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The capability of an Atlantic bottlenose dolphin to discriminate wall thickness differences of hollow cylinders by echolocation was studied by Au and Pawloski (1992). A standard cylinder of 6.35 cm wall thickness was compared with cylinders having wall thicknesses that differed from the standard by ± 0.2, ± 0.3, $\pm$ 0.4, and ± 0.8 mm. All cylinders had an O.D. of 37.85 mm, and a length of 12.7 cm. The standard and a comparison target, separated by an angle of $\pm 11°$, were presented simultaneously at a range of 8 m and the dolphin was required to indicate the location of the standard target. The standard was paired with a different comparison target for ten consecutive trials apiece. The experiment was conducted in the free field and in the presence of broadband masking noise.

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APPLICATION OF THE SONAR EQUATION TO DOLPHIN ECHOLOCATION

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The target detection capability of the Atlantic bottlenose dolphin (*Tursiops truncatus*) in the open waters of Kaneohe Bay, Oahu, Hawaii will be discussed using the noise-limited form of the sonar equation. In Kaneohe Bay, *Tursiops* typically emit short duration transient-like broadband echolocation signals with peak frequencies between 110-130 kHz in (Au, 1980). Therefore the generalized or transient form of the sonar equation based on energy flux density instead of intensity must be used (Urick, 1983). An example of a *Tursiops* echolocation signal and its frequency spectrum is shown in Fig. 1. The peak-to-peak source level is shown on the oscilloscope display.

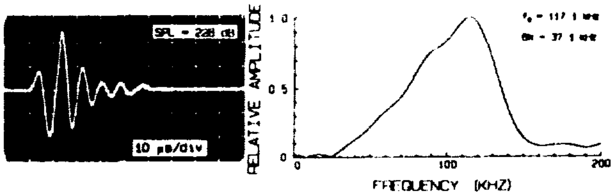

Fig. 1. An example of an echolocation signal of *Tursiops truncatus* measured in Kaneohe Bay.

I. GENERALIZED SONAR EQUATION: NOISE-LIMITED FORM

The generalized form of the noise-limited sonar equation applicable to a dolphin can be expressed as (Urick, 1983)

$$DT_E = SE - 2\ TL + TS_E - (NL - DI) \qquad (1)$$

The detection threshold, DT_E corresponds to the energy-to-noise ratio used in human psychophysics and is equal to 10 Log (E_e/N_o), where E_e is the echo energy flux density and N_o is the noise spectral density level. SE is the source energy flux density, TL is the transmission loss, TS_E is the target strength based on the ratio of the energy in the echo and incident energy, NL is the ambient noise density, and DI is the receiving directivity index.

In order to use Eq. 1, the target detection capability of the dolphin must be measured along with other parameters associated with the animal's sonar and the environment. Murchison (1980) performed a maximum range detection experiment with two *Tursiops*, using a 2.54-cm diam. solid steel sphere and a 7.62-cm diam. stainless steel water-filled sphere as targets. The composite 50% correct detection threshold were at ranges of 72 and 77 m for the 2.54-cm and 7.62-cm spheres, respectively. However, the dolphins performance with the 7.62-cm sphere was affected by reverberation from a bottom ridge located at a range of 73 m.

Au and Snyder (1980) remeasured the maximum detection range in a different part of Kaneohe Bay using one of the same dolphins (Sven) and a 7.62-cm diam. sphere. Sven's target detection performances for the 2.54-cm sphere (Murchison, 1980) and the 7.62-cm sphere (Au and Snyder, 1980) are plotted in Fig. 2 as a function of range. The 50% correct detection threshold for the 7.62-cm sphere occurred at 113 m, a considerably longer range than the 76.6 m measured by Murchison (1980).

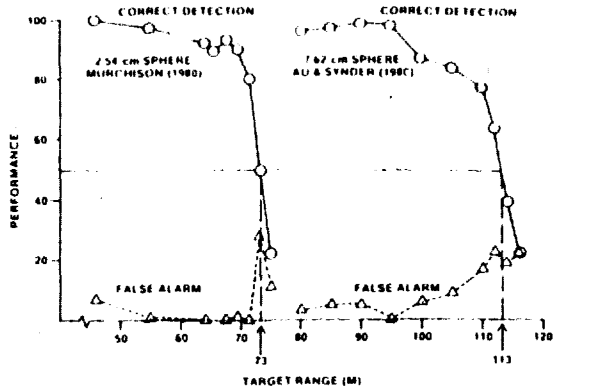

Fig. 2. Target detection performance a *Tursiops truncatus* as a function of range for two spherical targets (from Murchison, 1980; Au and Synder, 1980).

