



June 12, 2024

Jolie Harrison,
Chief, Permits and Conservation Division,
Office of Protected Resources,
National Marine Fisheries Service,
1315 East-West Highway,
Silver Spring, MD 20910-3226,

Attn: 2024 Update of Acoustic Technical Guidance.

Dear Ms. Harrison,

We have taken some time to review the “2024 Update to the Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing” (hereinafter “2024 Update”) and are pleased to see that there have been significant updates to the document.

The updates from the Finneran Report include some important distinctions, including the recognition of “Auditory Injury” defined as a “loss of cochlear neuron synapses, even in the absence of PTS.” This is an important distinction to make, and was initially brought into the noise exposure impacts discussion in Kujawa and Liberman (2009) where post-noise-exposure threshold shift recovery was accompanied by rapid loss of cochlear synaptic terminals and delayed loss of cochlear ganglion cells.¹

This is an important distinction to make, as it puts into question that, while threshold shift within the noise exposure band may recover, thresholds outside of the exposure band – particularly in the high frequencies, can be compromised.

The consequences of this in human hearing is that while someone may have typical age-related presbycusis, due to chronic elevated noise exposures over their lifetime, they may have exaggerated speech intelligibility loss due to the retraction of inner hair cells resulting from chronic “Temporary Threshold Shift” noise exposures. In this context, perhaps it is time to phase out the regulatory threshold term “Temporary” and replace it with an “Auditory Damage Index” under which TTS would be a variable.

¹ Sharon G. Kujawa and M. Charles Liberman (2009) Adding Insult to Injury: Cochlear Nerve Degeneration after “Temporary” Noise-Induced Hearing Loss. *The Journal of Neuroscience*, V. 29(45):14077–14085 • 14077

An “Auditory Damage Index” would more accurately reflect the impacts in the cases where Incidental Take Permits and Incidental Harassment Authorizations between operations and exposures that just straddle, or greatly exceed the Level A and Level B regulatory thresholds, and would allow for the inclusion of short or long-term, and temporary, occasional, or chronic impacts.

For example, loss of high frequency hearing sensitivity may not be as critical for Low Frequency Cetaceans, Otariids, or Phocids, because they don’t use short wavelength echolocation. But loss of high frequency hearing sensitivity is likely critical to Mid and High Frequency Cetaceans, because they do. This distinction could be made under the rubric of an “Auditory Damage Index” and better inform permitting.

This came up after the first iteration of the acoustic guidelines – which did not differentiate between the various hearing groups. This shortcoming soon became obvious when dolphins were riding the bow waves of seismic survey vessels, and when research vessels ran afoul of the regulations for using signal buoys that exceeded regulatory thresholds while providing calibration signals for marine mammal monitoring.

Another important inclusion in the “2024 Update” is the appearance of the term “Kurtosis” to express sound quality factor correlated to noise impacts. It has been known for decades that kurtosis is an important variable in determining hearing loss due to noise exposure,² and it is clearly known that high kurtosis signals inflict more damage to hearing organs than equal energy signals in the same bandwidth, but with a lower kurtosis.³

Ascribing a clear numeric metric to a kurtosis variable has been a bit more challenging. ISO-1999:2013 specifies a method for calculating the expected noise-induced permanent threshold shift in the hearing threshold levels of adult populations due to various levels and durations of noise exposure. In Hamernik et al. (2003) for kurtosis with respect to time - $\beta(t) > 40$, and a fixed probability of a transient occurring, the degree of trauma as measured by asymptotic and permanent threshold shifts (ATS and PTS, respectively), and by sensory hair cell loss remained constant despite changes in the statistical characteristics of the noise exposure. $\beta(t)$ – kurtosis with respect to time is an expression of amplitude and $\beta(f)$ – kurtosis with respect to frequency. (Hamernik et al. (2003) does not indicate a difference in ATS, PTS, or Auditory Injury between $\beta(t)$ and $\beta(f)$ except to indicate a correlation between exposure frequencies and frequency-specific Outer Hair Cell loss.)

