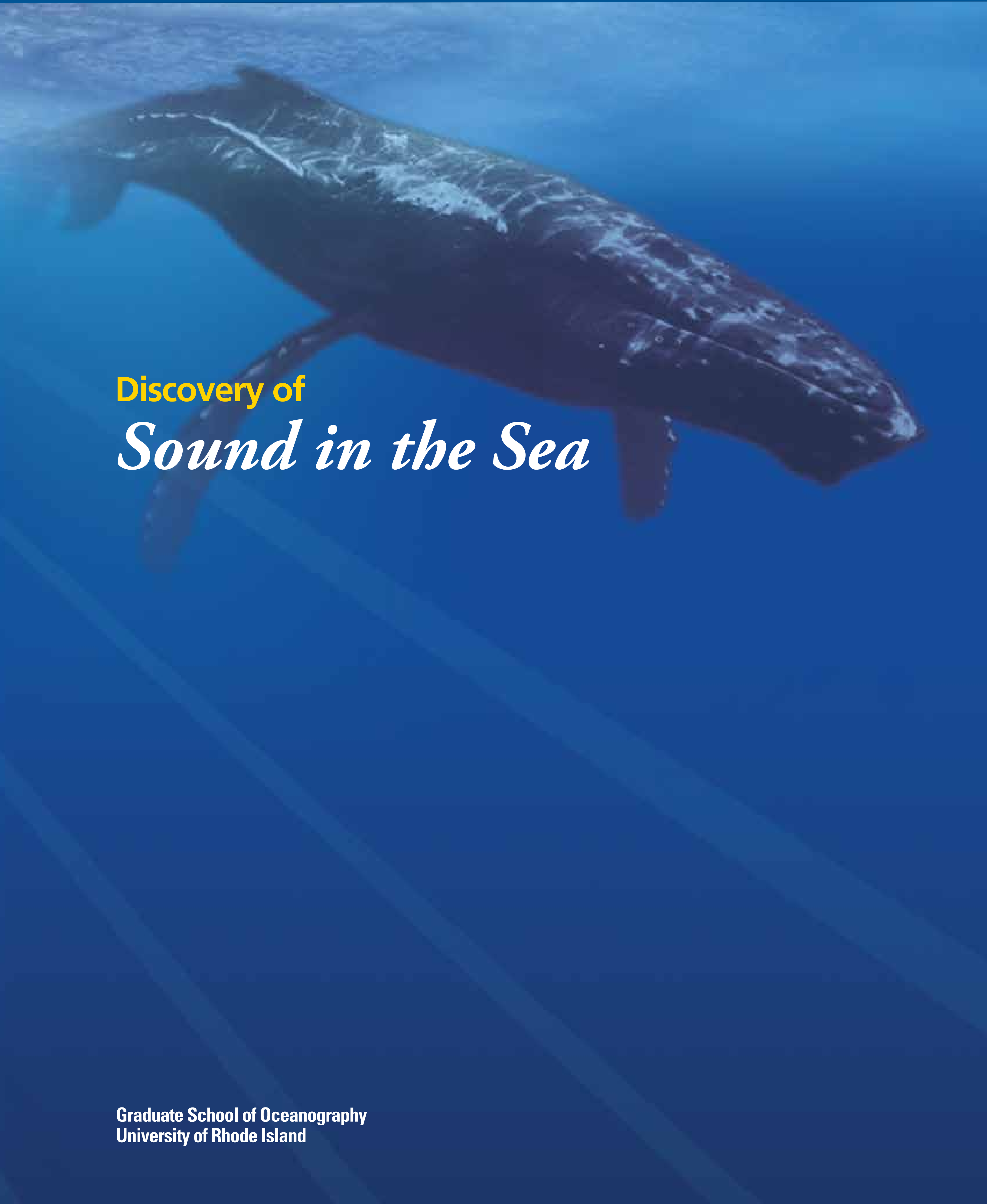
dosits.org



Discovery of *Sound in the Sea*

Graduate School of Oceanography
University of Rhode Island

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

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Acknowledgments

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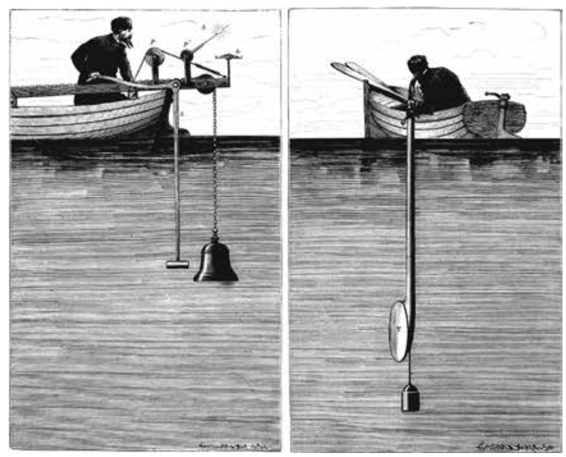
Importance of Sound in the Sea

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 underwater.

Sound travels far greater distances than light underwater. 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 underwater 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 underwater.

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 is a significant source of underwater noise.

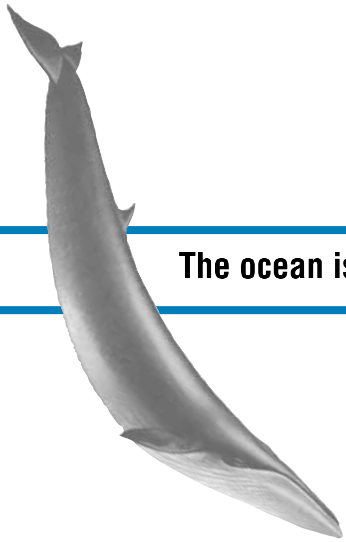


J.-D. Colladon, *Souvenirs et Memoires*, Albert-Schuchardt, Geneva, 1893

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 the oceans continue to be explored and marine resources are extracted, the conditions for safe and sustainable use of sound in the sea must be determined.

The *Discovery of Sound in the Sea* website (dosits.org) and associated resources provide information on the basic science of sound in the sea, how both people and animals use sound underwater, and the effects of sound on marine life. The following