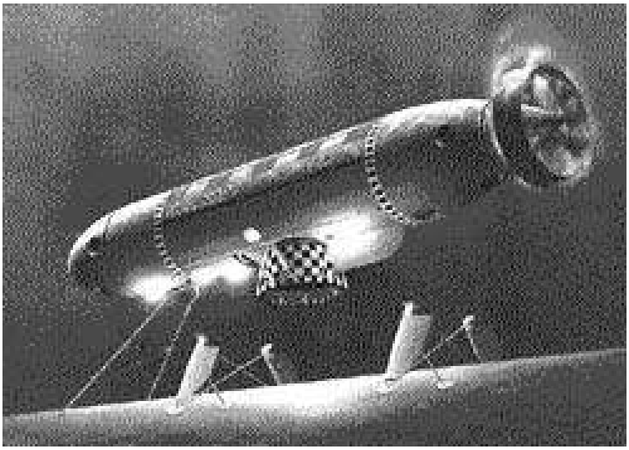
# Acoustic Surveillance

# 4

# Sonar



## 1. Introduction

Most people in western culture have heard the pinging sound of a sonar system in movies depicting submarines. This audible reference symbolizes the myriad sound surveillance technologies used to probe for vessels or structures under water, some of which are within human hearing ranges and some of which are not.

Chapter 2 on audio surveillance describes information that is gathered through sound technologies within human hearing ranges, such as phone taps, listening devices, tape recorders, and amplifiers. Chapter 3 focuses on infrasound and ultrasound, frequencies below and above human hearing ranges. This chapter focuses primarily on acoustic-sensing and sonar devices that are designed for underwater detection, ranging, and imaging applications.

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The DSRV Deep-Submergence Rescue Vehicle is designed for rescue operations on disabled, submerged submarines. It can dive up to approximately 1500 meters, conduct a sonar search, and attach itself to the sub's hatch to transfer personnel to another location. [U.S. Navy photo, released.]

Acoustic devices have several advantages as surveillance tools. It is easier to generate sound vibrations than it is to generate X-rays, for example, making it a less expensive technology in some respects. X-rays can cause damage if aimed at biological tissues, whereas sound waves, as they are typically used in surveillance devices, are not harmful (there are a few high-intensity experimental sound devices that can be harmful, but these are in the minority). In addition to being relatively safe, sound waves are versatile. They can be used to detect objects, to measure distance, and to create a 'picture' of objects within other objects or structures by bouncing the waves off objects and using the returned signal. Sound is used in applications as diverse as locating submarines, sending messages, testing the structural integrity of buildings, and imaging a growing fetus inside a womb. The ability to look through murky environments or 'inside' certain opaque objects is a very useful capability of acoustics.

## 1.a. Basic Concepts and Terminology

Sonar is currently used as an acronym for *so*und *na*vigation and *r*anging. The term has been ascribed various acronymic origins, but most historians agree it was coined around the time of World War II, when detection of submarines and other underwater craft and obstacles was an important concern. It replaced the World War I code-word ASDIC. Sonar encompasses a variety of applications that detect, locate, and map submerged objects and terrain. Sonar technologies share many concepts and basic terms with radar technologies. In practical applications, radar tends to be used in nonaqueous environments whereas sonar tends to be used in *aqueous* (liquid) environments, due to the fast-moving properties of sound in water.

When sound signals are emitted, they create pressure waves that move away from the source (gradually diminishing through attenuation). In the case of sonar, the emitted sound pulse is called a *ping*. If there are obstructions encountered as the ping travels outward, the waves are reflected off the obstructions in various directions; some may return to the transmitting area or another area to be picked up by a receiver (in most cases, the transmitter and receiver are near one another or housed in the same unit). As in radar, the intended deflecting structure is called the *target* and any irrelevant signals from other objects or the background are termed *clutter*. Interference from the technology itself, especially at threshold levels, is called *noise*. The signal that returns from the target is called the *echo* although it is more accurately termed a *reverberation*.* The traditional term *echo* is used in this text to refer to the reflected signal. The degree to which a target shows up in a sonar scan and its 'visibility' characteristics comprise the sonar *signature*.

The sending device in radio systems is typically called a transmitter, whereas in sonar it is more often called a *projector*. In sonar, the common basic receiving device is a *hydrophone*, since most sonar devices are used underwater. The device that converts sound waves to electrical impulses and vice-versa is more specifically called a *transducer*. The transducer, along with any mechanisms designed to amplify or focus the signal, comprises the projector. If more than one transducer is in the vicinity of a sonar transmission one system may pick up the signal emitted by another, resulting in a false signal called *crosstalk*. If more than one transducer signal is being intentionally generated, as in a multibeam scanning system, timing is introduced to avoid false detections by the receiver.

A sonar image created through image processing, usually from scanning or multibeam arrays, is called a *sonograph* or *sonogram*. This image resembles the negative from a black and white photograph, but is usually computer-processed to inverse the image and to add

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*An echo is a repetition of a sound due to reflection, whereas a reverberation is the resulting effect of an impact which may result in a reflection.

'false' color to aid in interpretation.

Part of the technology and interpretation of sounding echoes involves separating the target from the clutter. If the object that is being probed is very smooth and there are few nearby objects, signal scattering is minimized. If the object is very convoluted or rough, the signals will scatter in many directions and only a small number may return to the receiving unit. If the object absorbs the sound waves, few may return to the source. The density and composition of the object affects the degree to which the sound waves penetrate the object and the amount and intensity of the returning signal. These characteristics can be exploited to create devices and vessels with low sonar signatures. Sonar can also be used as a passive remote-sensing technology in that sound waves emanating from some source outside the receiver can sometimes be sensed without initially sending out a signal. For example, the sound of a boat propeller may reach a passive sonar receiver.

In practical use, sonar is very similar to radar in that signals are typically sent out with the intention of interpreting the pattern of returning signals. Sound surveillance differs from radar, however, in that sound is a transmission or *disturbance* through a medium (such as air or water), whereas radar, like light, does not require a transmission medium and can travel great distances through the empty regions of space. The essential characteristics of sound as they compare and contrast with electromagnetic sensing technologies are described in more detail in this and other chapters.

## Typical Frequencies

Most sonar equipment has been designed to take advantage of certain sound 'windows' that are known to have desirable properties and to give good results. Sonar does not inherently have to use frequencies that are outside of human hearing, but most commercial sonar technologies use ultrasound, frequencies above the human hearing range. These sounds can readily be heard by dolphins and many types of whales. Most commercial depth-sounding devices work at one specific frequency or two frequencies, as in dual systems. There are a few 'tunable' systems that allow a frequency to be selected from a wider range of options.

There is quite a bit of variation in the frequencies that are used from product to product, but for reference, some common frequencies are included in the following chart.

| Frequency | Common Applications |
|---|---|
| 2 to 8 kHz | passive and active hull-mounted DSP sonar |
| *20 kHz* | *for reference, the upper range of human hearing* |
| 27 kHz | some higher-speed towed sonars (e.g., 20 knots) |
| 50 or 192 kHz | commercial fishfinders |
| dual 24 kHz & 200 kHz | depth sounding (bathymetry) |
| dual 33 kHz & 210 kHz | depth sounding |
| 455 kHz | high-end, low-speed, high-res. bathymetry |
| variable, 3.5 kHz to 50 kHz | high-end, specialized applications |

Higher and lower frequencies have different properties when used in sounding devices:

**higher frequencies** - generally used in shallower depths; narrower beam angle (sometimes called the *cone*). Tend to have a higher target definition, to be less susceptible to noise, and more susceptible to absorption and attenuation.

**lower frequencies** - generally used for greater depths and ranges, as they are not absorbed quite as readily; wider beam angle due to diffraction, and higher susceptibility to noise. The higher beam angle necessitates a wider aperture.

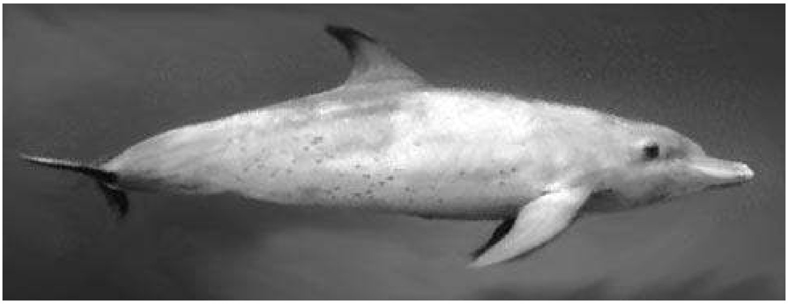
## 1.b. Signal and Background Interaction

Sound waves above and below human hearing that are synthetically generated must compete to some extent with natural sounds that are generated and perceived by other species or which result from natural activities. Thus, sound technologies fall between radar and infrared in terms of the difficulty of interpreting the signals. Since radar frequencies are mostly synthetic, there is very little background clutter, making radar targets relatively easy to detect and interpret. Infrared, on the other hand, is emitted by almost everything in our world, and it is technologically challenging to separate the information we desire from irrelevant background information. Sound technologies fall between these two; aquatic environments have a moderate amount of natural background clutter, but not as much as is found in most infrared-sensing technologies. Like radar, sonar is often used to detect objects and to determine the location of those objects. All three can be used as imaging technologies, to map terrain and objects in the surrounding environment. Unlike radar and infrared, which are primarily used above water and in space, sonar is primarily used below water and cannot be used in the 'empty' reaches of space that are insufficiently dense to propagate sound.

## 1.c. Biological Sonar Systems

*Sound travels faster through water than through air so it is not surprising that many sea creatures have senses that are very sensitive to sound vibrations and some even use sound as a means of communication.*

Human senses are optimized to understand and navigate our world mainly through our eyes and ears. Light doesn't penetrate water as easily as air and as we move into deeper waters, it becomes difficult or impossible to see. Water can also suspend many more particles than air. Although rain and dust can obscure vision in air, they are rarely as thick as kelp or plankton or sandy underwater sediments. For these reasons, even though many sea creatures have good visual senses, there are many that have even more highly developed sound-sensing organs to aid in their survival.



Dolphins are equipped with sophisticated biological sonar detection, ranging, and communications systems that have served as models for many different aspects of communications and surveillance research. They have a sonar sensor called a 'melon' located inside the front of their heads which allows them to seek prey and sense objects inside or behind some other types of objects, somewhat like our concept of 'X-ray vision' but using sound waves instead of X-rays. Dolphins also use sonar to communicate with one another while traveling together. [Classic Concepts image copyright 1996, used with permission.]

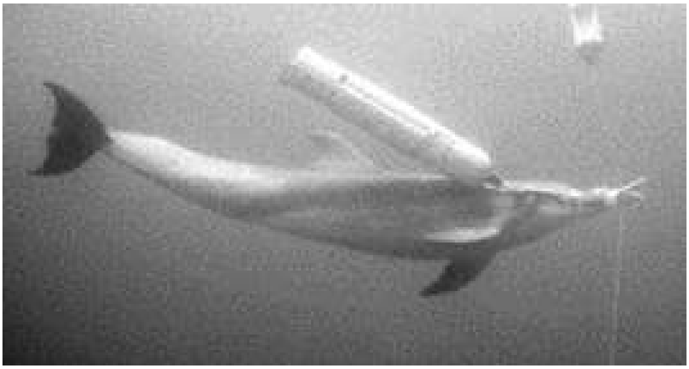
Dolphins are sociable, air-breathing mammals that live in the sea. They are highly intelligent, have a tight family structure, and can live for about thirty years. Like humans they bear only about one child every two years. This low birth rate means they can't replenish their numbers as readily as fish (which sometimes have hundreds or thousands of offspring) and are vulnerable to environmental changes and depletion of their numbers.

The auditory cortex of a dolphin's brain is highly developed and its auditory nerves have more fibers than human auditory nerves. The dolphin hearing range far exceeds that of humans. We can hear sounds ranging up to about 20,000 Hz, whereas dolphins can hear to over 100,000 Hz (perhaps as high as 150,000 Hz). Humans intercept most sounds through their external ears and vibrations in the skull. Dolphins, because they live in the water, have evolved biologically to receive sounds more readily through their jaws and through a separate bone called the *auditory bulla*.

Dolphins have good eyesight and even better 'soundsight,' a type of biological sonar imaging that humans don't have.

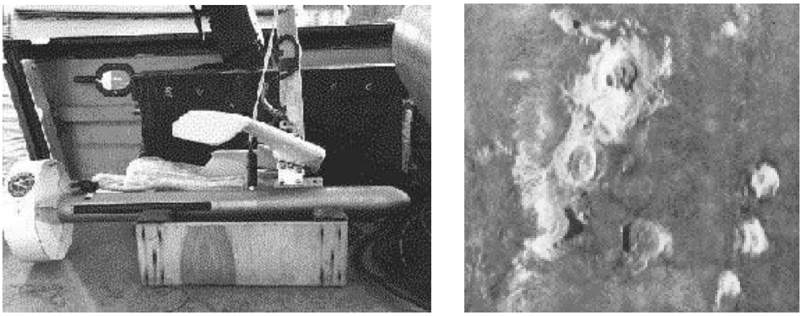
Dolphins emit a wide variety of clicks and chirps in order to intercommunicate and to determine their position and relationship to one another and other structures. They have an organ in their foreheads called a *melon* which focuses the outgoing sound pulses and a bony lower jaw that vibrates when it receives the returning sound waves, transmitting them to the inner ear. A dolphin's soundsight is so sophisticated a dolphin can sometimes identify an object *inside* another object and can be trained to match that object with a drawing with the same shape, thus communicating to us what it is able to see.

Some of the sounds emitted by dolphins can be heard by humans, but many are outside human hearing ranges and must be detected with instruments. This biological *echolocation* system is similar to synthetic radar and sonar in that outgoing clicks are timed with incoming clicks so that the dolphin can interpret the returning signal to form a sensory picture of its environment. Since dolphins are highly social animals, even more than humans, they have further developed a kind of 'mass communication' system in which they visually and aurally share information while swimming in pods (family units) or schools. This shared sensory environment helps them to navigate and hunt for food and may in part explain why they become disoriented and confused when forced into close quarters within circular fishing nets.



Dolphin are trained in the U.S. Navy Marine Mammal Program to assist in mine detection and marking. Dolphins have been taught to attach neutralization charges to the mooring cables of marine mines. Dolphins and sea lions have also been used to assist divers in carrying out search and salvage tasks and can serve as underwater 'watch dogs' to provide warnings. [U.S. Navy photo, released].

Dolphin sonar is of interest to researchers because of its sophistication and its practical applications. Dolphins themselves have been trained to assist in mine detection, diver assistance, and other tasks. Multibeam sonar systems that send out a simultaneous swath of pulses are somewhat similar to a group of dolphins sending out simultaneous pulses. Dolphins tend to group themselves in wide rather than long formations, each individual getting a part of a composite picture which is then communicated through sight and sound among members of the group somewhat in the same way that sonar imaging with several beams sent out in a swath allows us to create a composite picture of the underwater environment that we can then display or print. Multibeam sound-scanning or fast-moving-beam scanning can be digitally processed into a composite picture on high-resolution systems to create images that are very similar to normal photographs.

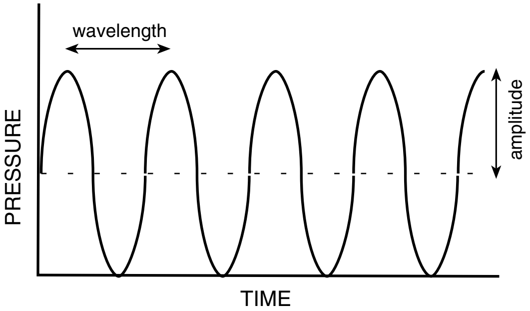


Left: A sidescanning sonar 'fish' in which the 'fins' are used to stabilize the device. The sonar transducers are located in the long black rectangle along the side of the body. The device is used to study the morphology of the sea floor. Right: A sidescanning sonar image of the sea floor near San Francisco showing the Taney Seamounts. These structures were discovered during the "EEZ Scan Project." [U.S. Geological Survey news photos, released.]

## 1.d. Components of Sound

There are three important components to a sound wave which help provide a better understanding of surveillance-related acoustics. It is more difficult to describe the propagation of waves in 3D space, since they interact with various media, and with each other in complex patterns, but the basic two-dimensional diagram can illustrate the essential characteristics.

Two-Dimensional Symbolic Representation of a Sound Wave

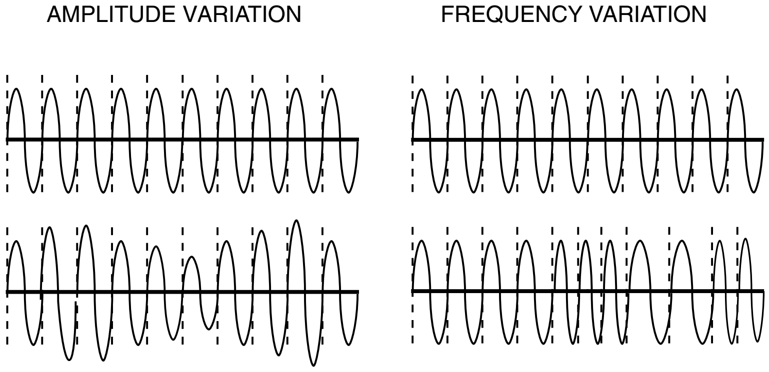


Acoustic waves are typically described in terms of amplitude, wavelength, and frequency. They are diagrammatically represented as periodic sine waves, with the peak indicating the highest pressure and the trough indicating the lowest pressure of the wave. Acoustic waves are longitudinal. (To picture this, imagine pulling on a spring that's attached at one end and watching the 'pulse' travel straight through the spring without bouncing up and down.)

**amplitude** Amplitude is the maximum distance that particles in a medium are displaced as the wavelike disturbance moves through the medium. People sometimes use the terms *magnitude* or *height* to describe wave amplitude. Amplitude symbolizes the phenomenon we perceive as loudness or softness. A higher amplitude tends to sound louder. Above certain amplitudes, damage can occur to biological structures; in other words, they can damage hearing. Amplitude is illustrated as the vertical height of the wave.

**wavelength** Waves represent a repeating phenomenon, sometimes called *cyclic,* or *periodic*, in which waves with similar characteristics succeed one another. Repetition of the wave is the *vibration* or *oscillation.* The distance between corresponding points on two successive wave disturbances, or *compressions*, is called a *wavelength*. Symbolically, a wavelength is usually illustrated as the horizontal 'width' of a wave.

**frequency** The rate of repetition or *periodicity* of a succession of waves is the frequency. We usually describe sound wave frequency in terms of repetitions or *cycles* per second. Older texts use the term cycles to describe the frequency of sound and radio waves. Newer texts, in honor of Heinrich Hertz, use the term *Hertz* or its abbreviation *Hz.* Thus, a sound of 10,000 cycles per second would be expressed as 10,000 Hz or 10 kHz. On a graph, narrower wavelengths are used to symbolize higher frequencies. The *pitch* of the sound increases as the frequency increases and decreases as the frequency decreases. Not all humans are able to perceive frequency changes in sound. Tone-deafness is a phrase used to describe the inability to recognize or remember sound pitch differences. Many humans are tone-deaf to lesser or greater degrees. *Perfect pitch* is a term used to describe individuals who can recognize a specific pitch without a reference pitch; in other words, they know that a specific tone might correspond to 'A' which has been assigned to 440 Hz, for example. Good *relative pitch* is when individuals can 'hold a tune' once they have a reference note to get them started in the right key. In most symbolic diagrams, frequency is illustrated by the number of wavelengths repeated over a given unit of time.



AMPLITUDE VARIATION

FREQUENCY VARIATION

Reference waves (top) are shown with varying waves (bottom). Bottom Left: Sound waves that are varying in amplitude (loudness) are shown with varying peaks and troughs. Bottom Right: Sound waves that are varying in frequency (pitch) are shown with narrower and wider repetitions. Deliberate manipulation of the frequency or amplitude of a sound or electromagnetic wave is called *modulation*. Modulation is an important technique used in many types of communications technologies. [Classic Concepts copyright 1997, used with permission.]

### 1.e. Sound Characteristics

The speed of sound is related to the density of the material through which the sound waves are moving. Since water is denser than air, sound travels more quickly through water. The speed of sound in air at room temperature at sea level is about 344 meters/second. The speed of sound in seawater is more than four times faster, about 1500 meters/second (depending on temperature, depth, and salinity). Sound speed in a direction is termed *sound velocity*.

When sound moves from one medium to another, as from air to water, the sound is *refracted*; that is, it is bent. Since this is difficult to predict or control under conditions of moving waves, aircraft carrying sonar devices must get close to the surface of the water in order to put the sonar in the water. Surface vessels and submarines are more suitable for deploying sonar, but aircraft are sometimes used for tactical purposes or to drop off self-contained sonobuoys with data-storage capabilities or radio transmitters.

Sound devices work well underwater because sound travels quickly through water. Basic sound-based vessel- and mine-detection systems work well in open waters where physical protuberances (turbulence, coastlines, reefs, wrecks, etc.) are less likely to attenuate or deflect the sound waves. Imaging systems, on the other hand, work well in clear, shallower waters where the reefs, shelves, coastlines, and other prominent features can be readily mapped.

Not all physical structures outside of the target will hinder a sound signal. Just as the ionosphere can be used to bounce radio signals in a desired direction, the ocean bottom or other physical structures or temperature regions can be used to bounce an underwater sound signal in a desired direction. Surrounding terrain can sometimes be used to channel or funnel sound communication.

Just as Earth's atmosphere has a variety of layers which have different conductive and refractive properties, marine environments have layers that are influenced by sunlight, pressure associated with depth, sediment, plant life (kelp, plankton, etc.), and marine animals (fish, mammals, corals, etc.).

## 2. Types and Variations

Sonar sensing is based on sending out a 'beam' and analyzing a returning signal (reverberation or *echo*). A single beam is limited in application and is usually used for the more basic applications, including depth-sounding and pinging. Sonar arrays are powerful 'clusters' or groupings of sonar beams that can be sent in different directions to form a 'picture' of the surrounding environment. These are useful for identifying specific types of objects and mapping terrain.

Sonar arrays are more complex than single-beam sonars and thus require more complex electronics to handle their timing and processing. Computers are often used in conjunction with sonar arrays, particularly the high-resolution arrays used for mapping. A *beamformer* is a type of spatial filter that aids in organizing and controlling the beams emitted by sonar arrays. In other words, it helps direct and focus the beam. Beamforming allows mathematical analysis of the results of multiple elements in order to process a narrow response in a particular direction. This aids in detecting the direction from which a sound has come. *Beamwidth* is expressed as the decibel-range of the beam, e.g., 3 decibels or 3 dB.

A *stave* is a type of electromagnetic element that is used to produce transducers. Staves can be used to create a curved array of hydrophone sensors, for example, so that the system doesn't have to rotate to sense in multiple directions.

