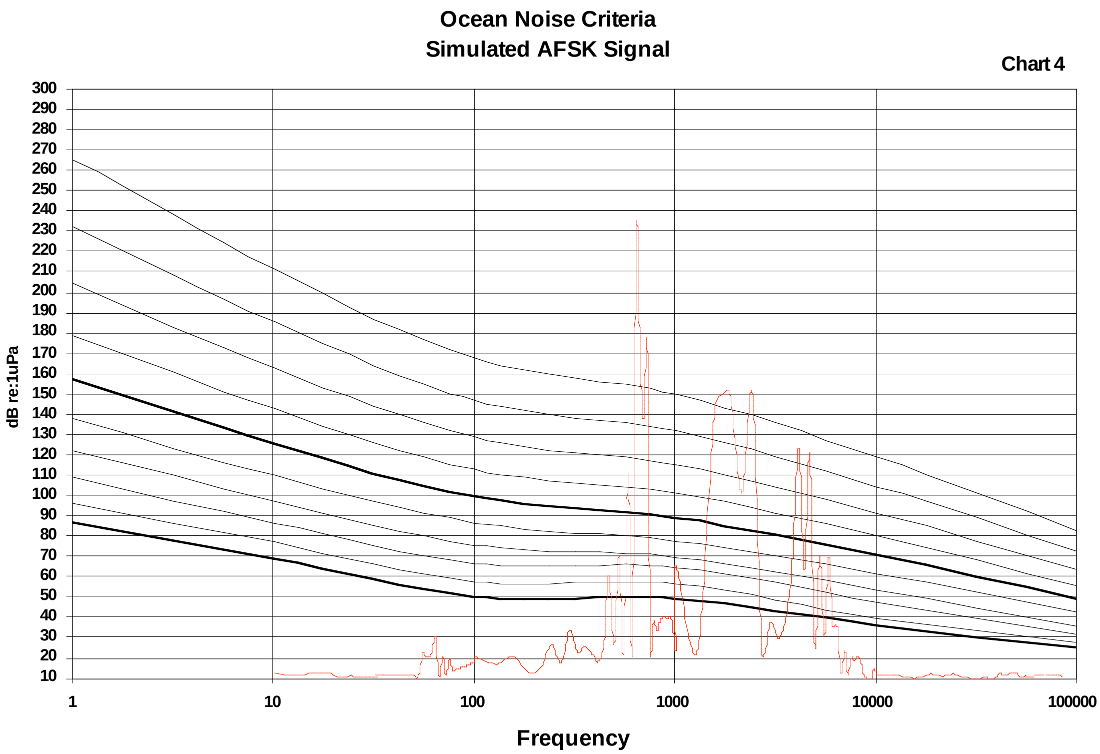
It is important to remember that any noise source with a fundamental frequency will also have a harmonic component which is a product of the complexity of the signal. The 1.25 kHz square wave spectrogram in Chart 2 illustrates this, inasmuch as the fundamental frequency at 1.25 kHz generates peaks on the odd-order harmonics. Combination and summation tones are also generated from the fundamental and the various harmonics – represented by the various peaks on the chart both above and below the fundamental frequency. (For comparison see Chart 3 "1.25 Hz sinusoid wave")





Broadband signals such as shipping noise, while complex, differ from narrow band signals inasmuch as any “harmonic content” in broadband signals are “buried” in the noise band.

