Manatees, Bioacoustics and Boats

Hearing tests, environmental measurements and acoustic phenomena may together explain why boats and animals collide

Edmund R. Gerstein

It's 2 o'clock in the morning, and, wouldn't you know it, Stormy is "in love" with that big Navy transducer again. Now I have to get in the cold water and pry him off so we can set up for Dundee's session. Oh, the joys of working with manatees under the Tampa moonlight! Even though I'll be tired, cold and wet, before sunrise we will have measured another critical aspect of the Florida manatee's hearing abilities. Over the next seven years of extended late-night auditory testing—more than 30,000 threshold trials in all—my wife Laura and I will measure two teenage manatees' ability to hear, locate and discriminate different underwater signals under various controlled acoustical conditions. In the end, we will have laid the groundwork for a sensory explanation for why manatees are hit repeatedly by boats.

The endangered Florida manatee, a subspecies of the West Indian manatee *(Trichechus manatus)*, is a gentle, bewhiskered herbivore that can reach 4 meters in length, weigh up to 1,300 kilograms and live over 60 years. Designated as Florida's official marine mammal, the manatee has been the focus of more controversy and polarization over conservation and protection than perhaps any other mammal. "Sea cows," as they are sometimes affectionately called, inhabit shallow coastal, estuarine and riverine habitats throughout peninsular Florida, where they graze on sea grasses and are routinely injured and sometimes killed by collisions with recreational boats, barges and commercial ships. These collisions are so prevalent that the majority of wild manatees are identified by their characteristic boat scars.

After more than two decades of manatee-protection policies that have focused on slowing boats passing through manatee habitats, the number of injuries and deaths associated with collisions has increased and reached record highs in the past two years. To help track the population, Florida and federal wildlife agencies maintain a growing scar catalogue of recognized living individuals who have survived collisions. Some of these manatees have propeller wounds from as many as 16 different boat strikes. Why does this happen?

When startled or frightened, manatees explode with a burst of power and can reach swimming speeds of up to 6.4 meters per second in an instant. My colleagues and I wondered: Given that manatees have the cognitive ability to recognize danger, a fear-flight reaction and the physical prowess to evade boats, why, after an individual has been hit once, twice or three times, doesn't it learn to avoid boats? Is it possible that manatees are unaware of the danger? Can they hear boats approaching, and if so, from how far away, from which direction and under what acoustic conditions?

These basic questions suggested a number of interdisciplinary behavioral and acoustic investigations that I conducted over the past decade with Joseph E. Blue, retired director of the Naval Undersea Warfare Center and the Naval Research Laboratory's Underwater Sound Reference Detachment and now president of Leviathan Legacy, Inc.; Steven E. Forsythe of the Naval Undersea Warfare Center; and Laura. No one had previously conducted rigorous, controlled underwater psychoacoustic (audiometric) studies, which are necessary to understand what sounds manatees can hear in their environment. In conjunction with audiometric studies, we conducted a comprehensive series of underwater acoustic surveys of various wild manatee habitats, along with critical boat-noise propagation measurements, to further understand why animals are so vulnerable to collisions. Defining and applying the physics of near-surface acoustic propagation are also necessary if collisions between boats and animals are to be reduced, not only in Florida's aquatic byways but also on the open seas, where great whales are regularly injured and often killed by large ships.

Our test results contradict several long-held beliefs that form the basis of current protection strategies. Manatees have good hearing abilities at high frequencies, however, they have relatively poor sensitivity in the low frequency ranges associated with boat noise. Ironically, manatees may be *least* able to hear the propellers of boats that have slowed down in compliance with boat speed regulations intended to reduce collisions. Such noise often fails to rise above the noisy background in manatee habitats until the boat is literally on top of the manatee. In addition, near-surface boundary effects can cancel or severely attenuate the dominant

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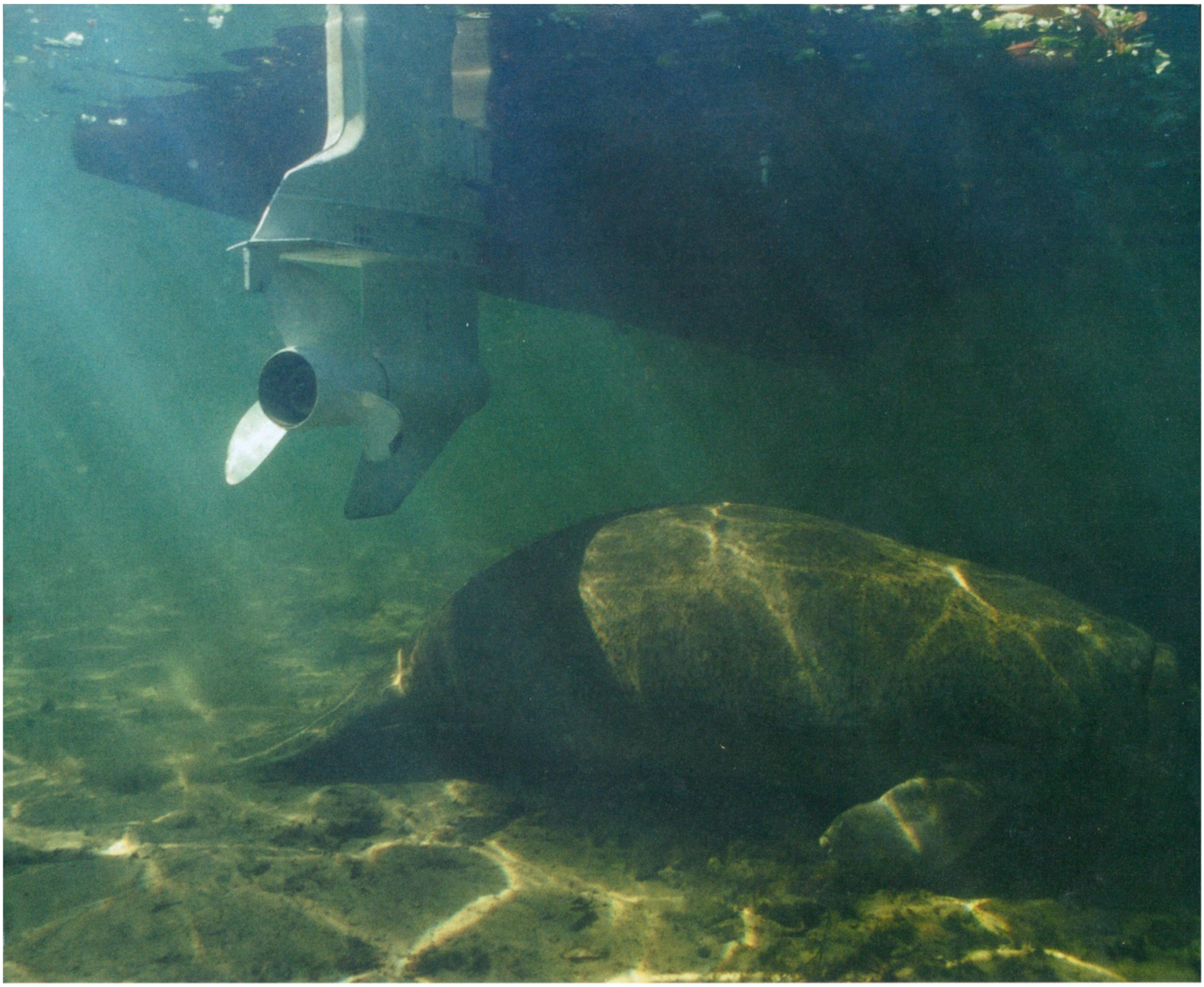

