The Dolphin Sonar: Excellent Capabilities In Spite of Some Mediocre Properties

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Abstract. Dolphin sonar research has been conducted for several decades and much has been learned about the capabilities of echolocating dolphins to detect, discriminate and recognize underwater targets. The results of these research projects suggest that dolphins possess the most sophisticated of all sonar for short ranges and shallow water where reverberation and clutter echoes are high. The critical feature of the dolphin sonar is the capability of discriminating and recognizing complex targets in a highly reverberant and noisy environment. The dolphin's detection threshold in reverberation occurs at a echo-to reverberation ratio of approximately 4 dB. Echolocating dolphins also have the capability to make fine discriminate of target properties such as wall thickness difference of water-filled cylinders and material differences in metallic plates. The high-resolution property of the animal's echolocation signals and the high dynamic range of its auditory system are important factors in their outstanding discrimination capabilities. In the wall thickness discrimination of cylinder experiment, time differences between echo highlights at small as 500-600 ns can be resolved by echolocating dolphins. Measurements of the targets used in the metallic plate composition experiment suggest that dolphins attended to echo components that were 20-30 dB below the maximum level for a specific target. It is interesting to realize that some of the properties of the dolphin sonar system are fairly mediocre, yet the total performance of the system is often outstanding. When compared to some technological sonar, the energy content of the dolphin sonar signal is not very high, the transmission and receiving beamwidths are fairly large, and the auditory filters are not very narrow. Yet the dolphin sonar has demonstrated excellent capabilities in spite the mediocre features of its "hardware." Reasons why dolphins can perform complex sonar task will be discussed in light of the "equipment" they possess.

INTRODUCTION

The echolocation system of a dolphin can be divided into three major subsystems: reception, transmission, and signal processing/decision making subsystems. The receiving subsystem consists of the auditory system of the animal, and its capabilities depend on the characteristics of the peripheral and higher auditory centers of the auditory central nervous system. The capability of a dolphin to detect objects in noise and clutter and to discriminate between various objects, and to recognize specific objects depends to a large extent on the information-carrying capabilities of the emitted signals. Also important are the extent to which the dolphin's auditory system can extract pertinent information from the echoes and the animal's cognitive capabilities. In order to make optimal use of acoustical information, the dolphin should have an auditory system that is very sensitive over a wide frequency range. The dolphin should also be sensitive in both quiet and noisy environments and should be able to detect short- and long duration sounds. A good spectral analysis capability is important in discriminating and recognizing predators, prey, and other objects in the environment. Other important characteristics of a good sonar receiver include the ability to spatially resolve and localize sounds, reject externally generated interferences, and recognize temporal and spectral patterns of sounds.

Most of the data that will be discussed here come from the Atlantic bottlenose dolphin, *Tursiops truncatus*. This species is the most common in oceanariums, marine parks, aquaria and other public display facilities. It is also the species that is most common in captivity. Occasionally, data from other species will be used when appropriate.

RECEIVER CHARACTERISTICS

The hearing sensitivity at different frequencies (audiogram) of a bottlenose dolphin was measured in a classic study by Johnson [1]. His results along with those of Au et al. [2] are shown in Fig. 1. The audiogram of the two dolphins indicate that

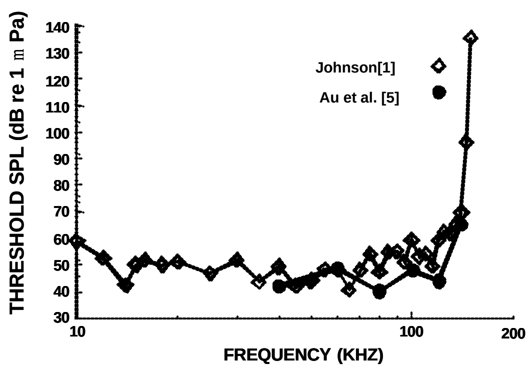


Figure 1. Hearing sensitivity of two Atlantic bottlenose dolphins as a function of frequency (from Johnson [1] and Au et al. [2]).

they have a very broad frequency range of hearing from 100 Hz to 150 kHz, covering approximately 10 octaves. The maximum sensitivity is approximately 40 dB re 1 μPa, which close to sea state 0 when taking into consideration the filter bandwidth in the dolphin's auditory system.