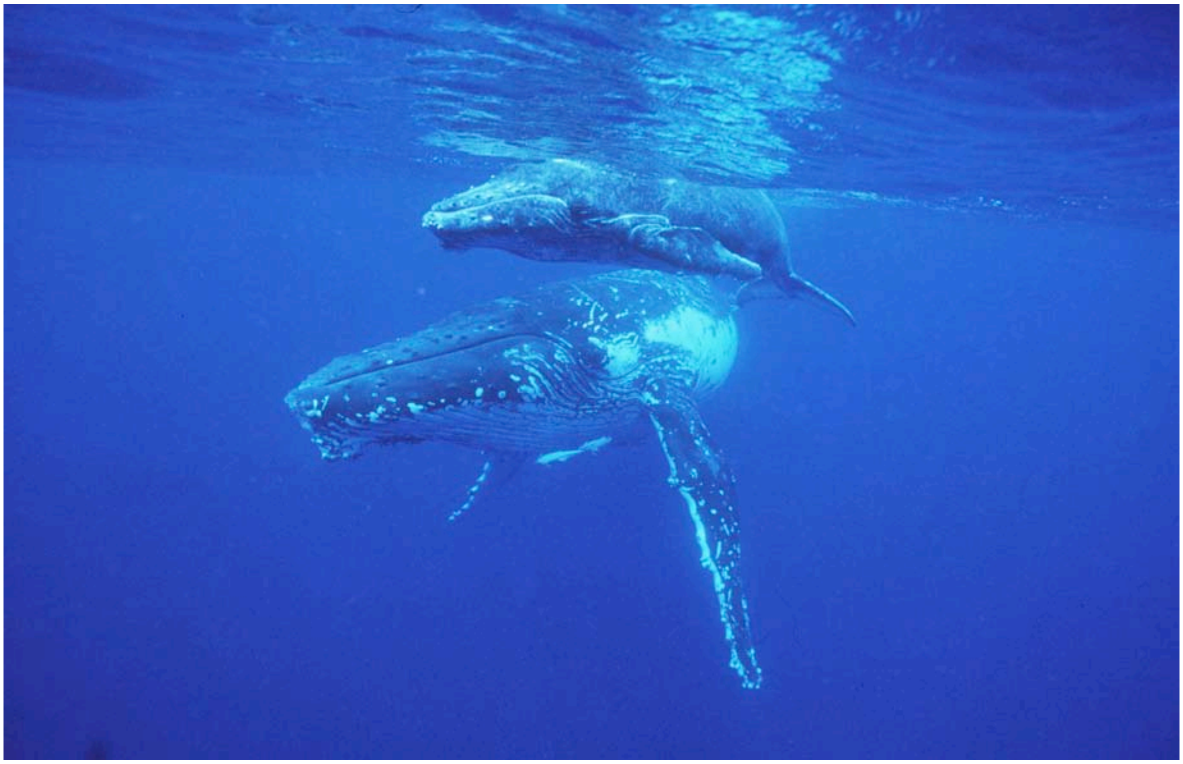
More complex signals such as Audio Frequency Shift Key (AFSK) communication signals include the various frequencies defined in the code key, the interaction of the frequencies by way of summation and differential combination tones, and higher harmonics that are a product of the switching frequency between the tones, as well as the transients generated by the switching speed between the FSK frequencies. (See Chart 4)



The AFSK signal represented in Chart 4 represents an entirely new type of underwater acoustical signal that has no biological equivalency. While there is some history for the use of coding schemes that utilize “analog” signals such as the Dual-Tone Multi Frequency (DTMF) signals (as in the common telephone key-pad signals), these “older” signal types use single or multiple sinusoidal tones to generate the key code which have some biological equivalencies.

The AFSK signal on the other hand is representative of digital modulation schemes characterized by very fast switching speeds, rapid signal rise times and combinations of “carrier” and “modulation” frequencies not found in nature. This is recognizable in Chart 4 by the high kurtosis (high variability in peak distribution) of the constituent frequencies.

High kurtosis signals are not found in nature and may bear a clue into the disturbing qualities of these sounds – both for humans as well as for marine mammals. In the “sound perception dominant” environment of marine mammals, these unnatural sounds may stimulate biological responses that cannot be predicted from what is known about common biological responses to simple frequency and amplitude cues found in nature, or established from sinusoid-derived auditory threshold tests on captive animals.



3.3 Form

As indicated in the preceding section, for a signal of any given amplitude, frequency or bandwidth, not all sounds (or noises) are equivalent. Some distinguishing characteristics include: [47]

- Wave form – the shape of the amplitude of the signal over time. Typically referring to a single cycle, common synthesized forms include sinusoid, “square wave” and “sawtooth wave.”
- Rise time – the speed at which a signal increases in amplitude from some specified small fraction to some specified larger fraction of the maximum value.
- Crest factor – of an oscillating quantity, the ratio of the peak value to the “root mean square” (RMS) value.
- Impulse response – the time integral of force over the time interval over which the force is being applied.
- Envelope – the time integral of the amplitude of an oscillating signal over the time interval over which the signal is being applied.

Each of these characteristics is found in all acoustical signals – whether biologically or mechanically generated, or electrically synthesized. The significant difference between biological sounds and anthropogenic sounds is in the quantitative range of each characteristic. Biological systems are constrained by qualities and characteristics such as acoustical compliance of tissues, acoustical compliance and impulse response of hearing organs, adapted range of sensitivity (based on habitat and niche), and required functional range within habitat and niche. Anthropogenic noise sources are not so constrained; they are as loud and persistent as the energy available to drive them, without biological limitations.