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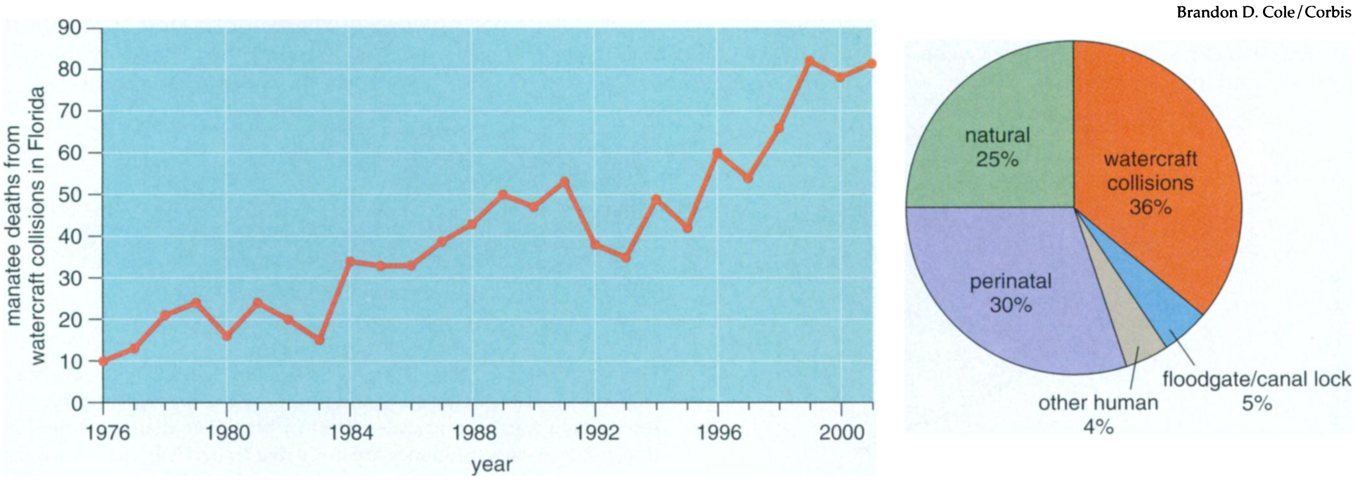


Figure 1. Boats and manatees: Can they coexist? As the graphs show, reported deaths of the marine mammals attributed to watercraft collisions increased from 1976 through 2001; although slow-speed zones have been in effect for two decades, collisions, which caused a significant proportion of all reported manatee deaths in Florida during the period *(pie chart)* is growing. The author's research on manatee hearing, environmental noise and the acoustics of boat-noise propagation near water surfaces suggests that in the turbid waters typical of Florida waterways, manatees have difficulty hearing and locating boats that have slowed in response to regulations intended to protect the animals. A high-frequency warning device designed to alert manatees to approaching boats is now being developed. (Data from the Florida Fish and Wildlife Conservation Commission.)

Figure 2. Behavioral audiogram plots the hearing sensitivity of trained manatees under very quiet conditions. In tests conducted at the Lowry Park Zoo in Tampa, Florida, each manatee subject was trained to position its head in an underwater hoop, where a hydrophone monitored all sound levels near the manatee's ears. The subject stayed in the hoop and listened. After a strobe light flashed, the manatee left the hoop and pushed the "tone" paddle *(striped paddle at left)* if it had heard a sound, or the "no tone" paddle at right if it had not heard a sound. One experimenter operated the test equipment and recorded results in an underwater laboratory; the second experimenter served as the trainer, cueing the animal to begin each test and offering rewards and encouragement to continue.

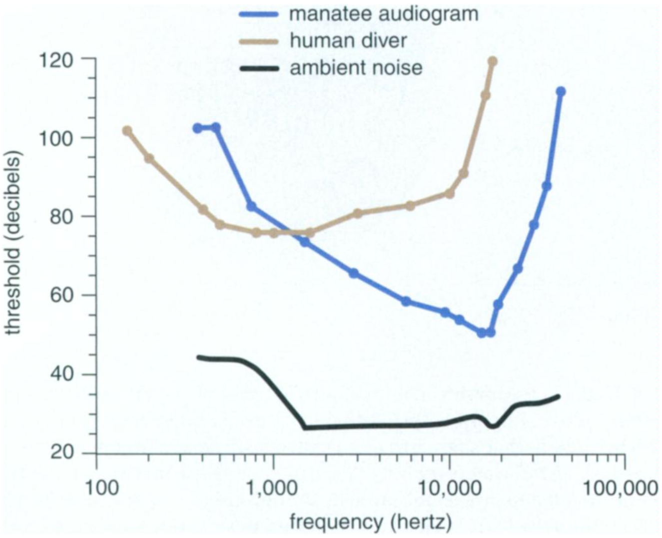
low-frequency sound produced by propellers. In many situations, ship noise is not projected in directional paths where hearing these sounds could help the animals avoid collisions. Our basic and applied research results suggest that there may be a technological solution to address the underlying root causes of the collision problem and resolve the clash between human and animal interests.

The Manatee Hearing Test

In 1991 we initiated experiments with two captive-born manatees, Stormy and Dundee, at the Lowry Park Zoo in Tampa. Our first objective was to define an *audiogram*—that is, to map the absolute hearing abilities of these subjects under very quiet conditions. The audiogram or hearing curve is a graph that demonstrates the overall range of frequencies an individual can hear as well as the subject's sensitivity within this range. An audiogram plots the intensity of a signal at its minimal detection threshold. The resultant plot for most mammals is U-shaped, with the lowest thresholds depicting the greatest sensitivity. The highest thresholds (areas of least sensitivity) are found at the low and high ends of the frequency range, where greater intensity or volume is necessary to reach detection thresholds.

Before we began testing manatees' hearing and making acoustic measurements of their habitats and boat noise, most of the wildlife biologists and managers charged with protecting manatees assumed the animals could readily hear boats but were just too slow or not smart enough to learn to avoid watercraft. Earlier electrophysiological measurements conducted by Ted Bullock, Tom O'Shea and John McClune in 1982 and anatomical measurements of dead manatees reported in 1992 by Darlene Ketten, Dan Odell and Darryl Domning had suggested that manatees heard *best* at low frequencies, in the 1,000- to 5,000-hertz range, and therefore could readily detect the sounds of boats. However, since hearing is a perceptual phenomenon, the most accurate way to find out what an animal can truly hear is to ask it. Hence the behavioral audiogram is recognized as the definitive measurement of hearing.

