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In this paper, the target detection capability of the Atlantic bottlenose dolphin (*Tursiops truncatus*) in the open waters of Kaneohe Bay, Oahu, Hawaii will be discussed and the dolphin's performance will be compared with an energy detector model.

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TARGET DETECTION IN NOISE BY ECHOLOCATING DOLPHINS

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It is well known that dolphins possess a sonar capability which allows them to project acoustic energy and analyze returning echoes in order to detect and recognize objects underwater. The use of acoustic energy is probably the most effective way to probe an underwater environment for purposes of navigation, obstacle avoidance, prey and predator detection, and object localization and detection. Acoustic and other mechanical vibrational energy propagates in water more efficiently than any form of energy including electromagnetic, thermal and optical energy. Since the natural habitats of many dolphin species include shallow bays, inlets, coastal waters, swamps, marshlands, and rivers that are often so murky or turbid that vision is severely limited, these animals must rely heavily on their active and passive sonar capabilities for survival. Some of the sonar capabilities of dolphins have been described in review articles by Nachtigall (1980) and Au (1988).

In this paper, the target detection capability of the Atlantic bottlenose dolphin (Tursiops truncatus) in the open waters of Kaneohe Bay, Oahu, Hawaii will be discussed and the dolphin's performance will be compared with an energy detector model. Tursiops typically emit echolocation signals with peak frequencies between 110-130 kHz in Kaneohe Bay (Au, 1980). Kaneohe Bay has one of the noisiest "snapping shrimp" population in the world (Albers, 1965; Urick, 1984). An example of the ambient noise in the bay is shown in Fig. 1. Also shown in Fig 1. is an example of the ambient noise in San Diego Bay, California and typical deep water noise spectral density for different sea states.

The target detection capability of any sonar system is limited by interfering noise and reverberation. The target detection sensitivity of a sonar can be measured by a variety of equivalent methods. The range of a target of known target strength can be increased until the target can no longer be detected. A fixed target range can be used and the size of the target can be reduced continuously until the target can no longer be detected. A fixed target range can be used and the echo signal-to-noise (E_e/N_0) ratio varied by either adjusting the amount of masking noise, or by varying the target size, until the dolphin can no longer detect the target. Whatever method is used, certain important acoustic parameters must be measured for the detection experiment to be meaningful. The source level, target strength, and noise levels should be measured so that the E_e/N_0 at the detection threshold can be determined.

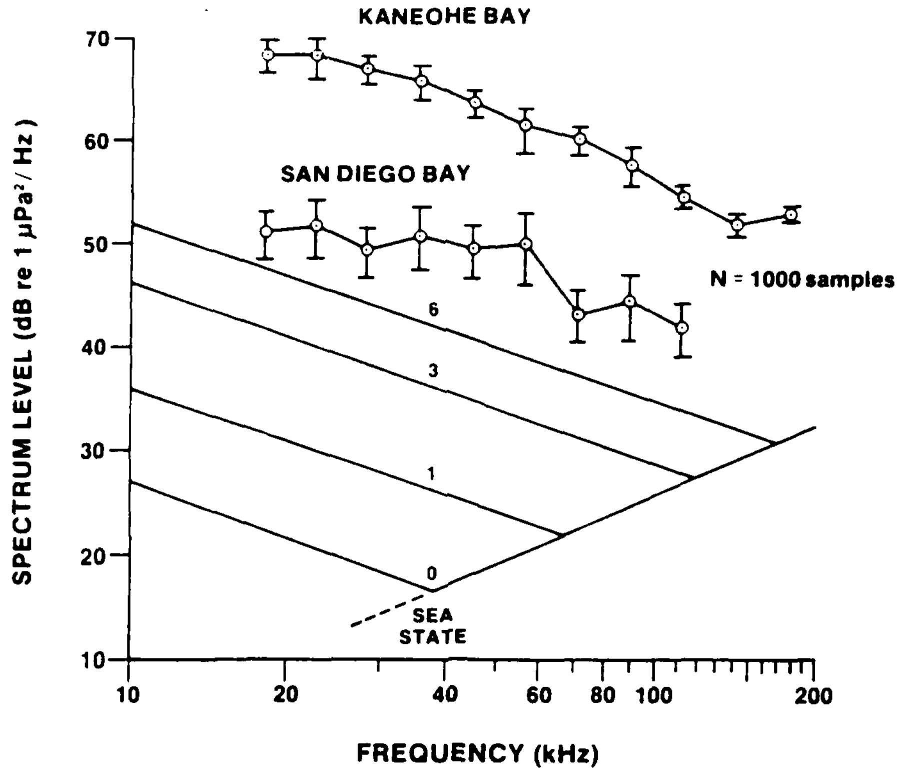

Fig. 1. Ambient noise of Kaneohe Bay measured in 1/3 octave bands. Deep water noise for different sea states are shown for comparison.

I. BIOSONAR TARGET DETECTION CAPABILITY

A variety of biosonar experiments using the three equivalent methods mentioned in the preceding paragraph have been performed in Kaneohe Bay to determine the sonar detection capability of _Tursiops truncatus_. 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, a bottom ridge at approximately 73 m limited the animals' ability to detect the 7.62-cm target beyond 73 m. The animals' performance degraded rapidly when the target was in the vicinity of the ridge, suggesting that the dolphins were probably reverberation-limited with the 7.62-cm sphere.

