MARINE MAMMALS, NOISE, AND SONAR IN SHALLOW COASTAL BUBBLY WATERS

D C Finfer ISVR, University of Southampton, Southampton UK
T G Leighton ISVR, University of Southampton, Southampton UK
P R White ISVR, University of Southampton, Southampton UK

1 INTRODUCTION

Recent events, including the stranding of a beaked whale in the Thames River[1] and the occurrence of several mass strandings off Cape Cod so far this season[2], have highlighted to the public the importance for the scientific community to continue to research and document the relationship between marine mammals and sound[3]. One environment in which the acoustic abilities of cetaceans are poorly understood is the near-shore coastal zone.

Acoustically, the surf zone is fraught with difficulties. The eventual convergence of the undulating reflecting air-water interface and the sea-bottom creates a wedge-shaped space which leads to a series of closely spaced image reflections in a near-circular geometry[4]. The distribution of small bubbles throughout the water-column causes further confusion. As air-sea interactions cause bubbles to be entrained into the water flow, each one will contribute its own size-dependent ringing sound. It is the superposition of millions of such events that will dominate the spectrum observed by the user of passive sonar in the surf zone. To the user of active sonar, the bubbles scatter, absorb, and otherwise distort impacting sound waves. As a result, the acoustical environment of the surf zone presents a great contrast to the cold, deep, bubble-free, and often quiet regions of the ocean depths.

Recent work within our research group has focused on attempting to understand how cetaceans, particularly odontecetes, might exploit nonlinear bubble dynamics to navigate and hunt near and under breaking waves. One way to consider this problem is from the perspective of the basic sonar equation, as given by Urick [5]:

$$\mathrm{SL}-2\mathrm{TL}+\mathrm{TS}=\mathrm{NL}-\mathrm{DI}+\mathrm{DT} \qquad (1)$$

where SL is the Source Level, TL represents the one-way Transmission Loss from the source to the target, TS is the Target Strength, NL is the Noise Level within the environment, DI is the source Directivity Index, and DT is the Detection Threshold of the system.

In the reverberation limited case, the term NL-DI is replaced by the Reverberation Level, RL, so that the appropriate equation instead becomes

$$\mathrm{SL}-2\mathrm{TL}+\mathrm{TS}=\mathrm{RL}+\mathrm{DT} \qquad (2)$$

The size-dependent evolution of the spatial distribution of bubbles below breaking waves dictates that the reverberation in the surf zone is time-dependent; and furthermore that in waters where there might be long pauses O(1 min) between wave-breaking events, a sonar system might cease to be reverberation limited and become noise limited. This renders both Eqns. 1 and 2 relevant to the following discussion.

Through vocalisation, self-positioning behaviour, and mental processing, 6 of the 7 terms appearing in Eqns. 1 and 2 could conceivably be controlled by an active odontecete. The obvious exception from the set is Target Strength, which is not a function of source/receiver characteristics, but only a matter of what happens to be ensonified. As such, this paper will not consider Target Strength in detail.

This analysis will first review the characteristic pulses emitted by cetacea in the surf zone to address the issues of Sound Level and pulse shape in conjunction with Detection Threshold, and then Directionality Index in conjunction with Reverberation Level. Transmission Loss will then be discussed in conjunction with the "sonar platform" advantage realised by a mobile animal. Finally, the Noise Level in coastal waters will be discussed, and it will be shown that some standard methods for comparing underwater noise to airborne sound are not well-founded.

2 SOUNDS CREATED BY CETACEANS IN COASTAL WATERS

2.1 Dual pulse methods

One of the challenges confronting an odontecete hunting and navigating in the surf zone is the presence of large numbers of bubbles. To the user of conventional sonar equipment, the presence of bubble clouds can render conventional target-location efforts useless for the purpose of finding solid targets. This difficulty is due largely to two problems: (1) Bubbles scatter sound *en masse*, in a fashion not dissimilar to what one would expect from an acoustic field filled with several million small, slow moving targets and (2) Once within a bubble cloud, imaging sonar signals are attenuated very quickly O(100 dB m^{-1}).

The high-amplitude dual pulse method has been proposed as a way of exploiting non-linear bubble dynamics for the purpose of locating targets in bubbly water[4]. The referenced method requires that the dual pulse consist of a sound (P_{in}) followed immediately by a switched-polarity version of that sound ($-P_{in}$), as illustrated below in Figure 1.