Cetacean vocalizations are either sinusoidal based tonal signals or broad-band impulsive sounds such as buzzing, creaks, bangs, pops and clicks. Tonal sounds are considered communication signals,[48] and impulsive sounds (often called "clicks") are used for echolocation and inspection.[49] These sounds can be produced separately or in combinations. [50] Some of these vocalizations can be quite loud, but we can assume that prior to the introduction of anthropogenic sounds into the marine environment that the range of cetacean bio-acoustic adaptations was suitable for the sustenance and evolution of their life; that the "very loud" signals were loud enough for their purpose, and that animals subject to hearing these signals have adapted to their amplitude.

Increasing evidence indicates that marine mammals have not so readily adapted to anthropogenic sounds. While human generated sounds may also include sinusoidal and broad-band impulsive sounds, these sounds are increasingly characterized by extremely fast rise-times, high crest factors, lengthy power envelopes and various frequency combinations that are entirely alien to nature.

Cetacean "drive fisheries" have been exploiting avoidance responses to such alien, human generated sounds for 500 years.[51] More recently, electronics-based submarine detection technology (ASDIC), the precursor to modern sonars, was used in the same manner. This system "…frightens the animals, which then swim very fast and near the surface, making them easier to see and tiring them more quickly." And "…many whalers reported that the sounds of the ASDIC appeared to irritate or frighten whales, and … that in the presence of ASDIC whales were more likely to bolt directly away from the boats rather than dodge or cut from side to side."[52]

There is no record of the received levels in these reports, or any mention of the signal form, but it is clear that the signals induced a negative biological reaction in the whales. Consistent with this are the catastrophic biological responses to Anti-Submarine Warfare (ASW) signals indicated in the Bahamas stranding – at levels between 160dB and 180dB.[53]

Other synthetic signals "like the sound of a computer modem" produced "severe discomfort" in harbor porpoises at 125 dBw.[54,55] Additionally, signals crafted to cause avoidance behavior induced this behavior in harbor porpoises at Source Levels (SL) of 119dB (unweighted). In this case, the signal was a 2.5 kHz fundamental sinusoid with 275ms bursts at a 40% duty cycle[56] – similar in fundamental frequency range to mid-frequency ASW sonar. Significantly, and despite the behavioral response it induced, this signal was also below the dominant hearing range of the subject animal.

It is clear from the above that cetaceans can have negative biological responses to various anthropogenic signals even when the signals are significantly below "recommended mitigation levels" – or even below the subject animal's vocalization levels. This is particularly the case if the signals do not have form equivalence to biological signals. This phenomenon may be akin to human reaction to the irksome sound of fingernails on a chalkboard – the very idea of which can make some people cringe.

3.4 Periodicity

All of the signals qualified by the characteristics above occur in a larger time domain; from single events, to intermittent events, through pulsed or rhythmic cycles to continuous operation. Single or intermittent events are more likely to startle an animal and put them on alert for the possibility that the event "might" occur again, while continuous noise compromises the habitat for communication and an animal's bio-acoustic awareness of their surroundings.

Little is known about the synergistic effects of intermittent or single acoustical events on marine mammals, but there are many studies of catastrophic single acoustical events on whales and other animals.[57] Systematic tests on masking or phonotaxis consequences of "single event" acoustical stimulus would be inconsistent with the definitions of "single event."

Pulsed or rhythmic acoustical events may or may not affect animals as a consequence of the rhythm. The biological role of rhythm – or temporal synchrony – is complex. The rhythm of acoustic signals is a documented factor in critical biological functions such as mate choice in some insects[58] and birds.[59] In humans, rhythm serves in speech communication,[60] as well as social and community bonding.[61] In this context, rhythmic entrainment and synchrony are a characteristic of humans, but not of other primates[62] (i.e. in terms of rhythm, chimpanzees don't "swing"). Lower primates do not have a social structure or a communication form that involves group synchrony, and they do not "school" or "flock" like dolphins or birds. While the author is unaware of studies about synchrony in marine mammals, marine mammal schooling behavior (and dolphin "play" behavior) would indicate that cetaceans can entrain or synchronize to external stimulus. Humpback whale and other mysticete "codas" can be and often are "rhythmic" inasmuch as they contain repetitive figures that occur in metered temporal cycles. Recordings taken from humpback whales in a controlled exposure experiment have demonstrated that introduced rhythmic sounds in the same frequency range of an ongoing humpback song can disrupt both the rhythm and length of the song.[63] The impact or significance of this remains unclear, but it is possible that rhythmic acoustical signals [64] – particularly ongoing rhythmic signals such as navigation beacons or seismic surveys– may have a biological impact as a consequence of their rhythm quite apart from the frequency or amplitude of the signal.

