Sound Navigation and Ranging Technology

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Chapter 1

Sonar

French F70 type frigates (here, *La Motte-Picquet*) are fitted with VDS (Variable Depth Sonar) type DUBV43 or DUBV43C towed sonars

Sonar (originally an acronym for **SO**und **N**avigation **A**nd **R**anging) is a technique that uses sound propagation (usually underwater, as in Submarine navigation) to navigate, communicate with or detect other vessels. Two types of technology share the name "sonar": *passive* sonar is essentially listening for the sound made by vessels; *active* sonar is emitting pulses of sounds and listening for echoes. Sonar may be used as a means of acoustic location and of measurement of the echo characteristics of "targets" in the water. Acoustic location in air was used before the introduction of radar. Sonar may also be used in air for robot navigation, and SODAR (an upward looking in-air sonar) is used for

atmospheric investigations. The term *sonar* is also used for the equipment used to generate and receive the sound. The acoustic frequencies used in sonar systems vary from very low (infrasonic) to extremely high (ultrasonic). The study of underwater sound is known as underwater acoustics or hydroacoustics.

History

Although some animals (dolphins and bats) have used sound for communication and object detection for millions of years, use by humans in the water is initially recorded by Leonardo Da Vinci in 1490: a tube inserted into the water was said to be used to detect vessels by placing an ear to the tube.

In the 19th century an underwater bell was used as an ancillary to lighthouses to provide warning of hazards.

The use of sound to 'echo locate' underwater in the same way as bats use sound for aerial navigation seems to have been prompted by the *Titanic* disaster of 1912. The world's first patent for an underwater echo ranging device was filed at the British Patent Office by English meteorologist Lewis Richardson a month after the sinking of the Titanic, and a German physicist Alexander Behm obtained a patent for an echo sounder in 1913.

The Canadian engineer Reginald Fessenden, while working for the Submarine Signal Company in Boston, built an experimental system beginning in 1912, a system later tested in Boston Harbor, and finally in 1914 from the U.S. Revenue (now Coast Guard) Cutter Miami on the Grand Banks off Newfoundland Canada. In that test, Fessenden demonstrated depth sounding, underwater communications (Morse Code) and echo ranging (detecting an iceberg at two miles (3 km) range). The so-called Fessenden oscillator, at ca. 500 Hz frequency, was unable to determine the bearing of the berg due to the 3 metre wavelength and the small dimension of the transducer's radiating face (less than 1 metre in diameter). The ten Montreal-built British H class submarines launched in 1915 were equipped with a Fessenden oscillator.

During World War I the need to detect submarines prompted more research into the use of sound. The British made early use of underwater hydrophones, while the French physicist Paul Langevin, working with a Russian immigrant electrical engineer, Constantin Chilowski, worked on the development of active sound devices for detecting submarines in 1915 using quartz. Although piezoelectric and magnetostrictive transducers later superseded the electrostatic transducers they used, this work influenced future designs. Lightweight sound-sensitive plastic film and fibre optics have been used for hydrophones (acousto-electric transducers for in-water use), while Terfenol-D and PMN (lead magnesium niobate) have been developed for projectors.

ASDIC

In 1916, under the British Board of Invention and Research, Canadian physicist Robert William Boyle took on the active sound detection project with A B Wood, producing a

prototype for testing in mid 1917. This work, for the Anti-Submarine Division of the British Naval Staff, was undertaken in utmost secrecy, and used quartz piezoelectric crystals to produce the world's first practical underwater active sound detection apparatus. To maintain secrecy no mention of sound experimentation or quartz was made - the word used to describe the early work ('supersonics') was changed to 'ASD'ics, and the quartz material to 'ASD'ivite: hence the British acronym *ASDIC*. In 1939, in response to a question from the Oxford English Dictionary, the Admiralty made up the story that it stood for 'Allied Submarine Detection Investigation Committee', and this is still widely believed, though no committee bearing this name has been found in the Admiralty archives.