Sonar systems tend to be either mounted on the operating vessel, as on a submarine, surveillance ship, or helicopter, towed behind the operating vessel, or dropped off and *scuttled* or picked up later.*

The basic types of sonar schemes include

- **single-beam** - the traditional scheme of sending out a single focused beam, the predominant method in the early decades,
- **sweeping** - the beam is generated with spaced transducers, usually sweeping orthogonally to the direction of travel, a system that is utilized in scanning sonars, and
- **multibeam** - continuous beams are spread out from the source, usually in a fan-shape or swath, a more recent development as it involves more sophisticated timing and processing.

*Passive* and *active* sonar technologies have different strengths and weaknesses. Active sonar has a higher chance of detection and must balance the electronics and reverberating limits needed to send and receive signals from the same location. Passive sonar has a low probability of detection and doesn't have to perform the same balancing act to receive strong signals but it can't initiate a transmission.

*Bistatic* sonar uses a combination of active and passive technology. The transmission emanates from one location and is received at another. This takes advantage of the best characteristics of the different technologies and sometimes also provides tactical advantages.

*Variable-depth* sonar (VDS) is a means of overcoming some of the problems with trying to send signals at an angle through water that is 'layered;' that is, it has different temperature and particulate characteristics (sediment, salt, etc.) that might bend or *refract* the sound beam. Submarines have been known to 'hide' at greater depths to take advantage of the layered characteristics of water to mask their presence. By using variable-depth sonar systems, it is possible to take a series of soundings at different depths and evaluate the information to correct for beam refraction. Fixed-depth sonars are those which are attached to a hull, drilling rig, or other single-depth platform. Variable-depth sonars are dropped or towed and may be attached by electrical or fiber-optic cables.

*Doppler* systems are designed to exploit or compensate for the physics associated with movement in relation to the sound pressure wave. A Doppler sonar can detect and sometimes measure the change in frequencies of the sonar echo, based on the magnitude and direction of the change relative to the motion of the sensor or transmitter. Doppler shift can be used to aid in target classification of a moving target. (For a brief explanation of Doppler physics, see the Radar Surveillance chapter.)

*Sonobuoys* are self-contained sonar systems that can be dropped off and picked up later to analyze the collected data, or they can be monitored regularly through radio signals that are transmitted to a ship, sub, satellite, or coastal ground station. When sonobuoys are dropped in clusters, they can also be used to compute directional information.

*Expendable* devices are those which decay, sink, or self-destruct when their useful life is over or, in covert operations, if they are in danger of being detected. These devices are usually self-contained and can store or transmit information until they are picked up or until they become nonfunctional. Sometimes the information is relayed through satellite communications systems. Sonobuoys are sometimes designed to be expendable.

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*The term 'scuttle' comes from the name for a hole in a ship that is covered with a lid, which can be opened to admit a sailor or for tossing objects through. It is now also used more generically for things that are tossed overboard or punctured so they will sink.

In commercial implementations, common ways to categorize sonar include

- **scanning sonar** (SS) - This is a type of stationary or mounted sonar which either sends simple signals in a general direction, usually to detect incoming objects (e.g., on a dock), or which rotates slowly over some or all of a 360° arc to scan the surrounding region. Scanning sonars are used for navigation and monitoring applications. More complex data computations are required if the system is fixed on a moving vessel.
- **sidescanning sonar** (SSS) - This is the most common type of high-frequency sonar. SSS is used for object-detection (e.g., sunken wrecks) and marine surveying and mapping. The *along-track* beam-width is narrow and the *vertical* beamwidth is wide. Sidescanning sonar is towed. The beam usually scans to both sides of the vessel resulting in a display or printout in which protuberances are recorded as an image, though some may image only to one side. Objects as small as a coffee mug can be resolved with high-end systems. Commercial SSS systems typically use an operating frequency of about 100 kHz, though a few systems are multifrequency, and can be mounted on vessels or towed at speeds up to about 15 knots. Sidescanning sonars are optimized for imaging on one or both sides of the vessel equipped with the sonar (usually a surface vessel) and thus there is usually a channel in the center, called a *water column* that is not imaged (essentially a blind spot). Most SSS systems are linear and do not use focusing.
- **forward-looking sonar** (FLS) - FLS systems are useful for object and area surveillance. FLS can help detect the presence of vessels, marine life, mines, etc. A basic FLS is typically configured with pulsed or continuous scanning arrays. More complex systems with multiple beams and fast scanning rates can scan a region within a single pulse period for 1D or 2D imaging. FLS systems vary in the pulse rates at which they operate, from about 100 kHz to about 600 kHz, depending on the system. Some FLS systems are dual-axis allowing the scan to be set to side-by-side or top-to-bottom.
- **downward-looking sonar** (DLS) - DLS, also known as bathymetric sonar, is less common than SSS and FLS. It is used for depth sounding, fish finding, and marine contour mapping. Single-beam systems scan over a wide, vertical swath, similar to a sidescanning sonar, while multibeam systems are more similar to multibeam FLS systems. Frequency ranges vary from about 12 kHz to about 1 MHz. Most DLS systems are vessel-mounted though a few are used as towed systems.
- **sector-scanning sonar** (SSS) - This is similar to sidescanning sonar and can be used on a towed platform. Sector-scanning sonar can be used in both active and passive modes. Sector-scanning systems can be rotated through two axes. Operating frequencies for active systems are around 160 kHz. Passive modes have been used to detect frequencies up to over 300 kHz. The range is up to about 250 meters.

Most sonar systems are used for one-dimensional or two-dimensional imaging, but scientists are studying ways in which the angle of the swath and the frequency of the pulses can be adjusted to yield three-dimensional images through computer processing. This is particularly effective when imaging stable structures (shipwrecks, reefs), but experimental systems have had some success in imaging moving targets (schools of fish, underwater vessels).

Beam direction and synchronization are important aspects of multibeam sonar arrays. The geometry of an array, consisting of the spacing and directing of the beams, is called the *beam formation.*

*Sonar targets* are objects that are deliberately designed to show up well on sonar scans. They are installed temporarily or permanently underwater to serve as reference points, to aid in the subsequent interpretation of sonar images. They are especially useful in areas that are being monitored for environmental changes where precision may be important.

*Towed arrays* are interesting because they can be towed behind marine vessels or towed by air vehicles, usually helicopters hovering a short distance above the surface of the water. There are a variety of types of towed sonar cables and associated objects, some of which are called *towfish* due to their shape or the shape of a depressor that might be used to weigh down the end of the cable. Deadweights and hydrodynamic depressors are commonly used. The shape of a towed sonar cable is influenced by the drag of the water and a flexible cable assumes a curved *hyperbolic* shape called *catenary*.

Historically, the *dipping* sonars that could be dropped into the water by helicopters became available in the 1950s. They incorporated a specialized compass that provided bearing information to the helicopter.

*Multibeam* systems are becoming more prevalent and are gradually superseding many single-beam systems. In multibeam sonar, multiple beams are transmitted at the same time, thus covering a wider area. The returning data allow a three-dimensional contour image of the target area to be produced. Multibeam systems may incorporate motion sensors and a gyrocompass.

### Depth-Sounding

Depth-sounding is known in scientific jargon as *bathymetry*. In commercial marketing it is sometimes also called *echo sounding*. In its simplest sense, it involves sending a signal downward and measuring the time it takes to reflect off the bottom, and then calculating the distance. In real applications, many soundings are taken, as debris, sediment and other obstacles could give a false impression of the depth.

Commercial bathymetric products typically have the following specifications:

- The depths that can be sounded vary with the product, but are usually from about 100 to 1500 meters.
- The frequency ranges vary, but typically are around 24 or 200 kHz (or both, in dual systems).
- The number of beams may vary from 20 to 80 beams; some professional systems may have as many as 240 beams.
- The *swath coverage* (the angle of the beam-spread) is usually about 120° ± 30°. The adjacent beams fan out from a central point, like a peacock’s tail.
- A signal series of sound waves is sent out, the return signal recorded, and another signal series sent, with an update rate of about 10 to 40 swaths per second.
- Newer systems have serial ports and VGA or SVGA ports for interfacing with a computer system and displaying on a monitor.

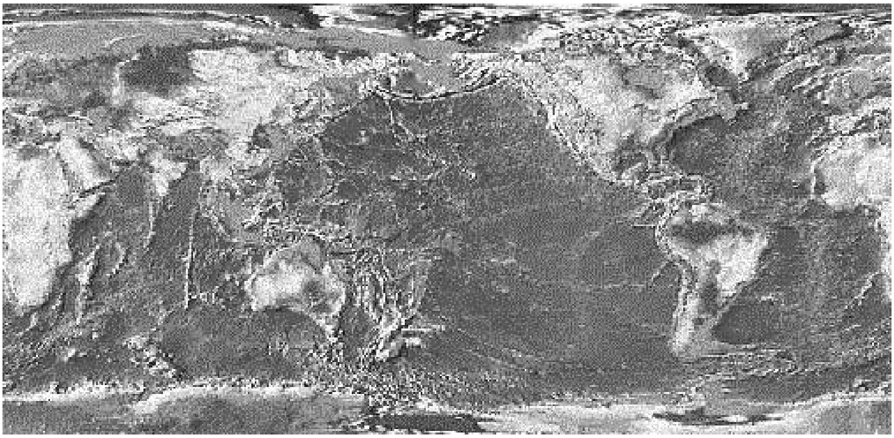
### Sonar Imaging

Imaging is the most recent of the major applications for sonar. Pictures of the seabed, marine objects, reefs, wrecks, or vegetation can be created by sending out a series of sonar signals along a series of swaths. Imaging incorporates many basic depth-sounding concepts, but typically uses a higher number of beams, more precise timing, and more complex computer processing. Imaging depths can range down to about 1500 meters.

# 3. Context

## 3.a. Applications Context

Because sound travels more readily through water than other types of energy, sonar has become an essential sensing, navigation, and imaging tool for surface and underwater vessels. Bodies of water cover almost 75% of the Earth's surface, so their importance to our survival, our transportation systems, our defense operations, and our communications should never be underestimated.



Most sonar technologies are used in lakes, rivers, and ocean environments. Since these bodies of water comprise almost 75% of the Earth's surface, underwater sensing technologies are extremely important to understanding our environment, our resources, and the security of our planet. [U.S. Geological Survey, public domain.]

The essence of most sonar applications is that the timing of sound reverberations is used to determine distance. Less often, sound is *modulated* to communicate messages. So, sonar isn't specifically an underwater technology. However, since sound travels more slowly through air than through water, there are more efficient ways to determine distance or communicate through the air and, hence, the vast majority of sonar technology is used underwater.

Water is a complex environment. It is not as homogenous as people may think. The oceans, great rivers, and large lakes are full of layers comprised of different temperatures, regions of sediment, plankton, and kelp, and other factors that greatly influence the characteristics of sound travel through water. An awareness of this complexity and the general principles of sound can aid sonar technicians, boaters, and imaging specialists in using sonar buoys, tow lines, depth sounders, and other sonar-related equipment to get the maximum performance from the technology.

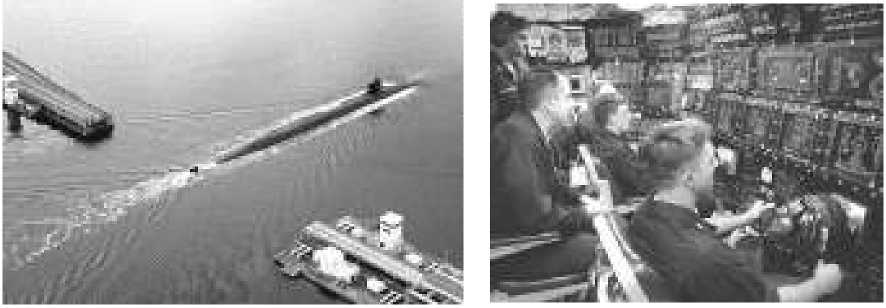
Sonar is chiefly used for the following applications:

- surface or underwater navigation,
- detection of other bodies underwater,
- object and terrain mapping,
- underwater communications, and
- robotics ranging applications (both underwater and above water).

Sonar devices are often towed along on a tether that may range from a few dozen yards to several kilometers in length. The vessel that is towing it usually moves slowly, up to about 1 knot in speed for high-end imaging applications, up to about 20 knots for basic depth-sounding. Future fast-processing or autonomous systems may be able to move faster. As pointed out by Robert Fricke in "Down to the Sea in Robots," towing at very slow speeds in open water can be tedious for the surveillants and the crew, a job that could perhaps better be handled by robots.

### Navigation

A large proportion of marine craft use sonar to determine depth and distance to objects and other vessels. These data make it possible to maneuver vessels and select regions of water where it is deep enough and free enough of dangerous obstacles to navigate safely.



Left: Sonar is essential to submarine navigation and reconnaissance. This Trident ballistic missile submarine, the USS Ohio, has tallied over 50 strategic patrols. Right: Subs are now equipped with sophisticated electronic control centers. This nuclear-powered sub, the USS Seawolf (SSN 21), was commissioned in 1997 and has command centers devoted to displays of the data from various sensing apparatus and vessel systems. [U.S. Navy 1998 and 1997 news photos by Shawn Handley and John E. Gray, released.]

### Mapping

The fact that sound is suitable for detecting distance underwater makes it a good technology for mapping applications. Three-dimensional terrain mapping at its most basic involves making a series of depth soundings and consolidating the data into a mathematical or visual picture. By sending out many of these signals at precise locations and creating a symbolic 'graph' of the results, a terrain map or map of submerged objects can be created that very much resembles an inversed grayscale photograph (which can then be further enhanced with pseudo-coloring). This type of imaging works best with stationary objects.

### Detection

Sonar is used to detect depth, debris, obstacles, reefs, fish, and whales. It is an essential tool in detecting hostile craft or foreign military vessels of unknown intentions. Passive sonar is widely used for national security operations.

Underwater vessels may also be spotted from the sky, but this is difficult if the water is murky, or the vessel is deep underwater. Since air vessels are faster and more flexible than sea vessels, they are frequently used in underwater-vessel spotting activities, but they need sonar to detect many types of vessels and the sonar devices need to be in the water.

To accomplish this, the aircraft will fly low over the water and tow or drop a sonar device that takes readings that need to be communicated to the craft. To transfer the information, the device will either send signals through a communications cable, or transmit them as wireless radio waves. The sonar device may also be left to gather and store data to be picked up later, sometimes by a different vessel or craft. If the data are stored, rather than transmitted, the device is usually picked up and interfaced to a computer to analyze the readings.

### Tactics

Deep-diving vessels will sometimes hide below the upper surface layer of the water to hide from sonar probes. Varying the angle of a sonar-detecting signal can sometimes aid in penetrating some of the layers in the water, but may also introduce refraction that confuses the signals. Thus, many soundings and more than one type of sonar may be used together to form a composite picture of the environment.

The speed of sound through water is pretty fast, but it is not instantaneous. For this reason, you can use passive sonar to find out if you are being scanned by active sonar some distance away. The signal may only provide a few seconds to react, but that small tactical advantage can sometimes mean the difference between life and death.

When a fleet is traveling in hostile waters, the individual vessels may use spring and drift tactics to vary the composite radiant noise level to make it difficult to pinpoint individual vessels or the overall size of the fleet.

### Communications

Sonar is somewhat limited as a communications technology, compared to radio, but there are circumstances where it is practical to modulate sound waves to carry content, particularly where radio frequencies can't be used or are more likely to be detected.

The range at which sonar can be used for oceanic communications varies greatly with the conditions of the weather, the terrain, and the amount of sea traffic that is generating noise (propellers, engines, hulls, etc.). *Sound channels*, areas of terrain or sediment that can funnel and bounce sound over longer distances (somewhat in the way the ionosphere can bounce radio waves) may extend sonar ranges. Ships can intercommunicate to a distance of about 10,000 meters in good conditions. Submarines may communicate over longer ranges, sometimes up to 20 kilometers.

### Robotic Ranging

Sonar is a useful way for robots to navigate, both above and below water. Since most of the sound technologies for robots are above ground (air-based) and use frequencies above the human hearing range, they are discussed more fully in the Infra/Ultrasonic Surveillance chapter.

### Sonar Displays

Because sonar technology is similar to radar in many ways, sonar displays and imaging systems share many common characteristics with radar displays and imaging systems.

A sonar *scope* provides an image of the sonar echo when the signal is apprehended by the transducer. Scopes range from simple depth-sounding displays to complex imaging displays. Some of the most common displays include

- A sonar *A-scan* display is based on a basic Cartesian Coordinate graph (somewhat like the heart-rhythm displays shown on TV medical monitors). As the beam traverses the screen, a vertical blip or pip (a raised section on the graph) indicates the presence of a 'hit' or target acquisition. Monitoring of the beam to see if the target reappears on subsequent passes of the beam helps to distinguish real targets from false signals or passing debris.

- A *plan-position indicator* (PPI) is a type of display that is familiar to radar technicians and anyone who has watched submarine movies. A PPI display has circular tick marks as reference points and a cross-hair dividing the screen into quadrants. As the beam sweeps through a 360° arc, it highlights bright blips when targets are sensed.
- A sonar *mapping or imaging system* usually provides a grayscale or false color display of the composite information on a computer monitor. The information may be a picture that has been built up from a number of swaths.

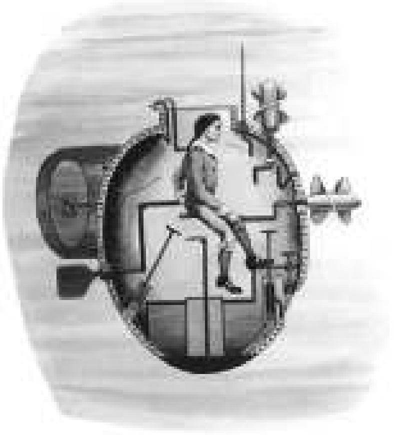
## 4. Origins and Evolution

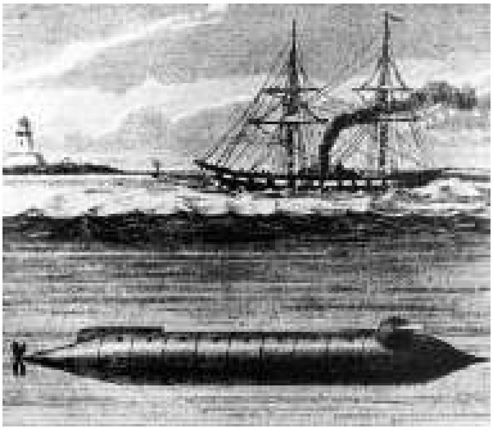
*Sonar and submarines are almost always discussed together. Sonar enables submarines and surface vessels to navigate, to detect dangerous obstacles, and to locate other vessels. More advanced sonar systems also allow underwater terrains to be mapped and imaged. The history of sonar is closely allied to the development of submarines, marine craft, unstaffed remote vehicles, and autonomous sonobuoys and vehicles.*

The concept of submarines has fascinated people for a long time. Early on, humans devised a way to stay underwater for longer periods by breathing through reeds or pipes. This simple concept led to the development of snorkels and submarines.

In 1578, William Bourne created plans for an enclosed wooden boat that could be rowed beneath the surface of the water. The whole vessel was bound in leather to make it waterproof. There is no evidence that Bourne ever built the boat, however.

John Napier, in 1596, mentioned the use of underwater sailing craft and his intention to direct their construction and use. A few years later, in 1605, a boat similar to the one designed by Bourne was actually built and tested, but it apparently ran into technical difficulties when it stuck to the river bottom.





Left: The “Turtle,” the first American submarine. It was designed by David Bushnell and was built in 1776, during the American Revolution. Powered by a hand propeller, it could stay mostly submerged, with only about six inches showing above the water. This drawing by Lt. Francis Barber in 1875 has a few technical flaws, but gives an idea of how the system looked and worked. Right: The “Alligator,” the first submarine purchased by the U.S. Navy for military use. [U.S. Navy Submarine Centennial Exhibit, drawings public domain by date.]

Cornelius van Drebbell was a Dutch physician and inventor of optical devices who was living in England when he created a greased leather submarine, in 1620. Apparently it was able to descend to depths of 12 to 15 feet. Bishop Wilkins mentions Drebbell's vessel in an English publication of 1648, noting that it was "already experimented here in England by Cornelius Dreble." Wilkins specifically mentions the surveillance and warfare applications of such a vessel and the fact that they could enable one's enemies to be "undermined in the water and blown up." David Bushnell, a graduate of Yale, built a historic submarine torpedo boat in 1776. It was hoped this new tool of warfare would provide a way to monitor and destroy British warships in the New York Harbor.

There were a lot of limitations and design problems associated with the early submarines, but once the technology began to mature, it became clear that sonar could greatly help in navigating the underwater vessels.

## Understanding Sound

*Developing practical sonar systems necessitated an understanding of the physics of sound. Although Leonardo da Vinci made some important early observations, most of our fundamental understanding of acoustics was developed between 1600 and the mid-1800s.*

It's difficult to find a technological concept that wasn't first anticipated by Greek philosophers 2,000 years ago, or drawn during the Renaissance by Leonardo da Vinci (1452-1519), and our understanding of acoustics and sound devices is no exception. The Greek philosophers evidently gave some thought to the properties of sound. Statements by Aristotle (384-322 B.C.) indicate that he may have grasped the concept of pressure or wave characteristics of sound in air.

Da Vinci's prolific imagination and gift for invention extend to many devices that could not even be built with the technology available in his time. This didn't stop him from experimenting, however, with the materials at hand or from drawing the mechanisms that couldn't be built. So perhaps we shouldn't be surprised that Leonardo was again centuries ahead of his time when he had an idea for lowering simple air tubes into water, an invention that is not unlike the early hydrophones developed for maritime sensing 400 years later. Da Vinci further contributed the important observation that sound travels in *waves*.

Around 1600, Galileo (1564-1642) began making some systematic studies of sound and developed fundamental theories that would later aid in the development of devices to exploit the properties of sound. Galileo noted that the *pitch* of sound was related to the physical properties of the objects used to generate the sound.

The concept that sound was an inherent property of physical substances was further demonstrated in 1660 by Robert Boyle (1627-1691) when he removed air from a bell jar and showed that the sound diminished in relation to the removal of air from the jar. This experiment led to the conclusion and experimental confirmation that *sound required a medium for transmission* and thus could not exist in a vacuum (but not before several scientists proposed contradictory and incorrect theories that sound was emitted through particles).

Marin Mersenne (1588-1648) studied the harmonic qualities of sound and described tonal frequencies in "Harmonic universelle" in 1636. In 1640, he measured the speed of sound to be about 1,100 feet per second. These contributions have earned him the name of Father of Acoustics.

Isaac Newton (1647-1727) contributed essential mathematical understanding to the emerging theories about sound. He studied the action of sound through fluids, noted that the speed of sound in a medium was related to its physical properties of density and compressibility, and used those observations to mathematically calculate the speed of sound through the air. Newton published his pressure theories of sound in *"Principia"* in 1686.

By the late 1700s, scientists were conducting experiments to try to determine the properties of sound in water. It was known that sound traveled faster through water than through air, but human curiosity is rarely satisfied with generalities and inventors eagerly sought to measure the speeds and characteristics of these sound waves. In 1822, Daniel Colloden lowered an underwater bell into Lake Geneva, Switzerland, in order to calculate the speed of sound. A bell on one vessel was rung underneath the water, while a vibrating sensor on another vessel some distance away indicated when the sound waves reached the other vessel. The time interval was then used to calculate the speed, with an accuracy that was quite good, considering the simplicity of the methods.