Receiving beam pattern

The receiving beam pattern of a bottlenose dolphin was measured by Au, et al. [3] and their results in both the vertical and horizontal planes for three different frequencies, 30, 60 and 120 kHz, are shown in Fig. 2. The major axis in the vertical plane is pointed between 5 and 10^o above the horizontal axis. In the horizontal plane, the beam axis is pointed directly in front of the dolphin. The beam patterns are relatively wide in comparison to many technological sonar. For example, the SimRad-Mesotech MS-2000 multibeam sonar has 128 beams in the horizontal plane, each with a beamwidth of 1.5^o covering a sector of 120^o.

a b

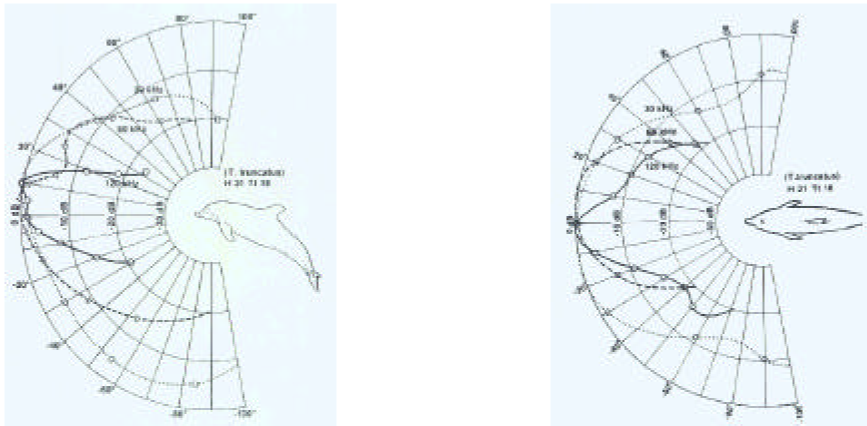


Figure 2. Receiving beam pattern for the bottlenose dolphin for three different frequencies, (a) in the vertical plane, (b) in the horizontal plane (from Au and Moore[3]).

Auditory filter shape

The auditory filter shape of a mammalian subject can be determined by performing a notched noise masking experiment where the tone signal is directly in the middle of the notch. Such a study was performed by Lemonds et al. [4] and their results are shown in Fig. 3 for frequencies of 40, 60, 80 and 100 kHz. Note that the filters are not very narrow. The shapes are similar to that of humans if we normalized

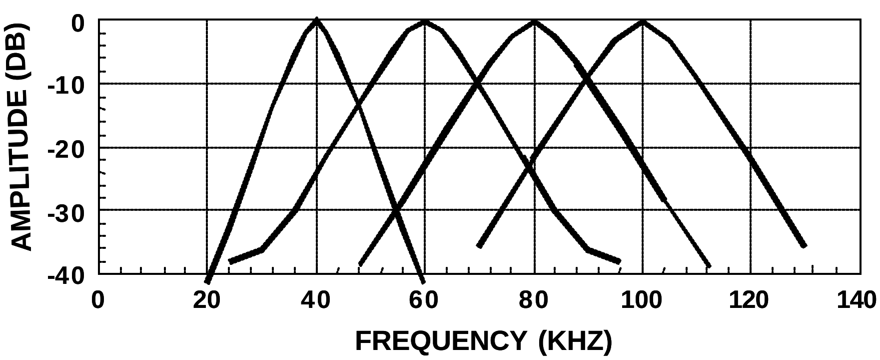


Figure 3. Auditory filter shape for a bottlenose dolphin.

the frequency by dividing by f_o for any given filter. If the 3-dB bandwidth is plotted as a function of the center frequency of each filter, a Q of 8.4 would represent the best constant-Q fit through the bandwidth points.

TRANSMITTER CHARACTERISTICS

Bottlenose dolphins emit short broadband clicks having peak frequencies as high as 120-130 kHz [5]. Signals typically have with 4 to 10 positive excursions and durations that vary from 40 to 70 μs,. Peak-to-peak source levels between 210 and 227 dB re 1 μPa have been measured [1]. Two echolocation signals of the bottlenose dolphin are sh own in Fig. 1. Dolphins in tanks naturally emit much lower level signals with lower peak frequency. Examples of echolocation signals are shown in Fig. 4. The frequency spectrum of transmitted signals is coupled to the output level of the signals having higher frequency as the output level increases. Typical bandwidth is between 40 and 60 kHz.