II APPLYING THE SONAR EQUATION

The parameters in the sonar equation (Eq. 1) will now be discussed according to the order they appear in the equation. The first term has to do with the signals used by dolphins. Sonar signals are projected in a beam directed forward of the animal. The composite transmit beam pattern from three dolphins in the vertical and horizontal planes (Au et al., 1978; Au, 1980; Au et al., 1986) are shown in Fig. 3. The 3-dB beamwidth in both planes have similar values, approximately 10°.

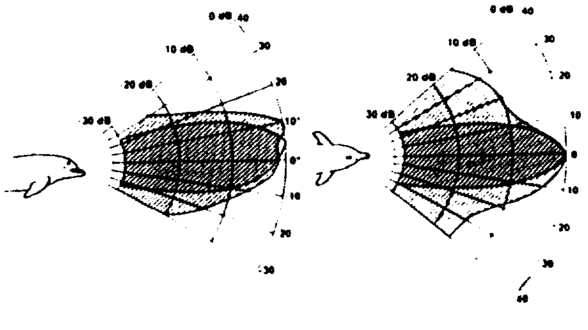

Fig. 3. Transmit (inner curves) and receive (for a frequency of 120 kHz; outer curves) beam patterns for *Tursiops* in the horizontal and vertical planes

The sonar signals of the dolphin used to obtain the data shown in Fig. 2 were measured in the study of Au et al. (1974) for target ranges of 59 to 77 m. However, dolphins can vary the amplitude of their sonar signals over a 20 dB range during a single sonar search, making it difficult to accurately estimate the detection threshold. Au and Pawloski (1989) performed an experiment to determine the relationship of the detection threshold based on the maximum source energy flux density per trial to a more accurate estimate of the detection threshold. Using an electronic phantom target which played back simulated echoes at a constant amplitude regardless of the amplitude of the dolphin's emitted signal, they found that the detection threshold, E_e/N_o, was 2.9 dB lower than the detection threshold based on the maximum source level. Therefore, an accurate estimate of the dolphin detection threshold can be obtained by using the maximum source energy flux density and subtracting 2.9 dB from it. Au (1980) also showed that the energy flux density is approximately equal to the peak-to-peak SPL minus 58 dB for signals used by *Tursiops* in Kaneohe Bay, so that an SE of 163 dB re (1 μPa)^{2}s, which includes the 2.9 dB correction, is appropriate for use in the sonar equation.

Let us now consider the TL or transmission loss term in Eq. 1. The relatively short ranges and the brief duration of the emitted signals indicate that the transmission loss will be caused by spherical spreading plus absorption. The one-way loss for a range r can be expressed as

$$TL = 20 \text{ Log } r + \alpha_f r \qquad (2)$$

where α_f is the absorption loss at the peak frequency of the signal. An absorption loss value of 0.44 dB/m will be used.

The target strength of the 2.54-cm and 7.62-cm spheres used to obtain the performance data shown in Fig. 1, were measured by Au and Snyder (1980) using a simulated dolphin sonar signal. The target strength based on energy was -41.6 dB for the 2.54-cm sphere and -28.3 dB for the 7.62-cm sphere.

The results shown in Fig. 2 are very specific to the ambient noise condition of Kaneohe Bay. Kaneohe Bay has one of the noisiest "snapping shrimp" population in the world, and at a frequency of 120 kHz, the ambient noise level is approximately 54 dB re 1 μPa^2/Hz (Au, 1988a).

We now consider the final term of Eq. 1, DI, or the receive directivity index. Au and Moore (1984) measured the receiving beam patterns of *Tursiops* at frequencies of 30, 60 and 120 kHz; the results for 120 kHz are shown in Fig. 3 (outer curves). The also calculated the receive directivity index by numerically evaluating the expression

$$DI = 10 \log \left(\frac{4\pi}{\int_0^{2\pi} \int_{-\pi/2}^{\pi/2} \left(\frac{p(\theta,\varphi)}{p_o} \right)^2 \sin\theta \, d\theta \, d\varphi} \right) \qquad (3)$$

For a peak frequency of 120 kHz, DI_R = 20.2 dB.

Using the sonar equation, the results shown in Fig. 2 are replotted as a function of the echo signal-to-noise ratio in Fig. 4. The results indicate that the animal's performance was consistent for the two studies. The 75% correct response threshold were at a DT_E of 7.5 dB for the 2.54-cm sphere and 9.8 dB for the 7.62-cm. This difference of 2.3 dB is small considering the fact that the two studies were done approximately two years apart.