The original experiments in sound were mainly physical experiments with boats and reeds, gongs and horns, but now that mathematics was being more fully developed, the properties of sound could be explored more precisely through theoretical calculations and then tested through physical experiments. The 1800s heralded an era when sound was explored as much with a pencil and paper as it was with horns and funnels.

As the symbology for mathematics evolved, so did the mathematical representation of sound. Sound could be expressed on paper with repeating sine waves in a two-dimensional coordinate system. Pressure and time could be assigned to the axes of a graph. The repetition of the sine waves could represent the periodicity of the sound waves. The stage was set for more advanced manipulations by mathematicians such as Johann Karl Friedrich Gauss (1777-1855) and Jean Baptiste Joseph Fourier (1768-1830).

In the 1820s, Fourier applied the superposition of sines and cosines to time-varying functions and showed that they could then be used to represent other functions. Fourier studied heat conduction through materials (a concept somewhat related to sound conduction) and his analytical techniques later led to many new techniques of mathematical modeling. Fourier's theories, when applied to sound, indicated that the analysis of the harmonic qualities of sound could provide a fuller understanding of the phenomenon.

In 1826, French mathematician, Jacques Sturm, provided more accurate measurements of the speed of sound in water than were calculated by Daniel Colloden. The experiments of Sturm and other scientists confirmed that density and elasticity were important attributes that contributed to the speed of sound through various materials.

### The Beginnings of Sonar

In 1880, scientists Pierre and Jacques Curie discovered the piezoelectric effect. Piezoelectricity is a form of electromagnetic polarity arising from pressure, particularly in crystalline substances. If this effect could be exploited, it might lead to the invention of new devices. Thirty-six years later it would contribute to the development of acoustical detection devices.

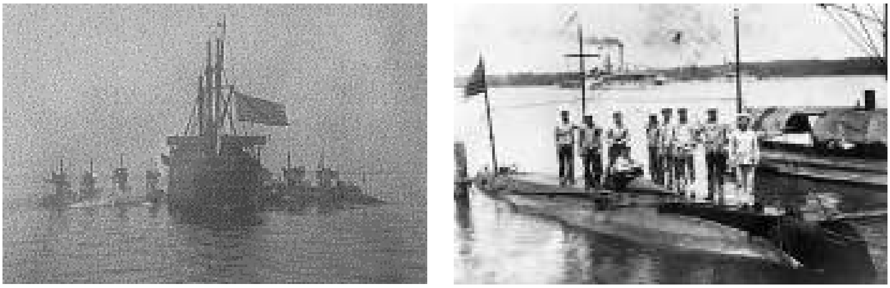
In 1900, the U.S. Submarine Force was established with the purchase of a 'modern' sub, the Holland VI, commissioned in October as the USS Holland (SS-1). The role of the early subs was coastal and harbor defense. One of the more important visual surveillance devices, the *periscope*, began to be used on subs at this time. A periscope was basically a mounted adaptation of the telescope that became specialized for covert, submersible situations.

The sinking of the Titanic in 1912 had a significant influence on the development and evolution of surveillance technologies. Not only were the rules for maritime telegraphy changed to prevent future accidents, but water microphones, called *hydrophones* were developed for detecting icebergs and other obstacles. Thus early sonar systems emerged at about the same time and for the same reasons as the original radar devices, to prevent collisions at sea. But whereas radar was initially designed to avoid collisions with other ships and large structures along the large rivers and coasts of western Europe, sound-ranging was originally designed to help prevent collisions with dangerous icebergs and to navigate in regions where there were lightships.

A lightship is somewhat like a lighthouse. It is a beacon to indicate position and the possible presence of dangerous obstructions. By equipping a lightship with a foghorn or other sounding device on the deck and a bell below the waterline which could be sounded at the same time, information could be conveyed to nearby ships equipped with hydrophones and sailors to interpret the acoustic information.

### Underwater Mine and Submarine Warfare

Entire wars have been won and lost at sea. For centuries, naval fleets had been an essential aspect of a country's military arsenal and explosives delivered by harpoons or barrels could be used to disable a fleet. This led to a new idea, underwater mines that would only explode when sufficiently disturbed. Mines are one of the most devilish inventions of man and, by the time World War I erupted, they were being planted underwater by ships and subs to protect coastal territory and to wreak havoc on enemy shipping lanes. Since no one appreciated being blown up by a mine hundreds of miles from land, surveillance technologies for detecting mines were avidly sought and tested. The submarines and ships that were planting them were also targets of the new technologies.



Left: Pre-World War I submarines resembled small ships more than modern subs and didn't have any of the deep-diving capabilities of later subs. Nevertheless, their low-slung, less-conspicuous design made them suitable for patrols, mine detection, and mine laying. Right: The commissioning of the USS Holland, in 1900, represented the beginning of the U.S. Submarine Force. The Spanish-American War had prompted Theodore Roosevelt to make the purchase of the Holland VI in 1898. [Library of Congress Detroit Publishing Company Collection ca. 1910, copyrights expired by date.]

In times of war, peacetime technology is adapted to serve the needs of national security. Federal funding is diverted to further its development, and improvements for war-related purposes are the natural consequences of the increased emphasis on research and development. Rudimentary hydrophones were already used for maritime safety by the time World War I broke out, but now hydrophones were seen in a different light, as not just a means for avoiding icebergs and ships, but also as a means to detect submarines, to avoid minefields, and perhaps even to chart a course through hazardous booby-trapped waters.

Thus, it may have been the outbreak of the war in 1914 that caused Constantin Chilowsky, a Russian scientist living in Switzerland, to propose the idea of using high-frequency sound for detecting submarines [Hunt, 1954.].

It became clear that scientists could be useful to the War effort and, in America, Thomas Edison was one of the pre-eminent inventors of the time. When the U.S. Navy set up the Naval Consulting Board (NCB) to advise the Secretary of the Navy in 1915, Edison was established as its director. Even before the U.S. took an aggressive position in the War, the NCB was engaged in research and development for devices that could detect submarines and other marine vessels. It soon became clear that the German *U-boat* submarines that were covertly attacking ships and laying minefields were a dangerous threat.

It was also around 1915 that Chilowsky began collaborating with Paul Langevin (1872-1946), a gifted French physicist, to develop hydrophones for detection purposes. In 1916, Langevin, a contemporary of Einstein, made a discovery that was important not just for the future development of sonar, but also for many important aspects of electronics. He found that the piezoelectric effect that was present in quartz crystals could be applied to his research on acoustics.* By 1917, Fernand Holweck (1890-1941), who later became the Director of the Curie Laboratory, was also collaborating with Langevin on his hydrophone experiments. The result of the work of these scientists was a mosaic of thin slices of quartz crystals sandwiched between two steel plates. By applying an electric current, the quartz slices could be influenced to change shape enough to cause them to resonate at a specific frequency.

The technology of anti-submarine warfare (ASW) was being debated in American literature at least as early as 1917 and that year a special Committee was set up to tackle the challenges of detecting and destroying German *U-boat* submarines, further leading to the establishment of the Naval Research Laboratory. The National Research Council contributed by arranging an international conference in June 1917, bringing together British, French, Swiss, and American experts to discuss the science and development of U-boat detection systems [Weir, 1997].

The details have been lost with time, but sometime during World War I, the British Royal Navy, which was closer to the front, established an Anti-Submarine Division to study applied acoustics and solve some of the challenges of marine warfare. Surviving references from about 1918 indicate there may have been an Allied Submarine Detection Investigation Committee in Britain by that time. For the next two decades, active hydrophones, the first modern sonar systems developed, were referred to as ASDICs.

Charles Max Mason (1877-1961), a mathematics professor, worked on submarine detection devices as a member of the NRC submarine committee during World War I. He was instrumental in the development of a naval multiple-tube, passive submarine sensor, a device that focused sound so that an operator, equipped with earphones, could use the sound levels to discern source and direction. Mason has been credited with inventing acoustical compensators.

High-frequency sound projectors had not yet been developed. The projectors used at this time tended to be tuned to the upper ranges of human hearing, around 18 kilo*cycles* ± 4 (the tradition of using kilo*hertz* had not yet been established). If more than one projector was used at the same location, it was important to make sure they weren't transmitting at the same frequency or the operator would get a blast on his listening frequency that was many times louder than a normal echo.

Early hydrophones were better suited to depth-sounding than to submarine hunting, but

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*Compressing a quartz crystal can cause its polarity to reverse. Langevin's discovery of this property in quartz, which has a constant vibrational interval, provided a way to generate sounds far above the range of human hearing. His subsequent experiments, and those of other scientists, led to active sonar systems, ultrasound transducers, and the use of quartz in various timing applications.

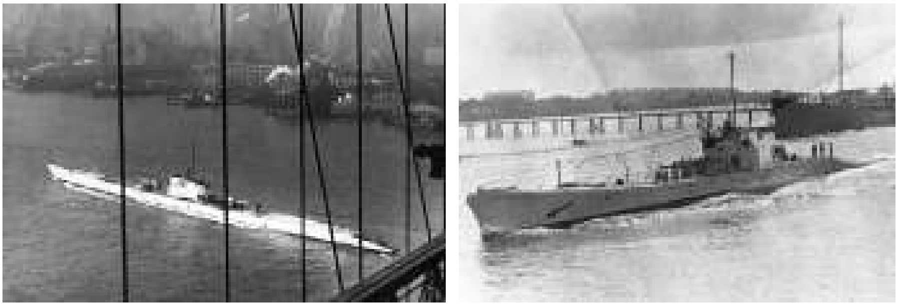
were apparently used to some extent to locate U-boats in the Atlantic and some claim that the UC-3 was the first German submarine to be located by hydrophones and sunk in April 1916, while other sources claim that the UC-3 was laying mines a month later and therefore could not have been sunk. However, the UC-49, a mine-laying submarine, is reported to have been pursued by the HMS Opossum using hydrophones, successfully attacking it with depth-charges and sinking it in August 1918 [Perkins, 1999].

Echo-ranging in those days was called *supersonics*, a term that now refers more generically to sound or other phenomena traveling faster than the speed of sound in air (thus a supersonic jet is one that breaks the sound barrier by traveling faster than the speed of sound).

The early, passive hydrophone systems had very little range, and thus were limited in use. However, vacuum-tube electronics were providing new ways to amplify electrical signals and scientists correctly speculated that this might be combined with a hydrophone to improve the signal, leading to experiments with active sound sensors. The actual application of these experimental systems on crowded, bobbing ships at the time was probably very limited if, in fact, they were even used before the end of the War.

### Post-War Developments

*There are many adjustments to be made in post-war societies. Unfortunately, mines don't just disappear when wars end, they pose a danger to vessels through subsequent years and decades, necessitating the development of many peacetime mine-detection strategies and devices. The detection and clearing of mines were as important after the War as it was during the War. With the resumption of commercial shipping, there was a danger to ships and crews who weren't familiar with mines or how to deal with them and mine-laying activities by hostile forces continued.*



Left: After World War I ended, research and development on submarines and sonar systems continued and some were diverted to scientific uses. War usually creates, as an aftermath, a nervous society, concerned about defense readiness and the prevention of future conflicts. The development of longer-range, more powerful, deeper-diving subs were priorities following the War. The V-4 was authorized in 1925 for mine-laying operations and was renamed the "Argonaut." Right: The S-class submarines were used in the 1920s and 1930s as test platforms for higher-frequency sonars with smaller, trainable transducers. Narrower-beam, lower-interference systems were being developed. [U.S. Navy historical photo, public domain; U.S. Navy historical photo from the Lt. Oscar Levy collection, released.]

Like mines, submarines don't just automatically disappear at the end of a war. After World War II, submarines continued to patrol the oceans, wary of the possibility of another global conflict. Crews who were trained to use sonar and who were seeking employment after the War, or who wanted justification to continue to use the technologies of War for other purposes, began to develop them for the oceanographic sciences. The first, rudimentary, underwater terrain-mapping technologies were being born. In the 1920s, hydrophones continued to be used for submarine-spotting and practical active sonar systems were slowly emerging. The earliest bathymetric charts, images of the seafloor terrain, were produced around 1923.

Other seafaring nations were making similar adjustments. In 1927, in Britain, an ASDIC research and development unit was established at the Portland Naval Base at HMS Osprey to study hydrophones, ASDIC, and other aspects of submarine detection. In 1929, this unit was renamed the Anti-Submarine Experimental Establishment (A/SEE).

The National Academy of Sciences in America emphasized the importance of oceanographic research in 1927 and recommended the establishment of a permanent facility for this purpose. The result was the Woods Hole Oceanographic Institute (WHOI), founded in 1930 in a lab on the east coast.

In 1933, the Washington Navy Yard manufactured 20 sets of echo-ranging systems, considered a major development in sonar. While the author could find only the briefest reference to these systems, it appears that their design may have been based on the steel-and-quartz-sandwich transducers first developed by Paul Langevin and his contemporaries at the end of World War I. Sound-echo-ranging equipment was installed on American destroyers in 1934, including the USS Rathburne (DD-113). Thus, sound-ranging systems, as we now understand them, had been established by this time.

By the mid-1930s, the use of radio or sound signals for civilian and commercial ranging applications was being documented in engineering texts and aircraft began to use radar (radio ranging), which is similar to sonar ranging, for navigation. Not long after, scientists began to understand how important salinity and water temperature were to underwater acoustical transmissions.

Sonar training centers began to spring up around the world. In 1939, the West Coast Sound School was opened at the San Diego Destroyer Base. The same year, the Atlantic Fleet Sound School opened at the submarine base in New London, Connecticut. (In 1940, this school was transferred to Key West, Florida.) In Canada, a small submarine-detection school was established in Halifax.

*When surveillance technologies improve in effectiveness, those who wish to remain unseen adapt countermeasures to maintain their secrecy. This was as true for sonar as for any other technology. Since visual spotting at the surface was effective in detecting submarines in World War I, postwar submarine designers devised ways for subs to dive deeper and to stay under for longer periods of time. As subs dove deeper and longer, sonar was improved to detect them under the water rather than at the surface of the water. As World War II progressed, the German U-boat crews realized that the current sonar systems were optimized for finding them in deeper water and were less effective when the subs attacked near the surface. This spurred the development of more specialized sonar systems and more effective radar systems, thus countering the countermeasures.*

## World War II

*By the late 1930s, submarine-spotting and sonar navigation systems were no longer peacetime technologies. The world was again entangled in a global conflict and both sonar and radar were important technologies contributing to the outcome of the War.*

After Britain's anti-submarine establishment on the south coast at Portland was bombed in 1940, it was moved to Fairlie, near Glasgow, and research and development continued through the War, including the design of mechanisms for sending out depth charges.

From 1940 to 1967, the Raven (AM 55) swept the oceans for mines. It was the lead ship of 93 minesweepers serving the U.S. and Britain in World War II.

During World War II, sonar had evolved to the point that submarines could no longer lurk in the dark undetected under the surface of the water. Anti-sonar measures became as important as sonar itself. In order to try to reduce their sonar signatures, the Germans experimented with synthetic rubber as a skin to counter Allied sonar probes. Special materials are now regularly used on subs and aircraft to selectively deflect or absorb sonar and radar probes.

Greater scientific research was being applied to acoustic sensing at this time. The U.S. forces were benefiting from private institutions and setting up new labs of their own. The Woods Hole Oceanographic Institute contributed important defense-related research to the U.S. forces during this time.

In 1941, Waldo K. Lyon established the U.S. Naval Arctic Submarine Laboratory. Since the Arctic was a particularly challenging environment in which to navigate, sonar research and development were essential to carrying out successful surveillance in icy regions.

In October 1941, the 'bathothermograph' was introduced to the naval fleet. The training of specialists and assignment of crew to take bathymetric observations from aboard ships were begun so the technology could be used in patrol and attack operations. Bathothermography helped a submarine hide in thermal layers to avoid detection by enemy sonar systems.

The *bathothermograph*, an early sonar imaging technology that became available during the war, was incorporated into submarines to aid them in covert patrol and attack operations. The USS Herring (SS-233) and the USS Scorpion (SS-278) were equipped with the *submarine bathothermograph* (SBT) system. The Herring spotted and sank the German U-163 in March 1943. The Scorpion was lost, perhaps to a mine explosion, soon after a rendezvous with the Herring in February 1944. The Herring was presumably sunk from Japanese attacks to the conning tower in 1944. [U.S. Navy historical photos, public domain.]

## The ASW Patrol Ships and Destroyers

In December 1941, after the attack on Pearl Harbor, the importance of the U.S. Submarine Force increased. Subs were used to hold the line in the Pacific and made hundreds of patrols. They even used FM-based sonar to pursue the Japanese into their own waters.

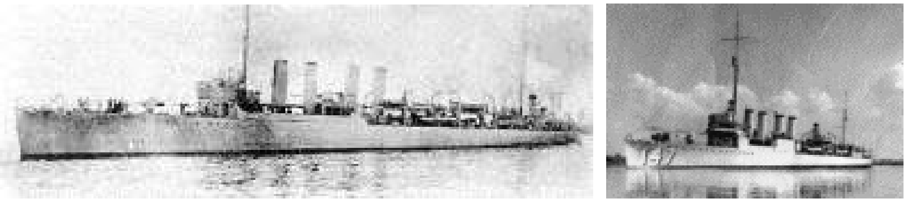
Since sonar equipment is installed or towed underwater, it is vulnerable to damage from debris, collisions, ice, and mine blasts. Retractable sonar domes existed before this time, but by the early 1940s, most of the larger ships were being fitted with retractable domes.

The new sonar equipment being made available to military ships necessitated new training and procedures in technical and strategic handling of the technology. Two ships of interest that were involved in anti-submarine activities were the USS Jacob Jones and the USS Roper.

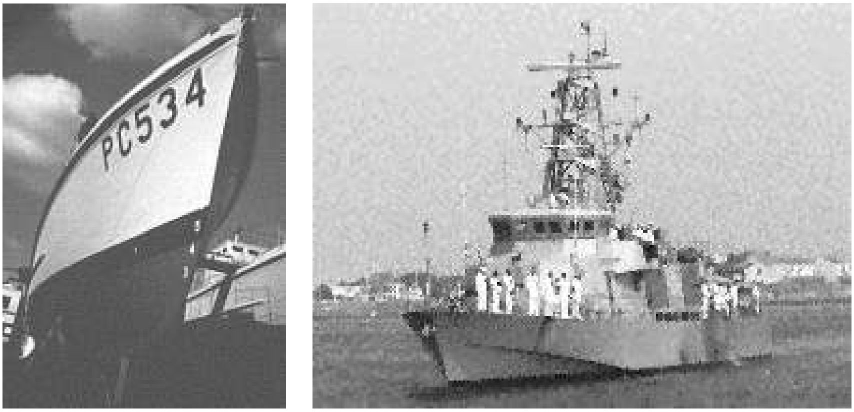
In February 1937, The USS Jacob Jones (DD 130) participated in minesweeping training and in 1940 joined the Neutrality Patrol, which had been formed in September 1939 to patrol the Western Hemisphere. After two months of duty, the ship returned to training operations.

In September 1940, the Jacob Jones sailed to New London, where the crew underwent acoustics training for anti-submarine warfare (ASW), after which she continued to Key West for further training before rejoining the Neutrality Patrol. Sometime late in 1941 or early in 1942, the Jacob Jones detected an underwater submarine and began to attack with depth charges. Contact with the submarine was lost, however, and the Jacob Jones continued on her way. A month later, while heading south from Iceland, she again detected a submarine, but depth charges were apparently ineffective.

In February the Jacob Jones became a member of a roving ASW patrol and soon detected and gave chase to a submarine. Depth charges yielded oil slicks, but no confirmation of sinking a sub. On 27 February 1942, the vessel searched for survivors around the wreckage of a torpedoed tanker off the coast of Delaware, then set course south. By the light of the following morning, an undetected German U-boat (U-578) fired at Jacob Jones, surprising her and ramming her with at least two torpedoes. The ship was destroyed and sank rapidly, and only 11 made it to shore alive. Wreck divers have reported that the Jacob Jones lies in pieces with its torpedoes intact near the Indian River. A month after the sinking of the Jacob Jones, the U.S. Navy established a Submarine Chaser Training Center.



The USS Jacob Jones was the historic anti-submarine training vessel that was sunk by U-boat torpedoes from an undetected submarine in February 1942 off the coast of Delaware. The USS Roper (DD 147) was also used as a ASW training ship, but was converted to a transport in 1943, and decommissioned in 1945 to be sold for scrap. [U.S. Navy historical photos, public domain.]



Left: A 110-foot Patrol Coastal (PC) submarine harrier in the construction yard in Stamford, Connecticut, March 1942. The responsibilities of the Patrol Coastal and Patrol Sub Chaser (PCS) vessels were to patrol various waterways and to conduct interdiction surveillance. Right: Current patrol ships like this Cyclone-class Patrol Coastal also provide support to Navy SEAL operations. [Library of Congress FS/OWI photo by Howard Liberman, U.S. Navy news photo, both public domain.]

The other vessel reported to have been used for ASW training was the USS Roper (DD 147), which also formed part of the Neutrality Patrol. This vessel was luckier than the Jacob Jones. In April, 1942, she sighted a German U-boat at the surface off the coast of North Carolina. The Roper pursued the submarine and succeeded in sinking the Nazi vessel designated U-85. The U-85 was the first German U-boat to be sunk in American waters. She sunk to a depth of about 95 ± 10 feet in waters with strong currents with all hands lost and is now a designated German grave site.*

Patrol Coastal (PC) and Patrol Sub Chaser (PSC) vessels handled many of the surveillance and ASW tasks from the time of World War II. Rushville (PSC-1380) was put into service in 1943. She was a Patrol Sub Chaser vessel that was assigned to ASW training duty at the Fleet Sonar School Squadron in Key West. In December 1944, the Rushville was outfitted with special experimental acoustic gear.

## Other Acoustic Applications

Acoustic devices are used for many purposes. A strong enough sound wave, such as a shock wave from a large explosion, can deform the ground in rolling waves, blast buildings into matchsticks, and knock a person off his feet. The pressure characteristics of sound can be used in other ways besides the detection of seafaring vessels. In 1942, U.K. scientists created a device to generate sounds that could clear a minefield by detonating the mines. This *hammer box* was usually lowered into the water well in front of the path of a minesweeper that was constructed to withstand the subsequent explosion.

The use of the term ASDIC for sound-ranging applications was specifically tied to submarines, but sonar was now being used in a broad range of military and commercial applications. The more familiar term *sonar* has been attributed to American underwater acoustics specialist and Director of the wartime Harvard Underwater Sound Laboratory, Frederick V. (Ted) Hunt, to provide a euphonious analog to ‘radar.’ Others maintain the term was coined to represent ‘sonic, azimuth, and range.’ Either way, it eventually replaced the British term ASDIC. Currently, it is used as an acronym for ‘sound navigation ranging.’