information is based on well understood scientific principles, peer-reviewed literature, and high-quality sources of scientific data and is a product of the Discovery of Sound in the Sea Project. All content has undergone a thorough review by a panel of independent scientific experts.

Dr. James P. McVey, NOAA Sea Grant Program



Sounds may be described with words such as loud or soft; high-pitched or low-pitched. These words describe, or characterize, how sounds are perceived. Scientists, on the other hand, describe sounds with characteristics that can be measured using instruments. Scientists measure intensity and amplitude, which can be related to the common words loud and soft. Scientists measure frequency, which can be related to the common word pitch. 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 people hear best around 3,000–4,000 Hz, where human speech is centered.

The ocean is full of a variety of sounds.

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 toadfishes and drums, and marine invertebrates, such as snapping shrimp, also produce sounds.

National Oceanic and Atmospheric Administration

Tom Kieckhefer

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

Courtesy of Moonraker Australia

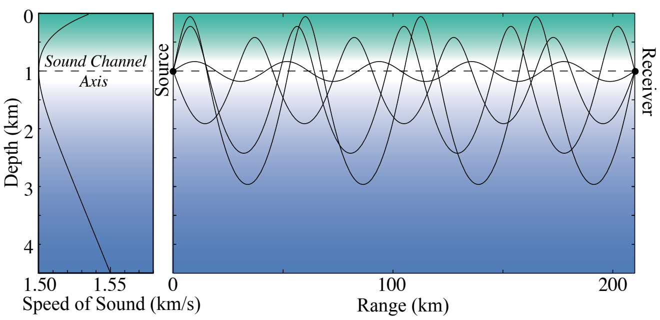
Decibels in water and air are not the same

