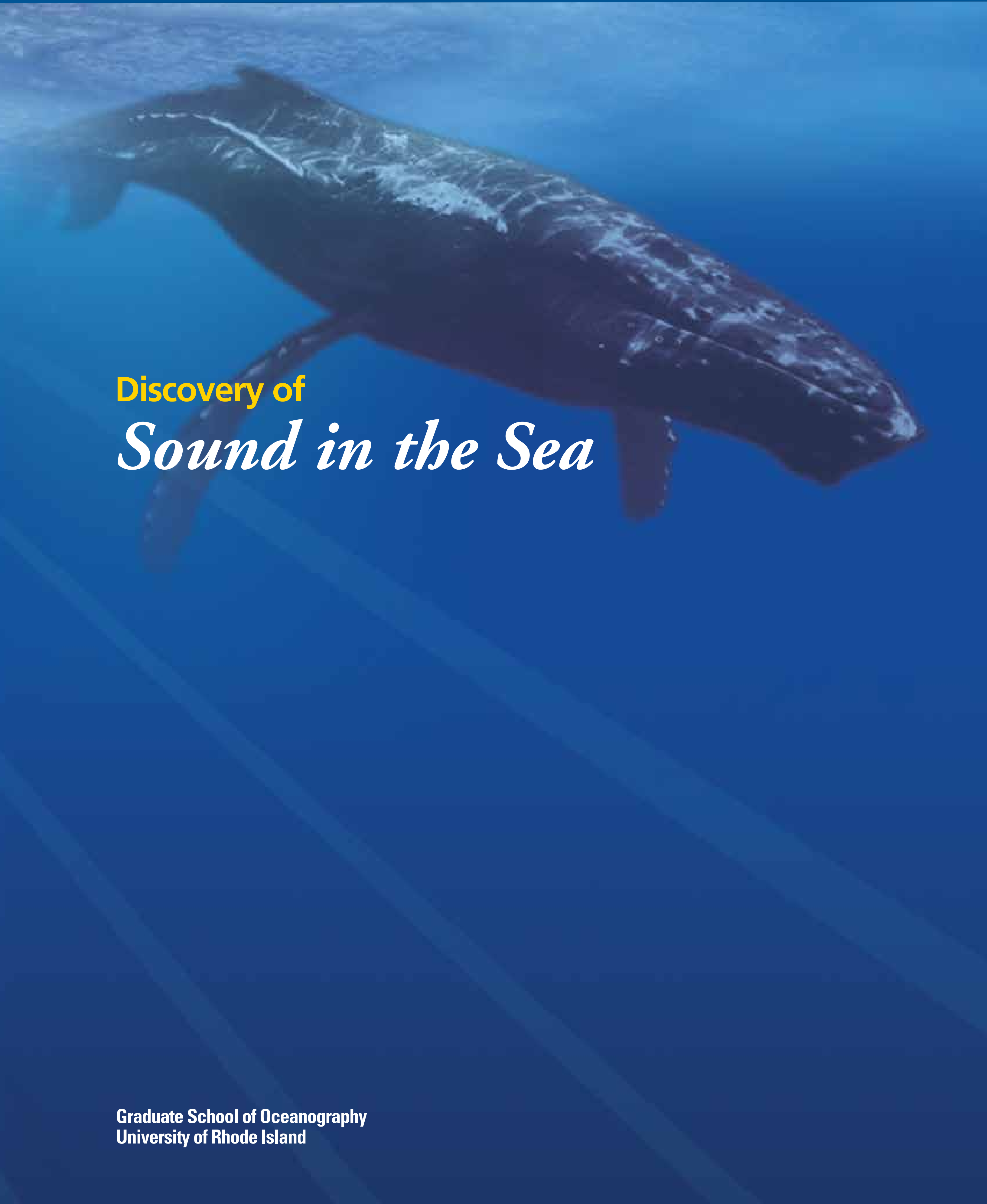
www.dosits.org



Discovery of *Sound in the Sea*

Graduate School of Oceanography
University of Rhode Island

The *Discovery of Sound in the Sea* website (**www.dosits.org**) and associated educational resources provide information on the science of sound in the sea, how both people and animals use sound under water, and the effects of sound on marine life. There are also technology, audio, and scientist galleries as well as special sections for educators, students, and the media.

Contents

Acknowledgments

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Graduate School of Oceanography Team
Gail Scowcroft, Project Director
Christopher Knowlton, Marine Research Associate
Holly Morin, Marine Research Associate
Darrell McIntire, Graphic Designer

Marine Acoustics, Inc.
Dr. Kathleen Vigness-Raposa, Senior Scientist

Scientific Reviewers
Dr. Danielle Cholewiak, NOAA Fisheries Northeast Fisheries Science Center
Dr. Darlene Ketten, Woods Hole Oceanographic Institution
Dr. James Miller, University of Rhode Island
Dr. Arthur Popper, University of Maryland
Dr. Peter Scheifele, University of Cincinnati
Dr. Jacqueline Webb, University of Rhode Island
Dr. Peter Worcester, Scripps Institution of Oceanography

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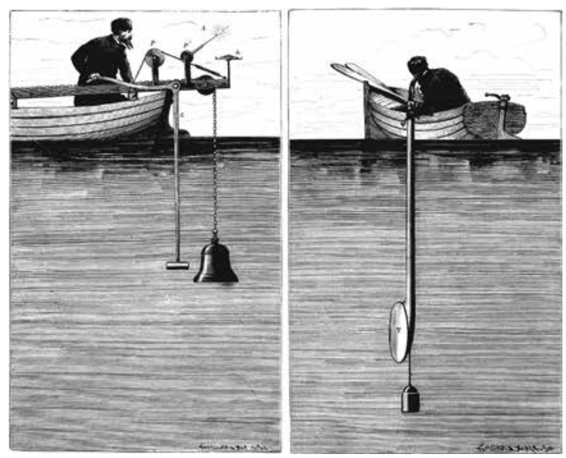
Importance of Sound in the Sea

Sounds produced by marine animals, natural processes, and human activities fill the world ocean. Because water is an effective medium for the transmission of sound, both marine animals and people use sound as a tool for finding objects, navigating, and communicating under water.