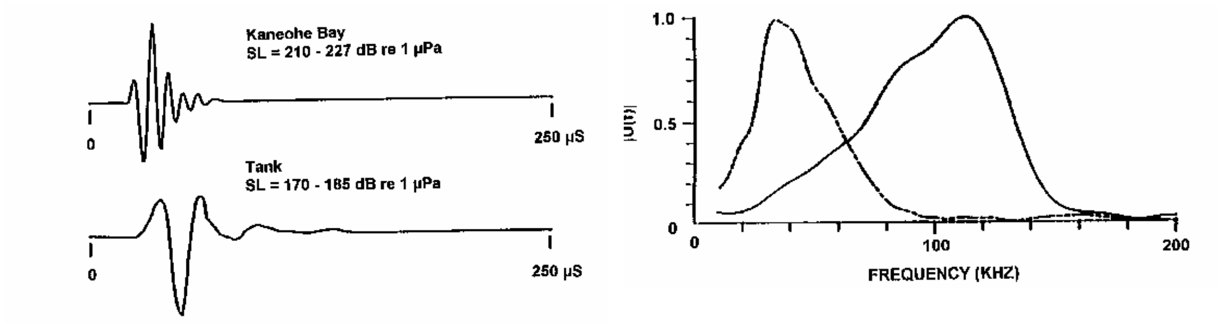


Figure 4. Representative echolocation signals of Tursiops truncates in a tank and in open waters. The waveforms are on the left and the frequency spectra on the right (from Au [5]).

Source levels

The source levels used by a dolphin will vary as a function of the loss involved in a sonar task. Au [5] examined the variation in the source level of five different bottlenose dolphins as a function of the total loss that the animals experienced from two-way spherical spreading loss and target strength and obtained the results shown in Fig. 5. The highest averaged peak-to-peak source level of 224 dB re 1µPa occurred for the dolphins Heptuna and Ehiku searching for a 3-in diameter thin-walled stainless steel water filled sphere at 72.8 m. The target strength shown in the legend is based on energy.

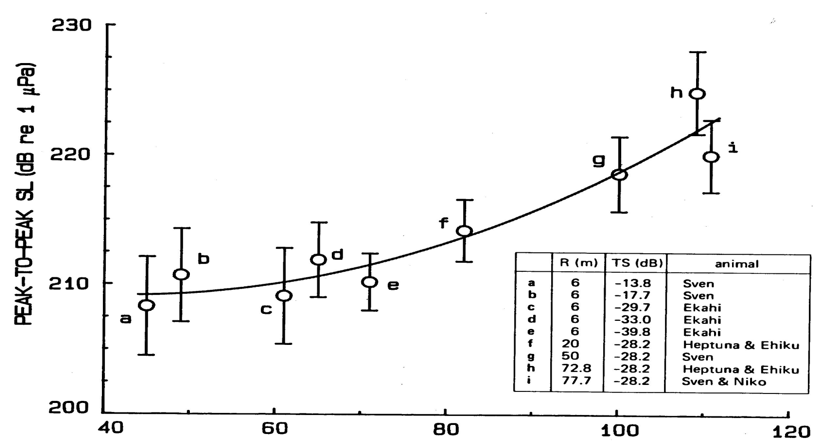


Figure 5. Peak-to-peak source levels used by 5 dolphins as a function of the total loss due to spherical spreading and target strength (from Au [5]).

Although the peak-to-peak source level of the sonar signal can be relatively high the energy flux density is relatively low because of the short duration of the signals. Let us compare the energy flux density of a typical sonar tone burst and that of a dolphin sonar signal by first defining the dolphin sonar signal as p(t) = A s(t), where A is the peak amplitude and s(t) is the normalized waveform. The energy flux density of the dolphin signal can be expressed as

$$E_{dolphin} = SPL_{pp} - 6 + 10\log\left(\int_0^T s^2(t)\,dt\right) \qquad (1)$$

For the echolocation signals shown in the top panel of Fig. 4, the integral term in db is approximately –52 dB [5], so the Eq. 1 can now be expressed as

$$E_{dolphin} = SPL_{pp} - 58 \qquad (2)$$

A similar expression can be written for a tone burst signal of duration T as

$$E_{dolphin} = SPL_{pp} - 9 + 10\log(T) \qquad (3)$$

The difference in the amount of energy is a tone burst over a dolphin signal with the same peak-to-peak source leve l can now be expressed as

$$\Delta E = E_{TB} - E_{dolphin} = 49 + 10\log(T) \qquad (4)$$

A graph of the amount of energy a tone burst would have over a dolphin sonar signal of the same peak-to-peak amplitude is shown in Fig. 6. A very short tone burst of 100 μs will have about 9 dB more energy than the high-frequency dolphin sonar signal