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 32 degrees outside is confusing because 32 degrees Fahrenheit is equal to 0 degrees Celsius, whereas 32 degrees Celsius is equal to 90 degrees Fahrenheit. To make sure there is no confusion, it is important to indicate what temperature scale is being used. It is the same with dB scales in air and in water. To avoid confusion, one must specify that sounds in water, a denser medium, were measured relative (re) to 1microPascal(μPa) and that sounds in air were measured relative (re) to 20μPa. To make the distinction clear for the reader, Discovery of Sound in the Sea resources use "underwater dB" to designate underwater sounds.

The primary sources of ambient noise in the ocean 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.

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 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.

As a 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 sea water. High frequency sounds are absorbed more rapidly and do not travel as far through the ocean as low frequency sounds.

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

The intensity and amplitude decrease very rapidly for waves spreading out in all directions from a source at mid-depth in the ocean. This is called spherical spreading. Sound cannot propagate uniformly in all directions from a source in the ocean forever. Beyond some range, the sound will hit the sea surface or sea floor, and the spreading will become approximately cylindrical. For example, the intensity of a humpback whale song measured as 170 underwater dB at one meter, would decrease to 130 underwater dB at a distance of 100 meters (approximately the length of a football field). The following table compares the relative intensity and amplitude of sound waves at one meter from the source to their values at greater distances for cylindrical and spherical spreading.

Cylindrical and spherical sound spreading

	Relative Intensity		Relative Amplitude	
Distance from Source	Cylindrical Spreading	Spherical Spreading	Cylindrical Spreading	Spherical Spreading
1 meter	1	1	1	1
10 meters	1/10	1/100	1/3	1/10
100 meters	1/100	1/10,000	1/10	1/100

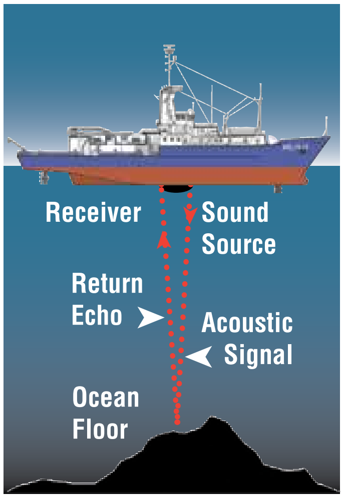
People and Sound in the Sea

People use sound in the ocean for a wide variety of purposes. Many important everyday activities, such as fishing, depend on using sound for success. A primary use of sound underwater 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 natural or anthropogenic sound source are received and can be used to identify or locate the object making the sound. Active sonar 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, ship, etc.) that is reflecting the sound as well as its range and speed.

Sonar

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 sea floor 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.



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

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. A multibeam system effectively uses up to 1,000s of sound beams to find the depth over 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, etc.), detailed mapping of the seafloor, investigating seafloor properties, such as grain size, 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.

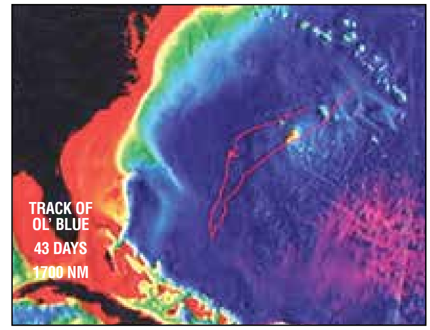
Fishermen use a version of echo sounding technology called a fish finder to locate fish. Fish finders detect the presence of fish primarily by detecting a large chamber of air, called a swim bladder, that is located in the abdominal cavity in most fishes. The air contained in the swim bladder reflects 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.