Sound travels far greater distances than light under water. Light travels only a few hundred meters in the ocean before it is absorbed or scattered. Even where light is available, it is more difficult to see as far under water as in air, limiting vision in the marine environment. In addition to sight, many terrestrial animals rely heavily on chemical cues and the sense of smell for important life functions (such as marking territorial boundaries). Olfactory cues are restricted in the marine environment. Some fishes use smell to detect nearby reefs, but in general, olfaction is for many marine species less important than for land mammals. Underwater sound allows marine animals to gather information and communicate at great distances. Many marine animals rely on sound for survival and depend on adaptations that enable them to acoustically sense their surroundings, communicate, locate food, and protect themselves under water.

In addition to the variety of naturally occurring sounds (e.g. breaking waves, lightning, earthquakes) and sounds made by marine animals, there are many sources of anthropogenic (human-generated) sounds in the oceans. Sound in the sea can be a by-product of human endeavors. For example, over ninety percent of global trade depends on transport across the seas and shipping produces a great deal of underwater noise.

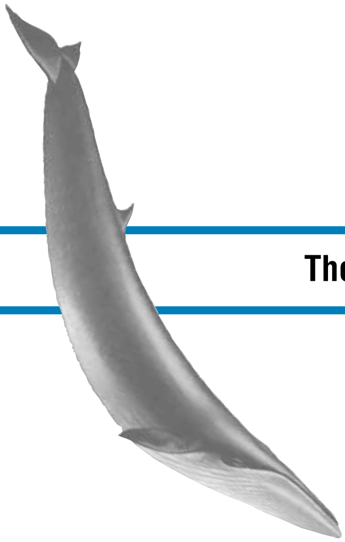


J.-D. Colladon, *Souvenirs et Memoires*, Albert-Schuchardt, Geneva, 1893

Not all anthropogenic sound is a by-product of human activities. Some underwater sounds are intentionally used for a variety of valuable and important purposes. Sonar systems use sound waves to map the seafloor and chart potential hazards to navigation, locate offshore oil reserves, and identify submerged objects. For the scientific community, underwater sound is fundamental in determining the basic properties of the oceans and studying the animals that live there. In addition, acoustics provides an effective means to document and analyze significant natural geologic processes such as earthquakes, volcanic activity, and sea floor slides. It is crucial to use sound to study these processes because they can have profound effects on coastal and island communities worldwide. As we continue to explore the oceans and use marine resources, we must determine the conditions for safe and sustainable use of sound in the sea.

The Discovery of Sound in the Sea website (www.dosits.org) and associated resources provide information on the basic science of sound in the sea, how both people and animals use sound under water, and the effects of sound on marine life. The following information is based solely on published scientific research and is a result of the Discovery of Sound in the Sea Project. All content has undergone a thorough review by a panel of scientific experts.

Dr. James P. McVey, NOAA Sea Grant Program



The ocean is full of a variety of sounds.

Sounds may be described with words such as loud or soft; high-pitched or low-pitched. These words describe, or characterize, how we perceive sounds. Scientists, on the other hand, describe sounds with characteristics that can be measured using instruments. There is a relationship betwen the words that scientists use and the common words used to describe sound. Whereas the common words are loud or soft, scientists talk about the intensity or amplitude of the sound. The common words describe the pitch of a sound; scientists use the word frequency. A piano has 88 keys that span the frequency range 27.5 to 4,186 cycles per second (one cycle per second is called one Hertz, Hz). People with good hearing can hear sounds from about 20 Hz up to 20,000 Hz, although we hear best around 3,000–4,000 Hz, where human speech is centered.

Underwater sound is generated by a variety of natural sources, such as breaking waves, rain, and marine life. It is also produced by a variety of human-made sources, such as ships and military sonars. Some sounds are present more or less everywhere in the ocean all of the time. The background sound in the ocean is called ambient noise. Other sounds are only present at certain times or in certain places in the ocean. Marine mammals, such as whales and dolphins, produce sounds over a much wider frequency range than people can hear. For example, some large baleen whales (mysticetes) produce sounds at less than 10 Hz whereas dolphin echolocation clicks can contain frequencies greater than 100,000 Hz. Certain types of fishes, such as the toadfishs and drums, and marine invertebrates, such as snapping shrimp, also produce sounds.

Physical processes generate sound in the ocean. These include rain, wind, waves, lightning striking the sea surface, cracking sea ice, undersea earthquakes, and eruptions from undersea

National Oceanic and Atmospheric Administration

Tom Kieckhefer

Courtesy of Moonraker Australia

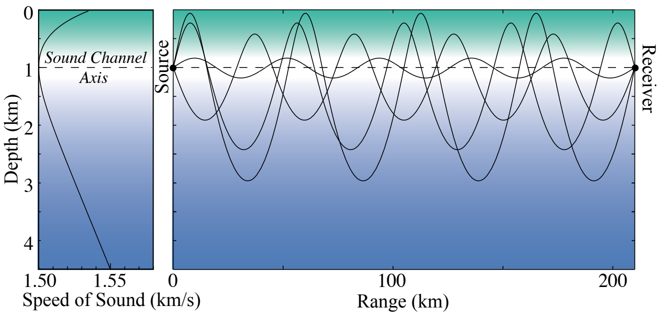
Decibels in water and air are not the same

Decibels in air vs. water

Sound waves in water and sound waves in air are fundamentally similar; however, the way that sound levels in water and in air are reported is very different. Relative sound intensities given in decibels (dB) in water are not directly comparable to relative sound intensities given in dB in air. This is similar to reporting the temperature. To simply say that it is 50 degrees outside is confusing because 50 degrees Fahrenheit is equal to 10 degrees Celsius, whereas 50 degrees Celsius is equal to 122 degrees Fahrenheit—quite a difference! To make sure there is no confusion, we indicate what temperature scale we are using. It is the same thing with dB scales in air and in water. To avoid confusion, you need to specify that sounds in water, a denser medium, were measured relative (re) to 1 microPascal (μPa) and that sounds in air were measured relative (re) to 20 μPa. To make the distinction clear for the reader, the Discovery of Sound in the Sea resources use “underwater dB” for underwater sounds.

volcanoes. Sounds are also generated by human activities such as shipping, oil exploration, military sonars, scientific research, fish finders, and other commercial sonar systems. These anthropogenic sounds cover a wide range of frequencies, from a few Hz up to several hundred thousand Hz.