Frequency adjustments on sonar systems at this time were still somewhat crude. If the system could operate at more than one frequency (or if the frequency needed tuning), the job was usually done with a screwdriver rather than a switch or knob as on modern systems. Secrecy further limited the number of people who were qualified to repair or calibrate a sonar system. In fact, quartz, which was increasingly used for its piezoelectric properties, was referred to by the codeword *asdivite* until about the time the term *sonar* caught on and the term ASDIC was relegated to history.

## The State of Sonar Technology

By the mid-1940s the variety of sound-sensing devices had increased. *Automatic* and *recording* sonars had been used during the War, and many continued to be used in military vessels after the War. These were used chiefly for navigation, submarine spotting, and automatic firing systems. During periods of hostile contact or attacks, *range recorders* could be used to make a visual record of sounds coming through a sonar receiver and could be used to activate depth chargers or thrown charges. *Bearing recorders* for monitoring gun bearings, were sometimes used in conjunction with range recorders.

Although sonar technology had improved from World War I to World War II, by the end of World War II, some aspects of sonar were still essentially the same. The frequencies used

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*Mike Leonard has created a built-from-scratch model of the German submarine U-85. A photo of the model can be viewed at the simplenet.com site. http://warship.simplenet.com/images/Leonard/U85.jpg were still primarily within audible hearing ranges and slightly above, and sonar range had not significantly improved. Sophisticated sonar systems emerged sometime after the conclusion of the War.

### Post-World War II

After the War, a number of wartime vessels were used as salvage, targets, or training vessels. The Canadian government acquired a British L-class submarine (L-26) and scuttled it a few miles off Pennant Point on the east coast. It was used as a *sonar target* for location and identification training purposes for at least the next twenty years.

The Fairlie anti-submarine research center near Glasgow was returned to its original site in Portland on the south coast in 1946. During post-war organizational changes in 1947, the name was changed to a broader term, the *HM Underwater Detection Establishment.*

Before the end of the War, a U.S. team had the opportunity to study German U-boat technology. As a result of this, both during and after the War, the advanced design features of the German subs were incorporated into U.S. subs, taking the best features from both worlds. Thus, Greater Underwater Propulsive Power (GUPPY) systems and streamlined hulls were created to increase cruising speed while submerged, snorkel systems were added, and array sonar systems were incorporated to keep pace with improvements in the subs themselves.

### Post-War and Cold War Sensing Applications

There were many important improvements in sonar technology following World War II. The invention of transistors in 1947 were in part responsible for significant improvements in electronics and size-reduction. Left: In 1951, the Guavina (SS 362) was equipped with an experimental *searchlight sonar* which made it possible to distinguish the sound signatures of specific vessels (a concept that was also being applied to radar identifiers for aircraft around this time). This new sonar system could differentiate signals far better than previous systems. Right: The Albacore (AGSS-569) was an experimental submarine with a streamlined hull that was designed to create less noise in the water and thus avoid registering on acoustic surveillance systems. It was also equipped with the first fiberglass sonar dome, in 1953. [U.S. Navy historical photos, public domain.]

The Woods Hole Oceanographic Institute, founded in 1930, had by this time established an Underwater Sound Lab (USL). In 1948, the U.S. Navy began working with the USL on countermeasures to the Soviet submarine force. This was apparently the origin of the Project KAYO, which explored the use of submarines with low-frequency, passive, bow-mounted sonar arrays for ASW tasks [Cote, Jr., 1998].

The range of sub-spotting sonars at this time was about 3500 ± 300 meters using analog broadband detectors. The expertise of the operator was crucial to interpretation of the signals and good pitch discrimination was an asset.

In the late 1940s, the U.S. began to install a more-or-less permanent system of 'underwater ears' in strategic ocean locations on the Atlantic continental shelf. These cable connected hydrophones allowed detection of any unidentified vessels approaching the seacoast, particularly submarines. It also provided a way to monitor and keep in touch with U.S. submarines or detect a vessel that might be acting erratically, indicating that it might be in distress and unable to radio for help. The system, called SOSUS (*so*und *su*rveillance *s*ystem) wasn't good at sensing very slow-moving vessels, since they didn't create enough of a disturbance to register on the system, but anything traveling more than about eight knots was vulnerable to detection.

By the late 1940s, sonar was increasingly being used for resource studies and environmental-sensing purposes, especially the study of gases, minerals, and fish behaviors and habitats, applications that have continued to grow.

### Post-War Adjustments to Acoustics Research

Cold War politics in the early 1950s resulted in a high priority being placed on sonar research and development. At the same time, training for sonar operators, which had been very practical and hands-on up to this time, began to include some of the theory and mathematics associated with sonar. The math was extremely valuable as it could be used to create lookup tables for predicting detection ranges, a step toward modern acoustics-sensing technologies.

More comprehensive and detailed mapping of the ocean floors was being carried out with sonar by the 1950s, revealing impressive features, mountains and valleys, a look at our ocean environment such as had never been seen before. Later developments of multibeam sonars would greatly enhance this process.

By this time, the U.S. was building nuclear subs. The first nuclear sub, the Nautilus (SSN-571), was commissioned in 1954 and was underway by January 1955. It was the first true U.S. submersible submarine and the first ship to reach the North Pole. After decommissioning in 1980, Nautilus was put on display at the Submarine Force Museum.

### Improved Diving and Acoustic Sensing

*The Soviet launch of the Sputnik satellite in 1957 was a wake-up call for politicians and an inspirational shot-in-the arm for scientists. As a result, there were many technological firsts in the early 1960s. Deep diving, improved sonar, and new space technologies all contributed to navigation, exploration, and communications in the 1960s and beyond.*

In 1960, Don Walsh and Jacques Piccard descended to the record-breaking depth of 10,912 meters in the "Trieste," to study the depths of the Mariannas Trench. This inspired the development of research submarines with greater maneuvering capabilities. Even forty years later, this is still a remarkable achievement, considering only a handful of vessels (e.g., the NR-1) can dive deeper than 7,000 meters and none has yet beaten the record.

In the U.S.S.R. and the U.S., submarines were becoming the basic strike force vessels and some military analysts in the U.S.S.R. suggested that surface vessels might eventually be superseded by underwater forces for strike activities. At this time, the Soviets had a force of over 400 subs, about half of them long range. The U.S. estimated that the Soviets were also constructing nuclear subs.

The operating range of early sonar systems was limited, but as transducers gradually replaced older quartz oscillating systems, the range was increased by about a factor of three, depending on conditions, a considerable improvement.

The problem of detecting or avoiding underwater mines had increased by this time as they were now being devised with sensitive non-contact detonators that could react to the physical emanations of marine craft.

Variable-depth sonar systems began to be used to overcome some of the limitations inherent in trying to track underwater vessels that might be hiding in other layers in the water where a refracted beam could provide erroneous data. The variable-depth sonar (VDS) technology was in part developed in Canada.

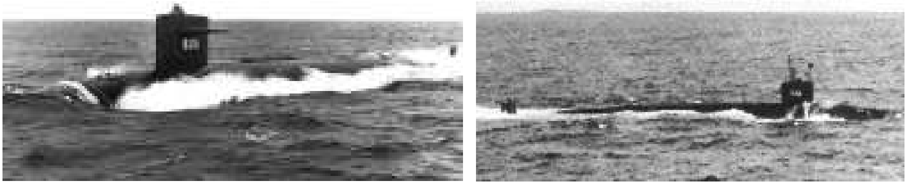
Postwar research labs in the early 1950 and 1960s were actively improving sonar technology, resulting in more powerful and flexible systems. More sophisticated submarine countermeasures, weapons-deployment, and improved sidescanning and dipping sonars for use with helicopters, were all initiated or developed during this time.

During the Korean War in the late 1950s and early 1960s, U.S. Naval submarines were used for both sonar and photo reconnaissance during surveys of Korean and Soviet mine fields, shipping lanes, and coastlines. Submarine hunter-killer groups were also dispatched. In 1964, the transport subs *Perch* and *Sealion* were recommissioned to support SEAL operations, to collect intelligence, and to aid in search and rescue operations.

In the early 1960s, the CIA, interested in Soviet military warfare communications, was intercepting secret Soviet publications such as “Voyennaya Mysl” (Military Thought) published by the Soviet Ministry of Defense, which discussed various tools and strategies of warfare, including naval surface vessels. These articles were translated into English and distributed to the Defense Intelligence Agency (DIA) and various defense and intelligence directors.

### Innovation and Disaster

The lead ship in a new class of stealth submarines was the USS Thresher (SSN 593). It was one of the Permit-class vessels that were quieter, more streamlined, and equipped with advanced sonar and weapons systems. In April 1963, only three years after it was commissioned, tragedy struck the U.S. Navy when the USS Thresher (SSN 593) ruptured and sank off the coast of New England, taking down the entire crew. Turning tragedy into technology, the Navy began research and development on vessels that could aid submarines in distress, hopefully offloading their personnel and bringing needed emergency equipment and supplies. This led to the establishment of the *SubSafe* certification program and the *Deep Submergence Rescue Program* and vessels that could carry out rescue dives to thousands of feet.



Left: The USS Timosa (SSN 606) is one of the Permit-class nuclear subs designed for quieter operation and greater stealth. These subs could also diver deeper than the older models. Right: The USS Thresher (SSN 593) was lost with all hands in 1963, possibly due to a defect in the piping system. Ironically, acoustics might have aided in detecting a possible defect, by more thorough application of ultrasonic testing to the joints and systems. [U.S. Navy news photo, public domain.]

In 1964, the U.S. Navy built Alvin, a submersible capable of taking two scientists down to a depth of about 4,000 meters. Alvin was equipped with measuring instruments, cameras, and mechanical arms for collecting samples. It was delivered to the Woods Hole Oceanographic Institute for civilian research.

By the 1970s, computer and satellite technologies were being utilized to create some interesting new sonar inventions. The ALACE system of temperature-measuring floats was developed by Scripps and Webb Research to gather information underwater and then surface about once a month to transmit the information to a satellite receiver. It would then resubmerge to continue its mission. This innovative concept could be applied to sonobuoys designed to take sonar readings and autonomously transmit the data through a satellite.

In May 1968, the USS Scorpion (SSN 589), a U.S. nuclear submarine first commissioned in 1960 disappeared southwest of the Azores with all hands, with no clear answers as to why she sank. She was found in October 1968 by a towed deep-submergence vehicle. The image on the right was probably taken at the time the deep-sub vehicle located the wreck on the ocean bottom late in 1968. [U.S. Navy historical photos, released.]

### Deep-Submergence Craft

In 1969, the U.S. Navy launched its first deep-submergence vessel, a nuclear-powered craft, the NR-1. The NR-1 is able to stay for extended periods at depths of about 700 meters and is designed for object recovery, geological surveying, oceanographic research, and the installation and maintenance of various types of underwater equipment. The vessel is equipped with sonar, special manipulators, cameras, and a TV periscope which enable it to be used for high-resolution mapping and searching operations. In 1986, the NR-1 had the unenviable task of searching for wreckage from the space shuttle Challenger which exploded shortly after launch. In 1997, it was engaged in the second of two archaeological expeditions in the Mediterranean in search of ancient Roman merchant ships along with the JASON remotely operated vehicle from Woods Hole Oceanographic Institute.

Left: The NR-1 is a unique nuclear-powered deep-sea vessel first used by the Navy in 1969. It can dive to more than 700 meters for extended periods of time to carry out sophisticated military, commercial, and scientific search and mapping operations. Right: A Deep-Submergence Rescue Vehicle (DSRV) designed to perform rescue operations on disabled, submerged submarines. The first DSRV was launched in 1970. This 15-meter Lockheed Missiles and Space, Co. vessel can dive up to about 1500 meters to conduct a search via sonar. It utilizes both search and navigation sonar systems. [U.S. Navy news photos, released.]

The NR-1 is equipped with visual viewing ports with external lighting, color, and black and white video and still cameras, manipulator arms for grasping and cutting, and sonar searching and navigation systems. The vessel also sports an Obstacle Avoidance Sonar (OAS) developed by the University of Texas.

The development of personal computers in the mid-1970s eventually led to ways for sonar equipment to be interfaced with computer processing systems and displays and provided new means to coordinate the timing and processing of multibeam and sonar array sensors two decades later.

### The 1970s - New and Improved Sonar Applications

*Acoustic systems in the early century were used mainly for navigation, submarine-spotting and mine detection. However, as the science improved and the use of torpedoes increased, acoustics began to be used for other purposes, including homing devices and torpedo detection. The frequencies at which sonar were used had also become ultrasonic. Whereas early sonar systems operated at about 18 kHz, newer systems could generate frequencies of 100 kHz and beyond. These systems were not yet realtime, however. Like early radar, which relied on sending out a pulse and then waiting for a returning pulse, with an interval between pulses, sonar didn't provide an up-to-date picture, but rather a picture of things as they were just a moment before the signal registered on the printout or display. Since microcomputer electronics were not yet established in the early 1970s, an additional delay was introduced by the limited signal-processing equipment in use.*

By the 1970s, sport fishing was changing from a quiet, contemplative pastime to a high-tech search for the biggest schools and the best fish. Like hunters seeking out the trophy stag, fishing enthusiasts began using sonar to track, identify, and catch fish big enough to match their fish stories. *Fish-finders*, as they have come to be called, weren't very sophisticated at first. The displays were rudimentary and the systems bulky and expensive, but they provided a new way to determine the presence and depth of fish below a boat. Distance calibrators could further convert the data into feet or meters. Due to the cost of the early systems, they were used more for commercial fishing than sport fishing, but with the microelectronics developed in the mid-1970s, the situation would change about a decade later.

By the mid-1970s, various systems with widely spaced sonar devices were being developed to provide more accurate estimates of range and location. These essentially used the concept of 'triangulation' to provide a more accurate picture of the incoming signals. In addition to this, newer improved concepts of digital signal-processing (DSP) were also being developed, which were to transform many aspects of electronics processing.

By the 1980s, the sensitivity and power of sonar had greatly improved over the systems used in the War or developed in the early 1960s, when transistors and computer components were coming on the scene. Improvements included the extension of the sensing ranges from less than 1,000 meters to almost 200,000 meters (200 kilometers) in good conditions. In the future, that range would be extended even further, with new communications technologies.

Important improvements occurred at this time in Doppler sonar systems. The early Doppler systems were not easy for untrained personnel to use and were not good at distinguishing objects that were traveling at varying speeds within moving currents. To improve on existing systems, the U.S. Navy devised ways for narrow-band filters to detect the Doppler frequency in order to combine the data with compensating circuits and reference measurements. This allowed the water velocity to be compared with the incoming data to create a more accurate sonic picture of detected objects [Skoures, Farace, 1970].

### The 1980s - Increasing Sophistication and Computerization

In the early 1980s, the U.S. Navy began to develop a mine countermeasures (MCM) force made up of two new classes of ships and minesweeping helicopters. The Avenger- and Osprey-class ships were designed to detect, classify, and destroy moored mines and bottom mines using conventional minesweeping techniques along with newer sonar and video systems, cable cutters, and remote-controlled detonating devices.

Improved diving equipment and techniques, combined with video and sonar surveillance technologies made the discovery of previously ‘unrecoverable’ wrecks a possibility. Many wrecks were found or salvaged with advanced technologies in the 1980s and 1990s, even vessels which had been given up for lost.

In June 1985, divers discovered the wreck of a German sub that had been taken over by the U.S. after the War and subsequently sunk during explosives testing. The U-1105, dubbed the ‘Black Panther,’ which had been commissioned for the War in June 1944, was an experimental German sub which incorporated the dark synthetic rubber skin code named ‘Alberich.’ At one point the U-1105 hid for 31 hours after attacking the HMS Redmill with acoustic torpedoes. The modified Type VII-C Kriegsmarine sub was able to evade detection for the duration of the war but was surrendered to the U.S. at the end of the War, where the rubber skin was studied by the Naval Research Laboratory and MIT’s Acoustic Laboratory. The vessel later became Maryland’s first underwater dive preserve.

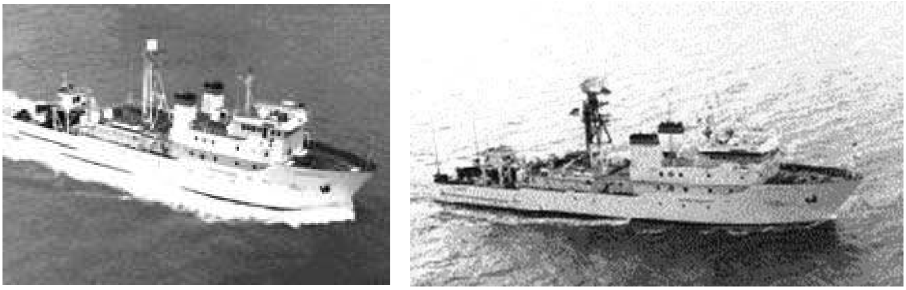
In 1989, the Key West Fleet Sonar School was closed, so that just the Fleet ASW Training Center in San Diego remained to serve the anti-submarine needs of the U.S. Navy.

In 1970, the U.S. Navy had launched the USNS Hayes as one of 28 special missions ships. The Hayes was converted to function as an acoustic research ship in 1986 and completed and reclassified as T-AG in 1992. The Hayes now transports, deploys, and retrieves acoustic arrays and conducts acoustic surveys and testing operations. The catamaran design provides a wide operating deck and a sheltered region between the hulls. Since high-end imaging applications generally require slow towing speeds, the Hayes has two engines specially equipped to maintain a speed of two to four knots.

### Acoustic-Sensing Challenges

The ‘littoral environment’ is the coastal region within which the tidal changes occur. Littoral environments in many regions are complex and craggy. They are filled with rocks, debris, fish, plants, corals, and thick layers of shifting sediment. The difficulty of distinguishing targets from the clutter in these coastal regions is significant. For scientific missions, diving boats, and specialized fishing vessels, there was a demand for more sophisticated systems that could aid in navigating and surveying these tidal environments. The same was true for military defense surveillance. Mines that were planted in tidal waters were difficult to distinguish from debris and outcroppings. Also, the new, smaller, remote-controlled and autonomous craft that were being developed in the late 1980s and 1990s could potentially hide in littoral environments. If they were developed by those with hostile intentions, they could escape detection from even some of the most advanced acoustic sensors.

In 1990, the Office of Naval Research established the *High Area Rate Reconnaissance* (HARR) program to develop both shallow and deep water technologies for countering mine threats. HARR used both *side-looking sonar* (SLS) imaging and *toroidal volume search sonar* (TVSS) for detecting unburied mines. The TVSS system is donut-shaped, providing omnidirectional beaming perpendicular to the direction of the tow. It was tested in the mid-1990s in the Gulf of Mexico, in water depths from 28 to 160 meters. The SLS was tested in the late 1990s, generating sonar images that could be processed and viewed in realtime on a display screen.



Left: A U.S. Navy Ocean Surveillance ship equipped with an advanced linear towed-array system for underwater detection. Right: Three Stalwart-class Ocean Surveillance ships were refitted for above-surface surveillance using radar and advanced communications systems. These are now being used in support of Navy counter-drug-trafficking surveillance. [U.S. Navy news photos, released.]

In the early 1990s, with a reduced Soviet threat, the U.S. Navy lowered the priority on certain ocean surveillance vessels that had been commissioned since the mid-1980s. Three of these Navy ships were converted to handle narcotics-trafficking detection rather than underwater acoustics surveillance. Their underwater acoustic arrays were removed and replaced with an above-water surveillance system, an air-search radar, and up-to-date communications systems.

Other ships in the fleet continued their ocean surveillance activities to support the anti-submarine efforts of other vessels. The *Surveillance Towed-Array Sonar System* (SURTASS) used on the ships is comprised of listening devices, computerized processors, and electronic satellite communications. Due to the needs of high-resolution sonar, the ships are designed to be stable at slow hull speeds, even under adverse weather conditions, to handle the towed linear-array system. The *Impeccable*-class ships have modules that house pairs of high-powered active-sonar transducers which can be used with either monostatic or bistatic receivers.

There are three computer-related technologies that were emerging at this time that were particularly important to surveillance technologies, including sonar:

- The development of fiber optics permitted the manufacture of longer, lighter sonar towing and communications cables and enabled higher bandwidth applications that were especially useful for sonar arrays with many elements, such as imaging systems.
- By the mid-1990s, the development of high-resolution Global Positioning System (GPS) technologies was beginning to have a substantial impact on the evolution of sonar technologies. The ability to pinpoint (or even more closely approximate) the location of sonar devices such as sonobuoys with the added GPS data, permitted applications that had not been previously possible.
- Digital signal processing (DSP) was another technology that made inroads in the 1990s and contributed to the development of more sophisticated computerized sonar systems. DSP permitted greater levels of automation.

Increasingly sophisticated sonar systems provoked the countering development of increasingly ‘quiet’ submarines, vessels that were developed with special skins, low sonar signatures, quiet propulsion and other features to improve their stealth capabilities. More than ever, the U.S. submarine force had earned the name of “Silent Service.”

### Upgrading to New Technologies

*In the late 1990s, computer electronics and software made some remarkable advancements. Virtual storage devices jumped in capacity and dropped in price, processors continued to become faster, software became increasingly sophisticated. The technology of instrumentation was advancing far more rapidly than the technology for large vessels. Submarines and ships were improving, but the basic designs, in many ways, were little different from those that existed around the time of World War I. The concepts of seaworthiness had been developed and refined over centuries, whereas modern computer electronics as a field was less than thirty years old and still in its growth and development stages.*

This technological incongruity created a dilemma for vessels equipped with large, built-in sensing systems. Console equipment was becoming obsolete in months or even weeks, compared to the vessels themselves, which could be used in one capacity or another for decades. Thus, during the late 1990s, many surveillance craft, from helicopters to submarine-chasers, were upgraded or retrofitted with advanced sensing systems, instead of retiring the vessels. One example of this is the *Acoustic Rapid COTS Insertion* (ARCI) upgrade for submarines. It was initially installed for evaluation in the USS Augusta in 1997 and subsequently planned for fitting into other vessels in the fleet over the next decade.

In September 1998, new U.S. Navy attack submarines were equipped with advanced stealth features, and sonar systems for anti-submarine and mine warfare. They could also launch unstaffed underwater or aerial vehicles for mine reconnaissance and intelligence-gathering.

### Scientific Applications

*The emphasis on peacetime scientific missions increased in the 1990s. Submarines and surface vessels equipped with advanced sonar systems were used for search and rescue, salvage, ecological studies, and scientific expeditions to the Poles. The information gained was valuable for both national defense objectives and civilian research.*

With the computerization of tracking systems, many types of technologies may be combined into one visual ‘map.’ Sonar signals may be included with data from radar and visual surveillance technologies. The days of discrete modes of sensing are probably over for many applications.

In 1998, the U.S. Navy, due to priority changes and funding cutbacks, gave up the maintenance and operation of its deep-submergence vehicles. Both the *Sea Cliff* and the *Turtle* were decommissioned and retired from service. The Turtle was put into storage and the Sea Cliff was transferred to the National Deep Submergence Facility at the Woods Hole Oceanographic Institute for alterations that would make it suitable for scientific research.

