HARBOR PORPOISE (*PHOCOENA PHOCOENA*) ACOUSTICS: IN MEMORY OF ANTHONY DAVID GOODSON

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1. INTRODUCTION

The harbor porpoise (*Phocoena phocoena*) is one of the smallest of all odontocetes and is the species that David Goodson has spent some time studying [1]. Therefore, to honour the memory of David, I will summarise the current knowledge of the acoustics of the harbour porpoise. Harbour porpoises typically weigh approximately 45-65 kg and have an average length of approximately 1.5 m. Females are slightly larger than males [2]. These animals are limited to cold temperate and sub-Arctic waters in the Northern hemisphere. They are routinely caught in a wide variety of fishing gear, a problem that David applied his energy to solve. Therefore, there is a strong conservational motivation to understand the acoustics of this species in order to find appropriate solutions to the by-catch problem.

The hearing sensitivity of a harbour porpoise was first measured by Andersen [3] and was recently re-measured by Kastelein et al. [4] and their results are shown in Figure 1. The audiogram measured by Kastelein indicates that *Phocoena* has a very wide frequency range of hearing with an upper cut-off at approximately 170 kHz and a low frequency roll off comparable to that of the bottlenose dolphin. This is the widest frequency range of hearing in the animal world. The bottlenose dolphin has an upper frequency of hearing of 150 kHz. The porpoise frequency of maximum sensitivity is about 90 kHz and the sensitivity is about 15 dB better than that of the bottlenose dolphin.

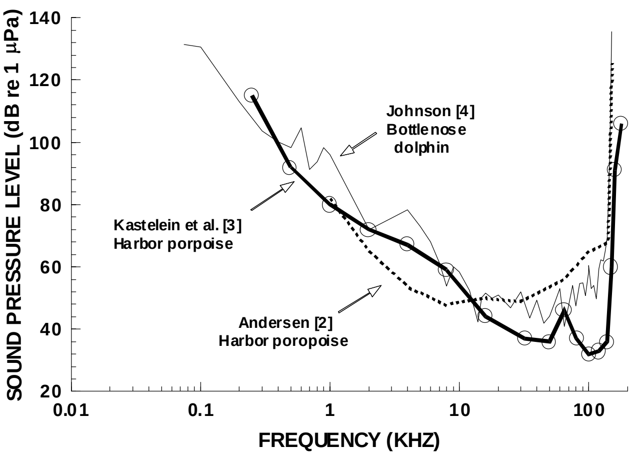

Figure 1. Hearing sensitivity of the harbor porpoise (from Kastelein et al. [4]) along with the audiogram of the bottlenose dolphin (from Johnson [5]) and the results of an earlier measurement of hearing sensitivity of a harbor porpoise by Andersen [3].

2. ECHOLOCATION SIGNALS

The echolocation signals emitted by odontocetes tend to fall into two broad categories. Dolphins that typically emit whistle signals also emit brief broadband echolocation signals having between four and eight cycles and duration of 40-70 μs [6]. Most odontocetes fall into this class. Odontocetes that do not emit whistle signals emit narrow-band echolocation signals having at a minimum of about 12 cycles with duration generally greater than 100 μs [6]. Among the odontocetes that emit signals in this category are the harbour porpoise, finless porpoise, *Neophocaena phocaenoides*, Commerson's dolphin, *Cephalorhynchus commersonii*, Hector's dolphins, *Cephalorhynchus hectori*, and pygmy sperm whale, *Kogia sp.* Examples of representative echolocations signals of harbor porpoises and bottlenose dolphins are shown in Figure 2. The harbour porpoise signal is longer, has higher peak

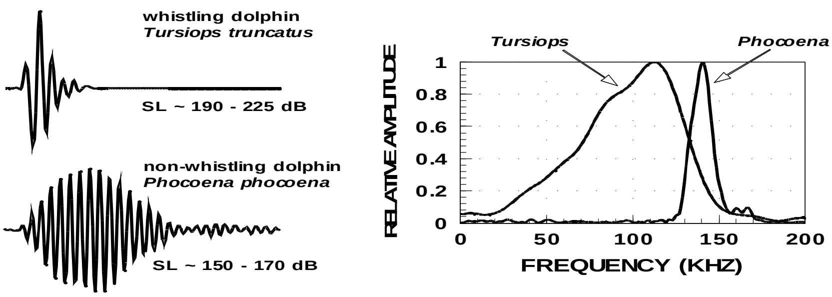

Figure 2. Examples of echolocation signals from a bottlenose dolphin and a harbour porpoise.

frequency and is much narrower in bandwidth than the signal of the bottlenose dolphin. The peak-to-peak amplitude at 1 m from the animal (source level) for the harbour porpoise typically falls between

150-170 dB re 1 μPa versus the 190-225 dB for the bottlenose dolphin. Therefore, the target detection range for the bottlenose dolphin is expected to be much larger than that of the harbour porpoise.