Sound travels faster and further in water than in air.



Speed of Sound/SOFAR Channel

Sound travels approximately 1500 meters per second in seawater. That's a little more than 15 football fields end-to-end in one second! Sound travels much more slowly in air, at approximately 340 meters per second, only 3 football fields a second. The speed of sound in seawater is not a constant value, and although the variations in the speed of sound are not large, they have important effects on how sound travels in the ocean. In mid-latitudes in the deep ocean, the slowest sound speed occurs at a depth of roughly 1000 meters. Sound bends or refracts towards the region of slower sound speed, creating a sound channel in which sound waves can travel long distances. This channel is called the sound fixing and ranging, or SOFAR, channel. The diagram on the left shows examples of sound paths in the SOFAR channel.

The primary sources of ambient noise can be categorized by the frequency of the sound. In the frequency range of 20–500 Hz, ambient noise in the northern hemisphere is primarily due to noise generated by distant shipping. In the frequency range of 500–100,000 Hz, ambient noise is mostly due to bubbles and spray associated with breaking waves.

The relative intensity of different sources of sound is described by the source level. Source levels are defined as if the receiver was one meter from the source. Underwater sound intensities are reported in units called underwater decibels (see sidebar on page 4). There is a relationship between loudness and decibels (dB): a 10 dB increase in intensity is perceived by people as a doubling of the loudness of a sound.

The source levels of various underwater sound producers are listed in the table below. As the sound travels away from the source, the intensity gets lower because the sound waves spread out (spreading loss) and because some of the sound energy is absorbed by seawater. For example, the intensity of a sperm whale click measured as 236 underwater dB at one meter, would decrease to 196 underwater dB at a distance of 100 meters (approximately the length of a football field). High frequency sounds do not travel as far through the ocean as low frequency sounds because high frequency sounds are absorbed more rapidly.

The intensity of sound in the ocean decreases away from the source.

Examples of source levels of common underwater sound producers

Source	Source Level (underwater dB at 1 m)
humpback whale song	144–174
snapping shrimp	183–189 (peak-to-peak)
bottlenose dolphin whistles	125–173
sperm whale click	236
large tanker	186
mid-frequency naval sonar	235
oil and gas exploration airgun aray (32 gun)	259 (peak)

People and Sound in the Sea

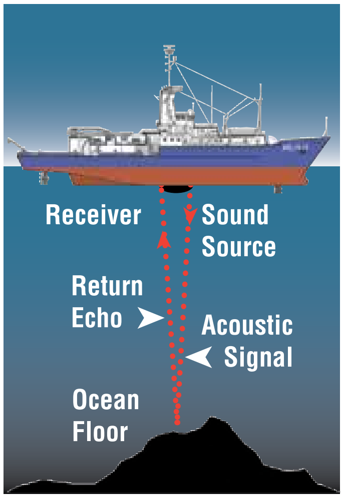
People use sound in the ocean for a wide variety of purposes. Many important everyday activities, such as fishing, depend on sound for success. A primary use of sound is to locate objects in the ocean, including rocks on the seafloor, marine animals, submarines, and shipwrecks. Sonar (sound navigation and ranging) is a technology that uses sound waves to identify objects and their locations in the ocean.

There are two types of sonar: active and passive. Passive sonar uses equipment that only listens. Sound waves produced by a sound source are received and can be used to identify or locate the object making the sound. Active sonar, on the other hand, sends out sound waves and then listens for (receives) the return echo. The return echo can be used to identify the type of object (whale, rock, boat) that is reflecting the sound as well as its range and speed.

Sonar

Sound can be used to map the sea floor and locate fish, shipwrecks, and submarines.

Sonar is an acronym for sound navigation and ranging technology. Active sonar systems use transmitted sound waves to detect underwater objects by listening to the reflected or returning echoes. The distance to the object or the seafloor can be calculated by measuring the time between when the signal is sent out and when the reflected sound, or echo, is received. By knowing how fast sound travels through water, the distance between a ship and the object of interest, such as another ship or animal, can be calculated.



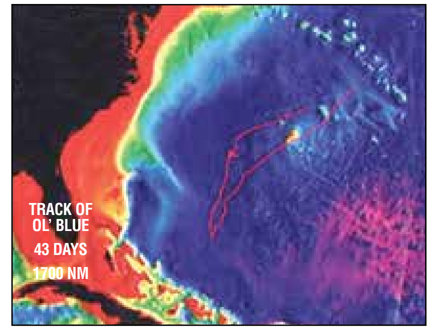
People commonly use sound to determine the depth of the ocean. The most common system for measuring water depth, and preventing collisions with unseen underwater rocks, reefs, etc., is the echo sounder, a form of active sonar. These sonar systems use a sound source that is usually mounted on the bottom of a ship. Sound pulses are sent from the bottom of the ship straight down into the water. The sound reflects off the seafloor and returns to the ship. To produce detailed maps of the ocean floor, scientists use a system called multibeam sonar. This system may use more than 100 sound beams to find the depth of a large area of the ocean at one time. Multibeam systems can produce very accurate maps of the ocean floor that are necessary for safe navigation, ocean habitat studies and geological research. Other technologies, such as side scan sonar, are used to examine details of the seafloor. Side scan sonar is very sensitive and can measure features on the ocean bottom smaller than 1 centimeter (less than half an inch). Typical uses of side scan sonar include: looking for objects on the seafloor (sunken ships, pipelines, downed aircraft, lost cargo), detailed mapping of the seafloor, investigating seafloor properties (grain size, etc.), and looking at special features on the seafloor like underwater volcanoes. For example, selecting the location of an offshore wind facility requires precise information on the seafloor characteristics.

Fishermen use a version of echo sounding technology called a fish finder to locate fish. Fish finders detect the presence of fish primarily by detecting a large chamber of air, called a swim bladder, that is located in the abdominal cavity in most fishes. The air contained in the swim bladder reflects the sound back to the fish finder, where echoes are interpreted as specific types of fish, and estimations of fish densities can be made.

Courtesy of Klein Associates, Inc.

A side scan sonar image of the British freighter *Empire Knight* that sank in 1944 off the Maine coast.

Scientists can track animals and study their behavior by listening to the sounds they produce.