These tests required tremendous commitments of time, patience and resources. Perhaps the greatest challenges lay in training manatees to understand the task and then keeping each of them motivated throughout sessions so that they could eventually complete the thousands of trials neces-



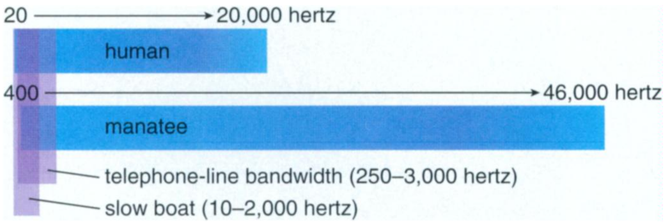


Figure 3. Results of the testing described in Figure 2 were consistent from one manatee to the other and produced the audiogram curve presented on a logarithmic scale at left in blue. The manatees' hearing thresholds at each frequency are measured in decibels against a reference sound pressure of 1 micropascal, the underwater standard. The animals' best sensitivity in the quiet ambient conditions of the test pool was at 16,000 to 18,000 hertz. Below 1,000 hertz they required much louder sounds to hear. Many people assumed that since people can hear boats underwater, surely manatees could as well. However, people hear low-frequency sounds much better than manatees, both underwater and in air *(linear scale, above)*.

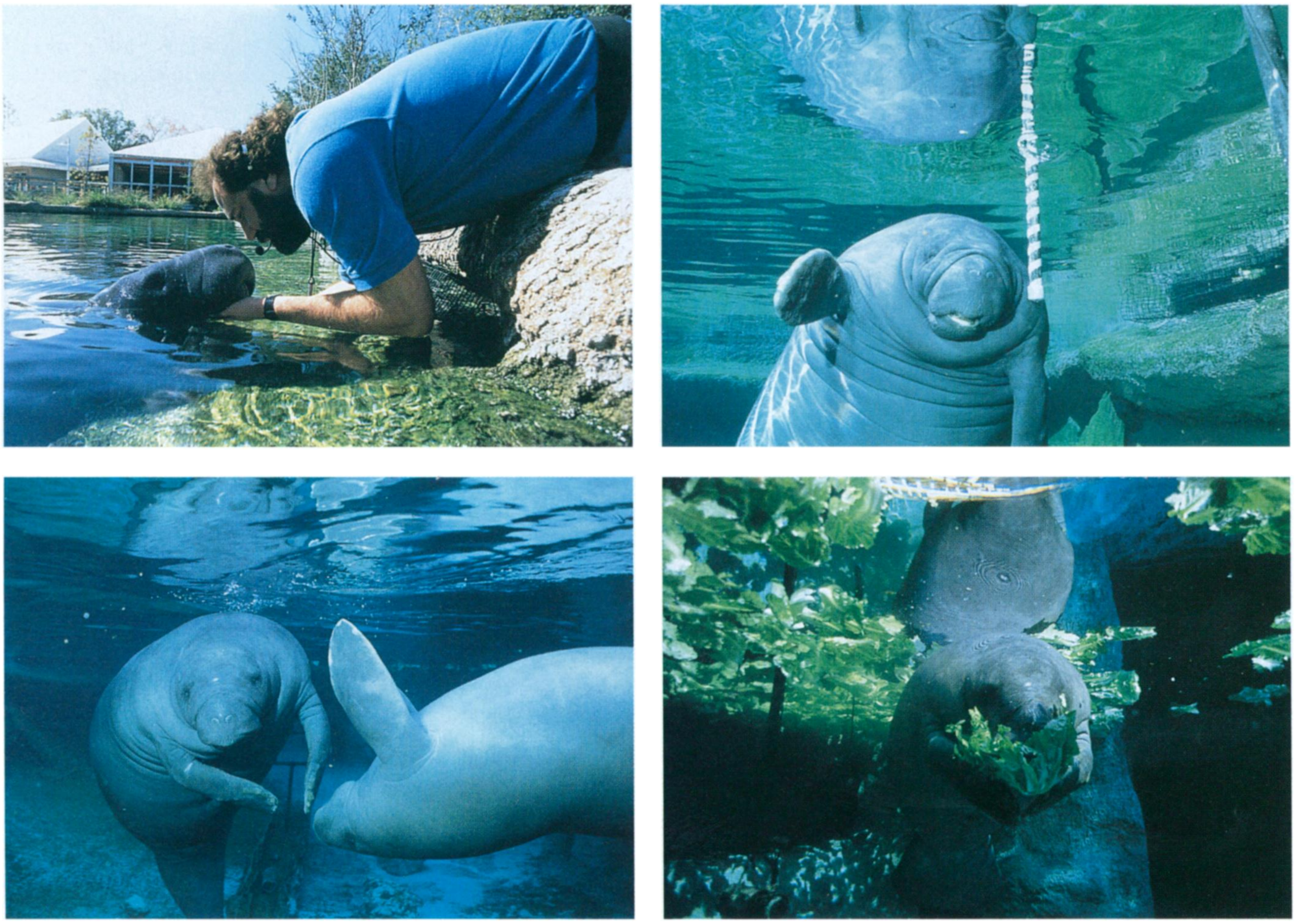


Figure 4. Stormy and Dundee *(bottom left)* were the first manatees to be trained as subjects of psychoacoustic testing; they required constant encouragement from the author, their trainer *(top left)*, but proved to be excellent subjects. The research employed a two-choice paradigm in which the paddles could be distinguished by both visual and tactile characteristics; one was smooth and striped black and white *(top right)*, the other solid white and rough-textured with a crossed pipe section near the bottom. The manatees normally feed on romaine lettuce all day at the zoo *(bottom right)*, but were given monkey chow and other treats as reinforcement during their nightly training sessions. (Photographs by Nick Caloyianis.)

sary to define their hearing. It took approximately one year to prepare both subjects for the tests—and thousands of monkey chow biscuits, along with a great deal of imagination and luck, to keep them interested throughout the subsequent years of testing. The demands of training during the day and testing at night required that Laura and I literally live in the zoo. Aside from the new discoveries and significant research findings, the most remarkable result of all is that after more than five years of living in a 19-foot trailer, without a working bathroom, in the back of the zoo, we are still married.