Echolocation signals are probably generated by a pair lips referred to as the monkey lip/dorsal bursae (MLDB) structures within the nasal system of odontocetes [7]. The signals then propagate through the melon and out into the water. The melon of odontocetes has an inhomogeneous density and sound velocity profile with a low-density,low-sound velocity core [7] . Such a structure can focus sounds propagating through it. Goodson, Flint and Cranford [8] applied a transmission line model, which is a time-domain numerical technique to study the sound propagation from the MLDB complex through the melon into the water. A grid was over laid on a vertical slice of a CT representation of a harbor porpoise melon, subdividing the melon into blocks and each block represented a node. By taking account of the signals arriving via the mesh connection the local absorption and transmission loss were calculated and passed to the immediate neighbour. The instantaneous pressure and particle velocities are then available at every point in the grid. In an example where an omnidirectional source is located at the aft-end of the melon, they clearly presented numerical results showing the wavefront for the signal flowing through the melon showed a distinct departure from a spherical wavefront, indicating a focusing effect by the melon. Unfortunately, the figures could not be clearly reproduced for this paper.

The echolocation signals pass through the melon in such a way that in the far-field a beam is formed. Au et al. [9] measured the beam pattern of a harbour porpoise in both the vertical and horizontal planes using an array of B&K 8103 hydrophones. Their results are shown in Figure 3. The beam pattern in the vertical and horizontal planes are rather similar. The 3-dB beamwidth in both planes was approximately 16°. In order to compare the beamwidth of *Phocoena* with the beamwidth of larger odontocetes, Au el al. [9] calculated both the directivity index and the 3-dB beamwidth for the Atlantic bottlenose dolphin, the beluga whale and the false killer whale. Their results as a function of the ratio of the head diameter over the wavelength at the peak frequency of the echolocation signals are shown in Figure 4. The d/λ values for the different species are shown along the horizontal axis. The harbour porpoise, having the smallest d/λ value of the four odontocetes considered in the figure, also had the largest beamwidth. The linear curve fitted through the 3-dB beamwidth had an r^2 value of 0.97 and the equation of the best-fit line is

$$BW = 23.9 - 0.6\left(\frac{d}{\lambda}\right) \qquad \textbf{\textit{(1)}}$$

Therefore, in a general sense, the beamwidth of odontocetes varies as a function of d/λ as a linear planar transducer.

One feature of the harbour porpoise echolocation signals is that signals measured at angles away from the major axis are not distorted when compared with the signals aligned with the major axis of the

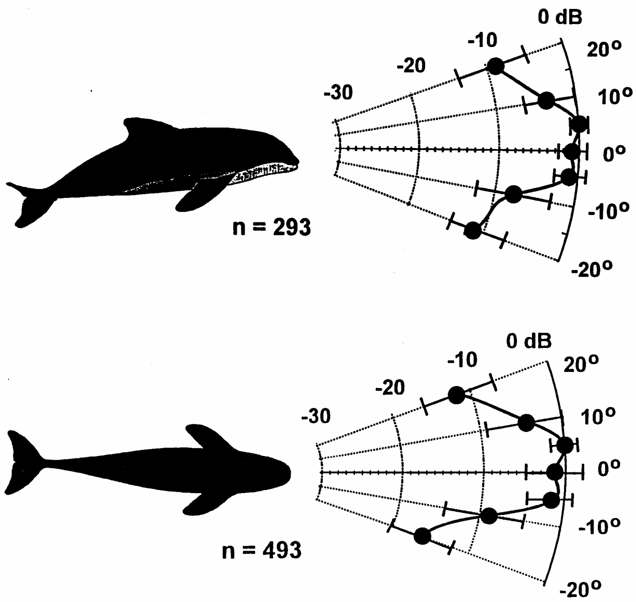

Figure 3. Beam pattern in the vertical and horizontal planes for a harbour porpoise (Au et al. [9]).