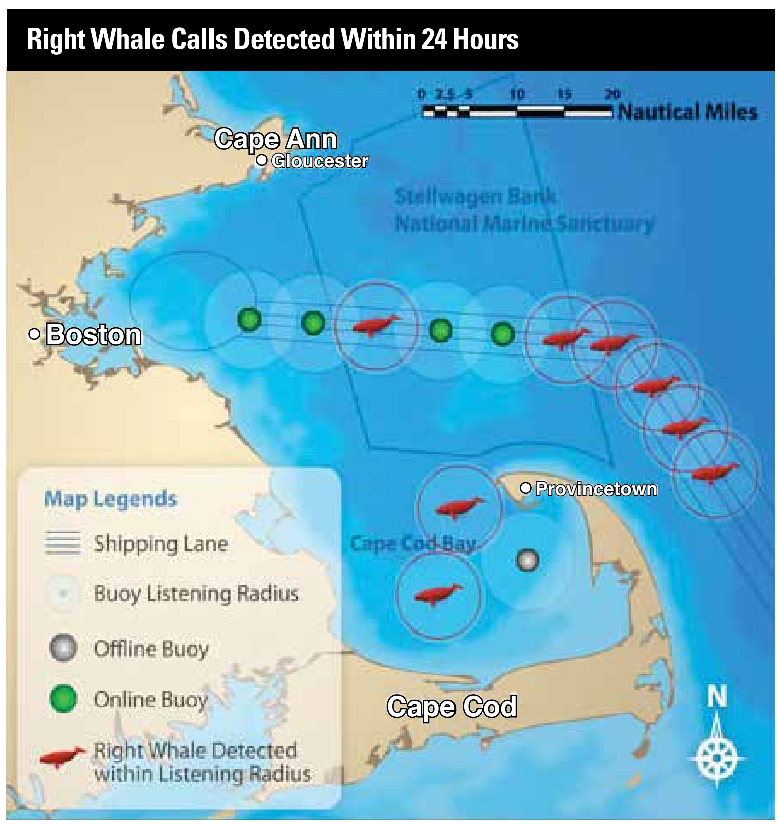


Courtesy of U.S. Naval Research Laboratory

An individual blue whale, Ol' Blue, was tracked for 43 days (dark red line) throughout the North Atlantic Ocean using the US Navy's Sound Surveillance System (SOSUS). The colors show the bathymetry.

Sound is used to study marine mammal distributions by listening to the sounds animals make (passive acoustics). Different species of whales and dolphins (cetaceans) produce different sounds including songs, moans, clicks, sighs, and buzzes. Scientists can listen for these sounds and detect, identify, and locate different marine mammal species. Passive acoustics is also being used to enhance estimates of animal abundance, or population size, proving to be an effective complement to traditional visual surveys. Scientists are using both techniques, especially for cetaceans, since passive acoustics can often detect more animals at longer ranges and under water than would be obtained from visual methods alone. Passive acoustics has successfully been used in abundance estimates for several cetacean species including right whales, minke whales, beaked whales, sperm whales, humpback dolphins, and finless porpoises.

The critically endangered North Atlantic right whale has benefited from the use of passive acoustics. Passive listening systems have been deployed along the U.S. Atlantic coast to continuously monitor for the presence of whales to reduce the risk of ship strike, as the entrance channels to busy commercial ports can overlap with right whale habitat. In connection with the development of a Liquefied Natural Gas (LNG) terminal in the Port of Boston, Massachusetts, ten real-time, auto-detection buoys were deployed in the port's shipping lanes. Computers onboard each buoy estimate a sound's similarity to a right whale call. Information on which buoys detected whale vocalizations are transmitted to vessels, and LNG tankers are mandated to reduce their speeds in the areas around buoys that have detected whales. All other ships are encouraged to check whale-buoy alerts and slow down if necessary.



Courtesy of Cornell/WOHI

Real-time. automatic-detection buoys are an acoustic tool being used to monitor right whales off the coast of Massachusetts. This is an archived image from April 2008 showing buoys that detected right whale calls (the red whale icons) within the last 24 hours.

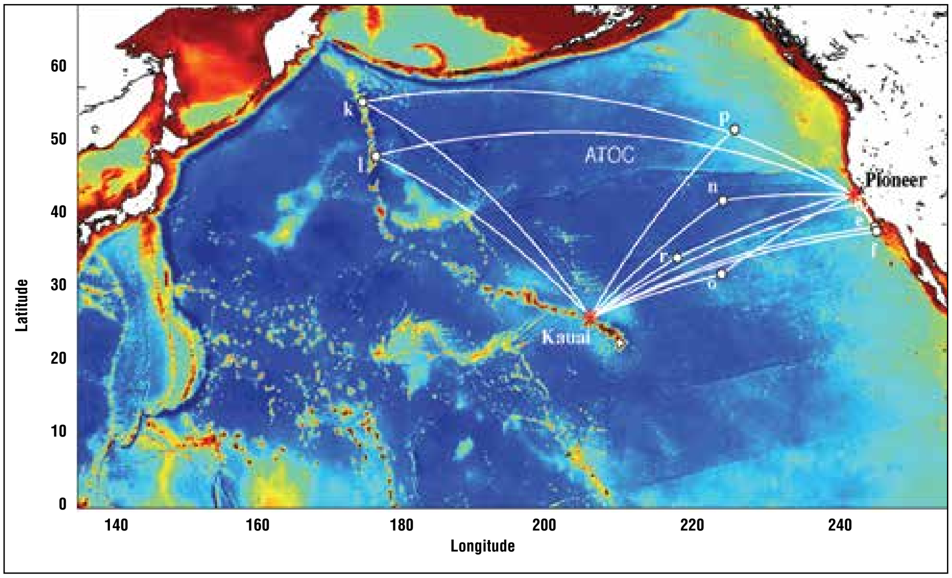
Currents are commonly measured with sound. An instrument called an Acoustic Doppler Current Profiler (ADCP) is often used to measure the current in specific places like shipping channels, rivers and streams, and at buoys. ADCPs can be placed on the bottom of the ocean, attached to a buoy, or mounted on the bottom of a ship. ADCPs measure currents by sending out a sound and listening to the returning sound for small changes in the frequency of the sound caused by the Doppler effect. The Doppler effect is a change in the frequency of

Sound can be used to measure ocean temperature, currents and waves.

a sound due to the motion of the source, the particles in the water that reflect the sound, or the listener. The most common example of the Doppler effect is the change in frequency of a train whistle. As the train comes toward you, the frequency increases. This Doppler effect occurs because the motion of the train is squeezing the sound waves. As the train moves away, the frequency decreases because the train's movement is stretching out the sound waves. The Doppler effect also occurs in the water.