² Henderson, D., and R.P. Hamernik.1982. Asymptotic threshold shift from impulse noise. Pages 37 265-298 in Hamernik, R.P., D. Henderson, and R. Salvi, eds. *New Perspectives on Noise-Induced Hearing Loss*. New York: Raven Press.

³ Hamernik, R.P., W. Qiu, and B. Davis. 2003. The effects of the amplitude distribution of equal energy exposures on noise-induced hearing loss: The kurtosis metric. *Journal of the Acoustical Society of America* 114:386-395

So the challenge here is expressing trauma on the continuum between $\beta(t)=3$ (Gaussian distribution) and $\beta(t)=40$. The “fixed probability of a transient occurring” brings up another factor; in what time context does a continuous string of transients become “continuous noise.” Continuous noise is defined in the “2024 Update” from ANSI (2005) as “A sound whose sound pressure level remains above ambient sound during the observation period.”⁴ Under this definition, airgun surveys in the near field would not be continuous noise – even while some surveys continue for weeks to months on end.

Martin et al. (2020) suggests a time integral to express kurtosis of 1 minute,⁵ in which case airgun surveys – that typically create explosion bubbles every 7 – 15 seconds, would qualify as a high kurtosis “continuous signal.”

This may be a clear metric in terms of Auditory Injury from noise exposure, but may have little to do with behavioral disruption and the regulatory threshold set for “continuous noise.” In the context of behavioral disruption, the “one minute” integral is rather arbitrary from a phenomenological perspective. For example: If the observation period is 24 hours, and I had a neighbor who shot off a gun a few times a day, or reliably leaned into his car horn at 10pm every night for the entire time of his residence, at what point does this leave the realm of “impulsive noise” and become “continuous noise?”

Leaving the continuum between $\beta(t)=3$ (Gaussian distribution) and $\beta(t)=40$ in the “inbox” for the moment, how do we integrate a kurtosis variable that meaningfully informs the noise exposure thresholds?

While the “2024 Update” suggests (from Von Benda-Beckmann et al. 2022) that the applicability of the Goley et al. (2011) fitting parameter (λ) for marine mammals needs to be further investigated. But this itself may be somewhat arbitrary, given that Goley et al. (2011) data was derived from chinchillas, and correlated to humans – both species having “in air” hearing organs, and with the exception of the “in air” otariids and phocids, all of the other curves represent “in water” mammals.

Goley et al. (2011) suggests three variations of the “fitting parameter” adapted exposure metrics; one with no frequency weighting, and two with frequency weightings. These three yield a range for the λ “fitting parameter” between 3.07 and 4.04 for the frequency weighted equations, and 4.80 for the non-weighted fitting parameter.

⁴ ANSI (American National Standards Institute). 2005. Measurement of Sound Pressure Levels in Air (ANSI S1.13-2005). New York: Acoustical Society of America.

⁵ S. Bruce Martin, Klaus Lucke, and David R. Barclay (2020) Techniques for distinguishing between impulsive and non-impulsive sound in the context of regulating sound exposure for marine mammals. *J. Acoust. Soc. Am.* 147 (4)

I would propose that the “A weighted” and the “.5,1,2,4kHz” frequency weighting be eliminated; The “A-weighted” curve being specifically adapted to human hearing, and the “ L'_{5124} ” weighted to Noise Induced Hearing Loss (NIHL) in frequencies more important to OSHA than to marine mammals. This leaves the unweighted formula:

$$L'_{eq} = L_{eq} + \lambda \text{Log}_{10} \frac{\beta}{\beta_G}$$

I also suggest that this kurtosis metric be implemented in the “2024 Update,” and following the 1-minute integral per Martin et al. (2020). It is a much-needed refinement, and implementing it will allow for further investigation of its use.

To date, all exposure thresholds have been based on operant conditioning and Auditory Evoked Potential (AEP) and Auditory Brainstem Response (ABR) testing using low kurtosis, band-limited gaussian noise, or sinusoidal signals which are rarely represented in the signals and noise to which we subject marine life. Arguing that there is not enough known about the Goley et al. (2011) “fitting parameter” to implement it flies in the face of using such simple signals to determine accurate audiograms of animals.