For more about people and sound in the sea

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

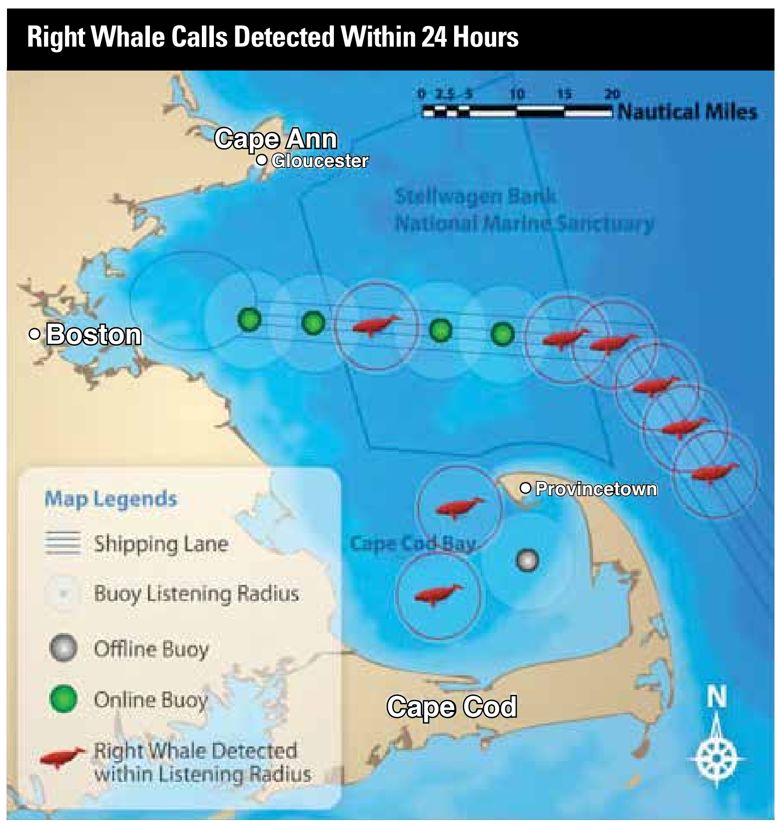


Courtesy of U.S. Naval Research Laboratory

An individual blue whale, Ol' Blue, was tracked for 43 days (dark red line) throughout the North Atlantic Ocean using the U.S. 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 underwater 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 habitats. 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. The locations of buoys that detect whale vocalizations are transmitted to vessels, and LNG tankers are mandated to reduce their speeds in the areas around buoys that have detected whale calls. 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.

Water 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 a sound due to the motion of the source, the

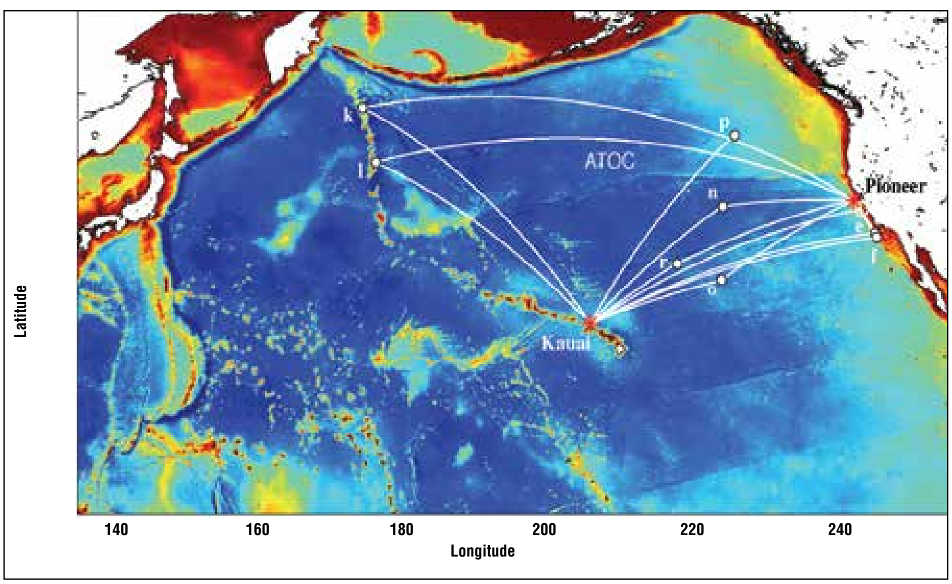
Sound can be used to measure ocean temperature, currents and waves.