### Aircraft Wreckage Search, Rescue, and Recovery

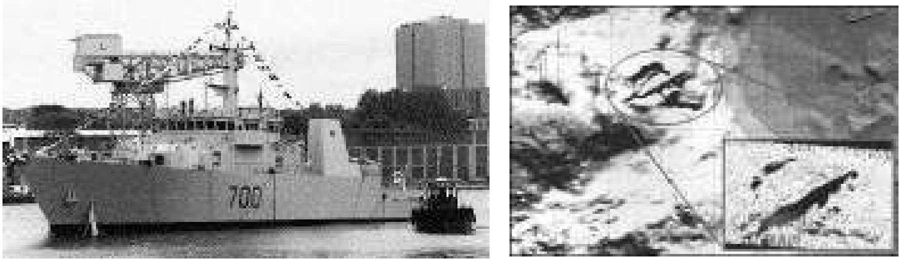
*Surveillance technologies have evolved to the point where many types of vessels are equipped for search and rescue operations. The use of these technologies in the recovery of downed aircraft is described both here and in the Applications section.*

The careful coordination of video, sonar, radio, and computer technologies was demonstrated by Canadian forces that searched for a jetliner that crashed into the sea near Nova Scotia in September 1998.

When Swissair Flight 111 crashed off of Peggy’s Cove on the east coast, one of the systems used in the search for wreckage was the Canadian Towed-Array Sonar System (CANTASS), along with a number of remotely operated vehicles (ROV). The Deep Sea Inspection System (DSIS) is equipped with both video and sonar surveillance systems. The Bottom Object Inspection Vehicle (BOIV) is a medium-sized remotely operated vehicle and the Phantom, is a small ROV. The Phantom, equipped with color video and high-definition, scanning sonar, created images of the ocean floor that revealed the contours of the stricken jetliner. In addition, the HMCS Okanagon, an Oberon-class submarine, used passive sonar to listen for the locating signal from the airliner's flight data recorder.

The data collected by the remote vehicles were transmitted by radio from the supply vessel HMCS Anticosti to military oceanographers stationed at the Bedford Institute in Halifax who were aboard a Coast Guard cutter. It was then fed into computer software that could be cross-referenced with a record of the airplane's seating plan. This coordinated effort allowed the staff to identify all the victims on behalf of the airline and the bereaved families.

In the process of searching for the Swissair flight, the searchers got an unexpected surprise, a large, old object, perhaps a ship, perhaps a submarine, was also spotted on the ocean floor.



Left: The HMCS Kingston, used at the scene of the Swissair Flight 111 crash as a sidescanning survey ship (along with the HMCS Anticosti). Right: This sonar image of what appears to be an old vessel was taken off the coast of Nova Scotia while searching for wreckage of the Swissair craft. The system used was the Canadian Towed-Array Sonar System (CANTASS) in conjunction with the Phantom video- and sonar-equipped remotely operated vehicle. [Canadian Department of National Defence 1998 news photos, public domain.]

The Matthew is a survey and research vessel that was dispatched for sonar search operations when Swissair Flight 111 crashed into the ocean. Right: Diving Tenders Grandby and Sechelt were used for diving operations in the recovery. [Canadian Department of Defence 1998 news photo, public domain.]

### Acoustic Homing Sensors

*Acoustic homing sensors are used on underwater torpedoes and still have limitations that require accessory guidance systems. Acoustic homing torpedoes are typically launched from submarines or advanced mines.*

Acoustical homing systems have been in use at least since World War II, when the Royal Air Force was equipped with acoustic homing torpedoes and used them along with depth charges to sink the U-954. In recent years, acoustic homing systems have become more practical and accessible and it was clear by the mid-1990s that the U.S. and her allies were not the only countries using this technology. American intelligence indicated that Iran had been testing wake-homing and wire-guided acoustic homing torpedoes in conjunction with their submarine fleet [Baus, 1996].

### Technological Advances

*Rapid-scanning sonars, laser sonars, and within-pulse electronic-sector-scanning sonars are just some of the technologies that have been more recently introduced.*

One of the most challenging applications for sonar ranging and detection is navigating beneath ice floes at the Earth's poles. Even with advanced sensing equipment and the best sonar operators, the challenge of navigating in tight quarters beneath massive, deep, jagged ice protrusions is not for the faint of heart. To add to the challenge, very little oceanographic data exist on regions permanently shrouded in ice.

In March 1999, the Sturgeon-class attack submarine USS Hawkbill dove beneath icefloes in the Bering Sea to begin an eight-week Arctic research mission. The vessel had been specially outfitted with sensing systems for navigating under the Arctic ice, including a forward-looking ice-finding sonar for detecting the protruding ice bergs and high-frequency sonar for constantly monitoring ice draft (extent below sea level). The Hawkbill was dispatched to collect scientific data and samples to further research on ocean warming, and geophysical and chemical structures. For surfacing maneuvers, an upward-looking video display was used in conjunction with sonar guidance.

One of the significant experiments from this mission was the Arctic Climate Observations Using Underwater Sound (ACOUS) project in which a vertical hydrophone array was dropped through a hole in the ice to receive transmissions from a 20-Hz underwater sound signal emitted from some distance away. This provided a measure of oceanic temperature along the range of a 2800-kilometer path.

### Satellite Communications

*During the late 1990s, with improvements in commercial and military satellite communications, a number of sonar-satellite technologies were invented.*

Since sonobuoys were often self-contained units that were left unattended for long periods of time, and might be difficult or expensive to relocate, they were sometimes scuttled after their useful life was over. Thus, for surveillance missions, they needed a way to convey the data they had collected to vessels or ground stations. Encrypted radio-wave communications with satellites provided a practical solution to this problem. Not only could the data be sent back to the station interested in analyzing it, but the buoy itself could be controlled to some extent with telemetric data relayed through the satellite.

This general idea could also be applied to communications between a submarine and a buoy. Using sonar signals, information could be sent to the buoy floating at the surface, which could, in turn, use radio signals to communicate with the satellite. This way, the submarine wouldn't have to surface to communicate with air or ground stations. The disadvantage of the sonar system is the submarine generally has to be connected to the buoy with a communications cable, thus necessitating it be in the physical vicinity of the buoy (see the Magnetic Surveillance chapter for some proposed improvements to this scheme).

### Automation and the Future

By the late 1990s, in spite of all the automation and improvements that had occurred in sonar technology, the main 'brain' of the system was still the human being who examined and analyzed the sonar screen or sonar images. The difference between a mine, a wreck, or a submerged sub was still largely determined by a subjective evaluation by a trained professional. Strides are being taken, however, to automate some of the recognition capabilities of sonar in an effort to create 'smart' sonar systems. This brings together the accumulated knowledge of many fields, including artificial intelligence, vision systems, robotics, and even medical imaging.

While electronics technology continues to improve in leaps and bounds, many of the breakthrough developments in sonar are not in hardware, but rather in software that provides new ways to mathematically model and analyze the sonar signals.

One of the inventions developed by Nelson and Tuovila with the U.S. Navy in 1997 is a fractal and nearest-neighbor clustering technique for identifying the clutter in sonar images; that is, it can help identify and screen out unwanted or unimportant information. While this technology was developed to help with mine detection, it clearly applies to many other types of sonar images and further can be adapted to other imaging systems, including radar, X-ray, and MRI.

Advanced concepts and mathematical data manipulation techniques will probably result in future sonar systems far beyond anything we can currently imagine.

# 5. Descriptions and Functions

## 5.a. Sound Units and Characteristics

While an in-depth knowledge of the mathematics of sound is not necessary to appreciate the information in this chapter, it is helpful to know some of the basic units and terminology associated with the physics and representation of sound. Here are the most essential sound measurement concepts and units.

### Loudness

Sound intensity or what we perceive as 'loudness' is described in *decibel* (dB) units. *Deci* refers to ten and *bel* is derived from Alexander Graham Bell. Our perception of changes in intensity as it becomes higher or lower is that the differences are not equal but progressively larger or smaller. The decibel scale is not a linear scale that increases in equal steps, but rather a *logarithmic* scale, in which changes are *exponential* as you move up or down the scale. Thus, 40 decibels is not 4 times 'louder' than 10 decibels, but rather $10^4$ (40) times 'louder' and the magnitude of difference continues to increase as you go up the scale.

What we call 'loudness' corresponds roughly with the concept of *intensity* which has been more objectively defined in math and physics for use in calculations.

As is discussed further in the sections on electromagnetic media, *wavelength* and *frequency* are mathematically related. In electromagnetics, the wavelength is equal to the speed of light divided by the frequency. Similarly, in acoustics, the *wavelength* is equal to the *speed of sound in the medium* divided by *frequency* or, expressed symbolically, $\lambda = c/f$ .

It is usually easier to understand the concept of intensity with a few examples common to everyday life. Here are some examples of approximate sound amplitudes/intensities of various occurrences as measured in air in *decibel* units:

| decibels | action or phenomenon |
|---|---|
| 0 | *human threshold - for reference* |
| 25 | soft whisper nearby |
| 60 | human conversation |
| 80 | public places, restaurants, subways |
| 85 | *level at which hearing protection should be worn* |
| 100 | carpentry shop, power tools; uncomfortable, cumulative damage |
| 125 | next to jackhammer; painful and harmful to human hearing |
| 140 | jet engine, arm's-length gunshot; damaging to human hearing |
| 160 | explosions; highly deleterious to human hearing |
| 200 | serious and permanent hearing damage |

You cannot directly translate sound levels in air to sound levels in water in terms of decibels. Not only have sea creatures evolved different types of sound-sensing biology, but the physics of sound travel through water (speed, propagation, absorption, distance, etc.) is different from that through air (see Impedance immediately following). There is, however, a basic calculation that can provide a rough idea of correspondence, at least from the point of view of human perception. Large cargo ships generate about 190-200 dB underwater and whales typically communicate at about 160 to 175 dB. If you want to convert the sound levels in air to sound levels in water, add 62 dB. Thus, a very loud sound like a 140 dB jet engine in air might equate roughly to a 202 dB roar in the water.

## Impedance

The concept of *impedance* is familiar to electricians and electronics engineers because they have to deal with the impedance levels of various materials in circuits and wiring distributions. Impedance is usually less familiar to lay readers who may not have encountered the concept and may not even be familiar with the term. Yet it helps to have a basic understanding of impedance because *decibel* measurements describing the 'loudness' or intensity of sound in one medium do not necessarily equate to the same levels in another medium. This is because of the *pressure* and *impedance* characteristics related to the medium.

To impede basically means to hinder. In electricity, impedance refers to a hindrance, an opposition, to current flowing through a circuit. In a sound-carrying medium, impedance refers to the *ratio of the pressure exerted* to the *volume displacement* within that medium. Water has a higher impedance level than air. What this means is that a 100 dB sound in air *isn't directly equivalent* to 100 dB in water. (To get a rough idea of the conversion, subtract 62 when converting air to water. Thus, 100 dB in air is about 48 dB in water and 180 dB in air is about 118 dB in water.)

To give some practical examples of sound travel in water that can be compared to sound travel in air as illustrated in the chart above, the intensities at which whales communicate underwater are typically from 175 to 190 dB and large ships (e.g., tankers) tend to generate louder sounds in the 190 to 200 dB intensity range. In fact, some scientists have suggested that whales may have been able to communicate for distances of more than 2,000 miles in the days before the shipping noise. Their communications range is now estimated to be a few hundred miles or less.

### Speed and Velocity

The speed of sound depends on the characteristics of the medium through which it moves since sound is essentially a disturbance or series of pressure waves in that medium. A wavelength of sound of a particular frequency in water is approximately four times as long as a corresponding wavelength in air. The speed of sound in water is approximately 1500 m/s whereas the speed of sound in room temperature air is approximately 340 m/s. Stated as an example, a message shouted from a beach to a boat 3,000 meters away takes about eight seconds to arrive at the boat, whereas the same message shouted from below the surface of the water to a dolphin or submerged hydrophone 3,000 meters away takes about two seconds.

Many things affect the speed of sound. If the medium through which sound travels is reasonably homogenous, like air or water, it is not too difficult to determine or predict how fast it will travel. If there are other substances present, however, especially those which might change periodically (dust or water vapor in air, kelp or sediment in water), the speed will be affected in less predictable ways and there will be increased scattering and absorption.

Temperature also affects sound. In water, as the temperature increases, the speed of sound decreases. As the depth, and hence the pressure, increases, the speed of sound increases. Sometimes the two effects counteract one another, as in deep oceans where pressure increases and temperature decreases. ???

When we talk about the *velocity* of sound, we are describing it not only in terms of its speed but also in terms of its direction. It's a handy way to describe two concepts together in one word. The concept of velocity is commonly used in physics to describe sound travel.

### Pressure

Sound pressure is expressed in terms of the force it exerts at one moment of time on a specified area, in most cases, the force it instantaneously exerts on one square meter. Sound pressure units are most often expressed as *micropascals* (µPa). One *pascal* (Pa) is the pressure of a force of one *Newton* exerted over one square meter.

Since this is just a basic introduction, it is recommended that you consult acoustics and physics texts listed in the Resources section for more advanced (and more precise) information. There is also a recommended site "An Introduction to Underwater Acoustics" that gives a good, short introduction at a level beyond the discussion here.
http://newport.pmel.noaa.gov/whales/acoustics.html

## 5.b. Basic Sonar Systems

Most of the aspects of basic sonar systems have been described in *Section 2. Types and Variations* and *Section 3. Context*. This section provides just a little extra information on some example systems and more are described in *Section 6. Applications*.

Most marine sonar systems are hull-mounted, towed, or self-contained. Sometimes the various systems are used in conjunction with one another.

### Hull-Mounted Systems

Hull-mounted sonar systems may be either active or passive and commonly have one or two transducers. The transducers are usually tuned to different frequencies, since range and noise-susceptibility vary with frequency. Hull-mounted transducers are usually not the highest in resolution but they can be used on a vessel that is charting an irregular course, whereas towed sonar works better if the course is even, slow, and straight. Hull-mounted systems are most often used for depth-sounding and navigation but may also be used for some detection purposes.

### Towed-Array Sonar

Towed systems tend to be higher in resolution and more often used in covert or in imaging applications. They are better at resolving small targets and are less subject to noise emanating from the towing vessel than a hull-mounted system. However, they can provide erroneous signals on turns or irregular moves and may not be suitable when vessels are used in evasive maneuvers.

Bearing-ambiguity-resolving sonar (BARS) is a system manufactured by British Aerospace to improve torpedo detection. The towed-array system provides rapid single-sensor location of incoming threats independent of the ship's maneuver or convergence-delay requirements. In 1997, the U.S. Department of Defense selected a BARS project for the Foreign Comparative Testing (FCT) program.

### Sonobuoys

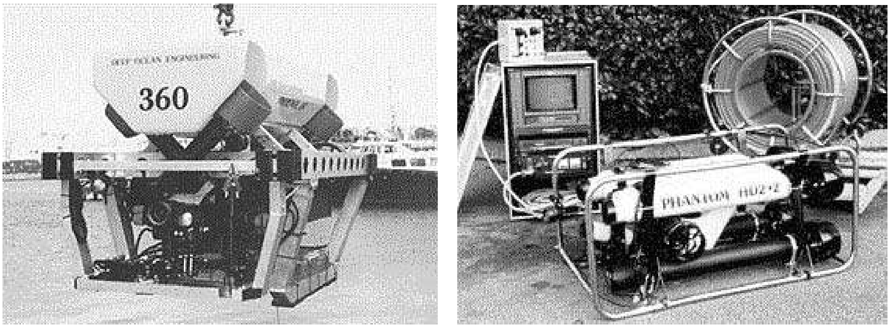
Sonobuoys can be dropped off and picked up later, contacted through sonar or through a cable for communications purposes, or can be designed to relay with communications satellites. They can collect data over a period of time and relay the data or store it until they are picked up. Sonobuoys are most often used for environmental research or tactical communications.

## 5.c. Remote-Controlled and Autonomous Vehicles

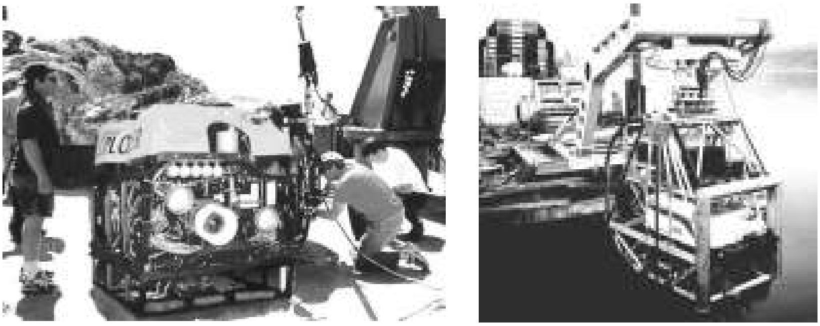
*With improvements in fiber-optic communications and radio transmitters, there has been an increasing interest in self-contained, remote-controlled, and autonomous vehicles for underwater applications. Since the vessels are often less expensive to build and operate than piloted vehicles, and since there is less danger of loss of life, they are suitable for some of the more dangerous search, rescue, and recovery missions.*

Sonar-equipped *remotely operated vehicles* (ROVs) and *autonomous underwater vehicles* (AUVs) are used for oceanographic research, insurance assessments, wreckage detection and recovery, structural engineering surveys and inspections, underwater repairs, underwater tunneling and drilling activities, cable-laying and mineral and gas exploration.

### Remote-Controlled Vehicles

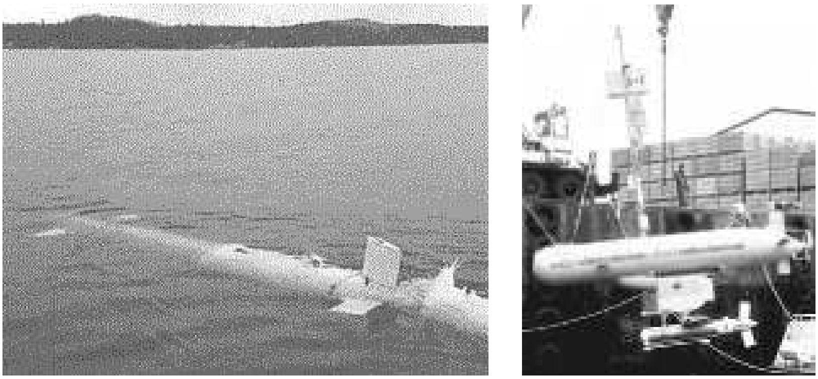


Examples of remotely operated vehicles. Left: The Phoenix LW is a deep-diving inspection and light work ROV. It can be used in inspecting underwater oil and tunnel work and mine countermeasures applications. It is controlled through fiber-optic telemetry. Right: The Phantom HD2+2 is a long-umbilical, multiple-sonar ROV suitable for contraband and evidence recoveries, inspections, and tunnel penetrations. It includes built-in video, auto-depth and heading, and accommodation for adding more sensors. [News photos courtesy of Deep Ocean Engineering, http://www.deepocean.com/]



Left: The HySub 25 built for Eastern Oceanics uses the ISE Advanced Telemetry Control System, a color camera, and 360-degree sector-scanning sonar. Right: The HySub 50 is a deep-seabed intervention system (DSIS) that has been supplied to the Canadian Department of Defence and was used at the Swissair 111 crash site. It features a cage, winch, and robotic manipulators, along with an ISE Advanced Telemetry Control System. [News Photos courtesy of ISE Ltd., http://www.ise.bc.ca/]

## Autonomous Vehicles and Robots



Left: The ARCS project was initiated to serve a need for an under-ice vehicle for hydrographic surveys for the Canadian Hydrographic Service. In 1986, it underwent obstacle-avoidance sonar trials. It was subsequently acquired instead by the Canadian Department of National Defence and became the forerunner of the larger Theseus Autonomous Underwater Vehicle. The vehicle uses a Data Sonics Acoustic Telemetry link, EDO 3050 Doppler Sonar and has a depth of about 400 meters. Right: The Dorado was developed to meet the growing need for systems to deal with deadly advanced mines. It is used by the Canadian Department of National Defence and is being sold with forward-deployed sidescanning sonar by DCN International of France. The system can pull a sonar-equipped towfish at speeds up to 12 knots and depths up to 200 meters. Lower depths provide stability for sidescanning sonar and the data can be transmitted through a 2.4 GHz radio transmission. [News photos courtesy of ISE Ltd., http://www.ise.bc.ca/]

## Robots

Robots are not really a distinct category from remotely operated and autonomous vehicles, but we tend to ascribe the term robots to mechanical/electronic devices that are smaller or friendlier or cuter, or more creature-like in one respect or another. The term *automaton* is also sometimes used. The more specific term *android* is reserved for robots which are distinctly human-like in their physiological and psychological makeups.

The Autonomous Lagrangian Circulation Explorer (ALACE) Float is an underwater robot developed by Davis and Webb which is neutrally buoyant and drifts for a month or so at depths up to about 680 meters, measuring the temperature of the marine environment. When its tour is complete, it rises to the surface and transmits the present location and its findings on temperature and salinity to a satellite. It then resubmerges and continues gathering information in this cyclic pattern for up to five years.

# 6. Applications

## 6.a. Depth Sounding

Acoustic devices are commonly used to measure the depth from a floating rig or marine vessel to the lake or ocean bottom. Depth sounders may also detect submerged objects that move between the sounder and the bottom. Since tides can dramatically affect the depth of water, depending on the season or time of day, it is important for vessel safety to know that the depth is sufficient to avoid dangerous obstacles or the chance of ‘bottoming out.’ A depth sounder can also be used to select fishing or diving locations.

Depth sounders are used for reconnaissance, hydrographic surveys, dredging operations, bridge building, and mineral prospecting. Depth sounders are widely used by marine forces, the U.S. Army Corps of Engineers, the National Oceanic and Atmospheric Administration (NOAA), corporate marine industrial companies, and others.

Depth sounders may be analog, digital, or both. Some can switch between analog and digital displays and others use separate screens for the two displays. Some units can interface with printers and some have memory buffers for storing a sequence of information or can upload to a computer. More sophisticated systems can provide an image of the data called a *bottom profile*.

When combined with computer processing and Global Positioning Systems (GPS) information, it is possible to take depth soundings from one location and compare them with another or to take soundings from one particular location and compare them with soundings taken at the same place at a different time. These could be overlaid on a computer screen or compared side-by-side.

Some of the variations on depth-sounding equipment that are of interest include

- Many new digital depth sounders can interface with existing analog depth sounders (or stand alone). These can further be connected to computer systems.
- A sounder may be equipped with an alarm to indicate that the depth has dropped below a certain predetermined level or user-selected level.
- Some depth sounders are self-contained, incorporating a transducer, others can be interfaced with the transducer as a separate unit, allowing a choice of transducers.
- Most depth sounders work on a single frequency or are switchable between two frequencies, but tunable sounders are also available. Dual-frequency sounders will sometimes display (or print) the results of the selected frequency as either a different shade or color.
- Some sounders must be used at slower speeds, others can be used at higher speeds.
- Depth sounders now come with a variety of ports for printers, computers, and video units, including VGA/SVGA, parallel, serial, keyboard, and floppy drive interfaces.
- More recent interferometry is being used for some depth-measuring applications.