Using the $\lambda=4.8$ only lowers the exposure threshold by 7.7dB when $\beta(t)=40$, which is all we might need if – according to Hamernik et al. (2003), increase of $\beta(t) >40$ does not significantly change ATS, PTS, or Auditory Injury.

Regarding the M-derived curve for Low Frequency Cetaceans; we are excited to hear that the National Marine Mammal Foundation has collected hearing data on Minke whales and enthusiastically await the release of these data (although the provenance from Norway – a whaling nation, does not warm my heart). I’m sure this will shed much needed light on how the *Balaenoptera* hear – at least the Minkes. But it is good to bear in mind that the *Balaenoptera* are just one genus of whale, and use sounds in ways differently than *Megaptera*, *Eschrichtius*, *Balaena*, or *Eubalaena* do.

This is represented in the various sounds they make, their behaviors, and their various physiologies. Unfortunately confirming the reasons for these differences is caught up in the same conundrum of testing and confirmation of their hearing capabilities; it is hard-to-impossible because these animals are just too large to comfortably take into a lab to ‘isolate the inputs,’ so we have to look at their habitats and behaviors, and conjecture how these various characteristics are represented in physiological (and behavioral) adaptations to their preferred environments.

One of the initial considerations which has never been taken into account in evaluating marine animal auditory thresholds is that the acoustical impedance differences between all sea creature's bodies and the water that surrounds them is not all that great. So while marine mammals do have auditory bullae, (for example), they also have other acoustic-sensory pathways that stimulate features of their bodies. These include vibrissae, extensive and large trigeminal nerves, bone conduction,⁶ tubercles on *Megaptera*, and enervation of the boundary between their hypodermic blubber (which in the *Eschrichtius* encapsulates their mammal hair).

These various acoustical pathways extant in various species - evolved as adaptations to their preferred habitats. Right whales and gray whales typically inhabit coastal areas in shallow water above the continental shelf, for example. Their phonations do not enter into the realm of "infrasonic" wavelength, because these long wavelengths are not useful in the shallower waters that these animals inhabit.

But *Megaptera* and *Balaenoptera* migrate across ocean basins where long wavelength phonations and infrasonic sound perception would be useful - bouncing long wavelength sounds off of distant geological features in a form of long-distance echolocation,⁷ or using the infrasonic pulse of waves and flow of currents as navigation cues.

Meanwhile *Eschrichtius* and *Megaptera* both have complex rostrums that include maxillary and pre-maxillary bones that are intricately hinged into their craniums through deep cranial sulci. These bones wrap around a remarkably large meso-rostral pocket which is an envelope for lipids which have been termed "acoustical lipids" in both odontocetes⁸ and mysticetes.⁹ The lipids in this meso-rostral envelope terminate through a porous boundary posterior to the meso-rostral pocket and leading into the inner cranium. While again we have no way of testing this organ, it strongly suggests some form of perpetual complexity.

Balenaptera do not have this complex structure, and while they do have a meso-rostral groove, also filled with fatty lipids, it is not so pronounced and they do not have the pre-maxilla or the complex maxilla hinging found in the *Eschrichtius* and *Megaptera*.

⁶ Per Cranford and Krysl (2015)

⁷ Clark CW and Ellison WT (2004) Potential use of low frequency sounds by baleen whales for probing the environment: Evidence from models and empirical measurements. In: Thomas, JA Moss C.F. and Vater M. (eds) Echolocation in Bats and Dolphins. Chicago, IL: University of Chicago Press.

⁸ Carter Litchfield, Anne J. Greenberg, David K. Caldwell, Melba C. Caldwell, J.C. Sipos, R.G. Ackman (1975) Comparative lipid patterns in acoustical and non-acoustical fatty tissues of dolphins, porpoises and toothed whales. Comparative Biochemistry and Physiology Part B: Comparative Biochemistry. V. 50:4

⁹ Maya Yamato, Darlene R. Ketten, Julie Arruda, Scott Cramer, Kathleen Moore, (2012). The Auditory Anatomy of the Minke Whale (*Balaenoptera acutorostrata*): A Potential Fatty Sound Reception Pathway in a Baleen Whale. The Anatomical Record. Volume 295, Issue 6.