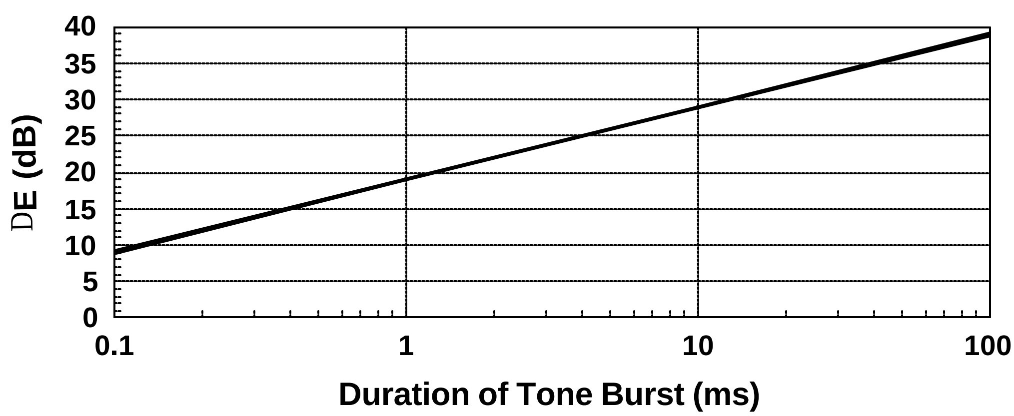


Figure 6. The amount of energy in dB that a tone burst would have over a dolphin echolocation signal of the same peak-to-peak amplitude.

shown in Fig. 4. The excess energy increase logarithmically with the duration of a tone burst.

Transmitting beam pattern

Signals are transmitted in a beam as shown in Fig. 7. The waveform of the signal measured by hydrophones at different angles about the animal's head. The transmit beamwidth of a high frequency sonar signal is 10.2° (horizontal plane) and 9.7° (vertical plane). The receiving beamwidth is slightly wider, 13.7° and 17° in the horizontal and vertical plane respectively. The directional projection and reception characteristics of bottlenose dolphin are poor compared to many technological sonar.

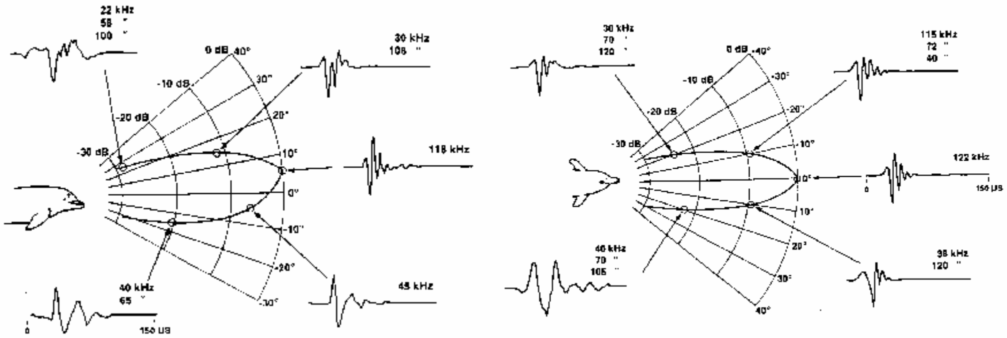


Figure 7 Transmission beam pattern for a bottlenose dolphin in the vertical and horizontal planes (from Au [5]).

One of the properties of the broadband nature of the dolphin sonar signals is the distortion of off-axis signals as can been seen in Fig. 6 for both planes. When a signal is measured at an angle greater than about 5^0 away from the beam axis, the signals become distorted and the amount of distortion increases as the angle increased.

SYSTEM'S PERFORMANCE

There are many experiments that can be discussed that would highlight the capabilities of echolocation dolphins in performing complex target discrimination tasks. Only three experiments will be discussed here, one on target detection in reverberation and two on target discrimination. Readers who would like to read more on dolphin sonar discrimination experiments should consider Au [5] and Nachtigall [6].