## 6.b. Commercial and Sport Fishing

Sonar can be used to locate fish and other marine prey. Phased-array sonar is used in commercial ‘fish finders’ as well as in modern nuclear submarines.

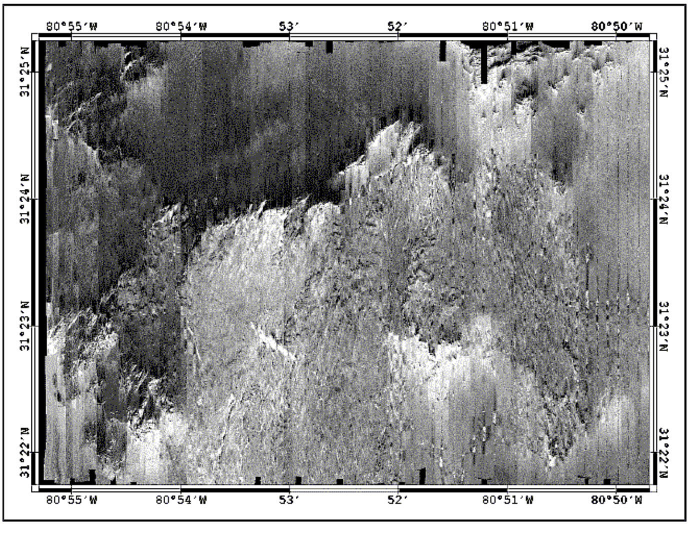
Identifying small objects can be pretty sophisticated technology. Many computer technologies have arisen from the development of resource- and speed-intensive video games and, similarly, many sonar technologies have arisen from the development of commercial products like fish-finders. After all, fish are much faster and smaller than submarines and just as anxious to avoid being caught. If you can resolve the technical problems of distinguishing small, moving fish in cluttered tidal regions, you can apply some of the knowledge to designing systems that can locate larger, slower-moving underwater structures and vessels.

## 6.c. Marine Mapping

*Terrain-mapping is used by marine geologists, biologists, and ecologists to study the characteristics and evolution of marine environments. It is also used by prospectors seeking shipwrecks, minerals, and gas deposits. Military strategists use it for mapping out underwater routes, strategic locations, and good sound channels for sending sonar messages.*

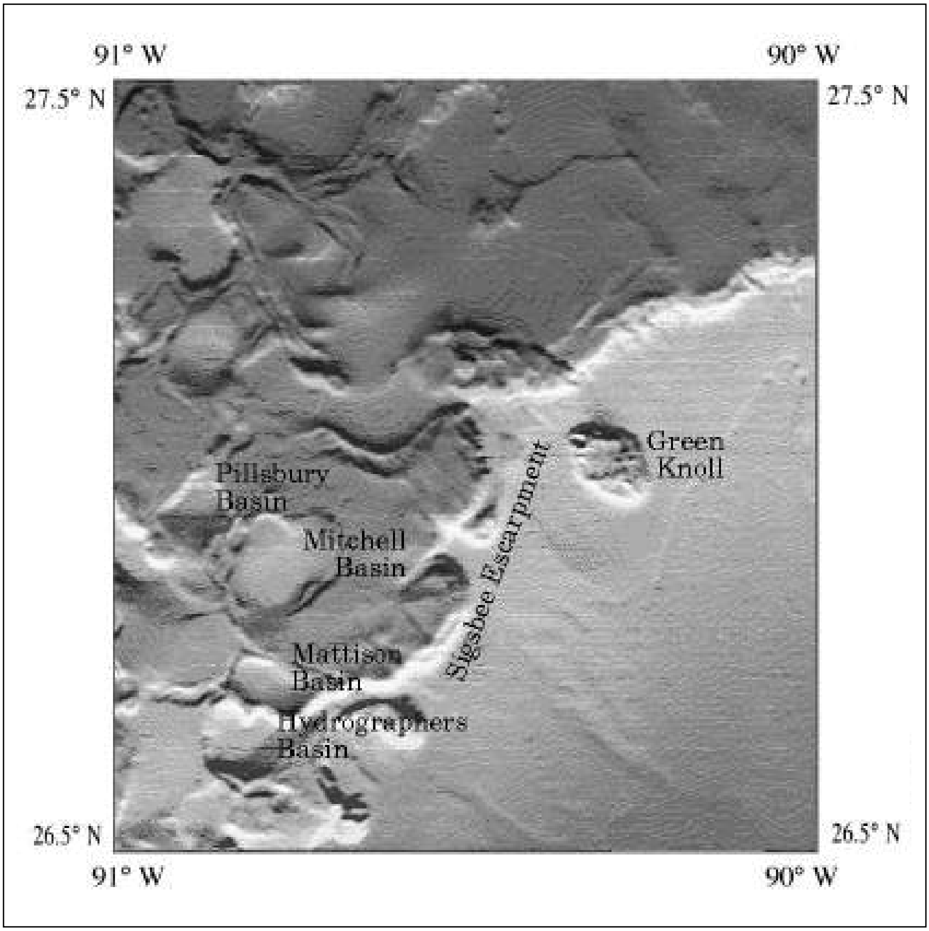
The U.S. Geological Survey (USGS) is one of the prominent departments engaged in surveying, mapping, and researching Earth’s environment, including the marine environment. Many of the surveys use digital sidescanning sonar, which collects data in swaths that are subsequently assembled into regional views. The images are further processed to correct for distortions and signal noise. When combined in sequence, the images can be viewed further as ‘flyby’ animations such as those seen in video games.

The USGS projects are funded with taxpayer dollars and an extensive library of images and MPEG animations is available to the public. The images can be download through the Web or by *anonymous ftp*. Here is an example of a composite digital mosaic.



Sidescanning sonar grayscale image of Gray’s Reef National Marine Sanctuary, Georgia, August 1994. A bathymetric map (map of depths) of this region is also available which uses ‘false color’ assignments to indicate the depths. [U.S. Geological Survey, public domain.]

The associated sonar mosaic and bathymetric images can be superimposed over one another to provide an image that incorporates both textural and depth information.



Sea-Beam Shaded-Relief Bathymetry. A shaded relief image combined with a NOS bathymetry false color image to provide a colored relief map (seen here in grayscale) that makes topological features clearer and easier to interpret. [U.S. Geological Survey, public domain.]

One of the important functions of marine mapping is to identify and monitor underwater hazards. When ships, submarines, and houseboats sink, they sometimes disappear under the silt and mud. Natural disasters or unusual tidal activity will sometimes uncover and move these objects to locations where they may pose hazards to shipping traffic. The U.S. Coast Guard marks these obstructions with buoys and will sometimes use sidescanning sonar mapping (sometimes through contractors) to locate potentially dangerous hazards.

The U.S. Coast guard contracted Aquatic Systems Corporation (ASC) to conduct a sidescan survey with their survey vessel, which was placed in a U.S. Army Corps of Engineers barge. The Coast Guard cutter Osage then placed buoys on identified obstructions to alert shipping traffic to the potential hazards. This particular survey of the Ohio River, after a major flooding episode, took seven days.

## 6.d. Active Submarine and Underwater Vessel Location

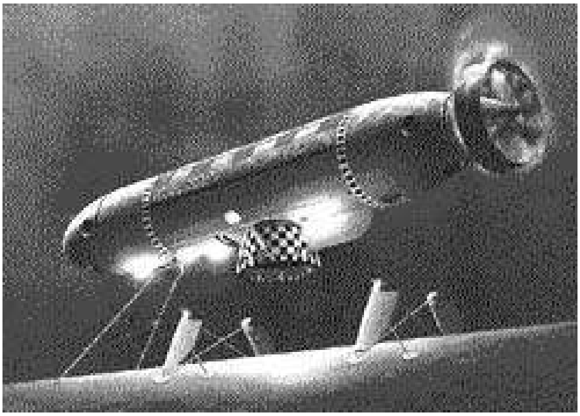
There are a number of marine vessel, coastal, and airborne surveillance systems especially designed for the detection of submarines. The Canadian Forces Sea King is an example of a ship-borne undersea surveillance and warfare (USW) helicopter that is carried aboard maritime frigates, replenishment ships, and destroyers. It is equipped to detect, locate, and optionally destroy hostile submarines. It is further equipped for surface surveillance, transport, and search and rescue missions. The Sikorsky Sea King uses forward-looking infrared radar and passive/active sonar.

Top Left: A U.S. Navy Seasprite helicopter is a ship-based helicopter with anti-submarine and anti-ship surveillance and targeting capabilities. Top Right: An SH-60 Blackhawk helicopter with a Helicopter Anti-Submarine Squadron hovering off the bow of the carrier USS Enterprise. Left: This Seahawk helicopter is from a Helicopter Anti-Submarine Squadron (HS-5) equipped with a *dipping sonar* which is submerged as the helicopter hovers only about 60 feet above the water. Right: Another Seahawk from the “Nightdippers” stopping for fuel on a range-reconnaissance mission. Seahawks are also used in search and rescue missions. [U.S. Navy 1996 news photos by Pat Cashing, Timothy Smith, Jim Vidrine, and Chris Vickers, released.]

Sometimes subs are located because they are in distress. In 1963, the USS Thresher was lost with all hands, at a time when rescue vehicles couldn’t reach subs that were very deep. Since that time, rescue vehicles have become more sophisticated and can locate and rescue crews that would have been unreachable in earlier times.

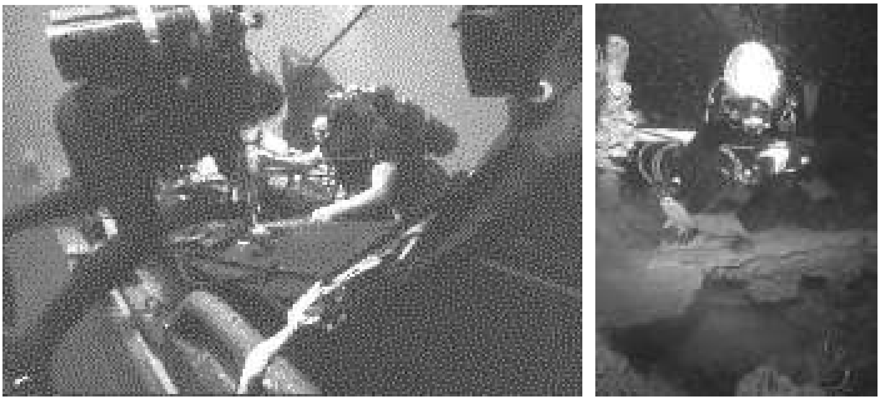
The U.S. Navy fleet of attack submarines is specifically designed to seek out and destroy any enemy submarines and surface ships. The Navy emphasizes the role of technology in this mandate. “The concept of technical superiority over numerical superiority was and still is the driving force in American submarine development." The attack submarines are also used for collection missions in intelligence operations. In 1989, the Navy began constructing their Seawolf-class submarines. These vessels are designed to be "exceptionally quiet" with advanced sensing capabilities.

Other technologies, such as magnetic surveillance in the form of magnetic anomaly detection (MAD) are sometimes used in conjunction with sonar.



The DSRV Deep-Submergence Rescue Vehicle is designed to perform rescue operations on disabled, submerged submarines. They are designed to be easily transported and deployed by truck, aircraft, or marine vessel, or by an appropriately fitted submarine. This 15-meter Lockheed Missiles and Space, Co. vessel can dive up to approximately 1500 meters, conduct a search via sonar, and attach itself to the sub's hatch in order to transfer up to 24 personnel to another location. It utilizes both search and navigation sonar systems. [U.S. Navy photo, released.]

## 6.e. Special Underwater Reconnaissance Missions



Left: U.S. Navy SEALs undergo rigorous training in underwater and parachuting operations. The underwater operations include a variety of reconnaissance, demolition, and clandestine operations in support of U.S. military objectives. Right: Divers involved in the detection and salvage of wreckage often carry handheld sonar devices and video cameras. [U.S. Navy photos, released.]

The U.S. Navy Benjamin Franklin-class subs are equipped for special operations and support the work of the Navy SEAL (Sea, Air, Land) groups (which evolved in 1962 from Combat Swimmer Reconnaissance Units). SEALs perform a wide variety of special functions and clandestine operations, as well as some that are more routine, including minesweeping. In 1983, the Underwater Demolition Teams (UDTs) were redesignated as SEAL teams, which added hydrographic reconnaissance and underwater demolition to the various SEAL responsibilities.

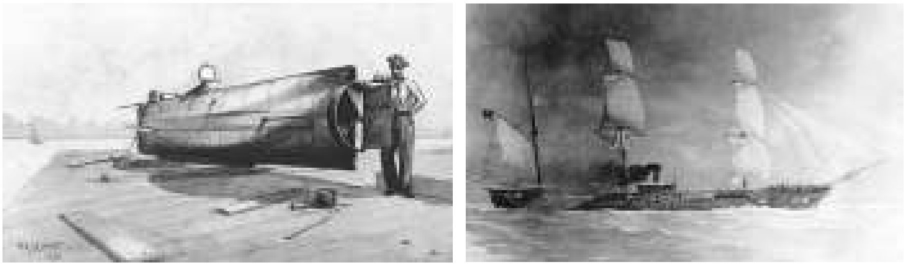
## 6.f. Undersea Wreckage Location and Recovery

*Sonar surveillance is an integral tool in the location of underwater wreckages including sunken ships, submarines, and downed aircraft. Divers have used sonar, acoustic listening devices, ultrasound, and remote-controlled vehicles to locate sunken vessels, and voice and data recorders (black boxes) from a number of commercial airline disasters. Often sonar is combined with cameras and radar. Here are just a few examples in which sound technologies have been used in conjunction with other surveillance technologies to locate and assess wreckages.*

### Submarine Recovery

The Confederate submarine H. L. Hunley is credited as the first submarine to sink a warship in battle. In the 1864 exchange, the Hunley itself sank. The Hunley has been evaluated in the murky waters in the past (e.g., 1996), but new technology made it possible to learn more about the submarine's structural status to aid in its recovery. Of special interest was whether any major corrosion or damage had occurred. A Coastal Inspection Inc. representative, Denis Donovan, worked with engineers to develop a custom ultrasonic transducer capable of measuring the thickness of civil war wrought iron to an accuracy of hundredths of an inch. This technology has applications in other aspects of surveillance as well.

Assessment and recovery of the Hunley also provide an example of how 'low tech' techniques are used. Molding putty was pressed against the hull in the murky waters to record impressions of surfaces, rivets, and seams. This molding technology can be applied above ground as well, in crime scene assessment, where putty or plaster may be used to record surfaces, footprints, or objects of interest.

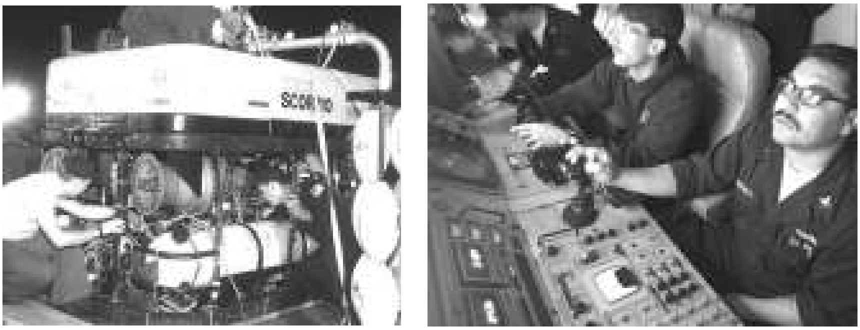


Using submarines for underwater surveillance was relatively new technology when the H. L. Hunley submarine (left) located and sank the USS Housatonic (right), an Ossipee class war sloop, in 1864. Submarine technology was so recent, in fact, that the sub was powered by eight people turning a hand-crank. The wreck of the Housatonic was dynamited at the turn of the 20th century to clear shipping lanes, but the Hunley was located by Clive Cussler with the National Underwater and Marine Agency (NUMA) in relatively good condition using surveillance devices that could probe the murky waters. [U.S. Navy historical archive photos of paintings by R. G. Skerrett.]

## Aircraft and Flight Recorder Location and Recovery

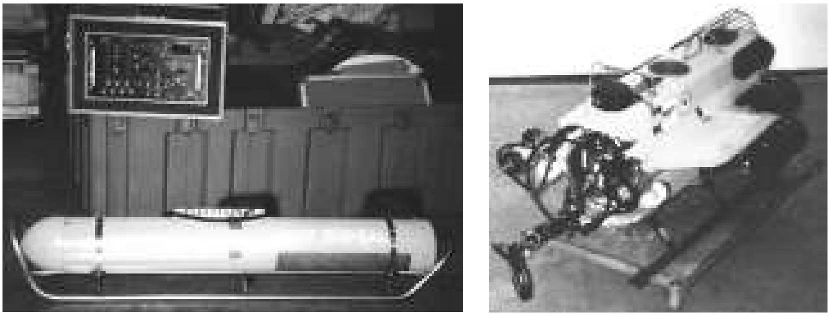
Left: A U.S. Navy-contracted representative, Andy Sherrell, of Oceaneering Advanced Tech is shown with headphones interfaced to an underwater acoustic locator. Sherrell was listening for pings from the downed EgyptAir Flight 990 flight recorder (black box). Right: The U.S. Navy Deep Drone 7200 remotely operated vehicle was used in the search and recovery of the EgyptAir flight. [U.S. Navy 1999 photo by Isaac D. Merriman.]

A support ship from the U.S. Navy fleet, the USS Grapple (ARS 53), provides remotely operated vehicle (ROV) and diving assistance at crash sites, including Swissair Flight 111 and EgyptAir flight 990. The rescue and salvage vessel is equipped with a variety of surveillance devices, including the Mobile Underwater Debris Survey System (MUDSS), synthetic-aperture sonar, and the Laser Electro-Optics Identification System, with which it can image details of the ocean floor. It further transports a Deep Drone remotely operated vehicle (top right) and provides equipment and support for divers. FBI Agent Duback is shown tagging the recovered cockpit voice recorder from EgyptAir Flight 990 (bottom left) which was located by the Deep Drone ROV and then flown to Washington, D.C., for analysis. [U.S. DoD 1998 and 1999 News Photos. USS Grapple by Todd P. Cichonowicz. Divers by Andy McKaskle. FBI-tagging photo by Isaac D. Merriman. ROV photo by Tina M. Ackerman.]



The SCORPIO (left) is the remotely operated marine surveillance vehicle (ROV) that successfully located the flight data recorders from downed Alaska flight 261 in February 2000. The pilots of the SCORPIO use video cameras and control panels to remotely monitor and steer the SCORPIO from on board the MV Kellie Chouest, a Submarine Support Ship. [U.S. DoD 2000 News Photos by August C. Sigur, and Spike Call.]

TWA 800, which went down in the ocean on 17 July 1996, was located by naval divers in approximately 150 feet of water off the coast of Long Island, New York, with handheld sonar sets, a towed pinger locator, GPS systems, and sidescanning sonar. A remote-controlled MiniROV vehicle which can dive to a depth of about 1,000 feet was also used.



Two types of technology used to probe the oceans are sensitive microphones and remote-controlled vehicles equipped with sonar. On the left is a U.S. Navy 'pinger locator,' a high-sensitivity underwater microphone, called a hydrophone, that is towed in the water to pick up marine signals. On the right is a sonar- and camera-equipped remote vehicle. Both were used to assist in the search and recovery of TWA flight 800 in 1996. [Photos: U.S. DoD 1996 News Photos by the U.S. Navy.]

A U.S. three-person, torpedo-bombing Douglas TBD-1 Devastator aircraft that crashed into the ocean in about 800 feet of water in 1943 was recently located by a diver and subsequently claimed by a private collector/salvager. This salvage operation is of interest because the collector staked a claim based on a videotape of the wreck by the diver and because there is a dispute over ownership claims between the collector and the federal government, with the initial judgment in favor of the collector. Similar cases are likely to occur as surveillance technologies improve. Many historic wrecks have been abandoned because the technologies did not exist to find or recover them. Now that location systems and diving/recovery equipment have greatly improved, private collectors are claiming ownership over the artifacts as 'abandoned' and the original owners are disputing the claims because they realize it is now possible to regain what they once thought was unrecoverable.

The National Underwater Marine Agency (NUMA) has used sonar to locate the wreck of the Carpathia, the ship that came to the rescue of the Titanic survivors in April 1912. The Carpathia was subsequently sunk by German U-boat torpedoes.

The 16th century wreck of the Mukran warship was located in the Baltic Sea in 1994 with a towed, color-imaging, sector-scanning sonar used in combination with radar buoy locators, GPS, and a video camera housed in a waterproof plastic ball that was towed at about two knots.

The USS Grapple (ARS 53) is a U.S. Navy rescue and salvage vessel which is dispatched to disaster sites in which planes, ships, or other wreckage are being sought underwater. It is equipped with synthetic-aperture radar (SAR) and a laser electro-optics identification system to create detailed images of the underwater terrain. It also has a number of diving systems and robotic vehicles to aid in search and recovery operations.

### Historic Artifacts Recovery

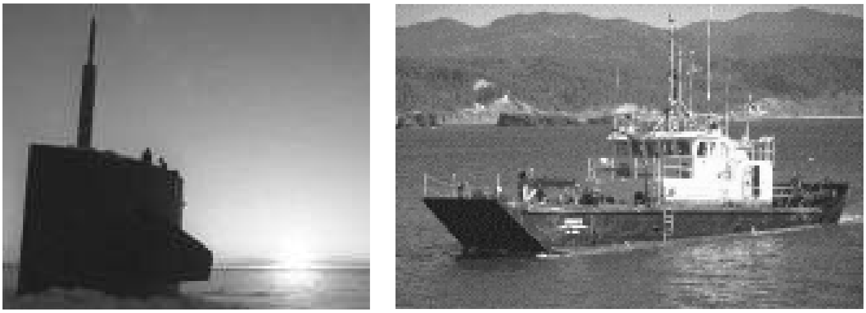
Many smaller items lost from sailing vessels, but not directly associated with shipwrecks have been located and recovered and many more remain to be found. Thousands of items old and new have been thrown from boats deliberately or accidentally during storms. Sometimes smugglers and poachers have unloaded contraband to avoid being caught, intending to come back later for the items (in shallower waters), but not always succeeding in relocating them. Many of these items are valued for their precious metals or gems or because they are historic collectors' items. Others have cultural and historic value for the stories they tell and the myths they confirm or deny. When items are lost in marine environments, sonar is one of the most important technologies used in detection and location.

- sidescanning sonar aided in the 1999 Underwater Atmospheric Systems, Inc. recovery of a ship's anchor identified by J. Delgado, Director of the Vancouver Maritime Museum, as being from the era of Captain Vancouver's explorations of the Pacific Northwest.
- years of sweeping the bottom of Lake Michigan with sidescanning sonar, allowed Harry Zych to discover the scattered debris of the Lady Elgin, sunk in 1860, with many historic artifacts of interest.