By 1918, both France and Britain had built prototype active systems. The British tested their ASDIC on HMS *Antrim* in 1920, and started production in 1922. The 6th Destroyer Flotilla had ASDIC-equipped vessels in 1923. An anti-submarine school, HMS *Osprey*, and a training flotilla of four vessels were established on Portland in 1924. The US Sonar QB set arrived in 1931.

By the outbreak of World War II, the Royal Navy had five sets for different surface ship classes, and others for submarines, incorporated into a complete anti-submarine attack system. The effectiveness of early ASDIC was hamstrung by the use of the depth charge as an anti-submarine weapon. This required an attacking vessel to pass over a submerged contact before dropping charges over the stern, resulting in a loss of ASDIC contact in the moments leading up to attack. The hunter was effectively firing blind, during which time a submarine commander could take evasive action. This situation was remedied by using several ships cooperating and by the adoption of "ahead throwing weapons", such as Hedgehog and later Squid, which projected warheads at a target ahead of the attacker and thus still in ASDIC contact. Developments during the war resulted in British ASDIC sets which used several different shapes of beam, continuously covering blind spots. Later, acoustic torpedoes were used.

At the start of World War II, British ASDIC technology was transferred for free to the United States. Research on ASDIC and underwater sound was expanded in the UK and in the US. Many new types of military sound detection were developed. These included sonobuoys, first developed by the British in 1944 under the codename *High Tea*, dipping/dunking sonar and mine detection sonar. This work formed the basis for post war developments related to countering the nuclear submarine. Work on sonar had also been carried out in the Axis countries, notably in Germany, which included countermeasures. At the end of World War II this German work was assimilated by Britain and the US. Sonars have continued to be developed by many countries, including Russia, for both military and civil uses. In recent years the major military development has been the increasing interest in low frequency active systems.

SONAR

During the 1930s American engineers developed their own underwater sound detection technology and important discoveries were made, such as thermoclines, that would help

future development. After technical information was exchanged between the two countries during the Second World War, Americans began to use the term *SONAR* for their systems, coined as the equivalent of RADAR.

Performance factors

The detection, classification and localisation performance of a sonar depends on the environment and the receiving equipment, as well as the transmitting equipment in an active sonar or the target radiated noise in a passive sonar.

Sound propagation

Sonar operation is affected by variations in sound speed, particularly in the vertical plane. Sound travels more slowly in fresh water than in sea water, though the difference is small. The speed is determined by the water's bulk modulus and mass density. The bulk modulus is affected by temperature, dissolved impurities (usually salinity), and pressure. The density effect is small. The speed of sound (in feet per second) is approximately:

> 4388 + (11.25 × temperature (in °F)) + (0.0182 × depth (in feet)) + salinity (in parts-per-thousand).

This empirically derived approximation equation is reasonably accurate for normal temperatures, concentrations of salinity and the range of most ocean depths. Ocean temperature varies with depth, but at between 30 and 100 meters there is often a marked change, called the thermocline, dividing the warmer surface water from the cold, still waters that make up the rest of the ocean. This can frustrate sonar, because a sound originating on one side of the thermocline tends to be bent, or refracted, through the thermocline. The thermocline may be present in shallower coastal waters. However, wave action will often mix the water column and eliminate the thermocline. Water pressure also affects sound propagation: higher pressure increases the sound speed, which causes the sound waves to refract away from the area of higher sound speed. The mathematical model of refraction is called Snell's law.

If the sound source is deep and the conditions are right, propagation may occur in the 'deep sound channel'. This provides extremely low propagation loss to a receiver in the channel. This is because of sound trapping in the channel with no losses at the boundaries. Similar propagation can occur in the 'surface duct' under suitable conditions. However in this case there are reflection losses at the surface.

In shallow water propagation is generally by repeated reflection at the surface and bottom, where considerable losses can occur.

Sound propagation is affected by absorption in the water itself as well as at the surface and bottom. This absorption depends upon frequency, with several different mechanisms in sea water. Long-range sonar uses low frequencies to minimise absorption effects.

The sea contains many sources of noise that interfere with the desired target echo or signature. The main noise sources are waves and shipping. The motion of the receiver through the water can also cause speed-dependent low frequency noise.