Being the first to train manatees for psychoacoustic testing, we didn't know their overall visual acuity, nor did we know which modality or weighted combination of modalities manatees might rely on the most. Therefore, I constructed the hearing test using a forced two-choice paradigm with two response paddles that were distinctly different both visually and tactually—one paddle was smooth, with a striped black-and-white pattern, the other solid white with a rough surface and a distinctly different-shaped end made of intersecting pipe sections. Both manatees were trained to position themselves inside a listening station (a hoop) where an underwater microphone, or hydrophone, recorded the signals sent to them. They were to stay in the hoop, listen and wait for a strobe light to flash. After the light flashed they could leave the hoop and select the striped paddle if they heard a sound ("yes"), or the solid white one if they did not detect a sound ("no"). These tests were repeated for many different types of sounds, including boat noise against various sound levels typical of wild ambient conditions.

We used a conventional staircase method of double-blind signal presentations, starting with very loud acoustic levels (at which the manatee would choose the "tone" paddle), stepping down the signal amplitude until the animal chose the "no tone" paddle and then stepping it back up again. Hundreds of trials were required to establish the threshold for each frequency point along the curve. The resulting audiograms for the two manatees were very similar.

Stormy and Dundee proved to be excellent test subjects. Their hearing may also be better than most manatees', since they are young, captive-born animals who have spent their lives in relatively quiet environments with minimal risk of hearing damage from continuous exposure to high noise levels. The ambient noise levels in captivity are significantly quieter than those recorded in the wild. Furthermore, these individuals were highly motivated and conditioned to listen for the slightest changes in the sound field. Wild manatees might not be expected to be as focused and attentive to acoustic subtleties as finely as our subjects were specifically trained to do. It is probable, therefore, that the hearing abilities exhibited by Stormy and Dundee are more acute than those of the population at large.

As the audiogram *(Figure 3, left)* illustrates, manatees have a functional hearing range from 400 to 46,000 hertz. Their peak sensitivity actually lies between 16,000 and 18,000 hertz, and not 1,000 to 5,000 hertz as previously thought. Below 16,000 hertz sensitivity decreases approximately 10 decibels per octave, and below 2,000 hertz it drops precipitously (20 decibels per octave) until functional hearing ends at 400 hertz. Unfortunately the dominant sounds produced by most boats and ships are below 1,000 hertz; these lower frequencies fall outside or overlap the lower fringe of the manatees' hearing range. The audiogram suggests that even in quiet conditions, manatees would have difficulty detecting these sounds at acoustic levels less than 90 or 100 decibels. (All underwater sound levels here are given against a standard underwater reference acoustic pressure of 1 micropascal.)

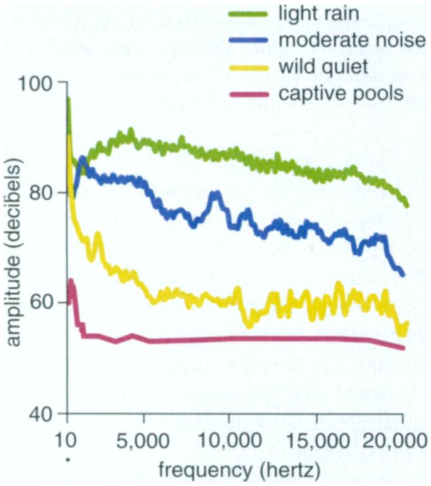


Figure 5. After measuring manatee hearing under quiet conditions, the author and his colleagues use samples of sound taken from manatee habitats to determine the manatees' critical signal-to-noise ratios. These tests measured the increased volume, or signal loudness, needed for the manatees to hear sounds over background noise. As the sound samples above indicate, manatees live in environments where ambient sound is commonly 70 decibels or more in the lower frequencies and can reach 90 decibels across frequencies during a light rain.

Living in a World of Sound

Although the audiogram provides a definitive measure of hearing under the quietest of conditions, manatees do not live in quiet habitats. In Florida, ambient noise in manatee habitats typically ranges from 60 to 90 decibels, over a frequency range of 1 to 20,000 hertz, but levels can reach 130 decibels during heavy rain or in industrial areas.

A perceptual phenomenon known as *masking* takes place when the audibility of one sound (the "signal") is decreased by the presence or occurrence of another sound (the "noise"). When we began our work, we knew that the ambient noise in manatee habitats could conceivably mask the perception of many kinds of signals. Manatee are immersed in a dynamic acoustic landscape filled with a cacophony of sounds, the most prominent biological sound being the continuous crackling from millions of snapping shrimp. Being passive listeners—unlike the echolocating dolphins, which can use active sonar to navigate and detect objects in the environment—manatees are restricted to listening to their auditory landscape. We wanted to understand how noise affects the manatees' ability to hear biologically important sounds, ambient events and the sounds of approaching boats. Toward this end we conducted a series of psychoacoustic investigations using pure tones, complex sounds and samples of typical boat noise and manatee vocalizations. These tests measured the masked thresholds and critical signal-to-noise ratios along the manatees' hearing curve against a background of continuous noise.

The critical ratio compares the intensity of a signal at the moment it is just detectable (the masked threshold) to the intensity of the background noise. For instance, if a manatee can hear a particular signal over 70 decibels of ambient noise when the signal reaches 90 decibels, then the critical ratio is 20 decibels; since decibels are a logarithmic expression, the ratio can be derived by subtracting one sound level from the other. It should be noted that critical ratios are conserved for each frequency regardless of increasing ambient levels, so if the ambient noise increased to 100 decibels, then the signal would have to be at least 120 decibels before the manatee could detect it. The size of the critical ratio has important ecological significance, as high ambient levels could conceivably raise detection thresholds beyond the absolute acoustic energy emitted by many boats.

We conducted hearing tests that used various noise levels representative of typical wild ambient conditions. We tested pulsed and continuous pure tones and broadband noise like that produced by boats. The masking studies showed that manatees have critical ratios that range from 9 decibels above the prevailing background noise for pulsed broadband noise up to 46 decibels for continuous tones. Manatees detected repetitive pulsed sounds at significantly lower critical ratios than continuous wave sounds. This was not an unexpected result, since biological sounds and, in particular, the manatees' own 200- to 500-millisecond vocalizations, are pulsed sounds. Pulsed signals provide additive signal width as well as temporal patterns that manatees may detect from an aperiodic background.

Finding the Sound Source

In addition to simply detecting sounds, manatees must be able to locate them. For manatees, as for other animals, the ability to localize sounds is critical to their survival. Unfortunately, the low-frequency sounds of many boats are omnidirectional and therefore, by their nature, difficult to locate. Prior to our studies, wildlife officials relied on anecdotal assumptions that manatees could readily hear as well as locate the sounds of slow-moving boats.

The objectives of the localization investigations were to measure the manatee's perceptual abilities to locate sound sources as a function of signal frequency, noise spectra, duration, projection angle and position to the left or right of the animal's head. To accomplish this, an egocentric or orientation paradigm was used, which required the subject to locate the sound source physically in space. Egocentric paradigms have traditionally relied on the subject to make simple head or body turns to indicate an orientation. For this test, manatees were required to swim to and touch the actual sound source. The test required the subjects to locate the sound source unambiguously relative to their own position in space. Whereas an otocentric (ear-centered) paradigm such as the minimal audible angle is arguably a more acute measure of sound localization, it is designed to measure a subject's ability to recognize a shift in sound location relative to an arbitrary sample reference. In the real world manatees must react by orienting themselves toward or away from the sound. Although there are significant procedural differences between egocentric and otocentric approaches, sound localization measurements using variations of both methods have resulted in remarkably consistent measurements of sound localization in animals (Brown 1994).