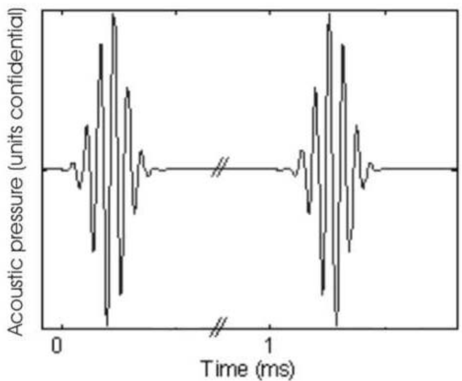

Figure 1. This figure shows the dual pulses proposed[4] for acoustic penetration of bubble clouds. The dual-pulse method requires that a pulse be emitted, and then followed a short time later by a switched polarity version of the first pulse. The pulses must be identical opposites, and high in amplitude. The high amplitude excitation gives way to nonlinear scattering by bubbles. The large stiffness of fish swim-bladders (in comparison to the wall of a gas bubble) suggests that there is an amplitude regime in which, for the same pressure excitation, a fish will scatter linearly while surrounding bubbles will scatter nonlinearly. It has been shown computationally that bimodal distribution in scattering behaviour can be exploited in the processing to reveal the presence linearly scattering targets.

The use of such a method would have interesting ramifications indeed for an odontecete sonar system. If odontecetes are capable of exploiting nonlinear bubble dynamics, the switch from a simple single pulse echolocation system to an advanced dual-pulse system (and the associated improved processing) would allow for a corresponding reduction in detection threshold as a result of bubble response suppression. Indeed, Au[6] has observed "double-" and "multiple-" pulses in conjunction with the presence of certain odontecetes. The characteristic absolute amplitude of such pulses is not known, and it is not entirely clear if these multiple pulses are emitted by the animals in question, or are a result of reflections.

2.2 Reverberation near bubble clouds

Bubbles influence strongly reverberation characteristics in the ocean[7]. For the environment beneath a breaking wave, the reverberation will vary with time, as wave activity affects bubble size population distribution[8]. When a large wave breaks, large bubbles with radii O(100 μm) are injected as deep as a few meters into the water column. As observed by Thorpe[9], "the bubbles carried downwards to even a 1 meter depth are very small, although clouds extend to many metres."[10] Local turbulence effects within the water column can dictate that these smaller bubbles actually get dragged to depths much below their injection depth before they are either dissolved within the water or are released to rise.

Volume reverberation theory dictates that, for a medium with randomly distributed backscattering elements, an increase in directionality will result in a reduction of the amount of backscattered sound[5]. Accordingly, for a monostatic system to be effective in a highly reverberant environment, the co-located source and receiver should be highly directional.

Interestingly, the send and receive beam patterns observed for many *odontecetes* are quite impressive. Consider for instance the bottlenose dolphin, which at 30, 60, and 120 kHz has been observed to have a receiving pattern with 3 dB bandwidths[11] of 30.4°, 22.7°, and 17.0°. The emit radiation patterns for bottlenose dolphins are so impressive that they have been compared to the adaptive beamformers used in some multi-element sonar operations [12].

3 NOISE IN THE COASTAL ZONE

Sonar, noise, and marine mammals have long been connected in underwater acoustics research, as some links have been established between the use of military sonar and the stranding of cetaceans. Cuvier's beaked whale *Ziphius cavirostris* is thought to be particularly vulnerable to stranding. From 1996-2003, 5 of the 11 strandings involving at least 2 Cuvier's beaked whales were linked to naval manoeuvres. A further 2 strandings were linked to seismic surveys, but the cause of 4 of those strandings continues to remain a mystery. Tragically, in one of these apparently sourceless strandings, as many as 8 beaked whales were found along Greek beaches[3]. This suggests either (or both) that (1) some human activities other than Naval Sonar are capable of triggering mass strandings; (2) mass strandings occur in the complete absence of human intervention.