Au and Synder (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 Synder, 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 reported by Murchison (1980).

The results shown in Fig. 2 are very specific to the ambient noise condition of Kaneohe Bay. In order to make the results more general and useful, the detection performance should be plotted as a function of the

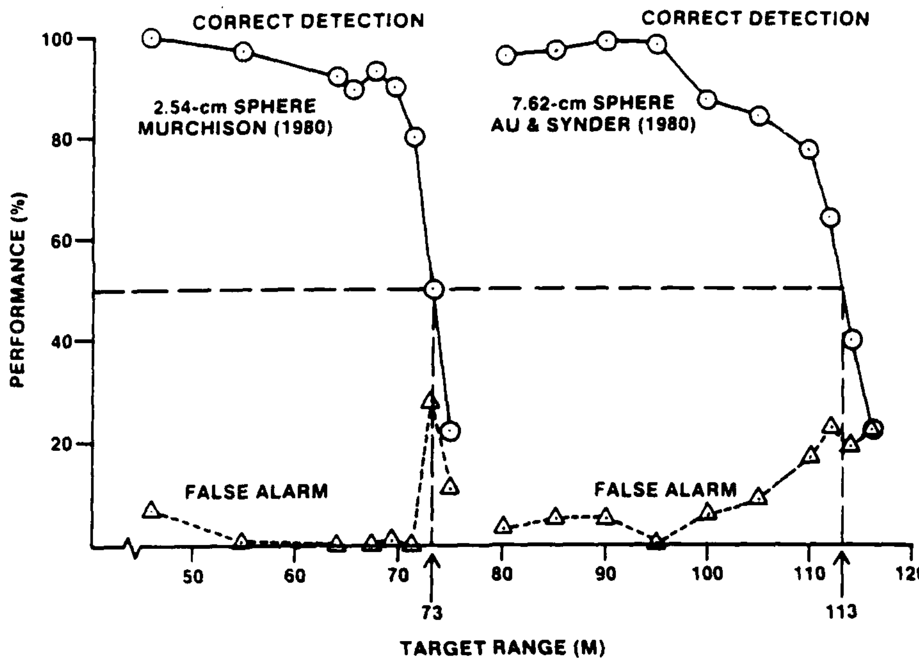

Fig. 2. Target detection performance of a _Tursiops truncatus_ as a function of range for two different spherical targets (From Murchison, 1980; Au and Synder, 1980).

estimated received signal-to-noise ratio. The transient form of the sonar equation for a noise limited situation can be used to analyze the dolphin's' performance of Fig. 2 in terms of the ratio of the energy in the received target echo to the noise spectral density. The transient form of the sonar equation expressed in dB can be written as (Au, 1988)

$$DT_E = SE - 2\ TL + TS_E - (NL - DI_R) \quad (1)$$

where: DT_E = detection threshold
SE = source energy flux density
TL = transmission loss
TS_E = target strength based on energy
NL = background noise level
DI_R = receiving directivity index

The detection threshold, DT_E, corresponds to the energy-to-noise ratio used in human psychophysics and is equal to 10 $Log(E_e/N_o)$, were E_e is the echo energy flux density and N_o is the noise spectral density level. During a sonar search dolphins typically vary the amplitude of their sonar signals over a large range (over 20 dB) making it difficult to estimate the detection threshold accurately. Au and Penner (1981) resorted to using the maximum source energy flux density per trial, which will lead to a conservative estimate of the detection threshold. Sven's sonar signals were measured in the study of Au et al. (1974) for target ranges of 59 to 77 m. The maximum peak-to-peak source level averaged over 12 trials at the 77 m range was 225 dB re 1 μPa and typical peak frequencies centered

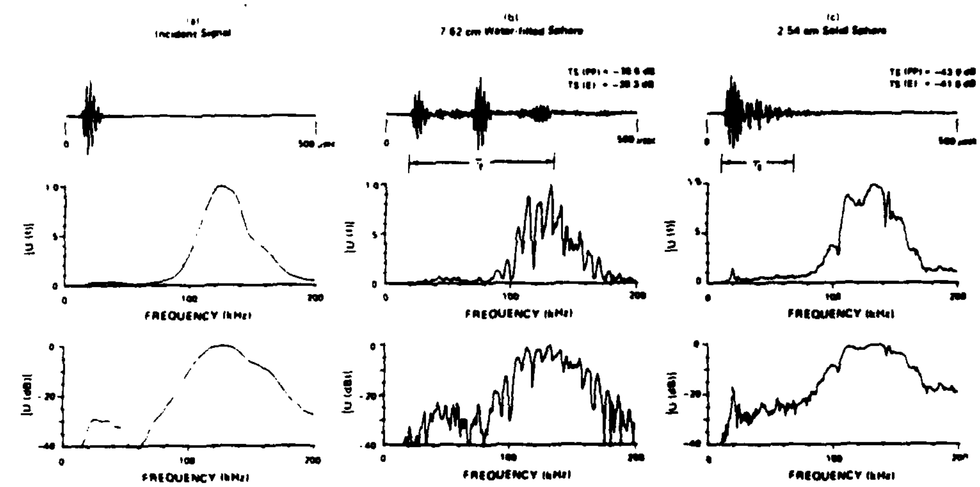

Fig. 3. Results of target strength measurements, (a) simulated dolphin click (incident signal), echoes from the (b) 7.62-cm and (c) 2.54-cm spheres (From Au and Synder, 1980).