To conduct all the directional tests, we lined the back pool with sound-absorbing open-cell foam panels to dampen surface, side and bottom reflections. The subjects were trained to position themselves inside a stationing hoop surrounded by underwater speakers. They were trained to leave the station immediately upon hearing a sound and push on the speaker that projected the sound. The speakers were triggered electronically and rotated periodically so that the manatees could not key in on any speaker artifacts.

Localization was significantly greater at higher frequencies across all conditions. When the signals lasted longer than 200 milliseconds, localization improved, as the manatees had the opportunity to make a slight head movement to scan the sound field. Manatees have fused cervical vertebrae, which restricts quick, sharp, angular head movements; this limited mobility suggests they may require relatively longer reaction times (compared with other marine mammals) to scan and sample the environment. Both manatees were tested using real-world sounds—manatee vocalizations and boat noise, as well as narrowband signals derived from our wavelet analysis of select manatee vocalizations.

Playback of these wavelets revealed salient features of the manatee vocalizations that are detectable below ambient levels. These "designer" signals derived from the higher harmonic frequency bands in manatee vocalizations are highly directional and easily detected by manatees against the most competitive of acoustic conditions. When it became apparent that manatees may not be able to reliably detect or locate the sounds of boats, we explored sounds that manatees could hear best. We hoped that this information could be applied at some stage to help manatees detect and localize approaching boats (*see* "In Search of Solutions," below). Stormy and Dundee heard and localized these signals with the same sensitivity and accuracy with which they detected manatee vocalizations.

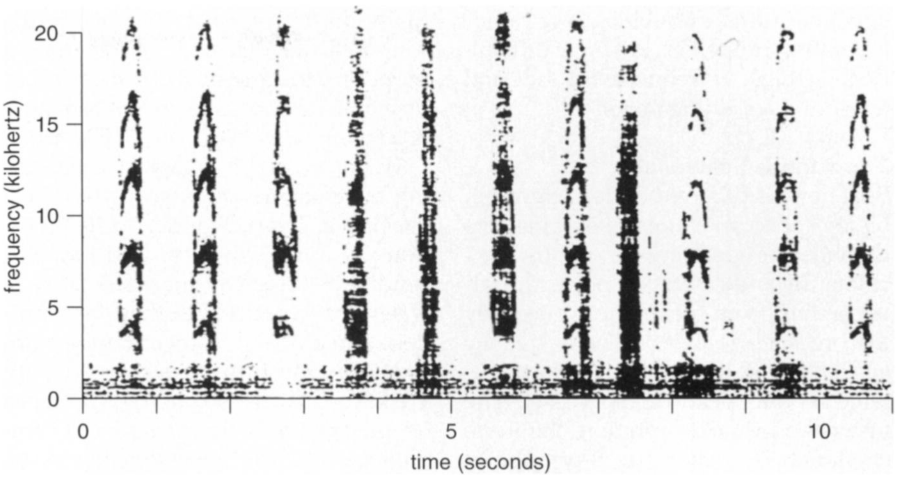


Figure 6. Manatee vocalizations are typically short, discrete, repetitive broadband signals with harmonic bands that cross a number of distinct critical bands. Manatees are able to hear and locate these calls at sound levels lower than the background noise. Unfortunately, they cannot hear or locate broadband low-frequency noise from idling boats at safe distances against wild ambient noise. The author has developed directional sounds that manatees can hear and locate as well as their own vocalizations.

The manatees demonstrated symmetrical localization abilities, meaning that their hearing accuracy was equivalent from the left and right sides. Sound localization was relatively poor at frequencies below 2,000 hertz but improved significantly with higher frequencies. The best directional sensitivity was at frequencies above 10,000 hertz. Manatee vocalizations and the designer wavelet signals were localized correctly 90 percent of the time, whereas the sounds of idling boats were correctly localized only 55 percent of the time. Ironically, the higher-frequency cavitation sounds produced by faster-moving boats were localized 65 to 75 percent of the time. The results demonstrate that manatees can reliably locate their own vocalizations and the frequency-modulated sounds we created with great accuracy. They can also readily locate the sounds of boat-propeller cavitation (the formation of

Figure 7. At the Outboard Motor Test Facility in Stuart, Florida, the author and his colleagues sampled sound from a variety of small boats at slow and fast speed, placing a hydrophone beneath the water to record the sound of an approaching boat in a typical manatee habitat. Results of one comparison are shown in Figure 8. (Photograph courtesy of the author.)

small vacuums, or bubbles, by a rapidly rotating propeller), but have difficulty detecting low-frequency sounds and the sounds of idling boats.

The Sounds Boats Make

Boat noise is different in character from biological noise. Underwater it has two domains, or operating conditions: noncavitating and cavitating noise, the latter arising from turbulence caused by the propeller rotations. The frequency and power of boat noise is directly related to the speed of the vessel. The faster the propeller rotation, the more cavitation is created. As tiny bubbles form and collapse, they produce a broad range of frequencies above prevailing ambient conditions at frequencies up to 20,000 hertz. Conversely, when the rotation of the propeller is reduced and a boat is traveling slowly, the turbulence is minimal, and both the frequency and power spectrum of the noise are significantly reduced. The dominant noise spectra are below 1,000 hertz at sound-pressure levels that barely reach the manatees' audiogram thresholds.

Under typical ambient conditions, the sounds of an approaching small boat can be indistinguishable from the background until they are loud enough to cross the masked thresholds. Since the intensity for a given sound source decreases with increased distance, a slow-moving boat with propellers turning at 400 rotations per minute needs to be virtually on top of a manatee before the sound can be detected. Unfortunately, propellers turning at 400 rpm can slice up a manatee just as readily as can those of a fast-moving boat going 3,500 rpm.

We recorded the sounds of approaching boats at the Outboard Motor Test Facility in Stuart, Florida. At this location we found physical and ambient conditions typical of manatee habitats: water 5 meters deep, isothermal conditions and ambient biological noise coming primarily from snapping shrimp. We suspended recording hydrophones 1.5 meters below the surface and sampled sounds from representative boats operating at various speeds

When we played the recordings of these sounds to manatees under controlled masking conditions, the higher-frequency broadband cavitation noise made by fast boats was detectable at 9 decibels above the ambient level—a relatively low critical ratio. Manatees could not detect the noise from idling boats under the ambient-noise conditions recorded in the field. The low-frequency spectra did not breach the audiogram threshold limits, and the remaining higher-frequency sounds were so low that they were masked by moderate ambient conditions of only 70 and 80 decibels. This noise had to be amplified 29 decibels above the ambient noise before it was detectable.

