Examination and evaluation of the effects of fast rise-time signals on aquatic animals.

(Notes for presentation to the Acoustics Society of America Meeting, December 2006 Honolulu, Hawaii. This presentation accompanied a "power point" slide show.)

Chapter 1: Metrics.

I am honored to be here this afternoon, in a room that includes people whose work I have followed over the years and whose papers I have been busily cribbing and cramming in the last few weeks.

When I submitted the abstract for this presentation last June, I didn't realize what a huge bite I took into one of the golden rings of marine animal bio-metrics. I was under the impression that I would be able to spend a few weeks reading through the published papers, correlate the findings with some of my assumptions and come out with a pretty solid argument for the evaluation of rise time to determine the impacts of human generated noise on marine animals.

As I rolled up my sleeves a few weeks back I became increasingly anxious to realize that there is a paucity of peer reviewed data or mathematical models on marine animal hearing mechanisms or even models of tissue compliance. The dearth of data was so bad that in one paper the authors used a ham to examine and model tissue response to acoustic energy.

I want to thank Art Popper who I called hoping to alleviate my anxiety. He assured me that there was even less peer reviewed literature on my topic than I had assumed, so not too long after our conversation I realized that I needed to take a light tack on my presentation.

My initial incentive for digging into this topic involved anecdotal accounts of the different impacts on animals exposed to different impulse noises of equivalent energy levels. I was talking with John Diebold with LDOE about his early days of seismic surveys. He said that the early practice was to toss a stick of dynamite over the transom and record the return signal – to the accompaniment of seagulls feeding on the fresh fish kill floating up to the surface. The current practice of airgun surveys is an apparent improvement over the dynamite technique – at least in terms of the instantaneous mortality issue.

Other accounts of the impacts of black powder on salmon, or the relative fish mortality between concrete and steel pile-driving operations highlighted the obvious; that the crest factor of various signals has a bearing on the relative damage to the subject animals.

I thought that the 50-60 years of research on this issue would yield a wealth of data to mine to come up with some way to mathematically express this characteristic so I started parsing through the books and journals.

The first clue I got that there was something amiss was the abundance of metric standards – and the range of differences between the various exposure metrics and the resulting observed impacts on an array of animals.

For example, any or all of these dB references for pressure standards will be found in the papers. Re: 1µPa, re: 1µPa^2-s re: 1µPa (peak) and re:1µPa (rms), used in conjunction with dB_{SPL}, "Total Energy Flux" - E_T,[1] "energy flux density" E_F, and "Sound Exposure Level" SEL.

All of these are useful in their various contexts, but when they play together to express biometrics, they can confuse us.

Particle velocity metrics are not as ambiguous. This is probably due the computational nature of the metric, coupled with the unavailability of off-the-shelf 'particle velocity meters.' Nonetheless, a true "energy flux density" incorporating particle velocity would be helpful.

A second challenge was coming up with good biological impact data. I should have anticipated this, because over the years there have been many different ways of performing audiograms on marine animals.[2] Trained behavioral techniques, startle response, in-habitat avoidance behavior, heart rate monitoring and "Acoustic Evoked Potential" and "single cell response" are all found in the literature.

The test environments are equally as diverse: From open ocean observation to sea cages, to open and closed wave guides, to aquariums of various dimensions and water baths on vibration isolated tables.

And then there is the various excitation signals used; from pure sinusoidal signals, amplitude modulated sinusoidal signals (SAM) to band limited pink and white noise, but all framed in the context of pitch discrimination. I am going to go out on a limb here, but I feel that this is pretty important.

We know that marine mammals – like all mammals – have a cochlea that allows them to discriminate pitch. Fish do not have such a clear-cut pitch discrimination organ; nonetheless many fish need to evaluate a complex auditory scene with what appears from the literature as a fairly narrow band of frequency sensitivities (except the shad[3]). I believe that if we looked at fish acoustical sensitivities in the time domain rather than in the frequency domain, with a focus on discrimination between particle velocity and pressure gradients in a signal, we might find the "stream segregation" cues that Bregman[4] suggests is required for proper auditory scene analysis.

I have also noticed a recent trend away from determining sensitivity thresholds of animals to determining the thresholds of biological damage. The upper limits of these 'impact metrics' are the thresholds for tissue damage, and temporary or permanent threshold shifts in the subject animals. There is also quite a range in the numbers here. This is largely due to the vagaries of the testing procedures, the variability of the test subjects, and the identified need for the information – along with the aforementioned variety of sound pressure metrics.

TTS and PTS threshold data are really important, but as a conservationist, I personally don't feel that destructive thresholds are the best starting place for determining the biological impacts of introduced noises on the habitat. For me a reasonable starting place lies in the determination of perceptual thresholds of the subject animals, then examining their biological (or physiological) response while raising the levels to determine how – and to what degree their survival abilities are compromised. This task is perhaps more cumbersome than destructive testing, but it does more directly address a leading purpose of the inquiry – how to limit habitat damage in our use of the sea.