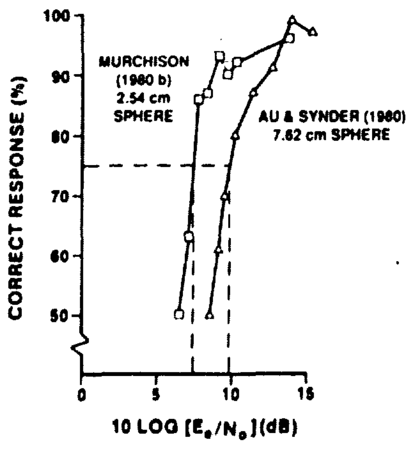

Fig. 4. Target detection performance of a *Tursiops* as function of the echo energy-to-noise ratio for the range detection data of Figure 2.

Tursiops' target detection capability in noise has also been studied using different techniques. Au and Penner (1981) and Turl et al., (1987) used a fixed target range and varied the level of masking noise source located between the target and the dolphin. Au et al., (1988) used a fixed target range and a fixed masking noise level and varied the effective size of the target using an electronic phantom target stimulator. The results of these studies are shown in Fig. 5, displaying performance accuracy as a function of the echo energy-to-noise ratio. The 75% correct response threshold for the data in Fig. 5 is approximately 7 dB. This DT_E compares well with the 7.5 dB and 9.8 dB obtained with the data of Fig. 4.

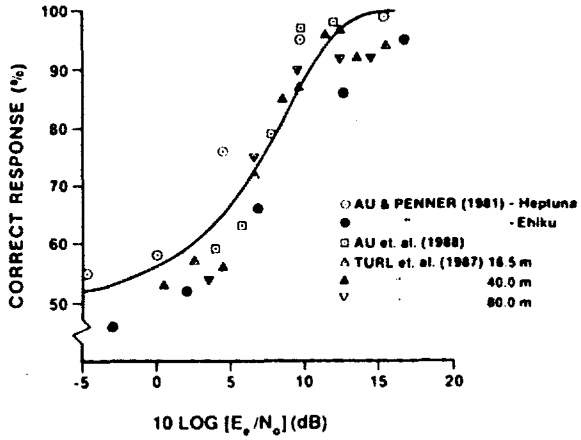

Fig. 5. Target detection performance of *Tursiops truncatus* in the presence of masking noise. The solid line is from the energy detector model of Urkowitz (1967) for TW = 10 (from Au, 1988b).

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COMPARISON OF SONAR DISCRIMINATION BY AN ECHOLOCATING DOLPHIN AND A COUNTERPROPAGATION NEURAL NETWORK

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The capability of an Atlantic bottlenose dolphin to discriminate wall thickness differences of hollow cylinders by echolocation was studied by Au and Pawloski (1992). A standard cylinder of 6.35 cm wall thickness was compared with cylinders having wall thicknesses that differed from the standard by ± 0.2, ± 0.3, ± 0.4, and ± 0.8 mm. All cylinders had an O.D. of 37.85 mm, and a length of 12.7 cm. The standard and a comparison target, separated by an angle of ± 11°, were presented simultaneously at a range of 8 m and the dolphin was required to indicate the location of the standard target. The standard target was paired with a different comparison target for ten consecutive trials apiece. The experiment was conducted in the free field and in the presence of broadband masking noise.

In this study, a counterpropagation artificial neural network was used to examine the broadband echo features from the same cylinders used in the dolphin experiment. Features of the echoes were determined by passing them through a bank of constant-Q filters. Constant-Q filtering was chosen because the dolphin's auditory system can be modeled as a bank of constant-Q filters (Johnson, 1969). The objectives were (1) to determine if a counterpropagation network could discriminate the target echoes using features from the constant-Q filter bank, (2) compare the performance of the counterpropagation network with the that of the dolphin, and (3) determine Q-values needed by the network for comparable performance as the dolphin.

Roitblat et al. (1989) used a counterpropagation network to emulate a dolphin performing a sonar discrimination task. The network performance was perfect with echoes collected in a test pool, and was 97% correct when selective "natural echoes" resulting from the dolphin's sonar emissions were used. However, the dolphin's task was not difficult; the animal's average performance was 94.5% correct. The discrimination task in this study was considerably more difficult with the dolphin's accuracy varying from 96% to 52% correct. Moore et al. (1991) used a backpropagation network and consecutive "natural echoes" to discriminate the same targets used by Roitblat et al. (1989). The backpropagation network achieved performances between 90 and 93% correct.