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 water 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 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.

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, as well as 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.



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

Marine animals use sound to sense their surroundings, communicate, locate food, and protect themselves underwater. Sounds are particularly useful for communication because they can be used to convey a great deal of information quickly and over long distances. Changes in rate, pitch, and/or structure of sounds communicate different messages. In particular, fishes and marine mammals use sound for communications associated with reproduction and territoriality. Some marine mammals also use sound for the maintenance of group structure. Marine invertebrates, such spiny lobsters and fiddler crabs, have been found to produce sounds for defensive and courtship purposes.

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

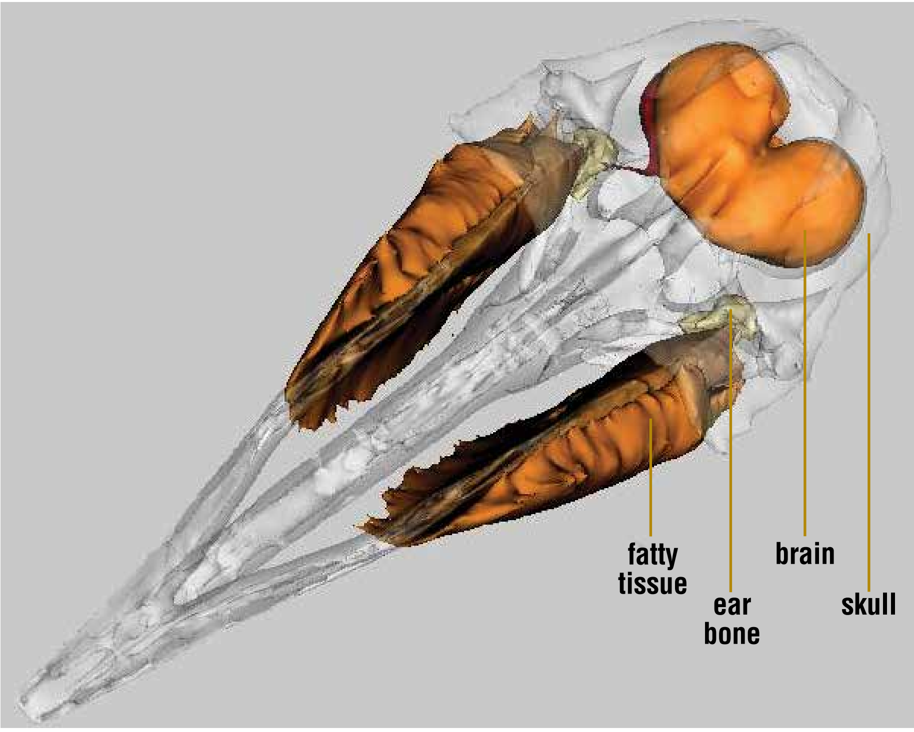
One of the best known examples of marine animals using sound as part of reproductive displays is the song of the humpback whale. Male humpback whales produce a series of vocalizations that collectively form a song. These songs can be heard miles away. Humpback songs are complex in structure and long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

Tsuneo Nakamura

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 fish'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.

Snapping shrimp close their enlarged claw to create a bubble that cavitates, producing a loud popping sound. The force of the cavitating bubble is so powerful it can ward off predators. Caribbean spiny lobsters that produced rasp sounds were found to better 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.

Janna Nichols, www.pnscuba.com



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.

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 have an amazing ability to detect and identify a target the size of a golf ball at a distance of 100 meters (328 feet). The echolocation beam is also very directional and can be controlled with a slight turn of the animal's head. The beam can also be widened or narrowed with a modification in shape of the animal's melon, the fatty tissue through which echolocation signals are transmitted in toothed whales.