about 120 kHz. Au (1980) 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 166 dB re (1 $\mu Pa)^2 s$ would be appropriate for use in the sonar equation. The target strength of the 2.54-cm and 7.62-cm spheres were measured by Au and Synder (1980) and their results are shown in Fig. 3. The target strength was -41.6 dB for the 2.54-cm sphere and -28.3 dB for the 7.62-cm sphere. From Fig. 1, the ambient noise level at 120 kHz is approximately 54 dB re 1 $\mu Pa^2/Hz$. Au and Moore (1984) measured the receiving beam patterns of Tursiops at frequencies of 30, 60 and 120 kHz, and used the results to calculate the directivity index. They found that the receiving directivity index can be described by the equation (Au, 1988)

$$DI_R(dB) = 16.9 \text{ Log } f(kHz) - 14.9 \quad (2)$$

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

The dolphin's performance 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 thresholds were at 10.4 dB for the 2.54-cm sphere and 12.7 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 year apart.

II. TARGET DETECTION IN NOISE

Au and Penner (1981) used the technique of fixing the target range and varying the level of a masking noise source to determine the target detection capabilities of two Tursiops. The animals were required to station in a hoop and echolocate a 7.62-cm stainless steel water-filled sphere at a range of 16.5 m. A noise source with a flat spectrum between

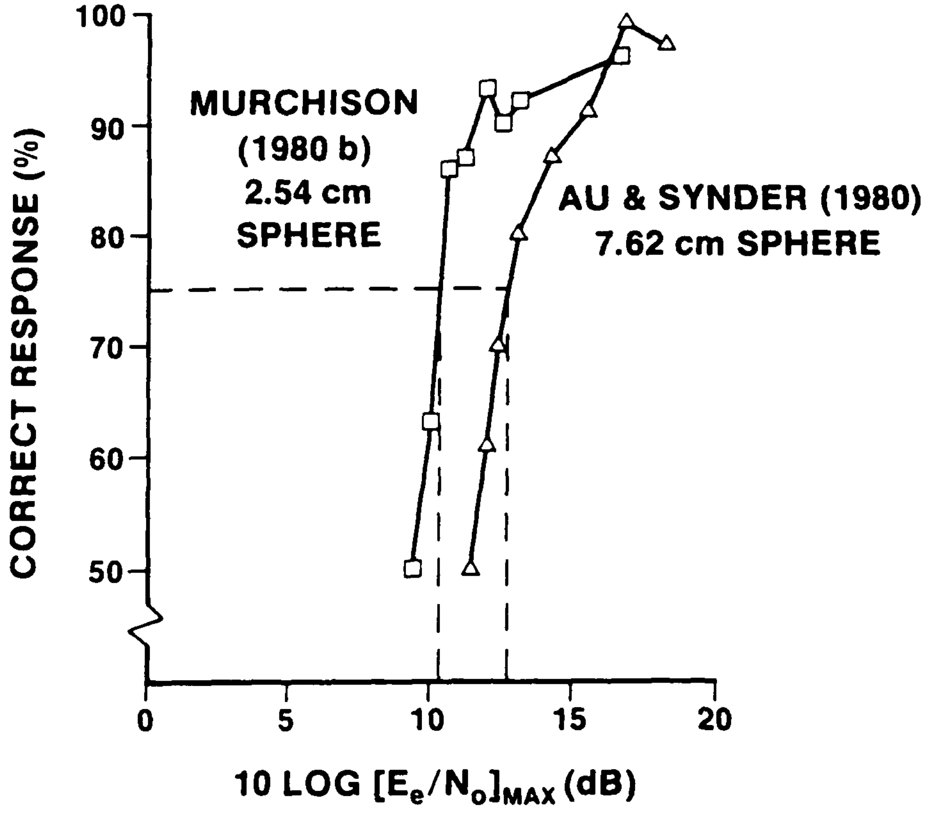

Fig. 4. Target detection performance of a Tursiops as function of the echo energy-to-noise ratio for the range detection data of Figure 2.

40 and 160 kHz was located 4 m from the hoop between the animal and the target. Masking noise levels between 67 and 87 dB re 1 $\mu Pa^2/Hz$ in 5 dB increments were randomly used in blocks of 10-trials for a 100 trial session. Turl et al. (1987) used the same technique to compare the detection capability of a Tursiops truncatus with a Delphinapterus leucas. A 7.62-cm sphere was used at ranges of 16.5 and 40 m and a 22.86-cm sphere at a range of 80 m. The experimental procedure was similar to that of Au and Penner (1981) except a smaller noise increment of 3 dB was used.