I. PROCEDURE

Target echoes were collected with a planar transducer that projected and received the echoes. The transducer was mounted on the dolphin's pen so that the target measurements would be made in the same environment and under similar conditions as for the dolphin. A simulated dolphin signal with a peak frequency of 117 kHz was projected and a 16-bit analog-to-digital converter operating at 1 MHz was used to digitize the echoes. Each echo consisting of 1024 points was stored on computer disk. Five disk files, with 10 consecutive echoes per file or 50 echoes were collected for each target.

Target features were determined by passing each echo through a bank of N contiguous constant-Q filters. The features of an echo consisted of the energy from each filter normalized to the output of the filter with the maximum energy. From the definition of Q, the frequency boundaries of the ith constant-Q filter can be expressed as

$$f_i = \frac{2Q+1}{2Q-1} f_{i-1} \tag{1}$$

where f_i is the upper frequency and f_{i-1} is the lower frequency limit of the filter. Let f_U = the upper frequency of the Nth filter and f_L = the lower frequency of the 1st filter of a bank of constant-Q filters, then from Eq. 1 the relationship between f_U and f_L can be expressed as

$$\frac{f_U}{f_L} = \left[\frac{2Q+1}{2Q-1}\right]^N \tag{2}$$

For a specific Q, three parameters can be varied, f_L, f_U, and N. A frequency of 150 kHz was used for f_U to coincide with the bottlenose dolphin upper frequency of hearing (Johnson, 1968). The lowest frequency was chosen so that, $f_L \geq 62$ kHz. For frequencies ≤ 62 kHz, the energy in an echo was at least 30 dB down from the peak. For a desired Q, N was chosen so that f_L was as close to 62 kHz as possible.

The counterpropagation neural network was simulated by the Neural Works Profession II Plus program from Neural Ware, Inc. The network consisted of an input layer of N elements, a normalizing layer of N+1 elements, a Kohonen layer of N elements and an output layer of two elements. Echoes associated with the standard target were paired with echoes from each comparison target. Twenty echoes from each target were used for the training set and echoes from the remaining thirty echoes were used for the test set. The network's capability to discriminate the standard from each comparison target was determined for different values of Q and N.

The performance of the network with noisy data was determined by first adding a different burst of Guassian random noise to each target echo. The noisy echo was then passed through the constant-Q filter bank. A noise burst was created by passing white noise through a cosine taper window having a half-power width of 264 μs. A width of 264 μs was chosen to correspond to the dolphin's integration time of 264 μs determined by Au et al. (1988).

II. RESULTS AND DISCUSSION

The performance of the counterpropagation network for the free-field echoes and Q values of 4 and 5 are shown in Fig. 1, along with the dolphin's performance. The value of N was equal to Q-1. The network's performance for a Q of 4 was not as good as the dolphin for most of the comparison targets. However, for a Q of 5 the network's performance was better than the dolphin for most of the comparison

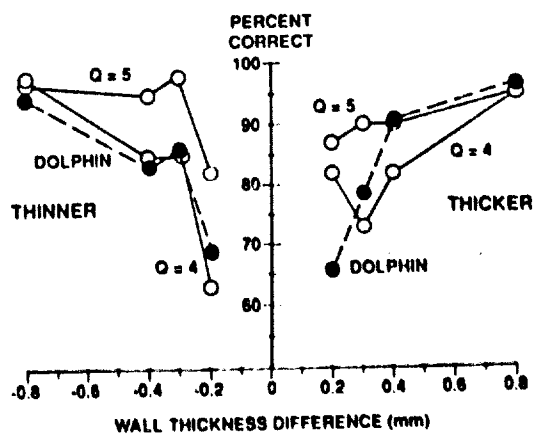

Fig. 1. Results of network in discriminating the standard and comparison targets.

targets. Therefore, a constant-Q filter bank consisting of 4 filters each having a Q of 5 produced target features that allowed the network to perform better than the dolphin.

The dolphin's critical bandwidth at 120 kHz is approximately 43 kHz (Au and Moore, 1990) indicating a Q of 2.8. Although the counterpropagation network could perform better than the dolphin, the filter bank had to have a higher Q than the dolphin. Furthermore, the network had a relatively simple task of sorting 50 echo pairs in files that were already time-windowed so that only target echoes were present. The dolphin had a more complex task of echolocating the targets, ignoring irrelevant echoes, determining the proper time window, remembering echo characteristics, as well as report to the experimenter.