Scientific misunderstanding can breed hostile and misinformed fingerpointing. In the case of the ill-defined links between common sonar practices and marine mammal stranding, comparisons between the sounds heard by cetacea in the presence of sonar, and the sounds heard by humans in the presence of turbomachinery and/or space rockets are not uncommon. Consider for instance a statement in a press release published by the National Resources Defence Council[13] (a US-based environmental lobby group) in October 2005:

> Mid-frequency sonar can emit continuous sound well above 235 decibels, an intensity roughly comparable to a Saturn V rocket at blastoff.

In considering the validity of such a claim, it is interesting to analyse how the conclusions are drawn regarding parables between airborne and underwater sound. Generally, underwater acoustic data are expressed in decibels with reference to 1 μPa, whilst air borne noise data are referenced to 20 μPa. The transfer from dB re 1 μPa to dB re 20 μPa is straightforward, as

$$10\log_{10}\left(\frac{P_2}{P_1}\right)^2 = 20\log_{10}\left(\frac{1\ \mu\text{Pa}}{20\ \mu\text{Pa}}\right) = -25.5\ \text{dB} \approx -26\ \text{dB} \qquad (3)$$

However, it is not sufficient to simply subtract 26 dB from an underwater level to make a viable comparison to an airborne sound. The specific acoustic impedance of water (given by the product *ρc*, where *ρ* is the density of the medium and *c* the sound speed) is some 3600 times greater in water than in air. So that

$$10\log_{10}\left(\frac{\rho_\mathrm{w}c_\mathrm{w}}{\rho_\mathrm{a}c_\mathrm{a}}\right)=10\log_{10}\left(3600\right)\approx -36\text{ dB} \qquad (4)^{a}$$

where the subscript "w" denotes the value of the specified quantity in water, and "a" the value of the specified quantity in air. Taking the sum of the two 'correction' quantities, one might draw the conclusion that, to 'convert' between an underwater sound measurement and its airborne equivalent, the underwater level referenced to 1 μPa should be lowered by 62 dB and the reference then simply switched to 20 μPa. In discussing this widely used conversion[b], Gisiner *et al.*[14] are helpful in pointing out that the very justification for the use of the conversion introduces difficult questions. In his words,

> One of the most interesting aspects of hearing in marine mammals is the fact that anatomically they follow much of the basic land mammal pattern, but they have also solved the fundamental problems of how to hear in water including the attendant complications for acoustic cues; *e.g.*, increased pressures and shortened interaural arrival times.

To further illustrate why such a conversion might be inappropriate, let us translate the underwater noise on a coral reef into an in-air equivalent as rated by the Noise Rating Curves (a simplistic but widely used system for expressing the magnitude of ambient noise signals as a single number). Consider then the noise that would be encountered by a human swimming in warm coastal water. In such an environment, the ambient acoustic spectrum is often dominated by so-called 'snapping-shrimp', in reference to a family of crustaceans, *Alpheidae*, in the genus *Synalpheus* [15]. The distinctive crackle made by snapping shrimp, which has been described[16] as being comparable to the "frying of fat", has been researched by several investigators. In their 1948 paper, Everest *et al.* recorded an acoustic spectrum, a portion of which is shown as white bars in Figure 1 depicting the sound pressure levels in octave bands between 200 Hz and 8 kHz.

The measured levels, shown in white, have first been corrected for the change in decibel reference value (Eq. 3) and then displayed in gray. These values have been further corrected to account for the difference in specific impedance between water and air (Eq. 4), and those values are shown in black. The spectrum is then displayed against the Noise Rating Curves to give an equivalent airborne Noise Rating. This method, while unorthodox, illustrates an important point. The final 'converted' values suggest that the ambient acoustic spectrum encountered by an observer in the water above a coral reef are comparable to NR 70. Interestingly NR 70 is the guideline for maximum acceptable noise level set forth by the UK Maritime and Coastguard Agency for the machine control room aboard a ship. That is to say, either the sound above a coral reef is comparable to an industrial environment, or the standard practice of subtracting 62 dB from an underwater sound level to give its airborne equivalent is overly simplistic to the point of distortion of information. Although such subjective comparisons are not rigorous, they indicate that it is no simple matter to transfer 'annoyance' levels of sound from one medium to another, even when we restrict it to one species: to make such comparisons with an interspecies transfer included (as is frequently done between humans and cetaceans) is unwise.