The dolphins' performance results for both studies plotted as a function of $(E_e/N_0)_{max}$ are shown in Fig. 5. The average value of the maximum source energy flux density per trial was used in the calculations. The 75% correct response threshold occurred at $(E_e/N_0)_{max}$ of 7 and 12 dB in the study of Au and Penner (1981) and at approximately 10 dB in the study of Turl et al. (1987). The results of Fig. 5 indicate good agreement and consistency with only a small amount of inter animal difference in target detection ability that did not exceed 5 dB. At the two highest noise level of the Au and Penner study, both dolphins began to guess. One dolphin did not emit any detectable signals in 20% and 41% of the trials at 82 and 87 dB noise levels, respectively. The other dolphin did not emit any signals in 14% of the trials at the 87 dB noise level. Therefore, the average of the maximum signal per trial for the noise levels between 67 and 77 dB were used to calculate $(E_e/N_0)_{max}$. The animal

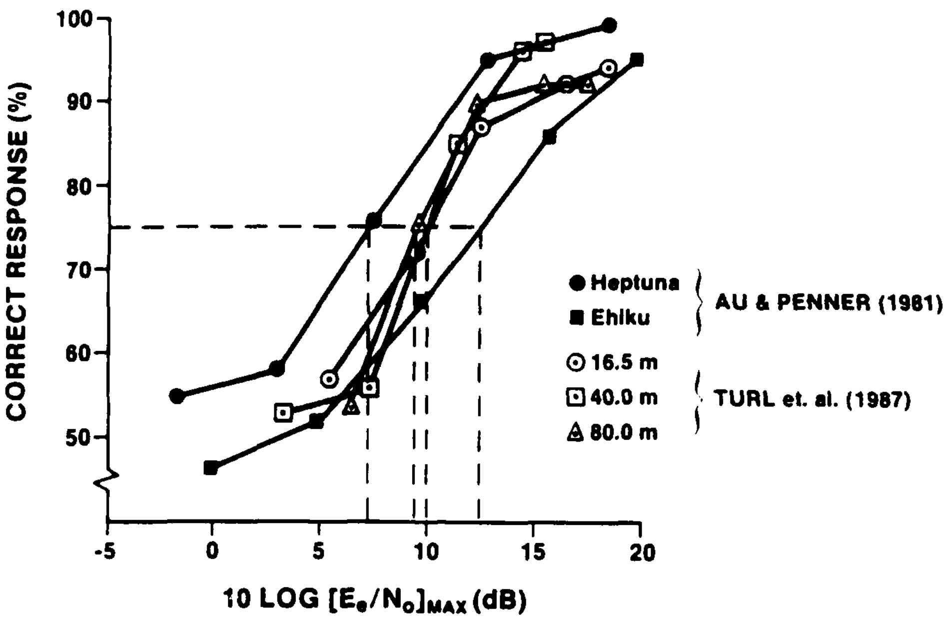

Fig. 5. Target detection in noise performance results as a function of the echo energy-to-noise ratio (from Au and Penner, 1981; Turl et al., 1987).

used by Turl et al. (1987) did not exhibit any "shut down" behavior probably because the highest noise level was 10 dB lower than that of Au and Penner (1981).

The third technique of fixing the target range and reducing the target size was used by Au et al. (1988) to measure the target detection capability of a Tursiops. An electronic transponder system was used so that the effective echo strength could be varied by adjusting the level of the simulated echoes. A hydrophone 1.9 m in front of a stationing hoop detected each projected signal which was digitized and stored in random access memory (RAM). The stored signal was then played back through a projector located 2.4 m from the hoop to simulate an echo from a target. Masking noise at a fixed level was also played to the animal and the intensity of the simulated echo was randomly varied in 10-trial blocks by increments of 2 dB. For each click emitted by the dolphin, two clicks separated by 200 μs were played back to the animal at a time delay corresponding to a 20 m target range. The dolphin was required to station in a hoop, echolocate and report if the phantom target was present or absent.

The phantom target results are shown in Fig. 6 along with the maximum range results (Fig. 3) and the noise masking results (Fig. 5). The results between the various studies agree extremely well considering the differences in animals, time periods and experimental procedures. Murchison (1980) and Au and Synder (1980) varied target range in small increments in terms of the resultant E_e/N_0. Au and Penner (1981), Turl et al. (1987) used a constant target range and randomly varied the masking noise levels. A relatively large increments of 5 dB was used by Au and Penner (1981) and a smaller 3 dB increment was used by Turl et al. (1987). Au et al. (1988) used a fixed phantom target range and noise