Typical echoes from the standard and the comparison target having the closest wall thickness to the standard are shown in Fig. 2. Small differences

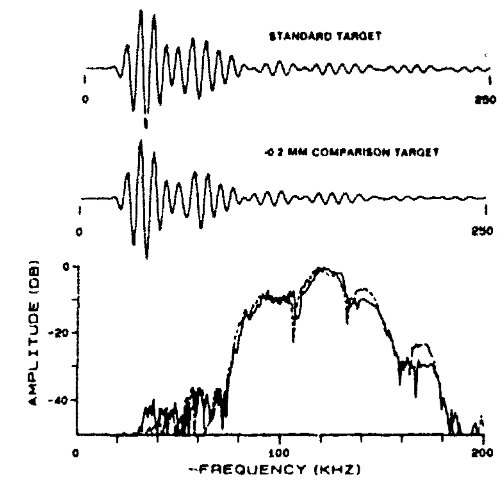

Fig. 2. Echoes from the standard and the ~0.2mm comparison target.

in the spectrum for the comparison target (dash line) compared to the standard target can be seen. The spectrum of the comparison target is shifted slightly toward the left of the spectrum for the standard target. Note that echoes from the same target may be slightly different as a result of wave and wind induced motion on the target and test pen.

The performance of the network for the noisy echoes is shown in Fig. 3 for signal-to-noise ratios of 15 and 10 dB. The network performed better than

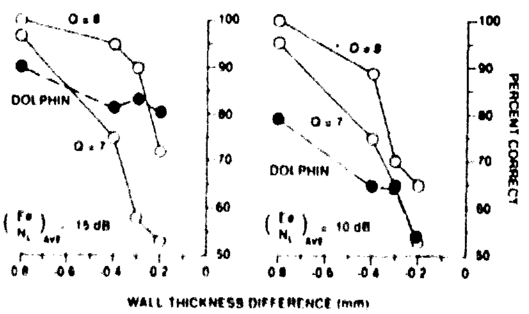

Fig. 3. Performance of the network with noisy data

the dolphin with most of the comparison targets when the Q was equal to 8. For a Q of 7, the network was worst than the dolphin for a signal-to-noise ratio of 15 dB and slightly better than the dolphin a signal-to-noise ratio of 10 dB.

The similarity between the standard and comparison targets can be expressed by a Euclidean distance measure. Let $\bar{E}_s(i)$ equal the normalized energy in the ith filter averaged over all the standard target echoes in the training set, where i = 1 to N. Let $E_c(i)$ be the corresponding energy for a comparison target in the test set and j be the index of the jth echo in the test set of M echoes. The Euclidean distance d_j of the jth comparison echo is

$$d_j = \sqrt{\sum_{i=1}^{N} [\bar{E}_s(i) - E_c(i)]^2} \qquad (3)$$

The similarity measure averaged over the M test set echoes is shown in Table 1 for a Q of 5 and no noise, and a Q of 8 with a 10-dB signal-to-noise ratio. The results indicate that the standard target can be differentiated from the comparison targets provided a good threshold value of $\bar{d}$ is chosen.

Table 1. Euclidean distance measure of similarity

	Standard (test)	THINNER COMPARISON TARGET -0.2 mm	-0.3 mm	-0.4 mm	-0.8 mm	No Noise Q = 5 N = 4
Standard (learn)	0.18±0.07	0.19±0.07	0.29±0.08	0.34±0.08	0.22±0.07	$\bar{d}$

	Standard (test)	THICKER COMPARISON TARGET 0.2 mm	0.3 mm	0.4 mm	0.8 mm	No Noise Q = 5 N = 4
Standard (learn)	0.16±0.07	0.23±0.04	0.40±0.07	0.41±0.08	0.42±0.02	$\bar{d}$

	Standard (test)	THINNER COMPARISON TARGET -0.2 mm	-0.3 mm	-0.4 mm	-0.8 mm	SNR = 10 dB Q = 8 N = 7
Standard (learn)	0.14±0.07	0.21±0.11	0.34±0.20	0.49±0.19	0.84±0.19	$\bar{d}$

CONCLUSIONS

The results suggest that a counterpropagation network can discriminate target echoes as well or better than a dolphin by preprocessing the echoes with a bank of constant-Q filters. However the filters must have a higher Q than the Q of 2.8 for the dolphin. A Q of 5 (N = 4) produced results that enable the network to perform better than the dolphin in the noise-free condition. A Q of 8 (N = 7) was needed when the echoes were mixed with white noise. The Euclidean distance measure indicated that the standard target echoes could be classified if the appropriate threshold value is chosen. Nevertheless, use of a neural network is a simple way of discriminating targets.

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