---

[a] The expression within the logarithm of Eq. 4 is not squared as intensity is an energy-based quantity. Contrarily, the expression within Eq. 3 is pressure-, not energy-, based; this necessitates that the ratio be squared.

[b] Many practitioners use 61.5 dB to convert between underwater and airborne sounds. 62 dB will be used in this analysis, but the approximation is trivial if not slightly conservative.

As a point of information, snapping shrimp are known to generate noise up to at least[17] 200 kHz. However, the argument presented here is concerned with a method of assessment for human perception of noise (the Noise Rating, or NR, family of curves in this case) which does not include sounds above the 8 kHz octave band, so acoustic information above that range has been neglected. This same noise perception assessment method specifies that acoustic information down to and including the 63 kHz octave band should be used to assessment, but detailed data regarding low frequency noise production snapping shrimp are not widely available. As such, the 250 Hz octave band is the lowest included in this study.

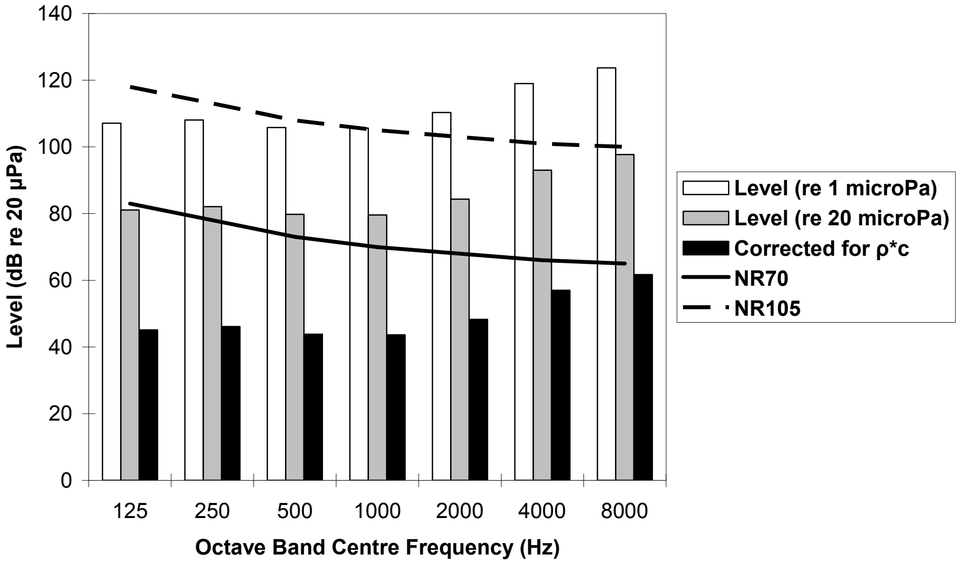

Figure 1. This figure uses the Noise Rating curves to shows why it might be inappropriate to suggest that subtracting 62 dB from an underwater sound pressure level "converts" that level to its airborne equivalent. To make this comparison as transparent as possible, the levels in each octave band are shown at three separate points during conversion. In white bars are shown unadjusted levels recorded in Kaneohe Bay by Everest *et al.*[18], where the ambient acoustic spectrum is dominated by snapping shrimp. To account for the fact that most acoustic measurements performed in water are referenced to 1 µPa, while those performed in air are referenced to the human threshold of hearing at 1 µPa, 26 dB is subtracted from the original levels to give the octave band levels illustrated by the gray bars. To account further for the difference in the specific impedance *ρc* from air to water (1.5e6 Pa s m^{-1} to 415 Pa s m^{-1}), the octave band levels are reduced by an additional 36 dB, for a net reduction of 62 dB per octave. These results are shown as black bars. The calculation indicates that according the conversion method indicated, the audible crackle of a coral reef might be rated as NR70; a level described in the Maritime and Coastguard Agency standard for good noise practice as being the maximum allowable in the control space for a ship's machine room[19].

4 CONCLUDING REMARKS

Having considered from the perspective of the sonar equation some aspects of sonar in the surf zone, it has been shown how many odontecetes are well-equipped to deal with the challenging acoustical environment encountered in the surf zone. Considerable progress remains to be made in developing a manufactured sonar system which is well-adapted to the surf zone. Large steps forward might be gained in the development of such a system through the continuing study of specificities with respect to how dolphins and porpoises navigate, hunt, and communicate.