Ocean temperatures can be measured using sound. Most of the change in the speed of sound in the open ocean is due to changes in temperature. Sound travels faster in warmer water and slower in colder water. To measure the temperature of the water, a sound pulse is sent out from an underwater sound source and heard by a listening device (a hydrophone) in the water a known distance away (up to thousands of kilometers). By accurately measuring the time it takes for the sound to travel from the source to the receiver, the speed at which the sound traveled can be calculated. This speed can be directly related to the temperature of the water between the source and the hydrophone. Measuring water temperature this way is very efficient and provides data useful for understanding ocean currents and studying climate change.

Sound levels in the ocean are not constant, but differ from location to location and change with time. Different sources of sound contribute to the overall noise level of the ocean, including shipping, breaking waves, marine life, and other natural sounds and anthropogenic sounds. The background sound in the ocean is called ambient noise. The primary sources of ambient noise can be categorized by the frequency of the sound. For example, in the frequency range of 20-500 Hz, ambient noise is primarily due to noise generated by distant shipping.



This image displays two sound sources (red astrisks) and several receivers (white dots) used to measure Pacific Ocean temperatures. The colors show the bathymetry.

A noise budget is a listing of the various sources of noise at a receiver and their associated ranking by importance. It compares different sources of underwater sound, at particular geographical locations and in different frequency bands, averaged over time. A noise budget characterizes the magnitude of sound intensity or energy in the underwater sound field from various sources. Researchers assess noise distributions and noise budgets in habitat characterization and environmental studies, and when they are designing acoustic communication and sonar systems. Noise budgets are also assessed during marine animal masking studies. Masking occurs when noise interferes with a marine animal's ability to hear a sound of interest. Just as it can be difficult to hear someone talking at a loud party, elevated noise levels may mask important sounds for marine animals.

Marine animals use sound to sense their surroundings, communicate, locate food, and protect themselves underwater. They generate sounds to attract mates, defend territories, and coordinate group activities. Marine mammals use sound to maintain contact between mother and offspring, for reproduction, and to display aggression. Fishes produce various sounds that are used to attract mates as well as to ward off predators. Some marine invertebrates, such as spiny lobsters, are thought to produce sound in order to scare away predators.

One of the best known examples of animals that use sound over long distances for reproduction is the song of the humpback whale. Male humpback whales produce a series of vocalizations that collectively form a song. These songs can be heard miles away. Humpback songs are complex in structure and long in duration. Whales have been known to sing the same song for hours.

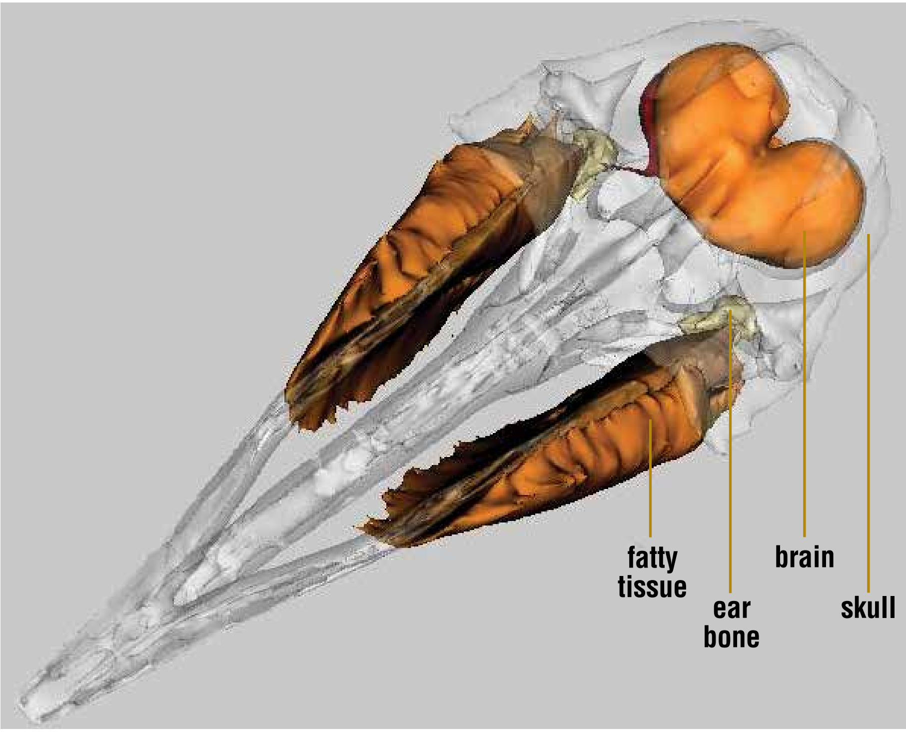
Humpback whales produce complex songs that can be heard miles away.

Reproductive activity, including courtship and spawning, accounts for the majority of sounds produced by fishes. During the breeding season, courting males of the plain midshipman fish hum at night to attract females and encourage them to lay eggs in the males' nests. The hum is a low-pitched sound generated by the rapid contraction of the drumming muscles on the male's swim bladder. Humming males chorusing together produce a sound like that of a huge hive of bees or a group of motorboats, a sound loud enough to be heard by people on nearby land and houseboats.