Target detection in reverberation

A sonar system is usually limited by noise or reverberation. Reverberation differs from noise in several aspects. It is caused by the sonar itself and is the total contribution of unwanted echoes scattered back from objects and inhomogeneities in the medium. Murchison [7] studied the effects of bottom reverberation on the target detection capabilities of two bottlenose dolphin in Kaneohe Bay. A 6.35-cm diameter solid steel sphere was used and eventually placed on the bottom. The animals' 50% correct detection threshold ranges for different target depth are shown in Fig.8. The threshold range for the target on the bottom was approximately 70 m. Au [8] used a simulated dolphin sonar signal to measure the scattering strength of the bottom where Murchison performed his experiment. Taking the target strength into consideration and the difference in the transmit and receive beam patterns of the transducer and the dolphin the reverberation form of the sonar equation was used to estimate an echo energy-to-reverberation (E/R) of approximately 4 dB. An example of an E/R ratio of 4 dB are shown in Fig. 9 (Au [8]). The highest highlight of the target echo is clearly detectable; however, the secondary highlights are masked by the reverberation so that the acoustic quality of the echo was altered. The dolphin probably could hear the largest highlight but the echo probably did not "sound" like the sphere they were trained to detect and consequently reported the target as not present.

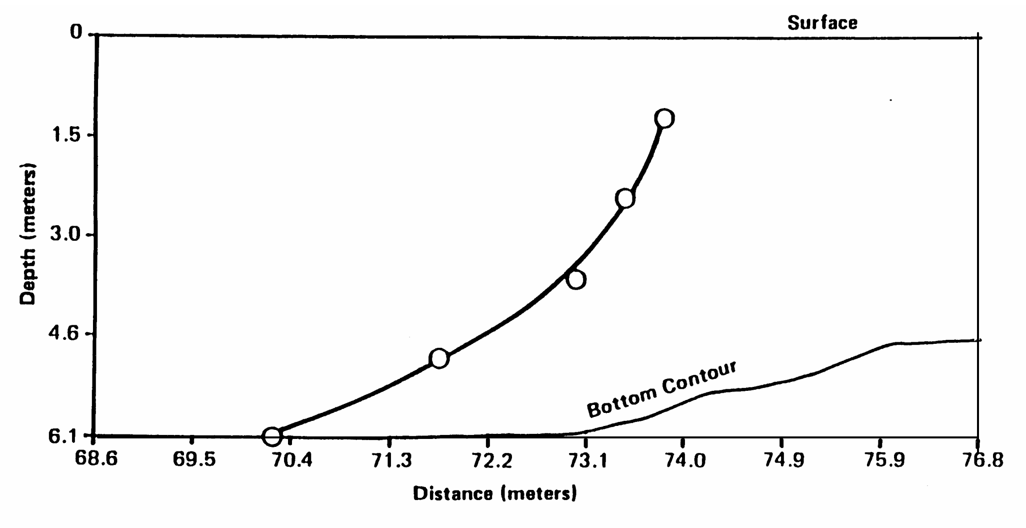


Figure 8. Target detection threshold as a function of target depth. The detection range when the 6.35-cm diameter sphere laid on the bottom was approximately 70 m (from Murchison [7]).

Therefore, it seems that a target detection experiment probably is not purely one of detecting signal in reverberation, but also involves discriminating the features of the echoes from a target. If the lower amplitude highlights are masked by reverberation or noise, the dolphins might hear the larger highlight components of the echo but the echo it probably would not "sound" like the target they were trained to detect. Therefore, target detection in noise and reverberation, also involves target recognition.

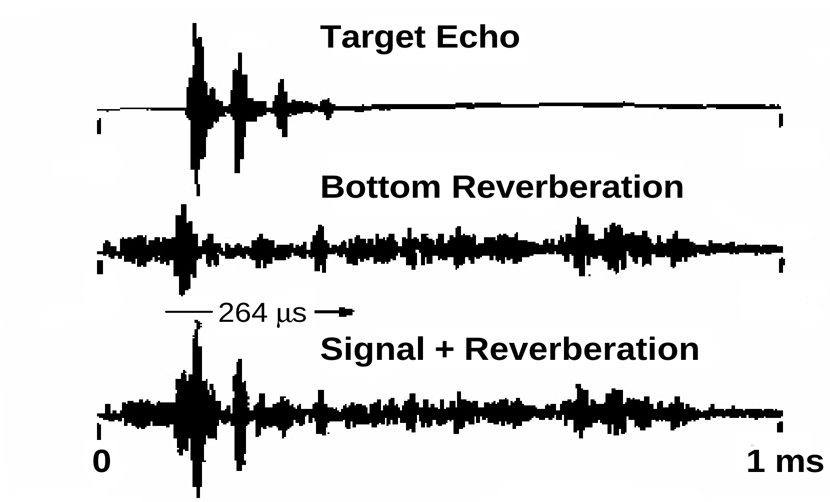


Figure 9. Target echo in reverberation at the dolphin's threshold of detection (from Au [8]).