This is all by way of saying that while the Norwegian data on the Minke will inform our understanding of how Minkes hear, there is much more to know, and that the model of auditory adaptations upon which the NOAA Guidelines are built remain simplistic and incomplete. This would suggest that while the Minke whale data may inform the general mysticetes auditory model, it should not limit it, if, for example it is found that the low frequency auditory threshold of the Minke is higher than the current general model suggests.

We do appreciate that the 2024 Guidelines remain open in terms of the Low Frequency curve, and the cumulative exposure L_{24hr} metric. Nonetheless we remain uncomfortable with the existing Low Frequency roll-off curve an f_l set at 412 Hz (“2024 Update,” Table 3). While the revised exposure threshold curves are more conservation-minded than the curves originally proposed in the July 2015 Guidelines, they are still more a product of assumptions and conventions than of any substantiating research or evidence. For example, given that a preponderance of blue whale vocalization occur below 19Hz¹⁰ and humpback whales also vocalize well below the f_l of 412Hz,¹¹ there is no reason that the LF weighting function should roll off at 412Hz.

The arguments in the “2024 Updates” are necessarily a composite of a number of assumptions: Bone conduction models from Cranford and Krysl (2015),¹² physiological models from Ketten and Mountain (2009)¹³ and Parks et al. (2007),¹⁴ and comparative physiology from Heffner and Heffner (1982).¹⁵

First off, Heffner and Heffner (1982) should be thrown out, especially as an argument that animals vocalize well below their auditory sensitivity, because they used an in-air loudspeaker aimed at the elephant’s ears, and it has since been established that elephants have a low frequency acoustical pathway through their feet – both to communicate through infrasonic phonation, and to perceive seismic vibrations of their conspecifics over long distances.¹⁶

¹⁰ David K. Mellinger, Christopher W. Clark, Blue whale (*Balaenoptera musculus*) sounds from the North Atlantic J. . Acoust. Soc. Am., Vol. 114, No. 2, August 2003

¹¹ James D. Darling Low frequency, ca. 40 Hz, pulse trains recorded in the humpback whale assembly in Hawaii J. Acoust. Soc. Am. 138 (5), November 2015

¹² Cranford, T.W. and Krysl, P. (2015). “Fin whale sound reception mechanisms: Skull vibration enables low-frequency hearing,” PLoS ONE 10, 1-17.

¹³ Ketten, D.R. and Mountain, D. (2009). “Final report: modeling minke whale hearing,” (submitted to 9 E&P Sound and Marine Life Programme).

¹⁴ Parks, S.E., Ketten, D.R., O’Malley, J.T., and Arruda, J. (2007). “Anatomical predictions of hearing in the North Atlantic right whale,” Anat. Rec. 290, 734–744.

¹⁵ Heffner, R.S. and Heffner, H.E. (1982). “Hearing in the elephant (*Elephas maximus*): Absolute sensitivity, frequency discrimination, and sound localization,” Journal of Comparative and Physiological Psychology 96, 926-944.

¹⁶ O’Connell-Rodwell, C. E., Hart, L. A., & Arnason, B. T. (2001). Exploring the potential use of seismic waves as a communication channel by elephants and other large mammals. American Zoologist, 41, 1157–1170.

O’Connell-Rodwell (2001) is also a substantiating argument for secondary auditory pathways, where the wavelengths may be too long to be resolved in the cochlea, and are rather bone-conducted into the body of the animal, which is the case that Cranford and Krysl (2015) make,¹⁷ albeit their proposed audiogram also falls apart as the frequencies get lower.

Neither of the other two citations stand on their own, for reasons expressed in the “2024 Updates.” Ketten and Mountain (2009) was based on Ketten’s previous work modeling human hearing, using from a continuation of her earlier work on modeling the human cochlea (e.g. Ketten et al 1998),¹⁸ and built off the “Greenwood Function:”

$$f = \int_0^x \Delta = A(10^{ax} - K)$$

Where:

- f is the characteristic frequency of the sound in hertz.
- a is the slope of the straight-line portion of the frequency-position curve, which has shown to be conserved throughout all investigated species after scaling the length of the cochlea.
- x is the fractional length along the cochlear spiral measured from the apical end of the cochlea to the region of interest. $0 < x < 1.0$
- K is a constant of integration that represents the divergence from the log nature of the curve and is determined by the lower frequency audible limit in the species.