Even marine invertebrates use sound to communicate. Snapping shrimp, spiny lobster, and fiddler crabs defend themselves with sound. Snapping shrimp close their enlarged claw to create a bubble that cavitates, producing a loud popping sound. The force of the cavitating bubble

Tsuneo Nakamura

Darlene Ketten, Computerized Scanning and Imaging Facility, WHOI

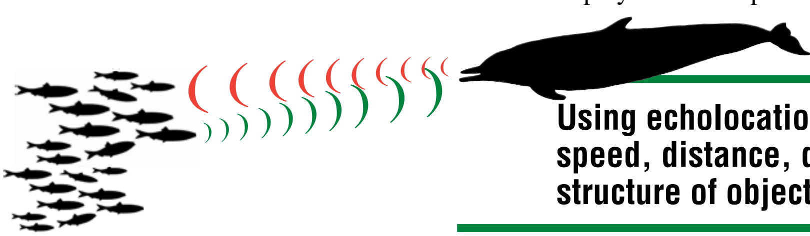


This image was produced from CT scan images of a beaked whale *(Ziphius cavirostris)* head. Tissues are segmented for reconstructing based on their X-ray attenuations. Only certain tissues are shown.

is so powerful it can ward off predators. Caribbean spiny lobsters that produced rasp sounds were better able to escape predatory octopus attacks and resist attacks for a longer duration than silenced lobsters. Cleaner shrimp clap one pair of their claws to advertise their cleaning services to reef fish. The hungrier the shrimp is, the more clapping it does. By clapping, the cleaner shrimp also protects itself from predators, announcing itself as a cleaner.

In addition to communication, marine animals use sound to locate food and navigate through the water. Toothed whales use echolocation to find prey and avoid obstacles. These whales send out sounds that are reflected back when they strike an object. Echolocation functions just like active sonar systems. The echoes provide information about the size, shape, orientation, direction, speed, and even composition of the object of interest, whether it is prey or an obstacle. Dolphins can echolocate so well that they are able to detect differences in the thickness of walls of less than 0.3 mm and discriminate between copper and aluminum objects.

Toothed and baleen whales produce other sounds during feeding. Humpback whales have developed a feeding technique called bubble feeding. Bubble feeding involves one or a few whales blowing air from their blowhole while underwater. This produces sound as the bubbles form a cloud, curtain, or column that rises toward the surface. The bubbles trap the prey between the surface and the whales' mouths. A bubble net is formed when the bubbles emitted by the whales form a ring and concentrate the prey inside. Both the sound and the bubbles work to concentrate prey so the humpback can capture more food per mouthful.



Using echolocation, dolphins can determine size, shape, speed, distance, direction, and even some of the internal structure of objects in the water.

Animals can also navigate by listening to the sounds around them. There is evidence that underwater reef sounds can be detected by the larval stages of coral reef fishes and invertebrates. These sounds guide the larvae to coastal areas, allowing them to identify suitable settlement habitats. Adults and juveniles of some reef fishes may also use the underwater sounds of coral reefs to guide their nocturnal movements.

Marine animals have unique physiologies for producing, detecting, and interpreting underwater sounds. Seals and sea lions (pinnipeds) produce sounds in air using similar mechanisms as humans (air is moved from the lungs and across the vocal fold ligaments, which then vibrate and produce sounds). Some pinnipeds also produce vocalizations underwater, such as clicks, trills, warbles, whistles, and bell-like sounds. These sounds are generated by cycling air through air pouches in the animal's head.

The vocalizations emitted by toothed whales and dolphins (odontocetes) are all produced underwater. These sounds include clicks, whistles, and pulsed sounds. The details of sound production in toothed whales are complex. Odontocete nasal systems are made up of a number of nasal air sacs and plugs that open and close when air is moved from one sac to another. Movement of air stimulates vibrations, which may be amplified by air sacs that act as resonators. The sound is then channeled through fats in the forehead (called the melon) to the water in front of the animal. The melon helps focus outgoing sound waves into directional beams.

Ed Stockard, National Science Foundation

Humming male midshipmen fish produce a sound loud enough to be heard by people on nearby land and houseboats.

Fishes produce sounds, including grunts, croaks, clicks, and snaps, using different mechanisms than cetaceans or pinnipeds. The three main ways fishes produce sounds are by rapidly contracting and expanding sonic muscles located on or near their swim bladder (drumming); striking or rubbing together skeletal components (stridulation); and by quickly changing speed and direction while swimming (hydrodynamics). The majority of sounds produced by fishes are of low frequency, typically less than 1000 Hz. The sonic muscles found in fishes such as drum fishes (Family Sciaenidae) are the fastest contracting muscles known in vertebrates.

Janna Nichols, www.pnscuba.com

Most marine invertebrates produce sounds by rubbing two parts of their bodies together. The snapping shrimp, however, produces sound in a unique way. Upon closure of its enlarged claw a bubble is formed that collapses, producing a loud popping sound. Sound generated by colonies of snapping shrimp is so prevalent in some shallow water regions that it interferes with underwater communications, military activities, and research.

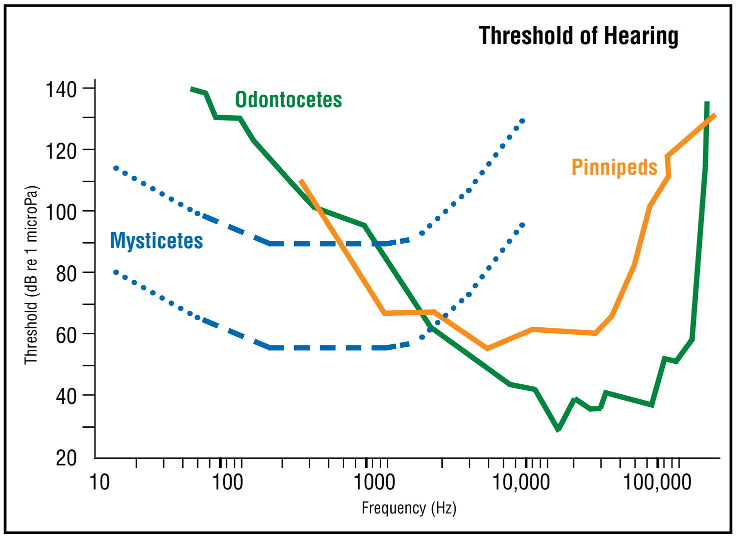
Detecting sounds also requires specialized structures. Seals, sea lions, walruses, otters, and polar bears live on land at least part of the time and have ears that are similar to terrestrial mammals. Whales, dolphins, and porpoises (cetaceans) that spend their whole lives in the water have developed a different mechanism for detecting sound. In toothed whales (odontocetes), the lower jaw is surrounded by specialized fats which, along with a thin bony area called the pan bone, are thought to play a role in channeling sound to the middle ear. Unlike land mammals that have ears attached to the skull, the middle and inner ears of cetaceans are encased in bones that are located in a cavity outside the skull. In odontocetes, these bones are attached to the skull by ligaments. In baleen whales (mysticetes), the earbones have bony connections to the skull. The exact mechanism that mysticetes use for hearing is still being researched.