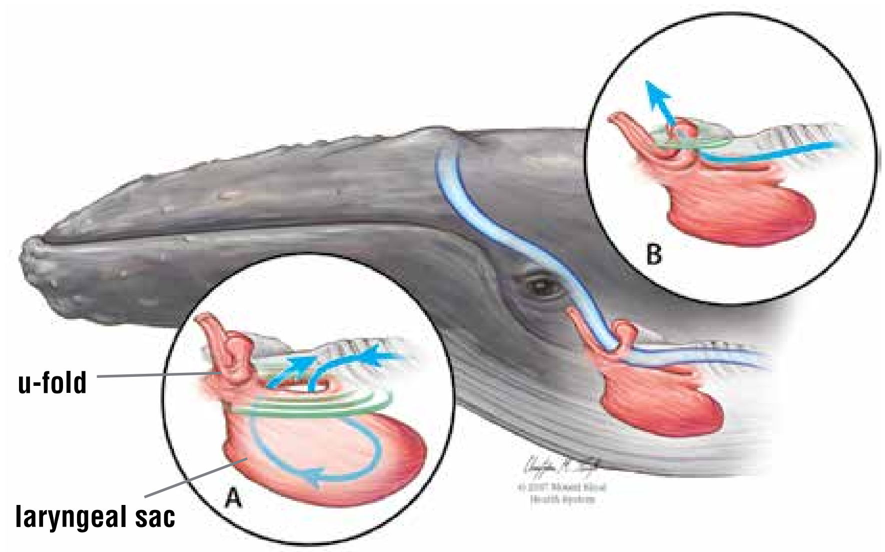
Toothed and baleen whales produce other sounds during feeding. Humpback whales have developed a feeding technique called "bubble netting." One or more animals will swim in an upward spiral or loop, while simultaneously blowing a ring of bubbles underwater. Bubbles may be produced in continuous streams or short bursts. The bubbles startle the fish and cause them to densely aggregate, which allows them to be more efficiently captured. Sounds are produced in association with bubble generation and explosive bursts as they rise to the water surface and break. It is not clear whether it is the sound or the sight of the bubbles that startle the fish.

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 using similar mechanisms as land mammals. Sounds are produced by vibration of the vocal folds in the larynx as air passes from the lungs through the larynx, into the throat, and out the mouth.

Odontocetes (toothed whales) produce a wide variety of sounds, which include clicks, whistles, and burst pulses. The blowhole is typically closed during sound production in water. Air from the lungs is retained and recycled in the narial passages and air sacs. Paired air sacs, the large fatty melon, and muscular and fatty bodies called the "phonic lips" are the source of echolocation signals in most odontocetes. The phonic lips vibrate to create clicks. Some studies suggest these structures may also be involved in whistle production.



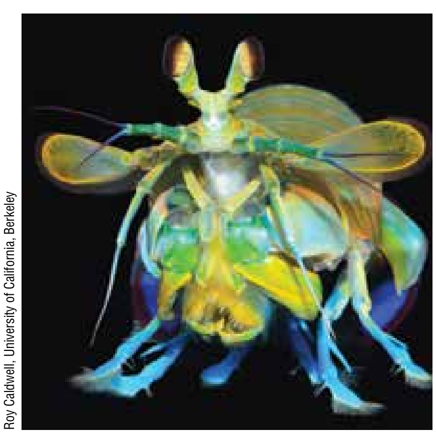
Schematic drawing of the larynx (red) and the vocal tract (blue) in a mysticete whale. Blue arrows represent airflow and green lines represent sound.

Mysticetes (baleen whales) have a thick, u-shaped, ridge of tissue (the u-fold) in their larynx that is adjacent to the laryngeal sac, a large inflatable "pouch" that is thought to be involved in both sound production and buoyancy. Baleen whales contract muscles in the throat and chest, causing air to flow between the lungs and the laryngeal sac. It has been hypothesized that alternating expansion and contraction of the lungs and sac drives air across the u-fold, causing it to vibrate and produce sound. Vibrations from the laryngeal sac may propagate through the ventral throat tissues into the surrounding water.