From a physiological standpoint, repetitive signals significantly increase chinchilla susceptibility to threshold shift over continuous noise with the same sound exposure level and spectral profile. In this case the (recorded hammer strike) impacts (at a repetition rate of 2.25/s) were played to one group. The second group was subjected to pink noise signal with a spectrum shaped to match the spectrum of the impact noise but run continuously. The exposure ran 4 hrs/day for 5 days. After the exposure the hearing loss in the impact group was 20 – 40 dB greater that the continuous noise. (The RMS values of both noises were equivalent at 110dB SPL (re: 20uPa) integrated over a 32 second window.)[65]

If there is an equivalence between chinchilla hearing and marine mammal hearing, this would indicate that acceptable exposure levels for repetitive signals (such as seismic airgun surveys) need to be set significantly lower than mitigation levels derived from static thresholds (e.g.: behavioral or TTS thresholds).

Continuous noise is most commonly considered in terms of masking important biological signals [66] and intermediate and long term physiological stress.[67] Heretofore the dominant source of continuous anthropogenic ocean noise under consideration has been omnipresent and increasing shipping noise.[68] While shipping noise has increased 10 – 15 dB over the past 50 years due to globalization and increase in vessel size, the increase of ocean ambient noise due to shipping may be leveling off; an unlikely doubling of the merchant fleet (~95,000 boats certified by Lloyds Register) would increase sound pressure level by 6dB (re: $1uPa^2$).

On the other hand, there are many growing sources of ocean ambient noise driven by the increasing global demand for energy, coupled with advances in technology that allow deepwater development ever further out onto the outer continental shelf. Some of these sources include:

- Off-shore Liquid Natural Gas facilities with processing, regasifying, compressing, cooling and shipping.
- Deepwater oil extraction and drilling platforms
- Sea bottom petrochemical processing such as “process fluids” injectors and separators.
- Deepwater minerals extraction.
- Fleets of acoustically controlled Autonomous Underwater Vessels (AUV’s) to tend to all of the above.

Currently there are few noise regulations or guidelines on any of these technologies. They are developing in most coastal waters world-wide. While each source will have a distinct sound or set of sounds – from single events, to rhythmic, to continuous, intersecting the various frequency bands form low to mid to high, with various signals characteristics – from broad band to frequency specific to high kurtosis, the overall effect will increase the broadband ambient noise in the ocean.

4.0 Recommendations

When crafting mitigation guidelines for anthropogenic noise, the subject noise should be evaluated in terms of the many ways in which it may induce biological responses, including stress, masking communication and environmental cues, and inducing avoidance and other phonotaxic behavior. Current noise pollution mitigation schemes, which tend to focus on amplitude alone, are not sufficient to prevent harmful impacts to whales.

Signal exposure mitigation should be evaluated in terms of the following characteristics:

Amplitude: In terms of how the noise approaches or exceeds the amplitude of naturally occurring sounds.

Frequency: In terms of how the noise intersects the perceptual pass band of the subject animal.

Form: In terms of whether the sound has a biological equivalence; if so, will the sound confuse the animal, if not will the sound harass or endanger the animal

In terms of sound forms that are alien to the natural environment by way of fast rise time, high kurtosis, high crest factor, impulse response, and envelope.

Periodicity: In terms of whether the sound interferes with the animals biological temporal cues

In terms of how the noise masks biological cues and obscures critical communication bands.

It is clear from the foregoing that mitigation levels for anthropogenic noise need to include more than just broadband exposure amplitude levels. In human epidemiology (and law), it has been accepted for decades that “inadequately controlled noise presents a growing danger to the health and welfare” of humans;[69] and that noise pollution does not have just one effect on human health, but a wide range of effects linked not only to the intensity of the sound, but to its characteristics (and to the characteristics of the receiving individual) [70] The body of scientific evidence is now sufficient to demonstrate that the same holds true beneath the ocean waves.

Appendix

Common Anthropogenic Noise Sources

Table 1. Common Ocean Noise Sources—
Incidental Noises

Noise Source	Function/Purpose/Cause/Objective	Frequency Spectrum	Detectable Range
Shipping: Propeller noise	Propulsion	1Hz – 1 kHz (Up to 195dB)	Individual vessels up to 15 km, cumulative fleet noise is globally widespread[i]
Shipping: Hull radiated mechanical noise	Hull mounted equipment	2 Hz – 20 kHz (Up to 195dB)	Individual vessels up to 15 km, cumulative fleet noise is globally widespread[ii]
Shipping: Hull friction	Biological growth on hull. Hydrodynamic forces on the hull and external hull mounted equipment	2 Hz – 5 kHz	Individual vessels up to 15 km s, cumulative fleet noise is globally widespread [iii]
Construction: Pile Driving	Impulse/impact noise	Broadband impulse every 1 – 4 seconds (Up to 240dB)	In shallow harbors and ports up to 8 km, in coastal areas 15 to 300 km.
Construction: Materials handling	Impact, friction and fastening noise	1 Hz – 5 kHz	In shallow harbors and ports up to 8 km, in coastal areas 15 to 300 km
Industrial Process: Mechanical noise	Machinery, pumps, materials handling, provisioning.	10 Hz to 5 kHz	Depending on the location and size of the operation, up to 30 km on coastal waters.