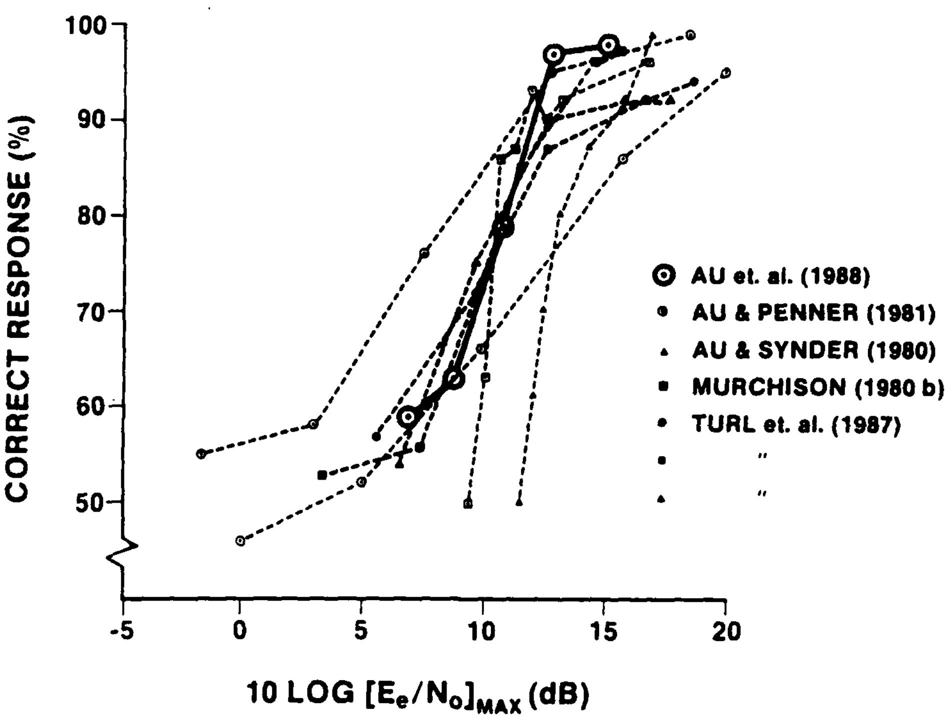

Fig 6. Phantom target detection performance of a Tursiops as function of the echo energy-to-noise ratio (from Au et al., 1988).

level and randomly varied the amplitude of the target echoes in 2 dB increments. The shallower slopes of the performance curves in the Au and Penner (1981) study were probably the result of using a large noise increment. The curves from the other studies have similar slopes.

III. DOLPHIN SONAR MODELED AS AN ENERGY DETECTOR

The auditory threshold as a function of signal duration and the critical ratio experiments of Johnson (1968a, b) with Tursiops truncatus indicate that the dolphin's inner ear functions like the human inner ear and that the animal integrates acoustic energy in the same way as humans. Green and Swets (1966) showed that an energy detector is a good analogue of the human auditory detection process. Therefore, it seems reasonable to approach the dolphin auditory process as an energy detector. From Johnson's (1968a) auditory threshold data for pure tone signals of varying duration, the integration at 120 kHz should be approximately 2 ms. However, experiments with pulse sounds by Vel'min and Dubrovskiy (1975; 1976) indicated that dolphins may process short duration broadband sonar signals differently than pure tone signals. Au et al. (1988) performed an experiment to measure a dolphin's integration time for sonar pulses using a phantom target with electronically simulated echoes that could be controlled with high precision. They first played back a single click for every click emitted by the dolphin and obtained a threshold in noise by progressively decreasing the amplitude of the single click echo. The threshold was obtained using a staircase psychophysical testing procedure. Next they played back two clicks for each click emitted by the dolphin and measured the dolphin's threshold. Various separation times between the first and second clicks of the double click echoes were used.

The results of the auditory integration time experiment are shown in Fig. 7, with the echo energy-to-noise ratio in dB plotted against the separation time between the double click echo. The dolphin's threshold shifted approximately 3 dB when the stimulus changed from a single click to a double click. This shift is exactly what would be expected for an energy detector since there is 3 dB more energy in the double-click stimulus. As ΔT increased to 200 μs, the threshold remained essentially the same. As ΔT increased to 250 μs, the threshold began to shift towards the single-click threshold, reaching the single-click threshold at a ΔT of about 300 μs and greater. Therefore, the presence of a second click with ΔT greater than 300 μs did not help the dolphin in detecting the phantom target. The solid curve in Fig. 7 is the response of an ideal detector with an integration time of 264 μs. The curve associated with an integration time of 264 μs best fitted the dolphin's data with a minimum least-square error. The 264 μs integration time corresponded well with the 260 μs critical interval reported by Vel'min and Dubrovskiy (1975; 1976) for echolocating Tursiops truncatus. They defined the critical interval as a "critical time interval in which individual acoustic events merge into an