Many practitioners lower underwater sound levels by ~62 dB to "convert" underwater sound levels to equivalent airborne levels. The Noise Rating (NR) system was applied to an ambient noise spectrum dominated by snapping shrimp to illustrate that such an adjustment is overly simplistic. The results indicated that it is no simple matter to transfer ‘annoyance’ levels of sound from one medium to another, even when we restrict it to one species: to make such comparisons with an interspecies transfer included (as is frequently done between humans and cetaceans) is unwise.

5 REFERENCES

1. P. Naughton, "Fears for the safety of whale stuck in Thames," in *Times Online,* (London, 2006).
2. C. Silva and P. McKenna, "13 dolphins beach themselves in Wellfleet: It was 7th mass stranding along Cape Cod this winter," in *The Boston Globe,* (Boston, 2006).
3. "Report of the IACMST Working Group on Underwater Sound and Marine Life," (Interagency Commitee on Marine Science and Technology, 2006).
4. T. G. Leighton, D. C. Finfer, and P. R. White, "Bubble acoustics: oceanic target detection problems and their biomedical counterparts," presented at the IEEE International Ultrasonics Symposium, Rotterdam, 2005 (In press).
5. R. J. Urick, *Principles of underwater sound,* 3rd ed. (McGraw-Hill, New York, 1983), pp. xiii, 423 p.
6. W. W. L. Au, *The Sonar of Dolphins* (Springer-Verlag, New York, 1993), p. 277.
7. T. G. Leighton, *The Acoustic Bubble* (Academic Press, London, 1994), pp. xxvi, 613 p.
8. T. G. Leighton, S. D. Meers, and P. R. White, "Propagation through nonlinear time-dependent bubble clouds and the estimation of bubble populations from measured acoustic characteristics," Proceedings of the Royal Society of London, Series A (Mathematical, Physical and Engineering Sciences) 460(2049), 2521-2550 (2004).
9. S. A. Thorpe, "On the clouds of bubbles formed by breaking wind-waves in deep water, and their role in air-sea gas transfer," Philosophical Transactions of the Royal Society of London A (Mathematical and Physical Sciences) 304(1483), 155-210 (1982).
10. S. A. Thorpe, "Bubble Clouds and the Dynamics of the Upper Ocean," Quarterly Journal of the Royal Meteorological Society 118(503), 1-22 (1992).
11. W. W. L. Au and P. W. B. Moore, "Receiving Beam Patterns and Directivity Indexes of the Atlantic Bottlenose Dolphin Tursiops-Truncatus," Journal of the Acoustical Society of America 75(1), 255-262 (1984).
12. W. E. Evans, "Echolocation by Marine Delphinids and One Species of Freshwater Dolphin," Journal of the Acoustical Society of America 54(1), 191-199 (1973).
13. "Navy sued over harm to whales from mid-frequency sonar," (Natural Resources Defense Council, 2005).
14. "Effects of Anthropogenic Noise in the Marine Environment," in *Proceedings of the Workshop on the Effects of Anthropogenic Noise in the Marine Environment,* R. Gisiner, E. Cudahy, G. V. Frisk, R. Gentry, R. Hofman, A. N. Popper, and W. J. Richardson, eds. (Office of Naval Research, Washington DC, 1998).
15. D. C. Finfer, "Biological sources of acoustic transients in the English Channel and adjacent waters," (University of Southampton, Southampton, 2005).
16. M. W. Johnson, F. A. Everest, and R. W. Young, "The role of snapping shrimp (*Crangon* and *Synalpheus*) in the production of underwater noise in the sea," Biological Bulletin 93, 122-138 (1947).
17. W. W. L. Au and K. Banks, "The acoustics of the snapping shrimp Synalpheus parneomeris in Kaneohe Bay," Journal of the Acoustical Society of America 103(1), 41-47 (1998).
18. F. A. Everest, R. W. Young, and M. W. Johnson, "Acoustical Characteristics of Noise Produced by Snapping Shrimp," Journal of the Acoustical Society of America 20(2), 137-142 (1948).
19. "Code of Practice for Noise Levels in Ships," (Maritime and Coastguard Agency, 1978).