Sources: [1] Ross, D. "Ship sources of ambient noise" First published in the "Proceedings of the International Workshop on Low-Frequency Propagation and Noise" October (1974), reprinted in IEEE journal of Oceanic Engineering, 30(2), pp. 257-261 (2005); [ii] Ibid.; [iii] Ibid.

Table 2. Common Ocean Noise Sources—
Intentional Noises

Noise Source	Function/Purpose/Cause/Objective	Frequency Spectrum	Detectable Range
Aquaculture: Acoustic Harassment Devices	Deter net predator marine mammals.	10kHz – 80kHz Sweeps, bursts, long tones (> 185dB)	20 km depending on frequency and amplitude[v]
Seismic Exploration: Airgun arrays	Mapping sub-sea bottom profiles for oil and minerals extraction industries	10Hz – 8kHz, periodic explosions at 5 – 20 seconds (Up to 250dB)	15 to 3000 km
Navigation: Underwater beacons	Identify underwater objects Locate underwater equipment	1kHz – 30kHz 160dB +	2 – 10 km
Communication: Mid and high frequency analog signals	Vessel to vessel communication, remote control of equipment and vessels (ROVs). Unmanned Autonomous Vessels (UAVs)	1 kHz – 100kHz (Up to 235dB)	8 – 30 km depending on frequency and amplitude
Communication: Digital signals	As with the analog signals, but with faster data rates, clearer resolution.	1 kHz – 100kHz (Up to 235dB)	8 – 30 km depending on frequency and amplitude
Communication: Low frequency signals	Long distance communication Surreptitious communication to submarines. Long distance surveillance Acoustic Thermometry	2 Hz – 1 kHz (Up to 240dB)	15 to 4800 km depending on frequency, location and amplitude
Surveillance: Active sonar	Locate and identify marine vessels. Navigation and mapping	2 Hz – 100kHZ (Up to 240dB)	Less than 2 km for HF signals. 8 – 30 km for mid frequency, up to 2400 miles for low frequency.

Sources: [v] Olesiuk et al. (1995). Effects of sounds generated by an acoustic deterrent device on the abundance and distribution of harbour porpoise (Phocoena phocoena) in Retreat Passage, British Columbia. Draft Report, DFO, Nanaimo, BC. 47p.

Citations and Endnotes:

JASA = Journal of the Acoustics Society of America

[1] Carolyn E. Schlundt, James J. Finneran, Donald A. Carder, and Sam H. Ridgway "Temporary shift in masked hearing thresholds of bottlenose dolphins, *Tursiops truncatus*, and white whales, *Delphinapterus leucas* , after exposure to intense tones." 2000. JASA. v. 107(6)

[2] Paul E Nachtigall, Alexendre Supin, Jeffrey L. Pawloski and Whitlow W. L. Au **"**Measuring recovery from temporary threshold shifts with evoked auditory potentials in the bottlenose dolphin *Tursiops truncatus*" JASA 110 (5), Nov.2001

[3] Stocker, Michael. "Ocean Noise and Ocean Policy" Journal of International Wildlife Law & Policy; Sept. 2007 v.10:3. In review.

[4] "America's Living Oceans: Charting a course for Sea Change" Pew Oceans Commission, Arlington, VA., 2003.

[5] Charles J. Moore , Shelly L. Moore, Molly K. Leecaster, and Stephen B. Weisberg "A comparison of plastic and plankton in the North Pacific central gyre" Marine Pollution Bulletin, v.42, n.12, Dec01

[6] Endo T, Haraguchi K, Sakata M. "Mercury and selenium concentrations in the internal organs of toothed whales and dolphins marketed for human consumption in Japan." Sci Total Environ. 2002 Dec 300(1-3):15-2

[7] Boesch, D. F., and R. E. Turner. 1984. "Dependence of fishery species on salt marshes: the role of food and refuge." Estuaries 7:460-468.