What do these results suggest? For one thing, a boat with a slowly rotating propeller generates low-frequency sounds impossible to locate and indistinguishable from the ambient noise until it is dangerously close to a manatee. A key management strategy used in Florida for protecting manatees over the past 20 years has been to slow boats in waters frequented by manatees by creating idling and slow-speed zones. This strategy can actually exacerbate the problem when it is implemented in turbid water conditions (which, along with tannin staining, are prevalent in Florida). Under such conditions, manatees and boaters cannot actively avoid each other using visual cues, and acoustic signals are the only means of detection available to the animals.

Consider the results from our boat-measurement studies simulating an encounter between an 8.2-meter boat and a manatee *(Figure 8)*. When the boat approaches at high speed, the noise level crosses the manatees' critical ratio approximately 16 seconds before the propellers reach the hydrophone—about 198 meters away from impact. The noise of the same boat approaching slowly remains undetectable and does not cross critical ratios until the propellers are only 0 to 2 seconds away, less than 3.7 meters from impact. Under moderately noisy ambient conditions, the sounds associated with slow-moving boats can become acoustically transparent.

Although slow-moving boats may arguably cause fewer fatalities than do fast-moving boats, they are also more likely to cause repeated injuries

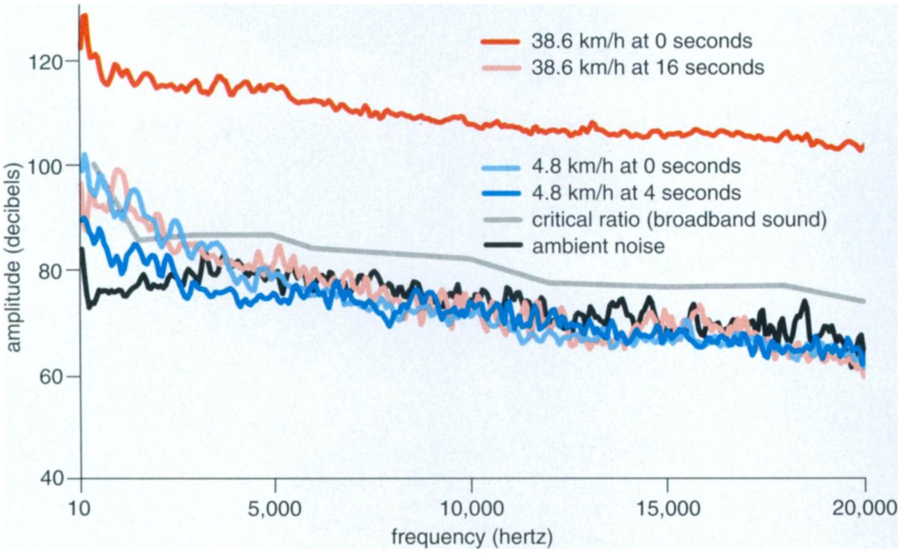


Figure 8. In the experiment in Figure 7, the sound of a boat traveling at 4.8 kilometers (3 miles) per hour *(blue lines)* barely rises above the ambient noise *(black)* in the manatees' hearing range and is indistinguishable until the boat passes over the hydrophone, at which point it crosses the manatees' critical ratio. The noise from the same boat approaching at 38.6 kilometers (24 miles) per hour *(red lines)* crosses the critical ratio for broadband noise about 16 seconds (or about 198 meters) before reaching the hydrophone. It is possible that many of the propeller scars seen on Florida manatees *(photograph)* are caused by slow boats whose sounds the animals are not able to detect. (Photograph courtesy of the author.)

to manatees that cannot detect their approach. The manatee scar catalogue of living survivors is consistent with, and bears some testimony to, this observation.

Sound Near the Water Surface

Manatees are not the only animals that collide with boats. Other passive-listening marine mammals, including great whales, are vulnerable to collisions when near the surface or in shallow water. Here, the physics of near-surface sound propagation significantly affects their ability to detect low-frequency sounds.

A phenomenon known as the Lloyd mirror effect can attenuate or cancel the propagation of lower-frequency sounds generated near the surface. The Lloyd mirror effect does its damage at the surface, where the risk of collisions with ships and boats is greatest. At the surface, sound reflections can be 180 degrees out of phase with incident waves and can cancel the low-frequency sounds of boats and ships. The sound pressure approximates 0, as the water's surface is a pressure-release boundary that is free to move in response to pressure in the water. The increase of pressure away from the water's surface is proportional to frequency, with pressure at shallow depths being inversely proportional to wavelength and thus proportional to frequency (the lower the frequency, the lower the acoustic pressure near the surface).

The details of these fluctuations at short distances depend on many factors, the most important of which are water depth, bottom shape and density, and surface roughness. Even if manatees or whales could ordinarily hear such sounds, the Lloyd mirror effect can attenuate them to levels that are indistinguishable from the ambient noise. Although some whales, unlike manatees, may have acute low-frequency hearing, it is no advantage at the surface. Animals cannot react to sounds that never reach them, regardless of their auditory abilities.

In concert with the Lloyd mirror effect, another acoustic phenomenon may be the cause of many ship and barge strikes on marine mammals. A*coustical shadowing* is caused when the sound rays from the propellers of a ship are blocked by the ship's hull from projecting forward.

Acoustical shadowing is particularly a problem when propellers are located above the keel depth of ships. Most large ships that strike whales, as well as tugboats that kill manatees, have this propeller configuration. The propellers of a traditional tug are recessed to reduce surface venting from propeller cavitation, to drive the tug in line with its center of mass and to protect the propeller from damage in case the keel strikes the bottom. With the propeller in this position, a sound ray reflected from a shallow bottom will again be reflected by the tug's structure before the sound can propagate forward. This causes both an acoustical shadow ahead of the tug or tug-and-barge combination and severe attenuation from multiple reflections. The attenuation loss alone is 60 to 100 decibels; thus propeller noise ahead of the tug-and-barge combination is completely masked by the ambient noise at the surface.

An acoustical shadow is cast all around a ship whenever the width of the ship is greater than the wavelength of the sound. A hull 10 meters wide will cast a shadow at frequencies higher than 150 hertz. The shadow's extent depends on the number of wavelengths across the ship. Little diffraction around this barrier will occur. Of course, extremely low-frequency (long-wavelength) sound can diffract around most hulls, but at these frequencies the Lloyd mirror effect loss is severe. The two effects together have significant ecological consequences.

We used a vertical array of hydrophones to document these combined effects from tugs and ships. Data obtained for tugs with barges show a more pronounced "quiet zone" subtending a large angle from the tug's propellers. The same shadowing effect is present with large ships that hit whales. A recent study by David Laist and his colleagues indicates that ships hitting whales tend to be 80 meters or more in length. In the shallow coastal sea lanes where whales are most frequently killed, the depth of the water is shallower than the length of these vessels—resulting in even greater shadowing effects. The same relative conditions are found in shallow manatee habitats, where the vessels are not as large but the water is much shallower.