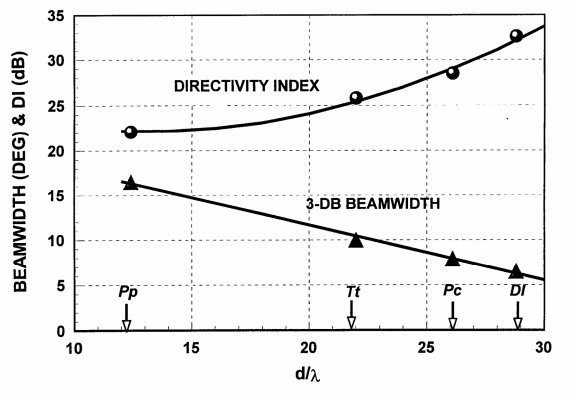

Figure 4. Directivity index and 3-dB beamwidth for four odontocetes, Atlantic bottlenose dolphin (*Tursiops truncatus*), beluga whale (*Delphinapterus leucas*), and the false killer whale (*Pseudorca crassidens*) and the harbour porpoise (from Au et al. [9]).

beam [9]. The same cannot be said for odontocetes that emit broadband echolocation signals such as the bottlenose dolphin, the beluga whale, and the false killer whales. The broadband echolocation signals measured away from the major axis are progressively more distorted with angle compared to the signals measured along the major axis.

3. TARGET AND NET DETECTION

The target detection range of a harbour porpoise was tested in a net pen by varying the distance of a 5.08-cm diameter and a 7.62-cm diameter sphere from the animal stationed in a hoop [11]. Both spheres were constructed of thin stainless steel and were filled with water. The results in terms of correct detection in percent versus range in meter for a 7.62-cm stainless steel sphere are shown in Figure 5. The results for a bottlenose dolphin in detecting a similar type sphere are also shown in the figure. The 50% correct detection threshold was 26 m for the harbour porpoise and 113 m for the bottlenose dolphin. For the 5.08-cm sphere, the threshold detection range was approximately 16 m. The echo level from the sphere an be determine with the equation

$$EL = SL - 40 \log R - 2\alpha R + TS_{pp} \qquad \textbf{(2)}$$

where SL is the source level, R is the detection threshold range in m, α is the absorption coefficient and TS_{pp} is the target strength based on the peak-to-peak values of the incident signal and the

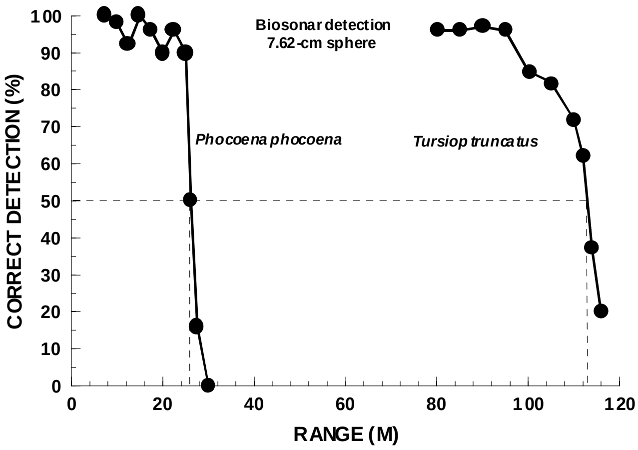

Figure 5. Target detection threshold range for a harbor porpoise and a bottlenose dolphin.

Back-scatter from 7.62-cm sphere. The porpoise source level during an echolocation trial varied over 10 dB so that only signals which were within 3 dB of the maximum amplitude on any trial were averaged. The averaged maximum source levels varied between 165 and 170 dB re 1 μPa. The target strength was measured using a harbor porpoise signal and the backscatter waveform is reproduced in Figure 6. Inserting the appropriate values into (2), the echo level at the threshold detection range of 25.5 m is between 79 and 84 dB re 1 μPa. The target strength using a bottlenose

simulated echolocation click is approximately -30.2 dB. Therefore at the threshold range of 113 m, the echo level for bottlenose dolphin was approximately 95 – 100 dB re 1 μPa. This is considerably higher than for the harbour porpoise, however, the bottlenose dolphin threshold detection range was determined in a noisy bay and the animal was masked by the snapping shrimp noise in the bay.