[8] Early research on the acoustical impacts of human enterprise on habitat typically involved the impact of explosives on fish. e.g; Fry, Donald H., Cox, Keith W. "Observations on the effect of black powder on fish life." 1953. California Fish and Game. V.39(2) p.233-236. Early research on the impacts of industrial enterprise on marine mammals in the U.S. was in response to the U.S. "Marine Mammal Protection Act of 1972" See: Malme, C.I., Miles. P.R., Clark, C.W., Tyack, P., and Bird, J.E. "Investigations of the potential effects of underwater noise from petroleum industry activities on migrating gray whale behavior, Phase II January 1984 migrations." Report by Bolt, Beranek and Newman, Cambridge, MA. U.S. Minerals Management Service, BBN Tech. Report No. 5586.

[9] Whitlow W. L. Au, Paul E. Nachtigall, and Jeffrey L. Pawloski. "Acoustic effects of the ATOC signal (75 Hz, 195 dB) on dolphins and whales" J. Acoust. Soc. Am. 101 (5), Pt. 1, May 1997

[10] Walter H. Munk, Robert C. Spindel, Arthur Baggeroer, Theodore G. Birdsall. "The Heard Island Feasibility Test" JASA. 96 (4), October 1994

[11] U.S. Department of the Navy "Draft Overseas Environmental Impact Statement and Environmental Impact Statement for Surveillance Towed Array Sensor System Low Frequency Active (SURTASS LFA) Sonar" July 31, 1999.

[12] In a personal communication with SURTASS LFA program manager Joe Johnson, he indicated that he was very surprised at the extent of the public response to the DOEIS/EIS (given what was then known about the impacts of low frequency acoustic energy on marine animals).

[13] National Oceanic and Atmospheric Administration and the US Department of the Navy "Joint Interim Report: Bahamas Marine Mammal Stranding Event of 15-16 March 2000"

[14] Hereinafter all decibel references in this paper are referenced to 1µPascal, unless otherwise noted.

[15] U.S. Department of the Navy "Draft Overseas Environmental Impact Statement and Environmental Impact Statement for Surveillance Towed Array Sensor System Low Frequency Active (SURTASS LFA) Sonar" July 31, 1999. Page 1-27.

[16] Ken Balcomb letter to Joe S. Johnson on the SURTASS LFA Overseas Environmental Impact Statement dated Feb. 23, 2001.

[17] Fromm, D.M., and J. F. McEachern. 2000 (unpublished). "Acoustic Modeling of the New Providence Channel." 29 August 2000, 56 pp. (available from the U.S. Office of Naval Research), excerpted in National Oceanic and Atmospheric Administration and the US Department of the Navy "Joint Interim Report: Bahamas Marine Mammal Stranding Event of 15-16 March 2000".

[18] California Coastal Commission "Consistency Determination No. CD-086-06: Revised Staff Recommendation On Consistency Determination for US Navy Onshore and Offshore U.S. Pacific Fleet military training exercises" January 2007.

[19] Stewart, B.S., F.T. Awbrey and W.E. Evans. "Belukha whale (*Delphinapterus luecas*) responses to industrial noise in Nushagak Bay, Alaska:1983." Outer Continental Shelf Environmental Assessment Program. 1986. Minerals Management Services OCS Study MMS 86-0057. p.702 Beluga whales avoided recorded playbacks of the sound of drilling operations that they had avoided in a different habitat.

[20] National Research Council "Ocean Noise and Marine Mammals" 2003 national Academies Press p.95

[21] T.A. Romano, M.J. Keogh, C. Kelly, P. Feng, L. Berk, C.E. Schlundt, D.A. Carder, and J.J. Finneran**.** "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 Science 61(7): 1124-1134 (2004)

[22] Peter Popham "Shipping lanes moved to boost dolphin numbers" Tuesday, April 24, 2007 The Independent, UK

[23] Whitlow W. Au, D.A. Carder, R.H. Penner, B.L. Scronce "Demonstration of adaptation in beluga whale echolocation signals." 1985 JASA 77:726-730

[24] Mark A. McDonald, John A. Hildebrand and Sean M. Wiggins "Increases in deep ocean ambient noise in the Northeast Pacific west of San Nicolas Island, California" (2006) JASA v.120. There is a "half hearted" conjecture in the paper that Blue whale vocalizations shifted down in frequency from 22.5Hz to 16 Hz in response to increased ambient noise levels – a frequency shift of 25%, but the advantage conferred by this shift is dubious.

[25] See "Frequency Range of Vocalizations." Color Plate 3 in National Research Council "Ocean Noise and Marine Mammals" 2003. National Academies Press.