Scattering

When active sonar is used, scattering occurs from small objects in the sea as well as from the bottom and surface. This can be a major source of interference. This acoustic scattering is analogous to the scattering of the light from a car's headlights in fog: a high-intensity pencil beam will penetrate the fog to some extent, but broader-beam headlights emit much light in unwanted directions, much of which is scattered back to the observer, overwhelming that reflected from the target ("white-out"). For analogous reasons active sonar needs to transmit in a narrow beam to minimise scattering.

Target characteristics

The sound *reflection* characteristics of the target of an active sonar, such as a submarine, are known as its target strength. A complication is that echoes are also obtained from other objects in the sea such as whales, wakes, schools of fish and rocks.

Passive sonar detects the target's *radiated* noise characteristics. The radiated spectrum comprises a continuous spectrum of noise with peaks at certain frequencies which can be used for classification.

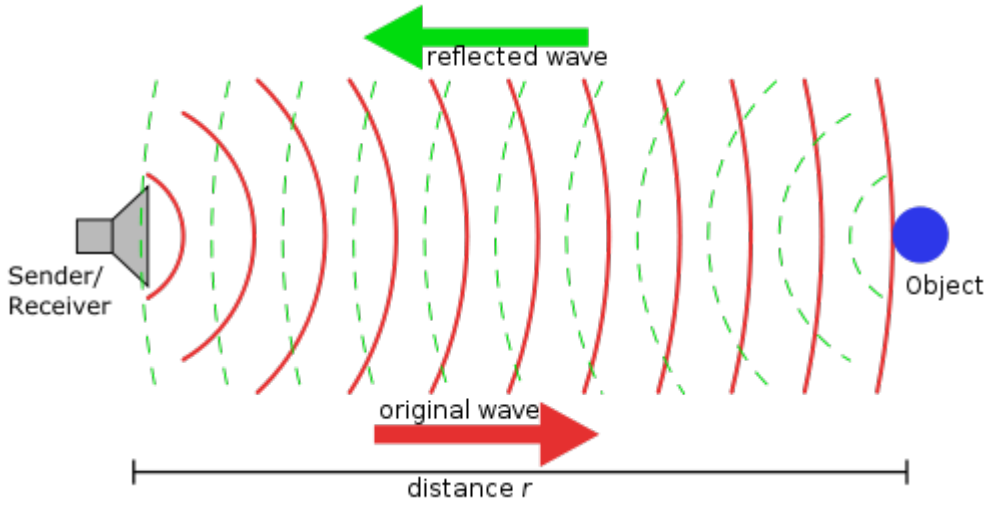
Countermeasures

Active (powered) countermeasures may be launched by a submarine under attack to raise the noise level, provide a large false target, and obscure the signature of the submarine itself.

Passive (i.e., non-powered) countermeasures include:

- Mounting noise-generating devices on isolating devices.
- Sound-absorbent coatings on the hulls of submarines, for example anechoic tiles.

Active sonar



Principle of an active sonar

Active sonar uses a sound transmitter and a receiver. When the two are in the same place it is monostatic operation. When the transmitter and receiver are separated it is bistatic operation. When more transmitters (or more receivers) are used, again spatially separated, it is multistatic operation. Most sonars are used monostatically with the same array often being used for transmission and reception. Active sonobuoy fields may be operated multistatically.

Active sonar creates a pulse of sound, often called a "ping", and then listens for reflections (echo) of the pulse. This pulse of sound is generally created electronically using a sonar Projector consisting of a signal generator, power amplifier and electro-acoustic transducer/array. A beamformer is usually employed to concentrate the acoustic power into a beam, which may be swept to cover the required search angles. Generally, the electro-acoustic transducers are of the Tonpilz type and their design may be optimised to achieve maximum efficiency over the widest bandwidth, in order to optimise performance of the overall system. Occasionally, the acoustic pulse may be created by other means, e.g. (1) chemically using explosives, or (2) airguns or (3) plasma sound sources.