This is a bit of a digression from the matter of establishing rise time metrics, but the point is that my original ambition was constrained by the lack of unified standards. Fortunately as our information needs are becoming clearer, unified standards are beginning to appear.

These four panels developed by Greenridge Science give a pretty clear idea of what is being measured. The spectral component is the foundation of a metric that we are developing that aims to expand spectral displays into a biological impact metric.

The foundation of this metric is well established in architectural acoustics in the form of "Noise Criteria" or NC curves. These are simply a set of curves that are drawn from human perception that provide guidance to architectural acousticians in the design of habitable spaces.

Our proposed ONC chart works under the same premise of establishing critical biological perceptual levels and using them as guidance in how we ensonify the ocean. This chart is merely a placeholder for future work. The bold lines are from Wenz[5] and represent the upper and lower limits of the prevailing noise levels in the ocean as a product of environmental conditions. We can safely assume that sea animals are biologically adapted to these noise levels. The lines above the upper bold line are somewhat arbitrary at the moment – extrapolated from the Wenz data, but are in place to illustrate the function of the chart.

In a better world the Y axis would be acoustical energy flux density. In a perfect world the chart would consist of three axes, with the Y axis being pressure, and the Z axis particle velocity. This would assume that the metric would be an actual "receive level" for the subject animals, but I believe we have yet to develop some new technologies before this happens.

The first step in detailing out the chart will involve integrating biological noises across the spectral bands such as vocalizations of various animals in their habitat, and collating what we know about threshold shifts and tissue damage in various animals.

So how does this chart work in terms of rise time? On my initial trajectory through this inquiry I was looking at rise time in terms of impulse response and acoustical compliance of the subject tissues and organs. I thought that I would be able to derive a set of curves to represent impulse response, and acoustical compliance of biological systems from hearing thresholds through tissue damage. Then I could draw a set of possible rise times and come up with a set of integrals expressing rise times against permissible impacts.

But as I mentioned before, it wasn't long before I found myself in the weeds of gray literature and unsubstantiated assumptions. I realized that by working from an "animal generated noise" starting point, I would run a better chance of filling in the data with measurable signals found in nature. We can safely assume that sea animals are biologically adapted to these signals – even prey animals that are killed or stunned by the noises of their predators.

Once the basic spectral curves are established we can run fast rise time or high crest factor signals through FFT and derive their spectral components. As the basic biological curves come into focus on the ONC chart they can give us some guidance on how our introduced noises intersect biological sounds – and presumably animal perception at least in terms of sound pressure.

What this chart will also display is the harmonic content of high crest factor signals. We can see high kurtosis sounds – when something is particularly "peaky." This may alert us to signals which may not be particularly loud, but are not in the typical envelope of biological sounds – such as the sound of fingernails scraping a blackboard.

Human response to "peaky" sounds is alarm. Many terrestrial animals share this in their vocal repertoire in that screeching sounds are sounds of alarm and panic. It will be interesting to see as we develop this metric if there is a correlation between high kurtosis signals and avoidance behavior in sea animals. This is important because many of the new technology communications signals are quite peaky, like this simulated FSK burst.

These signals are run through a math utility developed in C++ that takes signal derivatives and performs FFT on them. Currently we have to paste the output into an excel sheet to get the graph, but now that the deadline is over we will go back and give the tool some proper input and output features.

Other "next steps"

- Assemble database of marine biological sounds across the spectrum.
- Fill in "ONC Curves" above the Wenz maximum line as data become available.
- Evaluate biological acoustic thresholds in the time domain.
- Modify "ONC Curves" to reflect these data.
- Expand "ONC Curves" into the "Z" axis to represent particle velocity.

After the first week into this paper I was worried that I would come up empty handed. I hope that we have at least provided a fresh perspective at evaluating the impacts of anthropogenic noise on marine animals.

I want to thank my co-author Tom Reuterdahl for programming and hashing out the math models through this work. I also want to thank you all for your patience and many of you for you impeccable and sterling work towards understanding marine bioacoustics.

[1] James Finnerran, Carolyn E. Schlundt, Randall Dear, Donald A. Carder, and Sam H. Ridgway 2002. "Temporary shift in masked hearing thresholds in Odontocetes after exposure to single underwater impulses from a seismic watergun." JASA v. 111.

[2] Edmund Prince Fowler, (See: "Is the Threshold Audiogram Sufficient for Measuring Hearing Capacity?" 1943. JASA Vol.13 No.1 p. 57 – 60). "…the hearing mechanism is not just an electrical hookup."

[3] David A. Mann, Dennis M. Higgs, William N. Tavolga , Marcy J. Souza and Arthur N. Popper "Ultrasound detection by clupeiform fishes" 2001 JASA v.109(6)

[4] A.S. Bregman "Auditory Scene Analysis: the Perceptual Organization of Sound" 1990, MIT p.53

[5] Wenz, G.M. "Acoustic ambient noise in the ocean: Spectra and sources. 1962 JASA v.34