Discriminating composition and thickness of metallic plates

Evans and Powell [9] demonstrated that a blindfolded, echolocating bottlenose dolphin could discriminate between metallic plates of different thickness and material composition. The dolphin was trained to recognize a 30-cm diameter circular copper disc of 0.22-cm thickness from comparison targets of the same diameter A schematic of the dolphin performing a typical search and the various comparison material and plate thickness are shown in Fig. 10. The dolphins could perform the task well above chance.

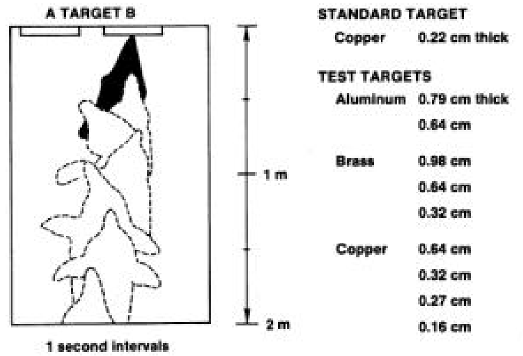


Figure 10. A typical sonar search by the blindfolded bottlenose dolphin and the various comparison targets comparison target used by Evans and Powell [9].

Au and Martin [10] examined the plates used in the experiment of Evans and Powell [9] with an echo ranging system that projected simulated dolphin echolocation signals. Backscatter results at normal incident indicated that virtually no cues for discrimination was present in the echoes. However, when the plates were examined at angles away from the normal, the different plates began to display unique highlight structures. Examples of backscatter at normal incident and at 14^o incident are shown in Fig. 11. The echoes from the 14^o incident angle are about 20 dB below that of the normal incident, yet the discrimination cues were present for the off-axis backscatter. This implies that dolphin are able to use cues that are at least 20 dB below the maximum amplitude of the echoes at normal incident in order to discriminate targets.

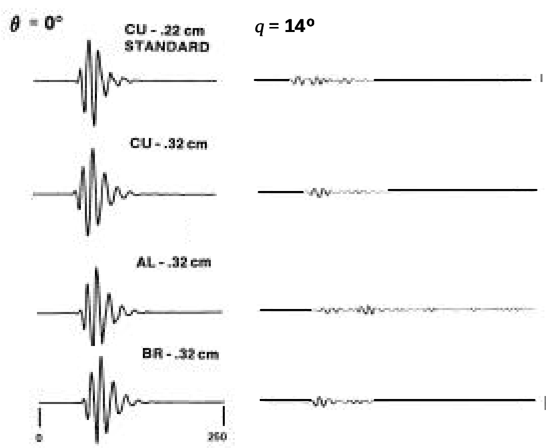


Figure 11. Examples of backscatter from the standard disk and some of the comparison disks used by Evans and Powell [9].

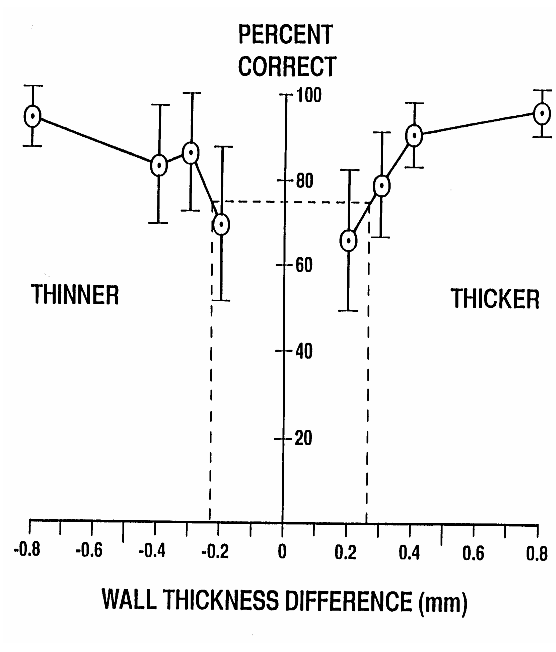
Cylinder wall thickness discrimination

The capability of a bottlenose dolphin to discriminate the wall thickness differences was measured by Au and Pawloski [11]. A dolphin was trained to station in a hoop and echolocate of two targets 8 m away separated by 22^o azimuth. The standard target was a 3.81-cm O.D. aluminum cylinder with a wall thickness of 6.35 mm.