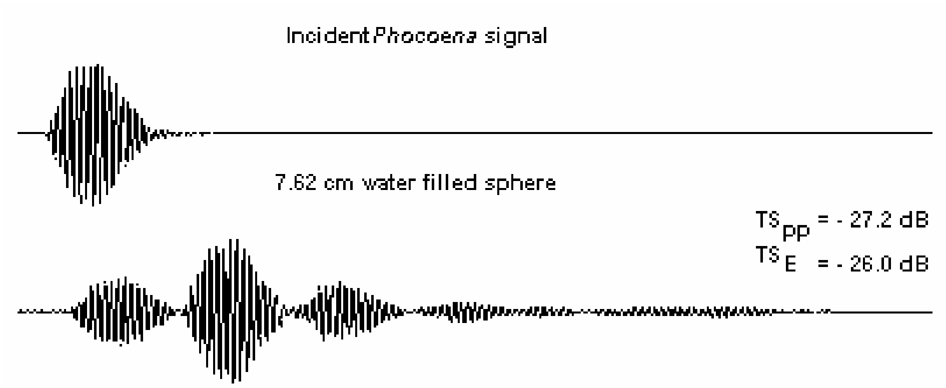

Figure 6. The waveform a simulated harbour porpoise signal and the waveform of the echo from a 7.62-cm water-filled sphere.

A subject of great interest to David Goodson centred on by-catch of dolphins and porpoises by fishing nets [12, 14, 15], and so I will now spend a brief moment to discuss this subject. The results obtained in the target detection study [11] can be used to determine typical detection range for an echolocating harbour porpoise of mono-filament nets used in gillnet fisheries. The target strength of 11 bottom-set gillnets in which harbour porpoises have been caught in were measured using both harbour porpoise and bottlenose dolphin signals shown in Figure 2. Target strength varied considerably depending on the net type and the angle of incidence of the signal. The largest echoes were obtained when the incident signal was normal to the plane of the net and the echo amplitude decreased progressively as the angle of incident approached 45^o from the normal, the largest oblique angle used. For the analysis of detection range, measured target strength varied between -48.5 to -62.9 dB and these values were used in the analysis of Kastelein et al. [13]. A very conservative detection range estimate was also used, based on the range for a 90^ocorrect detection of the 5.08-cm diameter sphere. If R_{sph} is the 90% correct detection range for the sphere and ignoring absorption losses because of the short ranges involved, the net-detection range was calculated with the equation

$$40 \log(R_{net}) + TS_{net} = 40 \log(R_{sph}) + TS_{sph} \qquad (3)$$

The results of this analysis are shown in Figure 7. The furthest distance at which an echolocating harbour porpoise has a 90% change of avoiding a net while swimming perpendicular to the net was approximately 6.2 m. This is the best-case situation for the nets measured. The detection range would decrease substantially if the harbour porpoise approaches a net at an oblique angle, and the range can be as low as 2.5 m.

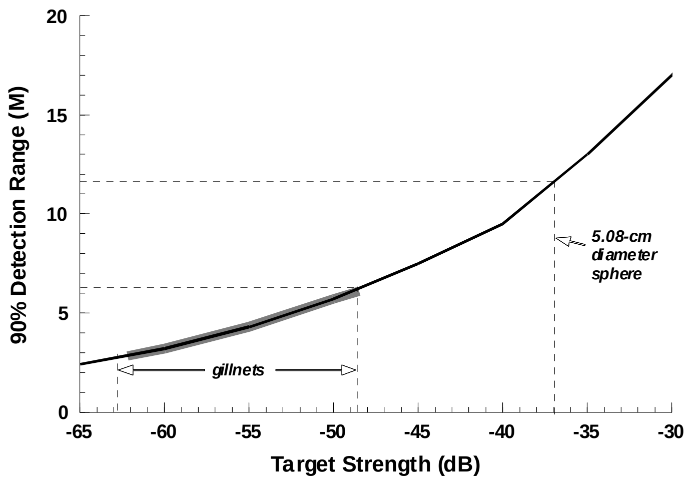

Figure 7. The calculated 90% detection range of some typical gillnets by harbour porpoises when echolocating perpendicular to the nets

4. DISCUSSION

The harbour porpoise has been studied much less than the most studied cetacean, the bottlenose dolphin. Nevertheless, sufficient information is available to surmise some important characteristics of its acoustic system. Its hearing sensitivity is slightly better than those of any odontocetes and it also has the largest frequency range of hearing (150 kHz for the bottlenose dolphin compared to 170 kHz for the harbour porpoise). However, being one of the smallest cetaceans the intensity of projected sound is much lower than that of other cetaceans, being at least 50 dB lower in peak-to-peak amplitude than the bottlenose dolphin. Therefore, its sonar detection range is considerably shorter than that of the bottlenose dolphin. The limited range of the harbour porpoise sonar probably plays a role in why so many of them are caught in nets. Even if they are actively echolocating, there are probably many instances in which monofilament nets are detected at such short range that the animals cannot successfully avoid the nets. Furthermore, Peter Bloom, working with David [16], found that a solitary bottlenose dolphin off the Northumberland coast of the UK hardly echolocated during the day except when foraging for food. Therefore, attaching passive reflectors on nets would not be effective. Realising this, David actively developed various types of active devices that could be placed on set nets and trawl nets to deter marine mammals from approaching these nets.