And where “suitable” constants (for humans) $A = 165.4$, and $a = 0.06$ (if x is expressed in *mm*) or 2.1 (if x is expressed as a proportion of basilar length).¹⁹

The shortcoming with this model is that while it seems to be a good predictor of mid and high frequency hearing acuity, the accuracy gets a little wooly as the frequencies go lower, and does not take into account any potential secondary auditory pathways. It also turns out the a and x are variables adjusted to fit the data – in humans, and matched to cats and chinchillas – all in-air species, making the resolution of this model looser at the longer underwater wavelengths.

¹⁷ Cranford, T.W. and Krysl, P. (2015). “Fin whale sound reception mechanisms: Skull vibration enables low-frequency hearing,” PLoS ONE 10, 1-17.

¹⁸ Ketten, D. R., Arruda, J, Cramer, S., Yamato, M., Zosuls, M., Mountain, D., et al. (2007). How low can they go: Functional analysis of the largest land and marine mammal ears. [Presentation abstract.] 17th Biennial Conference on the Biology of Marine Mammals, Cape Town, South Africa.

¹⁹ Donald D. Greenwood (1990) A cochlear frequency-position function for several species—29 years later. J. Acoustical Society of America. 2592–2605 <https://doi.org/10.1121/1.399052>

This is also the model used in Parks et al. (2007), which punctuates Right whale phonations at 10 Hz – which in C.M. Binder et al. (2021) appears to be a significant phonation range.²⁰

The predictive audiogram in the “2024 Updates” takes the “middle road” by averaging the various predictions cited in Appendix A.2 “Estimating the Low Frequency Cetacean Audiogram,” which I find baffling. The summary statement:

“Together, these model results broadly suggest best sensitivity (thresholds within ~3 dB of the lowest threshold) from ~1 to 8 1 kHz, and thresholds within ~40 dB of best sensitivity as low as ~30 Hz and up to ~25 kHz.”

...misses a clear opportunity. With a significant portion of Right whale phonations being in the 10 Hz band, it would seem that using this empirical data as a guide would be much more accurate than laying a bunch of predictions on top of each other and coming up with some numbers.

Shifting the low frequency hearing extent from the modeled 30 Hz to the empirical 10 Hz would shift f_l down a bit more than an octave – and a half, resulting in f_l being set to ~137 Hz (if there a linear correlation with f_l and low frequency acuity). Incorporating Blue whale 4 Hz phonations into this model would shift it even lower.

In the absence of any other compelling evidence, logic (and precaution) would dictate that the LF weighting function would not roll off as high as the “2024 Updates” weighting curve suggests. This is particularly in light of the argument above about multiple auditory pathways, different genus using and perceiving sound in differing ways, and including the informed speculation of Clark and Ellison, (2004) of mysticetes using infrasonic sounds as locating and navigating cues.

While the “2024 Update” is specifically focused on assessing “Criteria for Onset of Auditory Injury and Temporary Threshold Shifts,” more research will be needed on the “Level B” behavioral impacts of various continuous noises. This will increasingly come up as underwater acoustical communication systems are deployed. Unlike the continuous mechanical noise of seafloor processing equipment used in the extraction of fossil fuel, or the continuous broadband noise of marine vessels, digital communication signals run the possibility of being high kurtosis signals which, while not necessarily above an auditory injury threshold, are likely to produce elevated behavioral impacts. In Kastelein et al. (2005), behavioral disturbance was evoked by digital communication signals the were at

²⁰ Carolyn Margaret Binder; Dugald J. M. Thomson; Zachary Wallot-Beale; Jeff T. MacDonnell; S. Bruce Martin ;Katie A. Kowarski; Eric Lumsden; Briand Gaudet; Hansen Johnson; David Barclay (2021) Employing Royal Canadian Air Force Sonobuoys for Passive Acoustic Monitoring of Whales. Proc. Mtgs. Acoust. 44,

or below 130dB re:1 μ Pa.^{Ref. 21}

The subject animals were exposed to various high frequency signals at 116dB, 123dB, and 130dB, 1 meter from the source – so even quieter at the subject animals, which were trying to evade the noise source. Assuming that the kurtosis for these signals was above $\beta=40$, using Goley et al. (2011) “fitting parameter” of $\lambda=4.8$, the kurtosis-adjusted equivalent exposure signals would be 123.7dB, 130.7dB, and 137.7dB respectively.