Comparison targets with wall thickness both thinner and thicker than the standard were used. The comparison targets had incremental differences in wall thickness of ± 0.2, ± 0.3, ± 0.4 and ± 0.8 mm from the standard target. The dolphin was required to echolocate and to respond to the paddle that was on the same side of the center line as the standard target. The dolphin's performance as a function of wall thickness difference is shown in Fig. 11a. The 75% correct response threshold corresponded to a wall thickness difference of –0.23 mm for the thinner targets and +0.27 mm for the thicker targets. Echoes from the standard and the 0.3 mm thinner wall thickness comparison target are shown in Fig. 11b. The echo waveforms are shown in the top two traces, followed by the envelopes of the echo waveforms overlaid on each other and by the frequency spectra in the bottom traces.

The dolphin was able to perform the wall thickness discrimination represented by Fig. 12 b and was below the threshold for the next thinner target. If the animal was using time-domain cues, then the echo data suggest that it could discriminate a 600 ns difference between the arrival of the second highlight for each target. If frequency domain cues were used, than a frequency shift between 3.3 and 3.9 kHz could be detected in the broadband echoes.

(a)



(b)

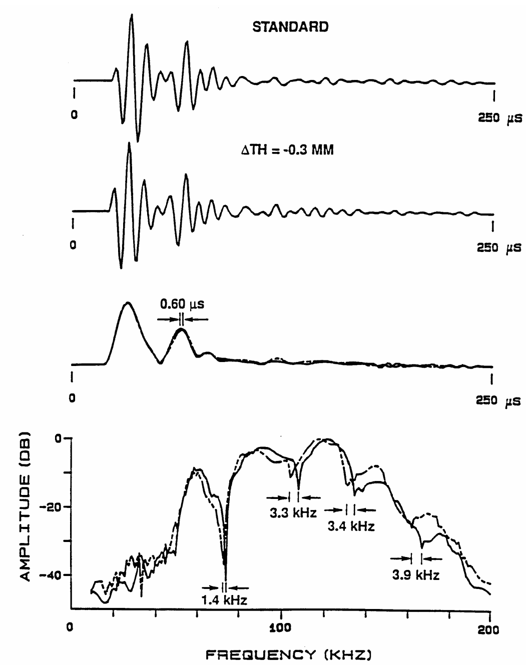


Figure 12. (a) Dolphin wall thickness discrimination performance, (b) Echo waveform, waveform envelope, and frequency spectrum for the standard and comparison target having a wall thickness difference of –0.3 mm. The dashed envelope and spectrum curves are for the comparison target (from Au and Pawloski [11]).

DISCUSSION AND CONCLUSIONS

The various discrimination experiments with echolocating dolphins strongly suggest that these animals possess a sophisticated and well honed sonar system in spite of some fairly mediocre acoustic properties of the sonar system. The transmit and receive beam patterns are not very narrow. The auditory filters are also not very narrow. The amount of acoustic power emitted is not very high when compared to technological sonar. There are many technological sonar with narrower transmit and receive beams and narrower receiver filters that emit more powerful acoustic signals. So we are left with the question: What are important factors that could allow dolphins to have such good sonar discrimination and recognition capabilities?

The first property of the dolphin sonar that contributes to good performance comes from the use of broadband echolocation signals. Shown in Fig. 13 is the envelope of the cross correlation function of the signal shown in Fig. 4 with the echoes from two point source separated by varying time τ. When the point target is separated in time by 15 μs, the two targets begin to be resolvable. When the two point targets are separated by 20 μs, the two peaks in the envelope response are almost completely resolvable. Therefore, the temporal resolution of a dolphin echolocation signal is approximately 15 – 20 μs, which translate to a distance resolution of about 0.015 m or 15 cm. The fine temporal resolution that can be obtained with dolphin sonar signals does not require special processing such as pulse compression making it possible for dolphin to process echoes in the time domain.