[26] Peter L. Tyack "Responses of Baleen whales to controlled exposures of low-frequency sounds from a naval sonar." JASA October 1999 v.106(4)

[27] W. Richardson, Charles R. Green, Charles I Malme, Denis H. Thompson "Marine Mammals and Noise" 1995, Academic Press. p. 340.

[28] Mate, B. R. and J. T. Harvey . "Acoustical deterrents in marine mammal conflicts with fisheries." 1987 Oregon Sea Grant Report ORESU-W-86-001. 116 pp.

[29] D. R. Ketten, J. Lien and S. Todd" Blast injury in humpback whale ears: Evidence and implications" JASA -- September 1993 -- Volume 94, Issue 3, pp. 1849-1850

[30] National Oceanic and Atmospheric Administration and the US Department of the Navy "Joint Interim Report: Bahamas Marine Mammal Stranding Event of 15-16 March 2000"

[31] P.D. Jepson, M. Arbelo, R. Deaville, I. A. P. Patterson, P. Castro, J. R. Baker, E. Degollada, H.M. Ross, P. Herráez, A.M. Pocknell, F. Rodríguez, F.E. Howie, A. Espinosa, R. J. Reid, J. R. Jaber, V. Martin, A. A. Cunningham, A. Fernández "Gas-bubble lesions in stranded cetaceans: Was sonar responsible for a spate of whale deaths after an Atlantic military exercise?" 9 October 2003. Nature vol. 425

[32] National Marine Fisheries Service, Office of Protected Resources "Assessment of Acoustic Exposures on Marine Mammals in Conjunction with *USS Shoup* Active Sonar Transmissions in the Eastern Strait of Juan de Fuca and Haro Strait, Washington 5 May 2003" Report dated January 21, 2005

[33] Jon Lien, Sean Todd, Peter Stevick, Fernanda Marques and Darlene Ketten "The reaction of humpback whales to underwater explosions: Orientation, movements, and behavior." JASA -- September 1993 -- Volume 94, Issue 3, p. 1849

[34] Peter M. Scheifele "Potential impacts of low-frequency anthropogenic noise on the hearing of subarctic beluga whales in the Saint Lawrence estuary" JASA. May 1997 Volume 101, Issue 5, p. 3164

[35] Gordon M. Wenz "Acoustic Ambient Noise in the Ocean" December 1962. The JASA Dec. 1962 v.34(12)

[36] P. T. Madsena) and B. Møhl. "Sperm whales (*Physeter catodon L.* 1758) do not react to sounds from detonators." Jan. 2000 JASA v.117(1)

[37] J. Engelmann, W. Hanke, J. Mogdans & H. Bleckmann "Neurobiology: Hydrodynamic stimuli and the fish lateral line" 2000 Nature 408, p.51-52

[38] Ross, D. "Ship sources of ambient noise" First published in the "Proceedings of the International Workshop on Low-Frequency Propagation and Noise" October (1974), reprinted in IEEE journal of Oceanic Engineering, 30(2), pp. 257-261 (2005)

[39] H. Carl Gerhardt and Franz Huber "Acoustic Communication in Insects and Anurans: Common Problems and Diverse Solutions" 2002. Chapter 6. University of Chicago Press

[40] A few insects are known to sense and respond to pitch, otherwise only mammals seem to respond to pitch-specific cues. See: Gabriella Gibson and Ian Russell "Flying in Tune: Sexual Recognition in Mosquitoes" 2006 Current Biology v.16(13) pp 1311-1316. In this study mosquitoes of the opposite sex will tailor their wing beat frequency until their flight tones match. Otherwise only mammals seem to respond to pitch-specific cues.

[41] An "octave" is a doubling of frequency e.g. 20Hz, 40, 80, 160, 320, 640, 1280, 2560, 5120, 10240, 20480 Hz represents the ~9 octave pass-band of humans.

[42] Richard R. Fay "Hearing in Vertebrates: A Psychophysics Databook" 1988 Hill-Fay Associates, Winnetka, Ill.