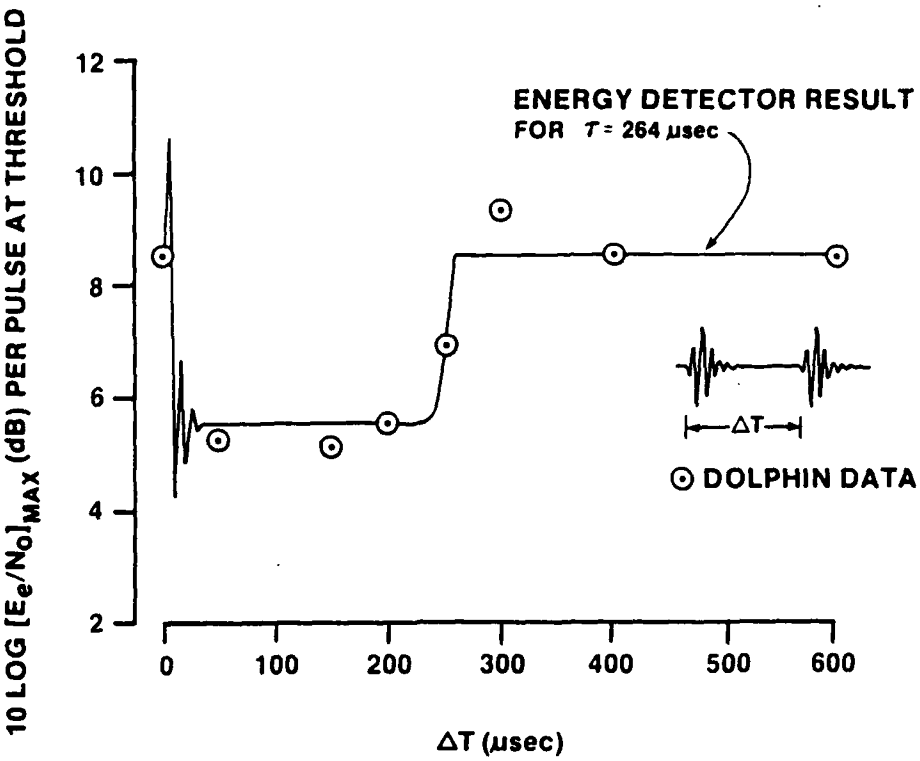

Fig. 7. Integration time experiment results showing the average of the maximum E_e/N_0 per pulse at threshold as a function of the separation time between pulses. Each echo at 0 μs consisted of a single click, while each echo at the other separation times consisted of double clicks. The solid curve is the response of an ideal energy detector that best fit the dolphin data (from Au et al., 1988).

acoustic whole," which may be another way of considering integration time. The integration time measured by Au et al. (1988) also agreed well with the backward masking threshold of 265 μs measured by Moore et al. (1984).

Energy detection processing by Tursiops was examined further by Au et al. (1988) using their electronic phantom target in another experiment. They played back echoes consisting of one, then two and finally three replicas of each emitted click and measured the shift in the dolphin's threshold. All pulses were within the integration time of the dolphin auditory system. Their results are presented in Fig. 8 along with an energy detector response curve. They found that the dolphin's sonar detection performance followed the response of an energy detector.

The dolphin's performance data obtain in the presence of masking noise shown in Figs. 5 and 6 can be compared with a theoretical model of an energy detector. Urkowitz (1967) examined the detection of a deterministic signal in white Gaussian noise using an energy detector, and derived expressions for the correct detection and false alarm probabilities as a function of signal-to-noise ratio, an adjustable threshold level and the time bandwidth product of the signal. The probability of a false alarm for a given threshold V_T is given by

$$P(FA) = 1 - Pr(V_T \leq \chi^2_{2TW}) \qquad (3)$$

where Pr is the area under the chi-square distribution curve with 2TW

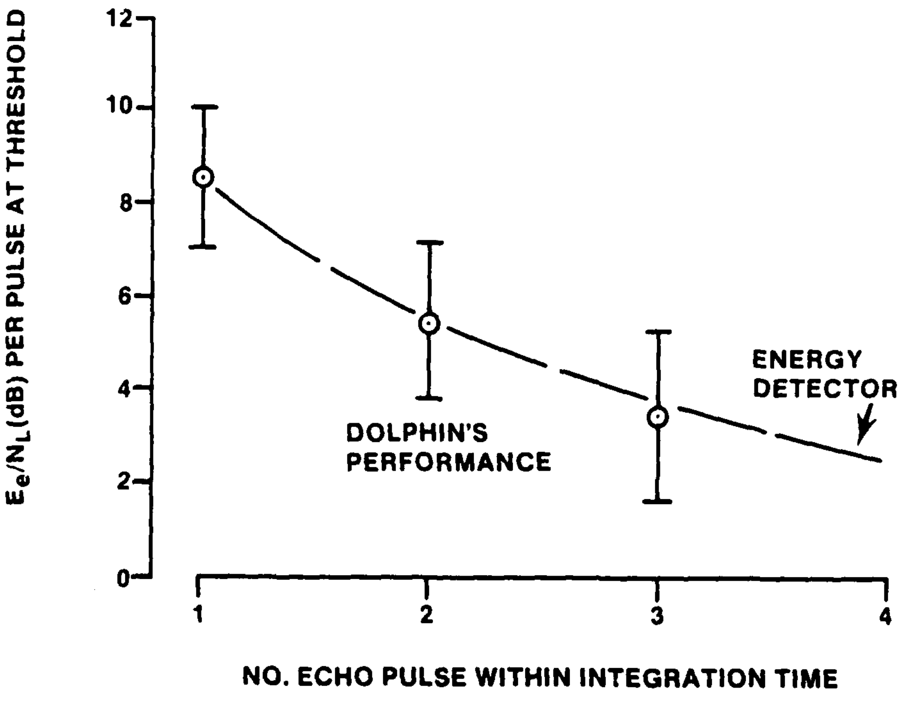

Fig. 8. Dolphin's performance as a function of the number of clicks in the echo with the animal's integration time (From Au et al., 1988).

(time-bandwidth) degrees of freedom. For the same threshold level V_T, the probability of a correct detection is given by

$$P(D) = 1 - Pr(V_T/G \le \chi^2_D) \quad (4)$$

where:

$$D = (2TW + E/N_o)^2/(2TW + 2E/N_o) \quad (5)$$

$$G = (2TW + 2E/N_o)/(2TW + E/N_o) \quad (6)$$

Pr is now the area under the noncentral chi-square distribution with a modified number of degrees of freedom D and a threshold divisor G.