The sounds generated by an 18.3-meter tug pushing a 76.2-meter barge are significantly shadowed. A sample of these measurements helps to illustrate how the sounds of the tug remained undetectable until 45.7 meters of the barge had passed the hydrophone array *(Figure 10, graph)*. A manatee or whale in the direct path of the barge would not have been able to acoustically detect the barge before the animal had been run over by it or become entrapped by the hydrodynamic force .

Large ships and barges differ in the way they reflect sound. A barge in shallow water may reflect sound between the sea bottom and the flat bottom of the boat several times. A ship, with its V- or U-shaped hull, will reflect sound off to the side rather than straight ahead, creating a more pronounced shadow zone with relatively loud noise radiating off to the sides.

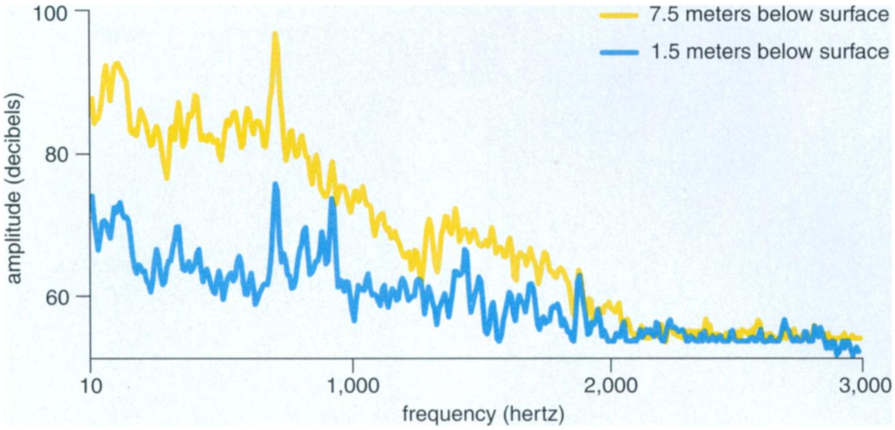
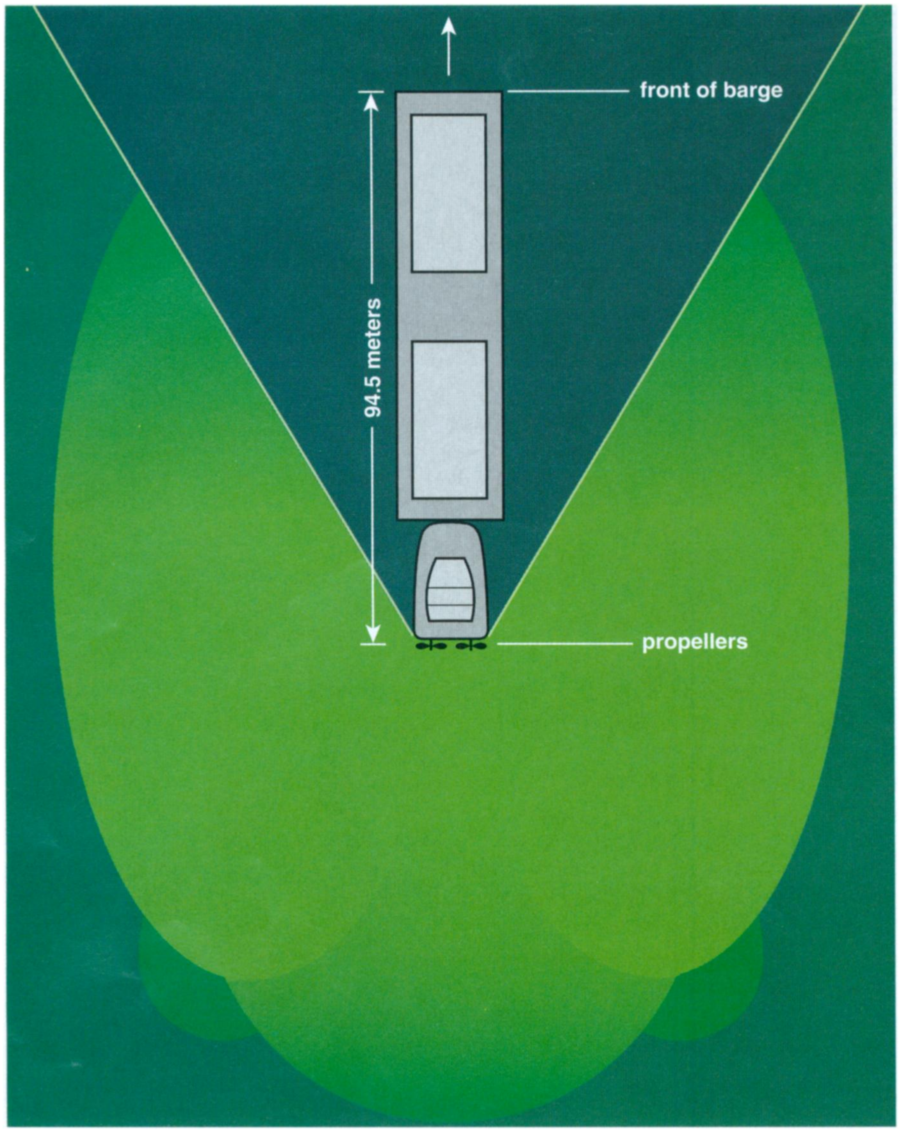


Figure 9. Low-frequency sound propagating near the surface of water is subject to a phenomenon called the Lloyd mirror effect, which complicates the problems marine mammals have in attempting to hear oncoming boats. The water surface releases pressure from long sound waves, weakening or even canceling them. Recordings of a cruiser made at 1.5 and 7.5 meters below the surface before, during and after its passage demonstrate the effect. The yellow and blue lines, representing measurements made at the bow at the two depths, diverge in the lower frequencies, indicating that the longer wavelengths are attenuated at the shallower depth.