To measure the distance to an object, the time from transmission of a pulse to reception is measured and converted into a range by knowing the speed of sound. To measure the bearing, several hydrophones are used, and the set measures the relative arrival time to each, or with an array of hydrophones, by measuring the relative amplitude in beams formed through a process called beamforming. Use of an array reduces the spatial response so that to provide wide cover multibeam systems are used. The target signal (if present) together with noise is then passed through various forms of signal processing, which for simple sonars may be just energy measurement. It is then presented to some form of decision device that calls the output either the required signal or noise. This decision device may be an operator with headphones or a display, or in more

sophisticated sonars this function may be carried out by software. Further processes may be carried out to classify the target and localise it, as well as measuring its velocity.

The pulse may be at constant frequency or a chirp of changing frequency (to allow pulse compression on reception). Simple sonars generally use the former with a filter wide enough to cover possible Doppler changes due to target movement, while more complex ones generally include the latter technique. Since digital processing became available pulse compression has usually been implemented using digital correlation techniques. Military sonars often have multiple beams to provide all-round cover while simple ones only cover a narrow arc, although the beam may be rotated, relatively slowly, by mechanical scanning.

Particularly when single frequency transmissions are used, the Doppler effect can be used to measure the radial speed of a target. The difference in frequency between the transmitted and received signal is measured and converted into a velocity. Since Doppler shifts can be introduced by either receiver or target motion, allowance has to be made for the radial speed of the searching platform.

One useful small sonar is similar in appearance to a waterproof flashlight. The head is pointed into the water, a button is pressed, and the device displays the distance to the target. Another variant is a "fishfinder" that shows a small display with shoals of fish. Some civilian sonars (which are not designed for stealth) approach active military sonars in capability, with quite exotic three-dimensional displays of the area near the boat.

When active sonar is used to measure the distance from the transducer to the bottom, it is known as echo sounding. Similar methods may be used looking upward for wave measurement.

Active sonar is also used to measure distance through water between two sonar transducers or a combination of a hydrophone (underwater acoustic microphone) and projector (underwater acoustic speaker). A transducer is a device that can transmit and receive acoustic signals ("pings"). When a hydrophone/transducer receives a specific interrogation signal it responds by transmitting a specific reply signal. To measure distance, one transducer/projector transmits an interrogation signal and measures the time between this transmission and the receipt of the other transducer/hydrophone reply. The time difference, scaled by the speed of sound through water and divided by two, is the distance between the two platforms. This technique, when used with multiple transducers/hydrophones/projectors, can calculate the relative positions of static and moving objects in water.

In combat situations, an active pulse can be detected by an opponent and will reveal a submarine's position.

A very directional, but low-efficiency, type of sonar (used by fisheries, military, and for port security) makes use of a complex nonlinear feature of water known as non-linear sonar, the virtual transducer being known as a *parametric array*.

Project ARTEMIS

Project ARTEMIS was a one-of-a-kind low-frequency sonar for surveillance that was deployed off Bermuda for several years in the early 1960s. The active portion was deployed from a World War II tanker, and the receiving array was a built into a fixed position on an offshore bank.

Transponder

This is an active sonar device that receives a stimulus and immediately (or with a delay) retransmits the received signal or a predetermined one.

Performance prediction

A sonar target is small relative to the sphere, centred around the emitter, on which it is located. Therefore, the power of the reflected signal is very low, several orders of magnitude less than the original signal. Even if the reflected signal was of the same power, the following example (using hypothetical values) shows the problem: Suppose a sonar system is capable of emitting a 10,000 W/m² signal at 1 m, and detecting a 0.001 W/m² signal. At 100 m the signal will be 1 W/m² (due to the inverse-square law). If the entire signal is reflected from a 10 m² target, it will be at 0.001 W/m² when it reaches the emitter, i.e. just detectable. However, the original signal will remain above 0.001 W/m² until 300 m. Any 10 m² target between 100 and 300 m using a similar or better system would be able to detect the pulse but would not be detected by the emitter. The detectors must be very sensitive to pick up the echoes. Since the original signal is much more powerful, it can be detected many times further than twice the range of the sonar (as in the example).

In active sonar there are two performance limitations, due to noise and reverberation. In general one or other of these will dominate so that the two effects can be initially considered separately.