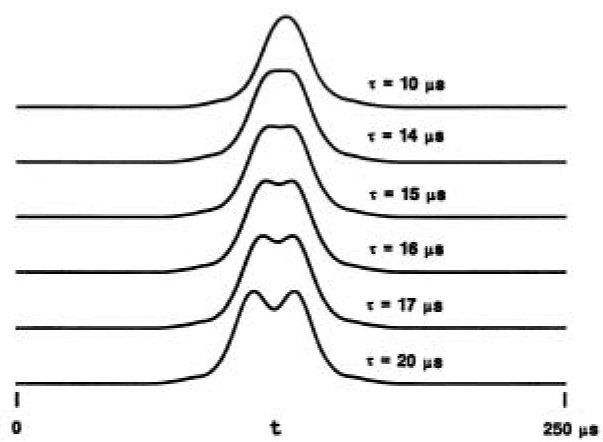


Figure 13. The normalized envelope of the cross correlation function of echoes from two point targets separated in time by τ and the transmitted signal shown in the top left panel of Fig. 4 (from Au [5]).

The use of broadband signals may also allow for the perception of time-separation pitch by dolphins. When a sound consisting of two correlated pulses are projected to humans, a pitch that is equal to the reciprocal of the time delay between the two pulses can be perceived by the human auditory system and may also be perceived by most mammal. If more than two highlights are present in an echo, a time-separation like pitch can still be heard. Therefore, a dolphin may discriminate targets from a pitch-like sound that multi-highlight echoes produce.

However, the short duration of the transmit signal limits the amount of energy within a signal so that the range of the sonar system is not very large. Typically, dolphins seem to be interested in objects that are within 100 m and are hardly concerned about longer ranges. So in a sense, temporal resolution was traded off with maximum range in the evolution process. However, within a 100 m range, there is not a technological sonar that can rival the dolphin in discriminating and recognizing targets. Bottlenose dolphins can even detect and discriminate targets that are buried in ocean sediment.

A second feature of the dolphin sonar system that is used to great advantage by the animals has to do with the dynamic range of its system. The metallic plate discrimination experiment discussed in Section 4.3 suggest that dolphins may gain information on an object by examining echoes that are 20 to 30 dB below the maximum level associated with a particular target. In other words, a dolphin does not seem to only seek out specific orientations to a target that will produce the highest echo levels but orientations that will provide the most information. In the metallic plate discrimination study, the orientation to the target that provided valuable information came from incident angles that were away from the normal to the plates. Therefore, the important parameter for the dolphin may be information level rather than echo level.

A third feature of the dolphin sonar system that is often overlooked is the fact that the sonar is mounted on a very flexible and mobile platform. Dolphins conduct sonar searches in an adaptive manner in that the trajectory of the animal at any given time will be the results of echoes received previously. A dolphin will not be restricted to running preprogrammed track lines or transect but is free to maneuver as the situation dictate. Therefore, a dolphin can approach and search on an object at different orientation and obtain whatever information it needs to recognize a target. The manner in which dolphins conduct sonar searches is another area of research that should be pursued. A system in which the sonar echoes dictate the specific trajectory of a mobile platform at any given time needs to be developed.

The dolphin sonar system has evolved over millions of years as nature’s way to optimize an important sensory modality. Humans can take advantage of the natural selection process that has been working in dolphins to improve technological sonar. One obvious direction that should be pursued is the use of broadband signals that imitate the signals used by dolphins. There may be a temptation to adopt a longer broadband signal such as FM signals used by some bats in order to project more energy into the water. I caution against such an approach and suggest that more weight should be placed on using natural section as a guide, and we should strive to first produce a short-range sonar system that can perform as well as the dolphin. Perhaps, after such a system is developed, tested and used should we seek to improve on nature. There are many problems that still need to be solved in terms of processing broadband sonar echoes.

Finally, the ultimate reason for the keen sonar capability possess by dolphins has to do with the entire sonar process being controlled by a mammalian brain that allows for versatility and continuous learning. As a contrast, a neural network is trained to recognize features of specific targets and then the training stops. The “learned” templates are then used to recognize those targets in the field. On the other hand, the mammalian brain continues to learn and in this manner it can adapt to different situations and environment and benefit from previous experiences. Futuristic sonars may need to process signals in a fashion akin to how the brain process signals and control the whole sonar process. This may seem to be a daunting proposition but progress can be made in little steps. For example, it would be useful to develop effective ways to process brief broadband sonar signals, making use of the good temporal resolution inherent in these type of signals. It would also be advantageous to develop techniques in which a sonar on a free-roaming vehicle can control and perform adaptive sonar search patterns. Research should also be done on the process of continuous learning in a sonar function. I believe that we can make considerable progress in developing better sonar by following along the path that has been provided by dolphins.

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