## 6.g. Scientific Research

*Sonar has many applications in scientific research, particularly the newer imaging systems that can create realistic terrain maps that resemble conventional grayscale photos. The stronger reflectors are actually imaged as dark areas on most systems, which give the appearance of a grayscale negative, but computerized systems will generally reverse the images so the 'highlights' are light and appear more natural to humans and thus are more easily interpreted as three-dimensional objects.*

The Remotely Operated Platform for Ocean Science (ROPOS) is a fiber-optic-controlled remote-sensing robot for deep sea research. It is Canada's primary means of reaching deep ocean terrain to a depth of almost 5,000 meters. The vehicle includes illuminators, mechanical arms, low-light video cameras, color imaging sonar, and instrumentation to carry out a variety of scientific and commercial tasks. ROPOS was lost at sea in 1996 during a severe west coast typhoon that partially disabled the American research vessel from which it was being operated. Surveillance aircraft were used to locate the lost robot vessel, but by the time recovery craft arrived, it had disappeared.



Left: The submarine USS Pogy (SSN 647) is primarily a frontline warship, but a portion of the torpedo room was converted into a research laboratory. It is shown here surfacing through an Arctic ice flow during a 45-day research mission to the North Pole in which data were collected on the chemical, biological, and physical properties of the Arctic Ocean. Geophysics, ice mechanics, and pollution were also studied. Right: A survey boat used for environmental missions by the Army Corps of Engineers. Sonar is used for a variety of surveys, including dredging and condition reports. [U.S. Navy 1996 photo by Steven H. Vanderwerff, released and U.S. Army Corps of Engineers 1995 photo, released.]

The Coast Guard Cutter Polar Sea (WAGB 11) has been providing support to scientific exploration in the polar regions since the 1970s. Its sister ship, the Polar Star (WAGB 12), has five laboratories and can accommodate up to 20 scientists for at-sea studies in fields such as geology, vulcanology, oceanography, and sea-ice physics. Here, Bill Chaney of Arctic Inc. is preparing to send a sonar measurement probe through a hole in the ice floe. [U.S. Coast Guard 1985 News Photo by C. S. Powell.]

In 1998, scientists used sonar and computer programs to survey the bottom of Lake Tahoe, which is gradually filling in and becoming more cloudy, due to erosion and the proliferation of algae. The results showed the lake to be shallower than expected, with a flat highly sedimented bottom. The sonar imaging provided a set of maps of the lake bottom topography which will aid ecologists and planners to budget and administrate a program to maintain the health of the lake.

## 6.h. Mine Detection

*There are many types of mine-detection technologies because there are many different types of mines. Metal detectors are not suitable for locating plastic mines; acoustic-triggered mines have to be located in different ways from vibration-triggered mines. Marine mines have different characteristics and visibility from land mines. There are moored mines, that trigger on contact, rocket-propelled mines, and vertical-rising mines.*

Sonar is one of the more important surveillance technologies for detecting underwater mines or navigating through them. Sidescanning and forward-looking are two of the common types of sonar configurations used in mine operations. A safe route through a marine minefield is called a *Q-route*. The process of detecting and disabling mines as they are encountered en route is known as *in-stride breaching*.

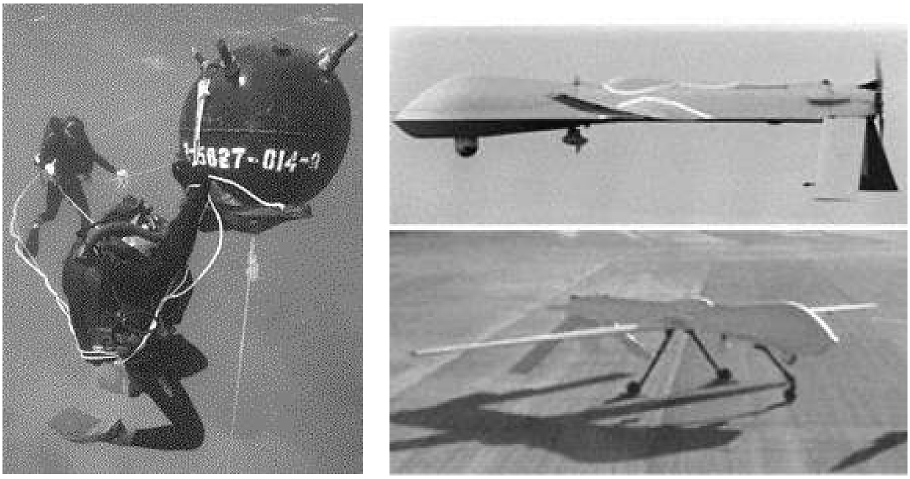
Mines have been used by many nations over the years, not only for warfare but, in some cases, to aggressively assert territorial rights over precious coastline resources. Unrecovered mines from previous wars still lurk in the ground and in the water and both military and commercial vessels need to be aware of their presence and danger. Almost three-quarters of the damage to U.S. Navy ships in the late 1980s and early 1990s is reported to have been caused by mines [Kaminski, 1996]. With the breakup of the Soviet Union, a large quantity of sea mines, estimated at almost half a million, became potentially available for purchase by various other nations. It has been estimated that more ship casualties can be attributed to mine detonations than to missile, submarine, and air attacks since 1950 [Baus, 1996].

Responding to the challenge of marine mines, the U.S. armed forces have formed a number of centers and strategies over the years, including the Army's Mine Warfare Center, and the Navy's Mine/Countermine Command Center. Centers like these, along with Marine Corps systems, provide coordination and communication for land and underwater mine detection and clearing strategies.

- New detection technologies deployed from ships and submarines include unpiloted aerial vehicles like the Predator. The Predator can communicate with a host vessel many miles away through a super-high-frequency-gain flat-plate antenna mounted on the controlling vessel. A computer controls the direction of the antenna and a control console rebroadcasts the video through a joint deployable intelligence support system (JDISS) terminal inside the host.
- The Falcon (MHC 59) and the Cardinal (MHC 60) are examples of U.S. Navy Osprey-class coastal mine hunters. They are equipped with high-definition, variable-depth sonar systems and remotely operated submarines for neutralizing mines. The vessels were commissioned along with the Shrike, in 1997, to form a fleet of 12 Osprey-class ships. There have been two previous Navy minesweepers with the name Falcon, one which conducted rescue and salvage during World War II, in operation from 1918 to 1946, and the AMS 190, which operated from 1954 to 1976. Three previous Cardinal minesweepers have also patroled coastal waters.
- In 1945, a ship called Robin helped to clear the mine barrage in the North Sea. In 1996, a minesweeper of the same name was commissioned as the fourth of 12 Osprey-class ships authorized by Congress. These large mine-hunting ships are built entirely of fiberglass. They are used for reconnaissance, classification, and neutralization of moored and bottle mines in harbors and coastal waterways. Robin uses a high-definition, variable-depth sonar and a remotely piloted vehicle for reconnaissance activities.

- In 1998, the USS Raven (MHC 61) was added as a U.S. Naval Osprey-class minehunter. The vessel is designed to clear harbor, coastal, and ocean waters of mines using a high-resolution sonar system and a remotely piloted mine-neutralization vehicle.
- The minesweepers are typically equipped with hulls with very low magnetic and acoustic signatures, to reduce the chance of detection, and are constructed with fiberglass to absorb the shock of a mine explosion.

Marine minesweepers now typically use a combination of ships and remote-controlled or autonomous vessels to locate and disable mines. Recent improvements in high-resolution sonar systems have resulted in significantly improved signal and image quality making it easier to identify and locate mines, which can be quite small and yet still deadly.



Sonar is important in locating minefields and navigating around or through them. Left: In a training exercise, U.S. Navy divers attach an inert satchel charge to a marine mine. Right: The Predator unpiloted drone can be launched from a submarine or ship to provide aerial reconnaissance of surface and underwater objects and hostile weapons-launching systems along coastlines. [U.S. DoD 1997 News Photos by Andrew McKaskle, Jeffrey Viano, and Linda D. Kozaryn, released.]

The dolphin squad, described in more detail in Chapter 18, is also used to detect mines through natural sonar. The dolphins, which are quite social and interested in interacting with people, have also been trained to attach neutralization devices to mines Sea lions have good underwater senses as well, and have been trained to a limited extent, but they are a little less serious about their work than dolphins, and appear to be more interested in pursuing extracurricular activities.

## 6.i. Military Applications and Intelligence-Gathering

*Information contributing to a body of intelligence is rarely gathered with just one device or type of technology. Sonar is only one category of device that is used to surveil bodies of water; most naval reconnaissance vessels use a combination of sonar, radar, and optical technologies (especially visual and infrared). Marine intelligence vessels are routinely equipped with multiple antennas and display and control consoles.*

There are a variety of types of seagoing intelligence-gathering vessels operated by nations such as Russia. Top Left: The Soviet Moma-class intelligence collector Seliger underway during a NATO exercise in 1986. Top Right: A Soviet Okean-class intelligence collection ship in a NATO exercise in the North Atlantic in 1986. Bottom: Balzam-class Russian intelligence collector, Belmorye (SSV-571) patrolling near Cuba and the U.S. east coast in 1993. [Photos: U.S. DoD Released Photos by Jeff Hilton (top) and unknown (bottom).]

### Military Applications

The military forces make extensive use of acoustic sensing devices for oceanographic terrain mapping, navigational charting, submarine detection, search and rescue, targeting, tracking, and wreckage detection and recovery. To counter hostile threats over the decades, the U.S. Navy has been particularly active in developing and improving acoustic-sensing technologies. Examples of some of the more recent and relevant projects include

*Advanced Deployable System* - A short-term, undersea, rapidly deployable surveillance system for monitoring submarine and other underwater vessels in shallow littoral regions. It is designed to use a large-area field array of passive acoustic sensors interconnected and tethered through fiber-optic transmissions cables.

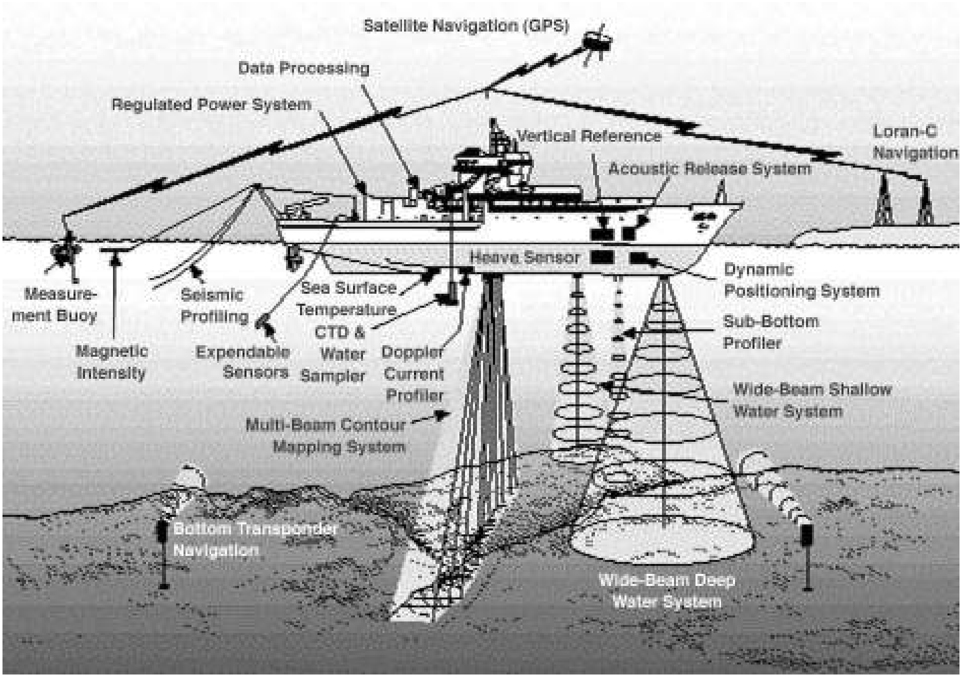
*Distant Thunder* - A project for the development of advanced signal-processing techniques for shallow water coastal environments which uses computer algorithms to process the target echo data received from low-frequency active (LFA) sources.

*AUTEC range systems* - The Undersea Test and Evaluation Center has been using a variety of acoustic beacons and underwater acoustic telemetry to create tracking systems for use both above and beneath the surface. These can be used for both firing platforms and targets. These systems can further be adapted for two-way communications systems. The Underwater Digital Acoustic Telemetry (UDAT) system provides modem-based, bidirectional communications. Outgoing data from the submarines are transmitted through a broadband, low-frequency transducer which doubles as the acoustic tracking device (a range pinger).

*Autonomous and Remotely Operated Vehicles* - The USNS Mohawk, for example, is equipped with a mini-rover MR-2, a remotely operated vehicle, a passive pinger-locator that is towed behind the vessel, and a shallow-water intermediate search system (SWIS), which is a sidescanning sonar. The pinger generally sounds the first alert, and then sidescanning sonar can comb the area more thoroughly, with the mini-rover to follow up with a camera and finally, with divers. The divers can take hand-held sonar devices which can detect signals from reflective objects and pinger locators.

*Weapons Guidance Simulations* - Since it is costly and sometimes dangerous to conduct live weapons training with new recruits, simulations are increasingly used for orientation and initial preparation. One such system at the Warfare Analysis Facility (WAF), uses a supercomputer to simulate the underwater acoustic environment and torpedo-target geometry. The software generates a representation of what the torpedo 'hears' through its travels. Acoustic input stimulates the torpedo's guidance system which, in turn, responds with appropriate steering commands to the computer system.

The Navy oceanographic program studies the influence of oceans on weapons and sensors in terms of both design and performance. The oceanographic ships aid in this research.



This U.S. Navy drawing illustrates the wide range of sensors that are used on the oceanographic survey fleet. Almost every type of data is collected from acoustical information to magnetic intensity, and seismic profiling. Both narrow- and wide-beam sonar are installed, along with measurement sonobuoys and satellite communications systems.

# 7. Problems and Limitations

*Since sound travels slowly through air compared to electromagnetic energy, but quickly through water, its use in above-ground surveillance is somewhat limited.*

The most common problems with acoustic technologies are typically *attenuation*, the gradual loss of signal, and *interference*, noise from undesired sources or from the inherent characteristics of the medium. There are many other limitations associated more specifically with sonar, and not all are discussed here, but there are enough to illustrate the main technical difficulties that occur with the technology.

## 7.a. Interference and Aberrations

Marine environments are greatly varied in texture, pressure, heat, and the presence and characteristics of living organisms. Movement can cause waves, surges, eddies, and bubbles, all of which may impact a sonar signal and attenuate it or alter its character or create a *discontinuity*. Here are some common sources of problems:

- The rhythmic jouncing motion of a vessel with a mounted sonar or a towfish is known as *heave* and may create artifacts in the sonar image. Significant interference with the signal resulting from water that is rough at the surface can increase *clutter*.
- Unwanted aberrations called *kiting* can result from the side-by-side motion of a long cable or trailing towfish.
- Bubbles can persist for some time, particularly in rough water or in the wake of a large vessel, and can significantly diminish a sonar signal in a process called *cavitation* that adds *noise* to the signal.
- Cavitation can arise not just from bubbles in rough water, but also from the acoustic effects of transducers placed close together. With the increasing prevalence of sonar arrays with finer and finer elements, cavitation from acoustics alone can be a serious problem. The U.S. Navy has been working on array-organization and the use of rubber separating materials to help minimize this problem.

In the case of fixed sonar transducers attached to a boat, it is generally advisable to place them in line with the azimuth of the vessel. The azimuth is the horizontal direction which is expressed as the angular distance between the heading of the vessel and the direction of the transducer. This is recommended in vessels that do not permit beam-steering (the beam is the broadest point across the width of the boat).

Other types of interference, from signals bouncing off terrain or noise generated by other vessels can also be a problem. For broadband sonar, systems of multiple receivers arranged in an array have been proposed for determining the strength and direction of the signals based on time-of-arrival at different receivers in the array, to process out the spurious information (e.g., Bourdelais interference-canceling, 1999).

## 7.b. Depth Sounding and Navigation

In many cases, the echo sounder must be set to point straight down, limiting the range of 'visibility.' In depth-sounding maneuvers where a vessel is moving back and forth along a region to map the terrain below, there can be aberrations in the data each time the vessel turns and there may be channels in the center (blank spots) and gaps in the track between successive tracks. Sidescanning sonar can overcome some of the limitations of channels and track gaps if the successive tracks (swaths) are overlapping. This takes longer, as some of the data will be redundant, but it also provides a more accurate reading of the terrain.

New interferometric technologies are overcoming some of the limitations of basic depth-sounders. These can survey a region up to eight times faster than a traditional depth-sounder, provide good three-dimensional data, and have a much wider angular coverage. They also require more careful installation and calibration, and a higher degree of computer processing.

Ambient noise problems are gradually being analyzed, predicted, and corrected-for with computer algorithms and digital signals processing, so there have been many improvements in the last half decade. Some inventors have even sought out ways to use the noise and clutter as reference points rather than screening them out, yielding some interesting results, particularly in littoral environments.

Ice has been problematic in the use of sonar, so polar ice prediction models (PIPS) have been developed to create energy disruption fields to indicate pressure ridge formations. Radar is sometimes used in conjunction with sonar to give a bigger picture of obstacles and their characteristics.

## 7.c. Ecosystem Disruption and Preservation

### Undersea Life

It is important to keep in mind that the oceans are home to many sensitive forms of life. Over the last century, the noise from shipping alone has reduced the effective communication distance of whales, in addition to possibly damaging the hearing of a variety of marine creatures.

Sonar is an important communications and sensing capability of many marine mammals. Synthetically generated low-frequency active (LFA) sonar from marine vessels may significantly endanger the hearing and physical well-being of human divers and the hearing, communication, breeding, and social structures of marine mammals such as whales. LFA sonar involves sending high-decibel, low-frequency sound waves through bodies of water. It is one of the technologies used to detect submarines. Current LFA systems operate at about 180 dB with potential up to about 260 dB with a field range of about 2 kilometers with source level at the transmission point at about 250 dB.

The U.S. Marine Mammal Commission has released reports describing evidence of trauma and disruptions to marine life from LFA sonar testing and deployment and the Natural Resources Defense Council has issued statements regarding the potential dangers of LFA to marine life. http://www.nrdc.org/

### Waste Monitoring

Another environmental aspect in which sonar is important is in the detection and monitoring of garbage and other wastes that are deposited by lake and ocean-going vessels.

Sonar is used to help monitor industrial and radioactive wastes that have accidentally or intentionally been deposited on seabeds and lake bottoms. It is not uncommon for industrial wastes to be stored in drums and dropped overboard to rest on the bottom of the sea. On other occasions, tankers with drums of PCBs, industrial effluent, medical waste, and nuclear waste sometimes lose parts of their loads or sink, leaving toxic materials at the mercy of the corrosive seawater. Sonar allows the containers and wrecks to be located and monitored. It is extremely difficult to recover or neutralize these oceanic waste dumps, but at least sonar can provide information on when the materials might leak or become dangerous to nearby shipping and marine life.

### Resource Exploration, Conservation, and Management

Sonar can be used to find new forms of life deep under the sea, to study thermal emissions, coral, and caves. It is further used to prospect for resources such as minerals, oils, and gas.

The monitoring of marine populations, particularly fish and endangered species, is carried out with help from sound-sensing systems. Conservation organizations can track the progress of protected and returning species and keep watch for violations and problems. Fisheries organizations use sonar to monitor and estimate fish migrations and numbers and use the information to manage fisheries permits, quotas, and species restrictions in order to help ensure resources for the future.

## 7.d. Image Interpretation and Analysis

It is important to take into consideration the limitations of sound travel through water when interpreting sonar data and images derived from mapping operations. Differences in the properties of thermal or sediment layers in the water can distort an image. Shadows can be misleading if their origins and characteristics are not understood. For example, sidescanning sonars not only will commonly have a ‘black spot’ in the center of the channel between right and left scans, but the shadows on either side of the scan will fall away from one another. These ‘shadows’ are not the result of light from the sun or other illumination, but rather the result of lower reflectance or complete absence of reflectance of the sides of obstacles not facing the origin of the scan.

A towed sonar system often has to be swept back and forth over a specific area. Care must be taken to interpret the information gathered during a turn, because misleading angles or anomalies in the signal related to the turn might look like actual structures in a sonar image. It is best to sweep in such a way that the turns are reimaged in another straight swath to provide good data, if possible.

## 7.e. Satellite Communications

Tactical satellite communications from submarines and other underwater vessels can be accomplished at the water’s surface, using radio waves, or for covert operations under the water’s surface using electrical signals sent to a sonobuoy through a tether. This has advantages of flexibility and lower visibility, but also has disadvantages. Typically the communications buoy must be connected to the underwater vessel, limiting the physical range and increasing the chance of detection when the buoy is communicating with a satellite or other receiver. The vessel is also more likely to be spotted if it is making noise near the surface or is near enough to be spotted by patroling aircraft.

If the vessel is engaged in untethered communications using sound (similar to using a wireless modem, except with sound rather than radio waves), then there is the danger that the sound signal itself may be intercepted by passive listening devices. Other limitations with sound communications include the slower data rates and greater susceptibility of noise. (See the Magnetic Surveillance chapter for some alternate solutions to submarine/satellite communications.)

# 8. Restrictions and Regulations

### Export Restrictions

Sound-sensing, more than ever, is dependent upon computer processing. This is especially true of acoustic guidance systems, sound communications, and high-resolution imaging systems. The export of software from the U.S. is restricted in many way. Thus, source codes for target detection and analysis and other acoustic technologies may not be exportable. In other words, American vendors can't sell some of their sound-related technologies on the global market.

### Underwater Diving and Salvage Operations

Acoustic surveillance technologies are frequently used to locate downed vessels and old sunken wrecks. There are a variety of local and federal laws and regulations concerning the preservation and salvage of sunken wrecks, especially those belonging to current commercial organizations and the Armed Forces. A sampling of the federal acts and regulations of relevance include

Archaeological and Historic Preservation Act of 1974 (16 U.S.C. 469)

Abandoned Shipwreck Act of 1987 (43 U.S.C. 2101)

Abandoned Shipwreck Act Guidelines (55 FR 50116)

Protection of Historic Properties (36 CFR 800)

Recovery of Scientific, Prehistoric, Historic, and Archaeological Data (36 CRF 66)

These laws have been debated in the courts quite vigorously since new technologies have become available. Divers using new sonar devices can now find and recover artifacts and vessels that were apparently abandoned, while those who have abandoned them are suddenly claiming prior rights. It is best to look up some of the recent cases on wreck diving and ownership, because the laws in this area are by no means clear or easy to anticipate with certainty.

# 9. Implications of Use

Because sound ranging equipment is mainly used for underwater navigation, scientific research, and national defense, there has not been a lot of political conflict over its use, compared to telephone wiretapping, for example. It is considered a valuable tool, much like a flashlight or hammer, and is not perceived as an immediate threat to the security of daily life.