These expressions derived by Urkowitz (1967) were applied to dolphin detection data by assuming an unbiased detector in determining the probability of a correct response P(C) from P(FA) and P(D) given in Eqs. 3 and 4. The calculation was done by first choosing desired values of P(FA) and 2TW and then determining V_T by an iterative procedure. Then with the iterated value of V_T, P(D) was calculated for different values of E/N_o. The procedure was continued for different 2TW degrees of freedom, until the values of P(C) were obtained as a function of E/N_o which best fitted the dolphin data. The performance data for Tursiops detecting targets in masking noise in three different studies are shown in Fig. 9 along with the results of Urkowitz energy detection model for 2TW = 22. Urkowitz's energy detection model agrees well with the dolphins' results, further supporting the notion of the dolphin being an energy detector. Insert-

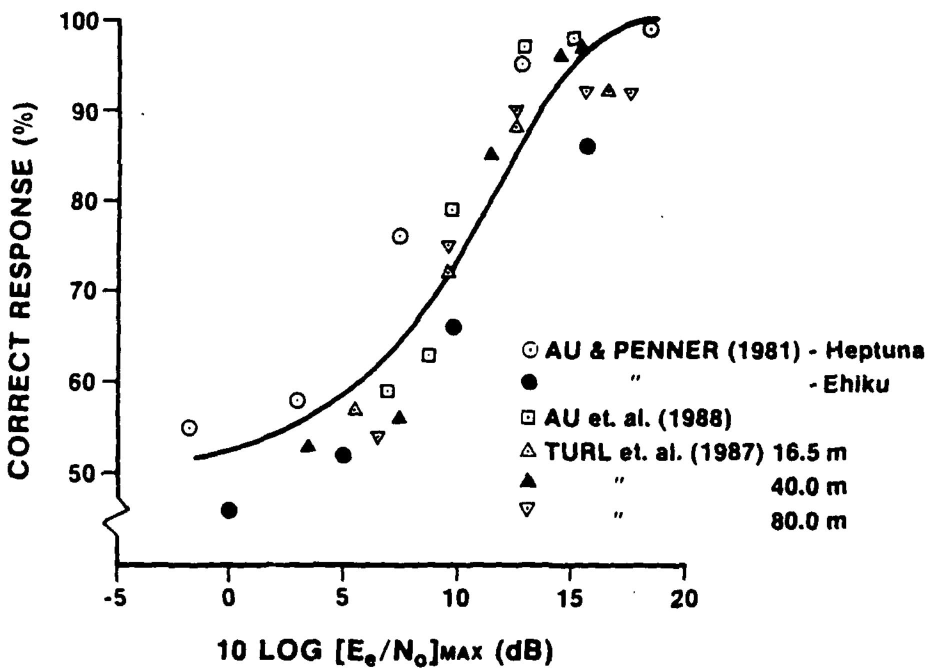

Fig. 9. Comparison between dolphin target detection in noise performance results and Urkowitz (1967) energy detection model for TW =11 (from Au, 1988).

ing an integration time of 264 μs into the TW product will result in a bandwidth of 42 kHz for the detector depicted in Fig. 8. Moore and Au (1983) measured a critical ratio of approximately 18 kHz at 120 kHz for Tursiops, which is in general agreement with the bandwidth for the energy detector model. The unbiased detector assumption used to derive P(C) is good for signal-to-noise conditions that correspond to performance at or above the 75% correct response threshold. Tursiops tend to be unbias for high signal-to-noise conditions (Au and Synder, 1980; Au and Penner, 1981)

IV. COMPARISON WITH AN IDEAL RECEIVER

An ideal or optimal receiver is the best receiver in detecting a known signal in white Gaussian noise. Petersen et al. (1954) related the receiver-operating-characteristic (ROC) curves [P(D) versus P(FA)] to the signal-to-noise ratio at the receiver input required for detection of a signal in noise. They showed that the optimal receiver for the detection of a signal known exactly in white noise was a cross-correlator receiver, in which the input signal plus noise is correlated with a noise-free replica of the known signal. An equivalent receiver is a matched filter whose impulse response is the same as the waveform of the known signal reversed in time. Since the ideal receiver will detect a signal in noise better than any other receiver, the efficiency or effectiveness of any other receiver can be compared against an ideal receiver.

Au and Pawloski (1989) performed two experiments with an electronic phantom target to compare the target detection performance of an echolocating bottlenose dolphin with that of an ideal or optimal receiver. The first experiment was conducted to establish a more realistic method of estimating E_e/N_0 at the dolphin's detection threshold. Two different types of echoes were used and the dolphin's threshold was determined by an up-down or staircase procedure. The first echo type consisted of two clicks, separated by 200 μs, which were replicas of each transmitted click. The amplitude of the echoes was directly proportional to the amplitude of the emitted clicks. With this echo type, the $(E_e/N_0)_{max}$ at threshold was determined in a similar manner as for the results shown in Figs. 4-6. The second echo type consisted of a previously measured and digitized echolocation click from the animal which was stored in erasable programmable read-only memory (EPROM). The electronic target simulator was modified so that every time the dolphin emitted an echolocation signal, the EPROM was triggered to produce two pulses separated by 200 μs. The amplitude of the echo was fixed for each trial independent of the dolphin's signal level, resulting in a fixed E_e/N_0 per trial, and an accurate estimate of E_e/N_0 at threshold. The difference between $(E_e/N_0)_{max}$ and E_e/N_0 was determined to be 2.9 dB indicating that an accurate estimate of E_e/N_0 can be obtained by subtracting 2.9 dB from $(E_e/N_0)_{max}$.