Fishes produce sounds, including grunts, croaks, clicks, and snaps, using different mechanisms than cetaceans or pinnipeds.

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.

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.


Roy Caldwell, University of California, Berkeley

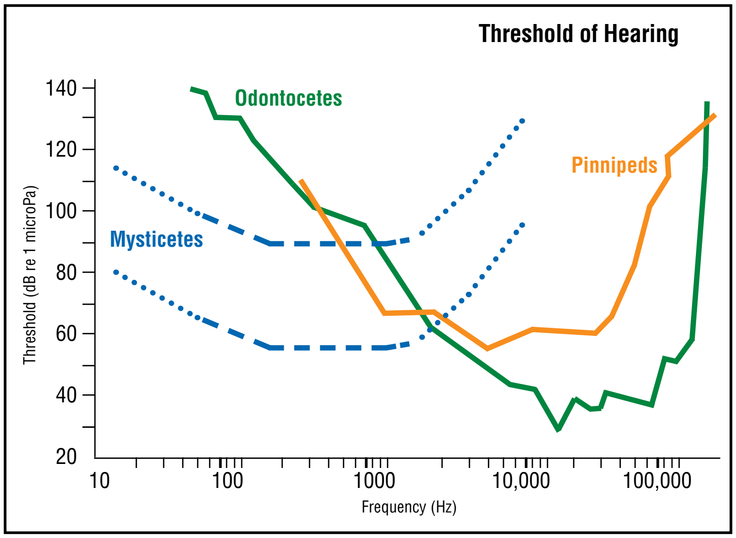
Detecting sounds also requires specialized structures. Seals, sea lions, walruses, otters, and polar bears live on land at least part of the time and have ears that are similar to terrestrial mammals. Whales, dolphins, and porpoises (cetaceans) that spend their whole lives in the water have developed a different mechanism for detecting sound. In toothed whales, 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, 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 for 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 sea turtles, nor is their ability to hear sound either in air or underwater well known, with only a few individuals having been tested. However, in some of their coastal habitats, turtles are subjected to high levels of anthropogenic noise. Auditory brainstem research on a few individuals has shown that sea turtles hear can low to mid-frequency sounds underwater but have poorer sensitivity than mammals at these frequencies and do not respond to sounds above 1000 Hz. The turtle ear has a relatively simple structure similar to that of birds, but with adaptations for underwater sound detection. The external surface of a sea turtle's ear is covered by a thick skin with a ring of scales (cutaneous plates) that are smaller than those on the rest of the head. Below this ring is a fatty layer. The thick skin and a fatty layer 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 50,000Hz). 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. Sounds may 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 a few well-documented cases, there is a relationship between the use of mid-frequency sonar and the stranding of cetaceans, particularly 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 provide "control" or "baseline" data and serve as 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 the natural variation in their 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 noise interferes with an animal's ability to perceive (detect, interpret, and/or discriminate) a sound. The degree of masking is influenced by the level, frequency band, and duration of the noise in comparison to the sound of interest. The potential impacts that masking may have on individual survival or the energetic costs of changing behavior to reduce masking are poorly understood. However,

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because of the widespread nature of anthropogenic activities, masking may be one of the most extensive and significant effects on the acoustic communication of marine animals.

Exposure to loud sounds can cause hearing impairment or loss. Hearing loss depends the hearing sensitivity of the animal in comparison to 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 less intense noise over long periods of time, as in a noisy work environment. Hearing impairment 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 coincided closely with military activities using sonar. How the sonars might have caused the strandings is still a mystery.