[43] C.S. Johnson "Sound detection thresholds of marine mammals" 1967 p. 247-260 in W.N Tavolga (ed.) Marine bio-acoustics, vol. 2 Pergamon, Oxford, U.K.
[44] Houser, D.S., D.A. Helweg and P.W.B. Moore. 2001. A bandpass filter-bank model of auditory sensitivity in the humpback whale. Aquatic Mammals 27:82-91.
[45] Wenz, G.M. "Acoustic ambient noise in the ocean: Spectra and sources. 1962 JASA v.34
[46] W.C. Verboom and R.A. Kastelein "Some examples of marine mammal 'discomfort thresholds' in relation to man-made noise" Proceedings from the 2005 Undersea Defense Technology conference 2005, Sponsored by TNO, P.O. Box 96864, 2509 JG The Hague, The Netherlands.
[47] See: Cyril M. Harris "Handbook of Acoustical Measurements and Noise Control" Third edition, 1979. McGraw Hill.
[48] E.g.: John R. Buck, Peter L. Tyack. "Qualitative measure of similarity for *Tursiops truncatus* signature whistles. 1993. JASA v.94(5).
[49] D.S. Houser, D.A. Helweg and P.W. Moore. "Classification of dolphin echolocation clicks by energy and frequency distributions" 1999 JASA v.106(3)
[50] Marilyn E. Dahlheim, Frank Awbrey "A classification and comparison of vocalizations of captive killer whales *Orcinus orca*." 1982 JASA v.72(3)
[51] Robert L. Brownell, Jr., Douglas P. Nowacek, and Katherine Ralls "Hunting cetaceans with sounds: a worldwide review" Report to the International Whaling Commission Scientific Committee SC57/E16
[52] Ibid.
[53] See ref. 17 above.
[54] W.C. Verboom and R.A. Kastelein. "Some examples of marine mammal 'discomfort thresholds' in relation to man-made noise." June 22, 2005. Proceedings from the 2005 Undersea Defense Technology conference 2005, Sponsored by TNO, P.O. Box 96864, 2509 JG The Hague, The Netherlands.
[55] "dBw" refers to "…a signal "weighted" to the inverse shape of the relevant audiogram." Ibid.
[56] R.A. Kastelein, A.D. Goodson, J. Lein, D. de Haan. "The effects of acoustic alarms on Harbor porpoise (*Phocena phocena*) behavior" 1995 in P.E. Natchtigal, J. Lein W.W.L. Au, and A.J. Reid (eds.) "Harbor porpoises – laboratory studies to reduce bycatch" de Speil pub.
[57] e.g.: D. R. Ketten, J. Lien and S. Todd "Blast injury in humpback whale ears: Evidence and implications" JASA 1993 V. 94(3)
[58] Kirsten Klappert, Klaus Reinhold. "Acoustic preference functions and sexual selection on the male calling song in the grasshopper *Chorthippus biguttulus*" (2003) Animal Behavior v. 65.
[59] *See, e.g.*, Hans Slabbekoorn, Carel ten Cate (1999) Collared Dove Responses to Playback: Slaves to the Rhythm Ethology 105 (5), 377–391. See more generally Eva van den Broek. "Piep Piep Piep - Ich Hab' Dich Lieb:" Rhythm as Indicator of Mate Quality" Unpub. Master's Thesis, Utrecht University. (June 2003) Available at: http://www.phil.uu.nl/preprints/ckiscripties/SCRIPTIES/024_vandenbroek.pdf.
[60] Condon, W.S. "Communication: Rhythm and Structure" in *Rhythm in Psychological, Linguistic and Musical Processes* J.R. Evans and M. Clynes (eds.) Charles C. Thomas, Springfield Ill.
[61] W.J. Freeman "A Neurobiological Role of Music in Social Bonding" 2000 in *The Origins of Music*," N.L. Wallin, B. Merker, and S. Brown, (eds.) MIT Press.
[62] Williams, L. "The Dancing Chimpanzee" 1980 Alison and Busby, London
[63] Kurt M. Fristrup, Leila T. Hatch, Christopher W. Clark "Variation in humpback whale (*Megaptera novaeangliae*) song length in relation to low-frequency sound broadcasts" June 2003 JASA v.113 (6).
The playback is at 10x speed.

[64] Airgun survey near Bay of Fundy at 10 x speed recorded near mid-Atlantic ridge 1500 miles from the source.

[65] D.E. Dunn, R.E. Davis, C.J. Merry, and J.R. Franks. "Hearing loss in the chinchilla from impact and continuous noise exposure." 1991 JASA. v.90(4)
[66] National Research Council "*Ocean Noise and Marine Mammals.*" p.95–102. 2003 National Academies Press, Washington DC.
[67] National Research Council "*Marine Mammal Populations and Ocean Noise: Determining When Noise Causes Biologically Significant Effects.*" p.48-49 (2005) National Academy Press, Washington, D.C.
[68] Mark A. McDonald, John A. Hildebrand and Sean M. Wiggins "Increases in deep ocean ambient noise in the Northeast Pacific west of San Nicolas Island, California" (2006) JASA v.120.
[69] U.S. Noise Pollution and Abatement Act of 1972, 42 U.S.C. 4901(a)(1).

[70] *Noise: A Health Problem* United States Environmental Protection Agency, Office of Noise Abatement and Control. August, 1978