The Kastelein et al. (2015) “Discomfort thresholds” were even lower than these signals, (between 97dB and 111dB) so there needs to be clearer – and much more conservative exposure guidelines for digital signals taken into account for “Level B” behavioral disruption. But we’ve known for some while now, that the noise of our activities are disruptive at even lower levels than we care to admit.²²

Of course this brings us to this point of considering what we are actually trying to accomplish. If residential noise ordinances were established around how much damage we could legally inflict on our neighbors, our neighborhoods would be completely different places. But here we are, giving ourselves permission to damage wildlife and habitats because some of the damage is “recoverable.” And what isn’t recoverable, well ‘it’s worth the sacrifice because we need to burn up more energy, prepare for important wars, and convert ocean minerals into money.’

But this is the blunt tool we get to work with, in the hopes that the damage we inflict does not irretrievably destroy the habitats we share with ocean life. Unfortunately the NOAA Acoustic Guidelines have always been a decade behind the science, so those of us focused on conservation know, and see plain evidence that we are exacting higher damage than what is intended “on paper.”

Although it is hopeful to see the inclusion of the term “kurtosis” finally appear in the document, for a metric that has been acknowledged for decades, it should be about time that we start using it.

It is also encouraging that the term “Auditory Injury” is being included – in recognition that hearing damage is more nuanced than just a loss of the ability to hear certain pitches. We also await the synthesis of the Norwegian Minke whale data, to see how it informs the

²¹ Kastelein, R.A., W.C. Verboom, M. Muijsers, N.V. Jennings, S. van der Heul. (2005) The influence of acoustic emissions for underwater data transmission on the behavior of harbour porpoises (*Phocoena phocoena*) in a floating pen. *Marine Environmental Research* 59 p.287–307

²² Blackwell SB, Nations CS, McDonald TL, Thode AM, Mathias D, Kim KH, et al. (2015) Effects of Airgun Sounds on Bowhead Whale Calling Rates: Evidence for Two Behavioral Thresholds. *PLoS ONE* 10(6): e0125720. doi:10.1371/journal.pone.0125720

Low Frequency Cetacean curves.

In summarizing our critique of the “2024 Updates,” substantiated by the foregoing arguments, we suggest the following:

- The guidelines should migrate away from TTS and PTS as threshold qualifiers and toward an “Auditory Damage Index” inclusive of long-term hearing degeneration as a result of chronic or periodic exposure to anthropogenic noise.
- Kurtosis with respect to time $\beta(t)$ and with respect to frequency $\beta(f)$ should be incorporated into the exposure metric.
- We suggest that the Goley et al. (2011) “fitting parameter” (λ) of 4.8 be used for kurtosis $\beta(t) > 40$ and/or $\beta(f) > 40$.
- We suggest that the time integral for kurtosis be 1 minute, unless the dynamics of the sound can’t be captured in that timeframe, in which case it should be expanded to capture the Δt of the noise.
- The kurtosis metric should be applied to both impulsive and continuous noise.
- Lacking a better integral for kurtosis between 3 and 40, a linear transfer function for the “fitting parameter” λ between 0 and 4.8 should be employed until more empirical data correlates kurtosis with hearing damage when $3 < \beta < 40$.
- In the predictive LF Cetacean audiogram, f_l should be shifted down to 137Hz.
- NMFS “Level B” behavioral impacts need to be reviewed in light of the progress that has been made on sound qualities and acoustical behavioral disruptions.

These recommendations would make the “2024 Updates” more current with the best available science.

Sincerely,



Michael Stocker
Director