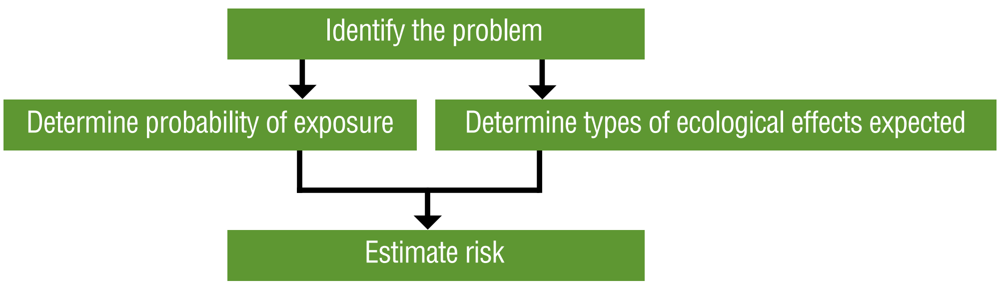
There is consensus that military sonar exercises may have contributed to mass strandings of beaked whales. However, it is still not clear if the sound of the sonar or other aspects of the military exercises, such as multiple ship maneuvers, may have resulted in the strandings. Mass strandings of beaked whales are rare, with only 136 mass stranding events reported from 1874 to 2004. Of these, two of the stranding events were reported to have occurred near the timing and location of sonar use. Ten other mass strandings coincided in space and time with naval activity that may have included military sonar. As of 2014, there are five additional documented events of beaked whale stranding in association with military sonar exercises. All of these 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) they occurred in areas where beaked whale mass strandings had previously been reported; and (3) all 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 five well-documented cases, there is sufficient information about the military exercises and the times and locations of the strandings to determine that multi-ship exercises with sonar contributed to the strandings. These events occurred in Greece (1996), Bahamas (2000), Madeira, Portugal (May 2000), and the Canary Islands (2002 and 2004). The necropsies that were performed found similar injuries, but none of the animals were found to have acoustic trauma, i.e. trauma caused by sound.

The mechanism by which the sonars or ship activity might have caused the strandings is still a mystery. Much more scientific research is needed to understand why a relationship in time and location exists between some beaked whale mass strandings and the use of multiple, mid-frequency sonars and/or ship exercises in critical areas.

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 using specific sounds in areas where marine animals are concentrated. 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 anthropogenic 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

The scientific method is a systematic set of principles and procedures for generating and representing knowledge as accurately as possible. Scientists use the scientific method as an orderly process to ask questions about phenomena and test the answers. Observations lead to a question. Possible answers to this question are refined into one or more testable hypotheses. There are many ways to test each hypothesis such as experiments, mathematical analysis, and modeling. The results are analyzed to reach a conclusion that supports or rejects the hypothesis. Hypotheses must be rigorously and repeatedly tested before they are 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 observable world. Examples of well-documented and widely accepted theories include plate tectonics theory and the theory of evolution. Scientific research is self-correcting. The publication process is one method used to detect errors and problems. Appearing in print, even in a prestigious journal, does not guarantee that the results are correct, but only that reviewers of the manuscript could find nothing wrong with the results or conclusions at that time. The scientific community considers the published paper within the sum total of what else is known in the field, adopting or rejecting the paper on that basis. Sometimes a paper is originally accepted, only to be later rejected as new evidence emerges.

John Jansen, NOAAs Alaska Fisheries Science Center

Internet Resources

The *Discovery of Sound in the Sea* website (dosits.org) is one of the most comprehensive Internet resources on underwater sound. In addition to in-depth science content, there are galleries and 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. Each audio gallery entry includes a description and image along with video for selected gallery entries.

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 **Career Gallery** provides descriptions and links to additional information about careers with links to marine acoustics.

The **Decision Makers** section is designed to highlight material on the DOSITS website that is most useful for decison makers.

The **Resources** section contains material for educators, students, and the media. These resources include education activities, tutorials, PowerPoint presentations, backgrounders, and fact sheets.

Jill Schoenherr

Print Resources

This booklet and an associated tri-fold brochure are available on the DOSITS website as PDF documents in multiple languages.

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