One area in which there is continuing controversy is over the use of high-decibel sound as a potential underwater weapon or sensing device. Testing a high-decibel sound wave underwater is somewhat like testing high explosives above ground. The noise and shock-waves can be disturbing or very dangerous to any life, including humans, nearby. By the same reasoning, powerful soundwaves under the water have the potential to significantly disrupt the aquatic flora and fauna, particularly the acutely sensitive hearing of aquatic mammals, including dolphins, whales, and sea lions. The blast of a bomb near a person's ear can cause irreparable damage. Clearly it is possible that the blast of a sound wave near a dolphin, whose hearing is far more sensitive and essential to its survival than a human's, may also create irreparable damage.

# 10. Resources

*Inclusion of the following companies does not constitute nor imply an endorsement of their products and services and, conversely, does not imply their endorsement of the contents of this text.*

## 10.a. Organizations

**Acoustical Society of America** (ASA) - ASA is an international scientific society dedicated to research and dissemination of knowledge about the theory and practical applications of acoustics. ASA sponsors annual international meetings and annual Science Writers Awards for articles about acoustics. The site includes digitized whale calls and other underwater sounds. http://asa.aip.org/ http://www.acoustics.org/

**Centre for the History of Defence Electronics** - In addition to general information on defense, the organization holds colloquia on specific topics, including a Sonar History colloquium in 1996 (information or contacts from this may still be available). Bournemouth University, School of Conservation Sciences. http://old.britcoun.org/eis/profiles/bourneuni/bmthfacl.htm

**Coastal Ocean Acoustic Center** - Involved in the development of the Pt. Sur Ocean Acoustic Observatory for undersea research which came about when the Navy was downsizing and preparing to abandon much of the Sound Surveillance System that stretched 25 miles out to sea, it has now been converted to a research platform. In addition to Acoustic Thermometry studies, there is a hydrophone operating at a depth of more than a mile which can be used to study the communications and migration patterns of whales. Information is available through the Naval Postgraduate School.

**Defence Evaluation and Research Agency** (DERA) - A U.K. Ministry of Defence agency involved with non-nuclear research, technology, testing, and evaluation. DERA, with a staff of about 12,000, is one of Britain's largest research facilities, involved with research and testing of aviation technologies, electronics, command and information systems, sensors, weapons systems, and space technologies. DERA provides research data on airborne radar, target recognition techniques, and active/passive microwave ground radar systems. http://www.dra.hmg.gb/

**The Federation of American Scientists** - A privately funded, nonprofit research, analysis, and advocacy organization focusing on science, technology, and public policy, especially in matters of global security, weapons science and policies, and space policies. Sponsors include a large number of Nobel Prize Laureates. FAS evolved from the Federation of Atomic Scientists in 1945. The site contains numerous surveillance, guidance systems, U.S. Naval documentation, and other radar-related information. http://www.fas.org/index.html

**Large Cavitation Channel** - The world's largest underwater acoustic research and development facility being developed by the David Taylor Research Center in Tennessee. Information is available through the Oak Ridge National Laboratory. http://www.ic.ornl.gov/HTML/ic94156.html

**Marine Corps Intelligence Association** (MCIA) - MCIA supports U.S. Marines and their counterparts who participate in collecting, processing, and analyzing intelligence data and products. MCIA is based in Quantico, VA. and publishes INTSUM, a quarterly journal, for its members. http://mcia-inc.org/

**Military Sealift Command** (MSC) - One of three commands reporting to the U.S. Transportation Command, MSC is associated with national security and specifically involved in marine salvage, oceanographic surveys, and replenishment. Sonar is one of the important technologies used for accomplishing these goals and the MSC handles a number of submarine support ships through the Washington, D.C. Navy Yard. The Special Missions Program provides services for the U.S. military and federal government including underwater surveillance, flight data collection and tracking, acoustic research, submarine support, and oceanographic and hydrographic surveys. Multibeam sonar is one of the technologies used by MSC to chart the ocean floor and most of the world's coastlines.

These data provide information that helps ensure safe marine surface navigation, supports submarine navigation and cables, and aids in weapons testing and the detection of hostile vessels. There is additional information and many photographs of the fleet on MSC's extensive Web site.
http://www.msc.navy.mil/

**National Oceanographic Atmospheric Administration** (NOAA) - This important organization provides a great deal of practical and educational oceanographic information. NOAA serves as a sales agent for the National Imagery and Mapping Agency (NIMA) and provides nautical charts available to the public. NOAA also includes the National Marine Fisheries Service (NMFS). MapTech is a free online resource that houses the largest source of NOAA digital charts and USGS topographic maps in the world. http://www.noaa.gov/ http://www.maptech.com/

**National Sonar Association** (NSA) - A nonprofit organization founded by Frank Crawford in 1982 to bring together the various sonar and sound technicians who worked in a variety of fields, without regard to time in service or career status. Publishes The Ping Jockey. The organization sponsors reunions to keep alive the knowledge, experiences, and social contacts of the organization's members. http://www.sonarshack.org/

**National Underwater and Marine Agency** (NUMA) - A nonprofit, volunteer and membership-supported foundation, founded in 1979. NUMA investigates, reports, and preserves our marine heritage by locating sunken vessels using a variety of search and surveillance technologies. For example, NUMA used *scan sonar* to pinpoint the location of the sunken Carpathia, the ship that rescued the survivors of the sunken Titanic but which succumbed to German U-boat torpedoes in 1918. http://www.numa.net/

**Naval Command, Control and Ocean Surveillance Center** (NCCOSC) - Established in 1992, this center operates the Navy's research, development, testing, engineering, and fleet support for command, control, and communications systems and ocean surveillance. NCCOSC reports to the Space and Naval Warfare Systems Command (NAVSEA). http://www.nswc.navy.mil/

**Naval Historical Center** (NHC) - The NHC has an Underwater Archaeology Branch which uses a number of surveillance technologies to locate, assess, and document sunken vessels of archaeological interest. Projects have included the location and excavation of battleships and submarines going back to the Civil War.

**Naval Intelligence Foundation** (NIF) - A nonprofit organization founded in 1989 in response to a 1986 bequest given to the Navy and Marine Corps Intelligence Training Center (NMITC). NIF seeks to preserve, advocate, and support the culture and heritage of naval intelligence and to recognize and reward achievement on the part of active duty intelligence personnel. NIF is closely affiliated with NIP and has no membership per se (see next listing)

**Naval Intelligence Professionals** (NIP) - Founded in 1985, this nonprofit organization aims to further knowledge of the art of maritime intelligence and to further camaraderie among naval intelligence professionals. Members include retired and active duty service members and civilians who serve within the naval intelligence community. NIP publishes a quarterly journal and maintains an email discussion list. http://www.xmission.com/~nip/

**Naval Research Laboratory** (NRL) - The NRL conducts multidisciplinary programs of scientific research and advanced technological development of maritime applications and related technologies as well as Internet security projects. The NRL reports to the Chief of Naval Research (CNR). The Navy also has an Acoustic Research Detachment in Bayview, Idaho.

**Naval Surface Warfare Center** (NSWC) - Established in 1992, this center operates the Navy's research, development, testing, and fleet support for ship's hulls, mechanical, weapons, and electrical systems. NSWC reports to the Naval Sea Systems Command. http://www.nswc.navy.mil/

**Naval Undersea Warfare Center** (NUWC) - Established in 1992, this center engages in research, development, testing, and fleet support for submarines and other underwater vessels and weapons systems. NUWC reports to the Naval Sea Systems Command (NAVSEA). http://www.nswc.navy.mil/

**Ocean Mammal Institute** (OMI) - A public awareness, research, and educational organization for the study and preservation of marine mammals. The Web site includes an information page on low-frequency active (LFA) sonar and its possible effects on marine life.
http://www.oceanmammalinst.com/

**U.S. Army Corps of Engineers** (USACE) - This corps is involved in research and development, navigation, flood control, environmental programs, and military construction. These tasks often involve work in marine environments involving the use of sonar. http://www.usace.army.mil/

**U.S. Geological Survey** (USGS) - The Coastal and Marine Geology Program department of the USGS conducts systematic geological mapping of coastal and marine environments and provides a seafloor mapping server online. Sidescan-sonar surveys are described and illustrated. Track maps can be downloaded in PostScript (vector) or GIF (raster) formats. http://kai.er.usgs.gov/

**U.S. Naval Intelligence** - Part of the Central Intelligence Agency, Naval Intelligence supports the Department of the Navy and the maritime intelligence requirements of various national agencies. It is located primarily in the National Maritime Intelligence Center in Maryland. http://www.odci.gov/
See also the Space and Naval Warfare Systems Center. http://www.nosc.mil

**U.S. Naval Salvage and Diving** - Uses Global Positioning System (GPS) and stationary and hand-held sonar devices to located sunken marine vessels, aircraft, and debris.

**U.S. Office of Naval Research** (ONR) - The ONR coordinates, executes, and promotes the science and technology programs of the U.S. Navy and Marine Corps through educational institutions, government labs, and a variety of organizations. ONR carries out its mandates through the Naval Research Laboratory (NRL), the International Field Office, the Naval Science Assistance Program (NSAP), and the Naval Reserve Science & Technology Program. ONR reports to the Secretary of the Navy and is based in Arlington, VA. http://www.onr.navy.mil/

**U.S. ONR Center for Autonomous Underwater Vehicle (AUV) Research** - Founded in 1987, through an interest in using unpiloted underwater vehicles for covert mine countermeasures, the Center has since expanded to include other types of surveillance and commercial monitoring. These craft are especially useful in shallow waters where it's difficult or dangerous to operate other types of vessels.
http://www.cs.nps.navy.mil/research/auv/

**U.S. Space and Naval Warfare Systems Command** (SPAWAR) - This department designs, acquires, and supports systems for the collection, coordination, analysis, and presentation of complex information to U.S. leaders. http://agena.spawar.navy.mil/

**Woods Hole Oceanographic Institution** - This prominent private, nonprofit research and education organization founded in 1930 includes an Ocean Acoustics Lab with information and publications on acoustic tomography, acoustic scattering, acoustic-mode coupling, and many other acoustic-related topics. http://www.oal.whoi.edu/

## 10.b. Print

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### Journals

"All Hands," monthly U.S. Navy publication from the Naval Media Center.

"Applied Acoustics," monthly U.K. journal.

"Journal of the Acoustical Society of America," monthly professional journal.

"Naval War College Review," a collection of articles and essays about Naval history, politics, technology, and strategies. 1992 to present are archived online.
http://www.nwc.navy.mil/press/Review/revind.htm

"The Ping Jockey," the official publication of the National Sonar Association nonprofit organization.

"Sea Technology," Compass Publications, Inc. A recognized authority for ocean design and engineering applications. http://www.sea-technology.com/

"Undersea Warfare," the official professional magazine of the U.S. Submarine Force. The general public may subscribe through the Superintendent of Documents.

## 10.c. Conferences and Workshops

*Many of these conferences are annual events that are held at approximately the same time each year, so even if the conference listings are outdated, they can still help you determine the frequency and sometimes the time of year of upcoming events. It is very common for international conferences to be held in a different city each year, so contact the organizers for current locations.*

*Many of these organizations describe the upcoming conferences on the Web and may also archive conference proceedings for purchase or free download.*

*The following conferences are organized according to the calendar month in which they are usually held.*

"International Conference on Electronics for Ocean Technology," an annual conference at least until 1987, with proceedings and articles by various contributors available for 1987 (5th conference).

"Oceanology International 2000," hydrographic and marine survey equipment conference, Brighton, U.K., 7-10 Mar. 2000.

"Connecting Technology: The Vision of the Future 2000," jointly sponsored by the Department of the Navy Chief Information Office and the DON Information Technology Umbrella Program. A government-sponsored international conference for Navy IT and Marine Corps technology and policy. Norfolk, VA, May 2000.

"Oceanic Imaging Conference 2000," with topics including side-looking sonar, active synthetic-aperture sonar, and radar surface-scattering techniques. Newport, Rhode Island, May 2000.

"Symposium On Autonomous Underwater Vehicle (AUV) Technology," Sponsored by the Oceanic Engineering Society, IEEE, Monterey, CA, June 1996.

"IEEE Symposium on Autonomous Underwater Vehicle Technology," Washington, D.C., June 1992.

"International Autonomous Underwater Vehicle Competition," sponsored by the Office of Naval Research (ONR) and the Association for Unmanned Vehicles System International (AUVSI), Panama City, Florida, 1-3 August 1998. Competitors design and build completely autonomous underwater systems capable of traversing a body of water, navigating a series of gates, returning to a designated recovery zone, and determing the maximum depth of the recovery zone.

"International Conference on Shallow-Water Acoustics," Beijing, China, April 1997 (Proceedings have been published). 1999 conference was planned. Funded by ONR.

"European Conference on Underwater Acoustics," Rome, Italy, Sept. 1998. Technical conference on acoustic science and the development, testing, and application of sonar sponsored by the European Commission and European Acoustics Association. The conference has been held every other year since 1992.

"MCIA 2000 Convention and Reunion," sponsored by the Marine Corps Intelligence Association, Virginia Beach, October 2000.

"SPAWAR/NDIA 1999," San Diego, October, 1999. PowerPoint™ presentations from this conference are available to the public. http://agena.spawar.navy.mil/pubinfo.nsf/$defaultview/8A73AB731D4F714A88256818006506C4/$File/spawar_ndia_99_industry_days.html

## 10.d. Online Sites

**alt.sci.physics.acoustics**. A USENET newsgroup initiated by Angelo Campanella which is the principal newsgroup for acoustics discussions. Another group, comp.dsp is also a good resource for digital signal processing discussions.

**American Pioneer Sonars**. This informational/historical site is hosted by H. B. Pacific Pty Ltd. It focuses somewhat on fish-finding, but there are also many general-interest diagrams and informational/historical references covering different aspects of sonar.
http://www.hbpacific.com.au/american.htm

**American Underwater Search and Survey, Ltd.** This is a commercial site with considerable educational content including many pictures and a history and background to sonar and sonar imaging.
http://www.marine-group.com/

**Basic Method of Conserving Underwater Archaeological Culture**. An extensive description of the handling and preservation of a variety of artifacts and remains that are apt to be found in underwater environments. Of interest to divers, salvagers, treasure hunters, and those studying underwater archaeology.
http://www.denix.osd.mil/denix/Public/ES-Programs/Conservation/Underwater/archaeology.html

**Jerry Proc's ASDIC, Radar and IFF Systems Aboard HMCS Haida**. This site is recommended. It provides a ten-part, well-illustrated historical and current highlights of sonar, radar, and minesweeping operations through the various wars and up to the present. It took the author a year to compile and present this material and it's worth reading. http://webhome.idirect.com/~jproc/sari/sarintro.html

**Lowrance Sonar Tutorial**. The Lowrance and LEI Extras, Inc. sites are commercial sites, mainly devoted to sport fishing, but this tutorial has some good diagrams and general information on sonar technologies (cone angles, frequencies, etc.), thermoclines, and some specific information on various transducers which are all worthwhile. http://www.lowrance.com/marine/tutorial/transducers.htm
http://www.lei-extras.com/tips/sonartut/Default.htm

**The Mukran Wreck: Preliminary Report**. An illustrated report on the Mukran Wreck with a short description of the technologies used to locate the 16th century Nordic warship in the Baltic Sea. Springmann, Maik-Jens, April 1999. http://atle.abc.se/~m10354/mar/publ/mukran.htm

**Reson Multibeam Sonar.** Reson is a commercial supplier of echosounders and imaging sonars which has a good online information site that includes a glossary, FAQ, and numerous charts comparing relative characteristics, range, and depth information for a variety of sonar devices operating at different frequencies. http://www.reson.com

**U.S. Navy Marine Mammal Program and Bibliography**. The U.S. Navy has an illustrated description of the use of dolphins and sea lions as members of a 'fleet' for a variety of marine tasks and studies. http://www.spawar.navy.mil/nrad/technology/mammals/

There is also an extensive annotated bibliography with over 200 references of sonar-related scientific dolphin/porpoise/whale studies listed at this site.
http://www.spawar.navy.mil/sti/publications/pubs/td/627/revd/ch1sound.html

**U.S. Navy Submarine Centennial**. The Navy is featuring a centennial celebration with a site devoted to submarine technology through the years, the history of the force, a chronology of important events and various campaigns. There is also a bibliography with further references.
http://www.chinfo.navy.mil/navpalib/ships/submarines/centennial/subs.html

**Welcome to Oregon Reference.** This is one of the best personal sites the author has encountered, organized by Sam Churchill. It includes well-illustrated educational sections on the use of remotely operated vehicles, including underwater vehicles used to salvage plane and ship wrecks off the Oregon coast. Of particular interest is "Under the Oregon Coast: An Underseas Adventure." The site has many links to sea vessels, aircraft, relevant news clips (some with sound), charts, and ROV companies which use sonar in their vessels.
http://www.teleport.com/~samc/ and http://www.teleport.com/~samc/seas/deep3.html

## 10.e. Media Resources

"Commander Charles Herbert Little CD RCN," a former head of Naval Intelligence is interviewed on his experiences in setting up a Canadian naval intelligence organization by John Frank in 1995. From the "Seasoned Sailors" video series by Policy Publishers Inc., Ottawa, 56 minutes.

"Fast Attacks and Boomers: Submarines in the Cold War," is a Smithsonian National Museum of American History exhibit which began 12 April 2000. It was scheduled to coincide with the centennial anniversary of the U.S. Navy's "Silent Service." The exhibit features recently declassified information and equipment from decommissioned U.S. nuclear-powered subs. Visitors can walk through the various submarine compartments, including the attack center, maneuvering rooms, and others. It will be open until April 2003. The U.S. Navy is also sponsoring smaller exhibits in other locations.

"The Hunt for Red October," feature film starring Sean Connery and Michelle Pfeiffer, Director John McTiernan. It takes place in 1984 with a Soviet sub heading for the U.S., 1990, 134 minutes.

"Leading Seaman Frank Curry RCNVR," A Canadian Naval ASDIC (sonar) operator assigned to HMCS Kamsack, a new corvette. He kept a diary about his experiences in this vessel and later, on the HMCS Caraquet minesweeper. Video interview by Peter Ward in 1997. From the "Seasoned Sailors" video series by Policy Publishers Inc., Ottawa, 56 minutes.

"Naval Undersea Museum," includes naval history, undersea technology, and marine science in a new building with 20,000 square feet of exhibits including deep-submergence vessels, Confederate mines, and a simulated control room. It holds a large naval undersea history and science artifacts collection. Keyport, Washington.

"Sea Hunt," television series from the late 1950s and 1960s starring Lloyd Bridges. There were 155 episodes, two of them in color. It depicts the adventures of a submarine and its divers. Episode 1127 is called the "Sonar Story" in which sonar is used to foil smugglers. In Episode 1132, a scientist is testing an underwater detection device.

"Submarine Force Museum and USS Nautilus Historic Landmark," opened in 1986, this official Navy submarine museum traces the history of the 'silent service' from the time of the Turtle submarine to modern submarines. Exhibits include the attack center of a WWII submarine and operating periscopes. Short films are also shown. The museum includes a research library. Groton, Connecticut.

"The U.S. Naval Memorial Museum," located in the Navy Yard in Washington, D.C., this museum includes the 1866 "Intelligent Whale," one of the earliest naval submarines as well as ship models, working periscopes, uniforms, medals, art, and photographs.

# 11. Glossary

*Titles, product names, organizations, and specific military designations are capitalized; common generic and colloquial terms and phrases are not.*

| | |
|---|---|
| ACS | Advanced-Concept Submarine. An exploration study by MIT graduate students to analyze and evaluate new technologies that can be used to design relatively low-cost state-of-the-art submarines. The ACS design includes a CAVES sonar system. |
| ALFS | Airborne Low-Frequency Dipping Sonar usually deployed from helicopters |
| ASW | Anti-Submarine Warfare |
| AUV | autonomous underwater vehicle |
| BARS | bearing-ambiguity-resolving sonar |
| batfish | a towed body containing instruments whose depth can be controlled |
| bathymetry | measurement of depths of water bodies such as lakes, oceans, etc. |
| bathysphere | a vehicle built for deep-sea exploration which is sturdy enough to withstand high pressure at great depths. |
| bioacoustics | the use of acoustic sciences and technologies to study biological organisms or systems (e.g., using fish-finders to study migration paths) and the study of acoustical systems in biological organisms (such as dolphin sonar, bird calls, grasshopper singing, etc.) |
| BSP | Barra Side Processor/Barrel Stave Projector |
| BT | bathymetry |
| CANTASS | Canadian Towed-Array Sonar System |
| CAVES | Conformal Acoustic Velocity Sonar |
| COMSEC | Communications Security |
| CTFM | Continuous Transmission Frequency Modulation. A type of system found in scanning devices such as forward-looking sonar. |
| DSV | deep submersible vehicle |
| EAD | expendible acoustic device. A sound-sensing device that may sink, decay, or scuttle itself when its useful life is finished or if there is a possibility of detection. |
| echo | the repetition of a sound resulting from reflection of the sound waves |
| FOTA | fiber-optic towed array |
| GLORIA | a wide-aperture, sidescanning, sonar-array, towfish imaging system that is being used in oceanographic research |
| IDR | initial detection range |
| LBVDS | lightweight broadband variable-depth sonar |
| LFA | low-frequency active |
| MAD | magnetic anomaly detection. A means of locating objects by their magnetic disturbance. While not a sonar method, it is one of the means for locating underwater vessels from under the water or from the air. |
| MCM | mine countermeasures |
| MIUW | Mobile In-shore Undersea Warfare program of the U.S. Navy which uses a variety of visual, thermal, radar, and sonar surveillance devices installed in vans to surveille shorelines to monitor and defend coastal regions. |
| NRL | Naval Research Laboratory |
| NSS | Naval Simulation System |

| | |
|---|---|
| ONR | Office of Naval Research |
| PSA | planar sonar array |
| QMIPS | a sidescanning sonar system |
| reverberation | an effect or result of an impact that resembles an echo |
| ROPOS | Remotely Operated Platform for Ocean Science. This is a robot system remotely controlled through a fiber optic cable built by International Submarine Engineers of Port Coquitlam. |
| ROV | remotely operated vehicle |
| SAD | sonar acoustic data |
| SAS | synthetic-aperture sonar |
| SIGINT | Signals Intelligence |
| SMB | submarine message buffer |
| SOFAR | sound fixing and ranging. A means of channeling sound through natural structures as those which exist in deep ocean regions. |
| SOSUS | Sound Surveillance System/Sound Surveillance Under Sea. A U.S.-deployed system of sound detection devices placed in strategic underwater locations throughout the world's oceans. |
| SURTAS | Surveillance Towed-Array Sensor/Sonar |
| SURTASS | Surveillance Towed-Array Sonar System. A low-frequency active sonar being tested and deployed by the U.S. Navy for international marine surveillance. |
| SVP | sound-velocity profile |
| SWARM '95 | 1995 Shallow Water Acoustic Random Medium experiment. An oceanographic-acoustic field study. |
| SWIS | Shallow-Water Intermediate Search, a type of sidescanning sonar |
| TACTAS | tactical towed-array sensor/sonar |
| TASS | Towed-Array Sonar System |
| TSP | tactical sonar performance |
| ULQ-13(V) | a countermeasures signal simulator system |
| VDS | variable-depth sonar |