R.P. Van Dam

Whales, dolphins, and porpoises have developed a different mechanism for detecting sound.

More research is needed on many of these topics, including species that have so far received little attention, like sea turtles. Sea turtles are found throughout the ocean, except in cold, polar waters. At present, scientists do not have any reliable underwater recordings of sounds produced by turtles, nor is their ability to hear sound either in air or underwater known well. However, in some of their coastal habitats, turtles are subjected to high levels of anthropogenic noise. Auditory brainstem research has shown that sea turtles can hear low to mid-frequency sounds under water, but with poorer sensitivity than mammals. The external opening into a sea turtle's ear is covered by thick skin, known as the cutaneous plate, which is a ring of scales that are similar to but smaller than those on the rest of the head. Below this skin is a fatty (subcutaneous) layer. The thick skin and fatty layer make it difficult for the turtle to hear well in air, but provide good tissue conduction for underwater sound to the middle ear and inner ear.

Hearing Sensitivity of Marine Mammals



Hearing sensitivity studies provide information on what frequencies an animal can hear and how loud a sound must be to be heard. Sounds that fall outside the detection range of an individual are not perceived. For example, people can't hear the sound a dog whistle makes, but dogs can. The hearing sensitivities of a few toothed whale species (odontocetes) have been measured and these species have been found to hear best in the high-frequency range (10,000 to 50,000 Hz). Very little is known about the hearing sensitivity of large baleen whales (mysticetes). The hearing ranges for mysticetes shown in the graph are based on models. Their anatomy and vocalizations strongly suggest they are adapted to hear low frequencies. Pinnipeds (seals and sea lions) have similar hearing ranges as odontocetes but are less sensitive.

The intensity at which animals can just barely hear a sound is known as the hearing threshold. The hearing threshold is the lowest sound level at a given frequency that is detected on average and varies between individuals and over time. The graph shows estimates of the hearing thresholds for three groups of marine mammals. The lowest points on each curve indicate the frequencies that the animals hear best. The two dashed blue lines are the estimated range of mysticete hearing thresholds.

Research suggests that increased background noise and specific sound sources might impact marine animals in several ways. The potential impacts include sounds that cause marine animals to alter their behavior, prevent marine animals from hearing important sounds (masking), increase physiological stress levels, or cause hearing loss (temporary or permanent). In at least four well-documented cases there is a relationship in time and space between the use of mid-frequency sonar and the stranding of cetaceans, particularly some species of beaked whales.

Underwater sound can affect marine animals in a variety of ways.

Behavioral responses to sound vary greatly. In order to understand how anthropogenic sounds may impact marine life, the animal's reaction to known sounds must first be measured. Observations of normal behavior, "control" or "baseline" data, provide the reference points for measuring any changes occurring during or after sound exposure. It is important to obtain baseline data that describe both the typical value of the measurements and the range of natural variability.

An animal's behavioral response depends on a number of factors, such as hearing sensitivity, tolerance to noise, exposure to the same noise in the past, behavior at the time of exposure, age, sex, and group composition. Some marine animal responses to sound are momentary inconsequential reactions, such as the turn of a head. Other responses are short-term and within the range of natural variation in these behaviors. In other cases, more significant changes in behavior have been observed. Some of the strongest reactions occur when the sounds are similar to those made by predators.

Just as it can be difficult to hear someone talking at a loud party, elevated noise levels in the ocean may interfere with marine animals' ability to hear important sounds. Masking occurs when a loud sound drowns out a quieter sound or when noise is at the same frequency as a sound

Tom Kieckhefer

Stranding events involving multiple beaked whales have coincided closely with military activities using sonar. How the sonars might have caused the strandings is still a mystery.

Protected Resources Division, Southwest Fisheries Science Center

signal. Masking is also influenced by the amount of time that the noise is present. The potential impacts that masking may have on individual survival, what things marine animals may do to avoid masking, and the energetic costs of changing behavior to reduce masking are poorly understood. However, because of the widespread nature of anthropogenic activities, masking may be one of the most extensive and significant effects on the hearing and communication of marine animals.

Exposure to loud sounds can cause hearing impairment or loss. Hearing loss depends on the intensity and frequency of the sound, and the duration of the animal's exposure to the sound. Just as humans exposed to extremely loud sounds for short periods of time (e.g. rock concerts) experience temporary or permanent hearing impairment (called temporary threshold shift or TTS and permanent threshold shift or PTS, respectively), marine mammals and fishes might also experience hearing loss from exposure to anthropogenic sounds. Hearing damage can also be caused by exposure to moderate levels of noise over long periods of time. Hearing loss due to noise does not occur if the frequency of the sound to which the animal is exposed is outside the range that the animal can hear.

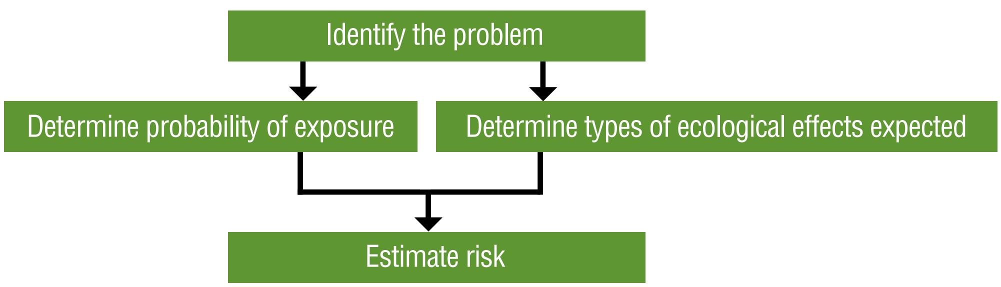
Stranding events involving multiple beaked whales have been reported that coincided closely in time and space with military activities using sonar. Mass strandings of beaked whales are rare; a review of all beaked whale strandings from 1874 to 2004 found only 136 mass stranding events. Of these, only 12 stranding events included evidence that naval activity coincided in space and time. These 12 events had three consistent features: (1) the stranding locations were less than 80 km from the 1,000-m depth contour (that is, where deep water occurs near shore); (2) 8 out of the 12 stranding events occurred in areas where beaked whale mass strandings had previously been reported; and (3) all 12 events included Cuvier's beaked whales *(Ziphius cavirostris)*, a species that does not commonly mass strand.