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REFERENCES

[1] Goodson, A. D., Kastelein, R. A., and Sturtivant, C. R. Source levels and echolocation signal characteristics of juvenile harbour porpoises (*Phocoena phocoena*) in a pool. In Harbour Porpoises 1995; edited by P. E. Nachtigall, J. Lien, W. W. L. Au and A. J. Read (De Spil, Woerden, The Netherlands), pp. 41-53.

[2] Evans, P.G.H. The natural history of whales and dolphins. Christopher Helm, London, 1987.

[3] Andersen, S. Auditory sensitivity of the harbour poropoise, *Phocoena phocoena* in Investigations on Cetacea, edited by G. Pilleri (Institute for Brain Research, Bern), 1970, 2, 255-259.

[4] Kastelein, R. Bunskoek, P., Hagedoorn, M., Au, W. W. L., and de Haan, D. Audiogram of a harbor porpoise (*Phocoena phocena*) measured with narrow-band frequency-modulated signals, J. Acoust. Soc. Am., 2002; 112: 334-344

[5] Johnson, C. S. Sound detection thresholds in marine mammals, in Marine Mammal Sensory Systems, edited by W.N. Tavolga (Pergamon, New York), 1967; 2, pp. 247-260.

[6] Au, W. W. L. The Soanr of Dolphins, Springer-Verlag, New York, 1993.

[7] Cranford, T. W., Amudin, M., and Norris, K.S. Functional morphology and homology in the odontocetes nasal comples: Implications for sound generation. J. Morph. 1998; 228: 223-285.

[8] Goodson, A. D., Flint, J. A., and Cranford, T. W. The harbor porpoise (*Phocoena phocoena*)-Modeling the sonar transmission mechanism. In Echolocation in Bats and Dolphin, 2004; edited by J. A. Thomas, C. F. Moss and M. Vater (Univ. Chicago Press, Chicago), pp. 64-72.

[9] Au, W. W. L., Kastelein, R. A., Rippe, T., and Schooneman, N. M. Transmission beam pattern and echolocation signals of a harbor porpoise (*Phocoena phocoena*). J. Acoust. Soc. Am. 1999; 106: 3699-3705.

[10] Au, W. W. L., Penner, R. H., and Turl, C. W. Propagation of beluga echolocation signals, J. Acoust. Am, 1987; 82: 807-813.

[11] Kastelein, R. A., Au, W. W. L., Rippe, H. T., and Schooneman, N. M. Target detection by an echolocating harbor porpoise (*Phocoena phocoena*). J. Acoust. Soc. Am. 1999; 105: 2493-2498.

[12] Goodson, A. D., and Datta, S. Acoustic detection of gillnets: The dolphin's perspective. Acoustic Letters 1992, 16: 129-133.

[13] Kastelein, R. A., Au, W. W. L., and de Haan, D. Detection distances of bottom-set gillnets by harbour porpoises (*Phocoena phocoena*) and bottlenose dolphins (*Tursiops truncatus*), Mar. Envir. Research 2000; 49:359-375.

[14] Kastelein, R. A., de Haan, D., Goodson, A. D., Staal, C., and Vaughan, N. The effects of various sounds on a harbour porpoise (*Phocoena phocoena*). In The Biology of the Harbour Porpoise 1997, edited by A. J. Read, P. R. Wiepkema and P. E. Nachtigall (D Spil, Woerden, The Netherlands), pp. 367-383.

[15] Kastelein, R. A., de Haan, D., Staal, C., and Goodson, A. D. The response of a harbour porpoise (*Phocoena phocoena*) to nets of various mesh sizes, and with and without deterring sound. In The Biology of the Harbour Porpoise 1997, edited by A. J. Read, P. R. Wiepkema and P. E. Nachtigall (D Spil, Woerden, The Netherlands), pp. 385-409.

[16] Bloom, P. R. S., Goodson, A. D., Klinowska, M. and Sturtivant, C. R. The activities of a wild, solitary bottlenose dolphin (*Tursiops truncatus*)." Aquatic Mammals 1995; 21: 19-42.