In the second experiment, Au and Pawloski (1989) obtained data that could be presented in an ROC format. The dolphin's response bias was manipulated varying the payoff matrix (number of pieces of fish reinforcement for correct responses). The payoff matrix was varied in terms of the ratio of correct detection to correct rejection in the following manner: 1:1, 1:4, 1:1, 4:1, 1:1, and 8:1. Six consecutive sessions were conducted at each payoff matrix, with the 1:1 payoff being the baseline. The results of the dolphin's target detection performance as its response bias was manipulated are plotted in an ROC format in Fig. 10 for two different target strengths. The ideal isosensitivity curves associated with d' values of 2.2 and 1.6 for the strong and weak echoes, respectively, are included in Fig. 10. The detection sensitivity, d', represents the minimum value of E_e/N_0 necessary to lead to the performance of an

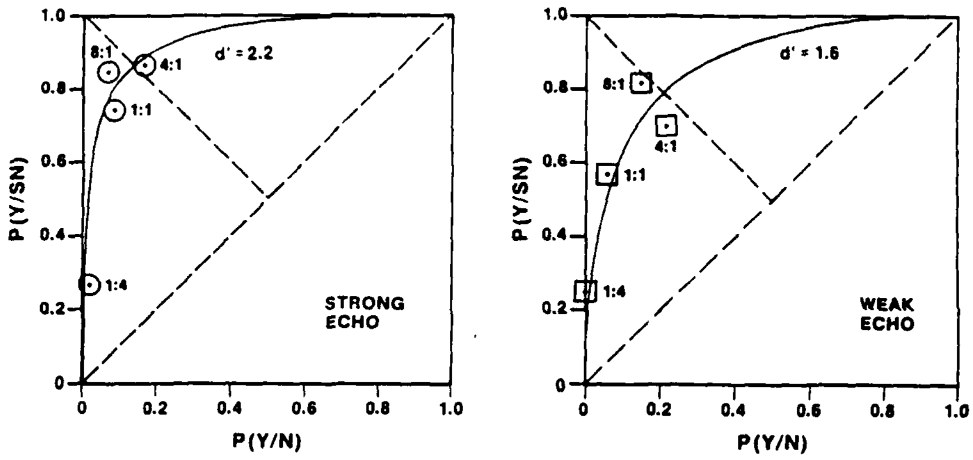

Fig. 10. Dolphin performance results plotted in an ROC format and iso-sensitivity curves that best matched the results. The ordinate is probability of detection, P(Y/SN) and the abscissa is probability of false alarm, P(Y/N) (from Au and Pawloski, 1989).

ideal receiver (Elliott, 1964). Each isosensitivity curve of Fig. 10 best matched the dolphin's performance with a minimum least-square error. From Fig. 10, the $(E_e/N_o)_{op}$ for an ideal detector to match the dolphin's performance can be determined and compared with the E_e/N_o for the dolphin. $(E_e/N_o)_{op}$ for an optimal receiver can be calculated from the definition of d' given in the equation

$$d' = \sqrt{2(E_e/N_o)_{op}} \qquad (7)$$

The echo energy-to-noise ratio in dB is

$$(E_e/N_o)_{op} = 10 \log(d'^2/2) \qquad (8)$$

Therefore, for an optimal receiver to approximate the performance of the dolphin, the following echo energy-to-noise ratios are needed

$$(E_e/N_o)_{op} = \begin{cases} 3.8 \text{ dB (strong echo)} \\ 1.1 \text{ dB (weak echo)} \end{cases}$$

The dolphin performance results were obtained with an E_e/N_o of 12.2 dB for the strong echo and 7.4 dB for the weak echo case. The difference in E_e/N_o between the dolphin and an optimal receiver can be expressed as

$$(E_e/N_o)_{dol} - (E_e/N_o)_{op} = \begin{cases} 8.4 \text{ dB (strong echo)} \\ 6.3 \text{ dB (weak echo)} \end{cases}$$

Averaging the differences for the strong and weak echoes, we can conclude that an optimal receiver would outperform the dolphin by approximately 7.4 dB.

V. SUMMARY AND CONCLUSIONS

The sonar target detection sensitivity of Tursiops truncatus has been measured by determining: (a) The maximum detection range for two targets. (b) Target detection performance for a target at a fixed range in the presence of variable artificial masking noise. (c) Target detection performance for a variable sized target at a fixed range in the presence of artificial masking noise. The results of the various methods when considered in terms of E_e/N_0 were very consistent with the detection threshold varying from 7.2 to 12.4 dB. The shape of the performance curves as a function of E_e/N_0 was also similar except for the case in which the noise levels changed in 5 dB increments.

Target detection performance data suggest that Tursiops process sonar echoes like an energy detector with an integration time of approximately 264 μs. The data also suggest that dolphins may process short duration broadband signals in a different manner than long duration tonal signals. The integration time of 264 μs is smaller by a factor of 7.6 from the approximately 2 ms integration time for a 120 kHz tonal signal. Different processing mechanisms for short duration signals and long duration tonal signals have been suggested by Vel'min and Dubroskiy (1975; 1976) under the nomenclature of "active and passive hearing."

An accurate estimate for E_e/N_0 at the detection threshold of a dolphin may be obtained by first calculating $(E_e/N_0)_{max}$ using the average of the largest energy flux density measured per trial and subtracting a correction factor of 2.9 dB. An ideal or optimal receiver requires approximately 6 to 8 dB less energy in order to perform at the same level of accuracy as a Tursiops truncatus in detecting targets in noise.

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