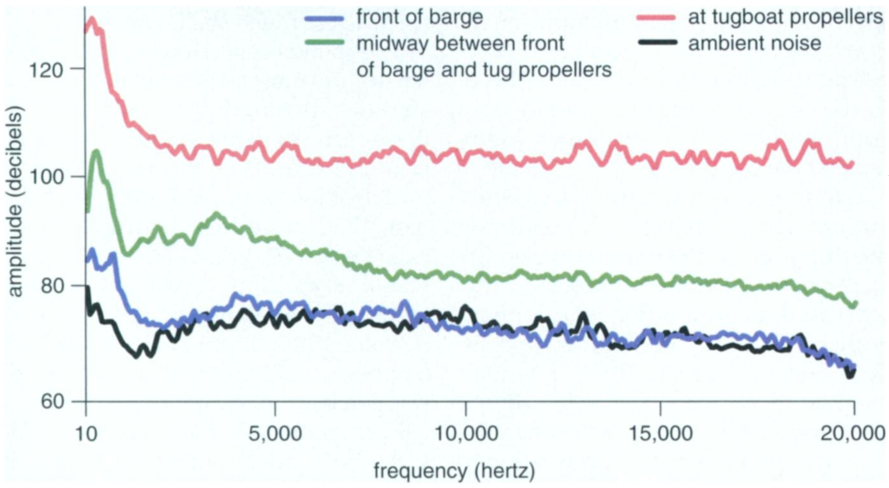


Figure 10. Large boats, by reflecting propeller noise, cast a large acoustic shadow in all directions. The shadow is particularly deep in front of a ship, whereas propeller noise may be intensified close to the ship's sides—which might drive marine animals into the deep shadow and therefore into the path of the forward-moving vessel. The graph shows sound measurements taken during the passage of a 76.2-meter-long barge towed by a 18.3-meter tug. Sound was most intense at the propellers *(pink)*, diminishing somewhat at the midpoint of the tug-barge combination *(green)*. At the barge's bow the sound level *(blue)* was approximately at the ambient sound level *(black)*, marking the beginning of a shadow that deepens in front of the barge.

Such noise may confuse animals and even cause them to swim into the quiet zone to seek refuge—placing them directly in the path of the approaching vessel.

In Search of Solutions

Just as speed limits for small boats in inland waters can reduce propeller noise and sound frequency, so reducing ship speeds could conceivably increase the risk of collision by increasing exposure time (and thus opportunities for collisions) while diminishing the ships' audibility. Current surveillance and avoidance programs are ineffective at night or in poor weather, just when the animals also must rely on sound detection to avoid ships. Today wildlife managers are focused on other protection methods that still do not address the underlying sensory and acoustic causes of collisions. These methods include active sonar to detect animals ahead of ships and passive-listening sensors that light up to indicate that manatees are in the area.

Interested in tracking manatees in turbid water conditions, we investigated the use of active sonar to detect manatees and conducted the first and only sonar target strength measurements on manatees (Gerstein and Blue 1997). Using direct and echo-reduction methods, we evaluated echo-ranging and shadowing sonar technologies. Unfortunately, the problems relating to bottom and volume scattering and reflection from the surface in the manatees' shallow-water environments make reliable detection at safe enough distances from boats impractical. Similar surface-reflection, false-alarm and absorption problems are confounding other investigators trying to detect whales (much bigger targets) near the surface in front of ships.

The use of sound-activated light sticks to alert boaters to manatees in their vicinity is also being explored. The proposed system would employ passive listening for manatee vocalizations to trigger warning lights on pilings along waterways frequented by manatees. Unfortunately, manatees are relatively quiet animals. Not only does this characteristic of manatee behavior reduce the effectiveness of a sound-activated device, it could also give boaters a false impression that no manatees are present, placing undetected animals at additional risk. We have an extensive catalogue of calibrated manatee vocalizations, and our analysis of these signals shows that although mothers and calves communicate more regularly, manatee calls are low-intensity signals averaging only 12 decibels over the ambient noise. We have documented that manatees can detect and locate these low-intensity calls below the ambient noise, but underwater acoustic instruments cannot filter these calls below the ambient noise as manatees can. Consequently, animals would need to be very close to a listening station in order to be detected above typical ambient levels. Another aspect that may be unrecognized is that many components of their calls are directional. Only if the hydrophone array is in line with a vocalizing manatee would it receive these impulses.

We decided that the best way to protect animals would be to address the underlying sensory and acoustical causes of collisions. Manatees and whales may be well adapted to hear and detect significant biological sounds in their environments; however, boats, ships and barges were never part of their evolutionary histories. Thus these animals are faced with modern ecological challenges for which they are at a sensory disadvantage. In light of the psychoacoustic measurements described above, the known acoustical characteristics of shallow-water habitats, the spectra of boat noise and the dangerous, deceptive problem of acoustical shadowing, it is apparent that manatees, and perhaps other passive-listening marine mammals, could benefit from an acoustic warning device designed to fit on the front of boats, ships and barges.

With this in mind, we developed an acoustic alerting device specifically designed to exploit the manatees' optimum hearing abilities. Using wavelet-derived acoustic signals that manatees can readily detect and locate at or near ambient levels, we were able to develop an environmentally friendly device that projects very low-intensity and highly directional acoustic signals in front of boats. The signals are designed to defeat the challenges posed by acoustical shadowing and the Lloyd mirror effect. Such highly directional, low-intensity sounds would pose no threat of cumulative noise effects even with thousands of devices operating simultaneously. Compared with 200-watt fish finders and depth sounders, our 10-watt device imposes no noise-pollution concerns. It provides a set of consistent, highly directional acoustic cues which marine mammals, most notably manatees, could quickly learn to associate with boats, ships and barges.

The bow-mounted manatee-alerting device we have been testing in manatee habitats incorporates a through-the-hull-mounted parametric transducer that creates a stable, directional beam of sound just under the surface of the water for distances of up to 200 meters (Gerstein and Blue 1996, 1997). The device incorporates a parametric design to deliver this narrow beam with a small transducer. It projects two ultrasonic source frequencies that are beyond the measured hearing limits of marine animals. The resulting difference or *parametric frequency* from the two oscillating source frequencies of 230,000 and 250,000 hertz results in a 20,000-hertz, centered parametric wave that is audible to manatees and dolphins but falls below the detection limits of fish and outside the hearing range of turtles and aquatic birds. As it is not designed to scare or harm manatees, the device could provide a consistent set of highly directional cues that manatees might learn to associate with boats. Being highly directional, manatees would only hear the signals when they are in the direct line of an approaching boat and in imminent danger of injury. Ignoring the signals would have negative consequences; thus the manatees would not become habituated to them. Critics have suggested that such an approach is untenable because manatees may need to get injured before they can associate the alerting signals with danger. However, manatees are getting hit repeatedly every day, not because they don't know boats are dangerous, but because they can't locate them at safe distances in time and space. If these devices were placed on slow-moving boats and barges, manatees could soon learn to associate the sounds with approaching vessels without having to suffer injuries repeatedly. Animals cannot learn to avoid boats that they cannot detect or locate.

For all our custodial efforts and regulations to protect manatees, even the most conscientious and best-intentioned boaters can still strike manatees they cannot see. When an animal cannot hear or locate a boat, it is at risk whether the boat is going fast or slow. In the end, the most reliable, motivated and responsive individual that can save any manatee at any place and time is the manatee itself—provided it has the sensory awareness to do so. An acoustic alerting device could give animals the opportunity to save themselves.

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Links to Internet resources for further exploration of "Manatees, Bioacoustics and Boats" are available on the *American Scientist* Web site:

http://www.americanscientist.org/articles/02articles/Gerstein.html