There are many causes of marine mammal strandings, some natural and some related to human activity. In two well-documented cases, there is sufficient information about the sonar operations, the times and locations of the strandings, and the nature of the injuries to the animals to determine that multiple sonar and multi-ship exercises with sonar contributed to the strandings. These events occurred in Greece (1996) and the Bahamas (2000). In two of the remaining mass stranding events that coincided with naval sonar activities (Madeira and Portugal in May 2000 and the Canary Islands in 2002), there is insufficient information about the timing and location of the strandings vs. naval activity to make a strong association, however necropsies (animal autopsies) that were performed on some of the animals found injuries similar to those seen in the Bahamian cases.

. The mechanism by which the sonars might have caused the strandings is still a mystery. Much more scientific research is needed to explain the observed injuries in the animals that stranded in the areas of mid-frequency sonar exercises.

A variety of methods are being applied or developed to help measure the effect of underwater sound on marine animals. Hearing sensitivity studies provide knowledge of the hearing abilities and other acoustic features of marine animals. This is important when measuring the effects of sound on marine animals because if an animal is unable to detect a sound due to limitations in hearing range or loudness, it is unlikely the animal will be affected by the sound. Visual and acoustic observations of marine mammals made during large-scale surveys or associated with a specific research project can provide detailed information on the behavior, movement, and abundance of these animals in the wild. In order to measure an animal's reaction to a sound you must first study the animal's behavior when the sound is not present. These observations of normal behavior, which are "control" or "baseline" data, provide the reference points for measuring any changes that take place during or after sound exposure. Data-logging tags can be attached to animals to provide information on what the animals are doing when they are underwater. Tags can also provide long-term continuous information on the behavior and movements of individual animals. Controlled exposure experiments are a field method in which controlled doses of sound are transmitted to focal animals in order to observe an animal's untrained, naturally occurring responses to a particular sound. The scientist controls the amplitude, frequency, and other characteristics of the sound. The levels to which the animals are exposed are limited to avoid harming them. Observations can be obtained from visual surveys and behavioral observations, tags, and passive acoustic monitoring. Using a combination of all three methods will provide the most complete picture.

The process for considering if and how much a sound source is likely to affect marine animals is called ecological risk assessment. The first step of this scientific process is to identify the problem. The next stage involves estimating the probability of being exposed to the problem and, based on that exposure, determining the types of ecological effects that are expected. Then the risk can be estimated.



This general model can be used to determine if a specific sound source might affect a particular species by answering the following questions:

- What is the level of sound at different distances and depths as sound travels away from the source?
- Where are marine animals likely to be located relative to the source?
- What are the sound levels and durations to which the animals are likely to be exposed?
- Can the animal sense these sounds?
- What effects might these sound levels have on the animals?

Actions may then be taken to reduce effects on marine life. If it is not possible to eliminate the sound source, it may be possible to change the frequency or amplitude of the sound source. Gradually increasing the sound source level ("ramp-up") or using bubble screens or barriers around stationary sources are other approaches that have been used. Another obvious way to mitigate the effects of anthropogenic sound is to avoid concentrations of marine animals. Federal laws such as the Endangered Species Act, Marine Mammal Protection Act, and National Environmental Policy Act that aim to protect animals from harassment (including impact from sound sources) have motivated studies of marine animals and the development of mitigation techniques and alternative technologies. The extent to which many commonly used mitigation measures are effective has not been determined.

Scientific Method

Science is a process for asking questions about the natural world and testing the answers. Science is not just a collection of facts. Scientists use the Scientific Method as the orderly process to ask questions and test observations. This method begins with observations of the natural world. From these observations a question is formed that is answerable using the tools of science. Next, a tentative answer to the question is formulated, which is called a hypothesis. Then predictions based on the hypothesis are made and tested through experiments or observations. If the predictions are wrong, then the hypothesis has been falsified. If the predictions are found to be accurate, then the hypothesis is accepted as provisionally correct. Hypotheses and their tests must be repeated by others to be considered valid. Hypotheses that have been consistently validated through additional observations or experimentation can eventually be advanced to the status of theory. A theory is a thoroughly substantiated explanation of some aspect of the natural world and comes as close to objective truth as possible. Like hypotheses, theories are still considered somewhat provisional because the possibility always exists that some day an observation will be made that is inconsistent with the predictions of the theory. Scientists must then construct a new hypothesis that is consistent with all available data. Science is a continually evolving process.

Internet Resources

The *Discovery of Sound in the Sea* website (www.dosits.org) is one of the most comprehensive Internet resources on underwater sound. In addition to in-depth science content, there are galleries and education resources that provide a wealth of information.

The **Audio Gallery** contains audio clips of more than 100 underwater sounds generated by marine animals, human activities, and natural phenomena. There are also images accompanying each audio file in the gallery and video for select marine animals.

Tom Kleindinst, Woods Hole Oceanographic Institution

The **Scientist Gallery** highlights the cutting edge research of five renowned scientists and provides interviews for each.

The **Technology Gallery** provides images and descriptions of the scientific and commercial equipment that employs underwater acoustic technologies.

The **Teacher Resources** section contains classroom activities developed by educators along with a list of select classroom resources.

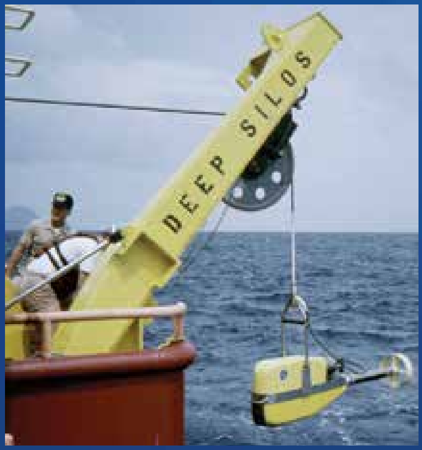
PowerPoint Presentations designed for education are available on the DOSITS website.

The **Media Resources** section contains material designed for the media on the basics of sound in the ocean.

The **Student Resources** section contains tutorials and features designed for students.

Print Resources

This booklet and an associated tri-fold brochure are available on the DOSITS website as pdf documents.



Jill Schoenherr

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