In noise limited conditions at initial detection:

$$SL - 2TL + TS - (NL - DI) = DT$$

where SL is the source level, TL is the transmission loss (or propagation loss), TS is the target strength, NL is the noise level, DI is the directivity index of the array (an approximation to the array gain) and DT is the detection threshold.

In reverberation limited conditions at initial detection (neglecting array gain):

$$SL - 2TL + TS = RL + DT$$

where RL is the reverberation level and the other factors are as before.

Marine mammals

A Humpback whale

Active sonar may harm marine animals, although the precise mechanisms for this are not well understood. Some marine animals, such as whales and dolphins, use echolocation systems, sometimes called *biosonar* to locate predators and prey. It is conjectured that active sonar transmitters could confuse these animals and interfere with basic biological functions such as feeding and mating.

Hand-held sonar for use by a diver

Scuba diver using INSS hand-held sonar

- The LIMIS (= Limpet Mine Imaging Sonar) is a hand-held or ROV-mounted imaging sonar for use by a diver. Its name is because it was designed for patrol divers (combat frogmen or Clearance Divers) to look for limpet mines in low visibility water. Links:

    - Abstract of article by the International Society for Optical Engineering
    - Used to find debris from the Space Shuttle Columbia crash
    - Used in fish passage research at hydropower facilities
- The LUIS (= Lensing Underwater Imaging System) is another imaging sonar for use by a diver. Links:
    - Used for counting salmon in a river
- There is or was a small flashlight-shaped handheld sonar for divers, that merely displays range.
- For the INSS = Integrated Navigation Sonar System see:
    - an image.
    - short description
    - description

Passive sonar

Passive sonar listens without transmitting. It is often employed in military settings, although it is also used in science applications, *e.g.*, detecting fish for presence/absence studies in various aquatic environments. In the very broadest usage, this term can encompass virtually any analytical technique involving remotely generated sound, though it is usually restricted to techniques applied in an aquatic environment.

Identifying sound sources

Passive sonar has a wide variety of techniques for identifying the source of a detected sound. For example, U.S. vessels usually operate 60 Hz alternating current power systems. If transformers or generators are mounted without proper vibration insulation from the hull or become flooded, the 60 Hz sound from the windings can be emitted from the submarine or ship. This can help to identify its nationality, as most European submarines have 50 Hz power systems. Intermittent sound sources (such as a wrench being dropped) may also be detectable to passive sonar. Until fairly recently, an experienced trained operator identified signals, but now computers may do this.

Passive sonar systems may have large sonic databases, but the sonar operator usually finally classifies the signals manually. A computer system frequently uses these databases to identify classes of ships, actions (i.e. the speed of a ship, or the type of weapon released), and even particular ships. Publications for classification of sounds are provided by and continually updated by the US Office of Naval Intelligence.

Noise limitations

Passive sonar on vehicles is usually severely limited because of noise generated by the vehicle. For this reason, many submarines operate nuclear reactors that can be cooled without pumps, using silent convection, or fuel cells or batteries, which can also run silently. Vehicles' propellers are also designed and precisely machined to emit minimal noise. High-speed propellers often create tiny bubbles in the water, and this cavitation has a distinct sound.

The sonar hydrophones may be towed behind the ship or submarine in order to reduce the effect of noise generated by the watercraft itself. Towed units also combat the thermocline, as the unit may be towed above or below the thermocline.

The display of most passive sonars used to be a two-dimensional waterfall display. The horizontal direction of the display is bearing. The vertical is frequency, or sometimes time. Another display technique is to color-code frequency-time information for bearing. More recent displays are generated by the computers, and mimic radar-type plan position indicator displays.

Performance prediction

Unlike active sonar, only one way propagation is involved. Because of the different signal processing used, the minimum detectable signal to noise ratio will be different. The equation for determining the performance of a passive sonar is:

$$SL - TL = NL - DI + DT$$

where SL is the source level, TL is the transmission loss, NL is the noise level, DI is the directivity index of the array (an approximation to the array gain) and DT is the detection threshold. The figure of merit of a passive sonar is:

$$FOM = SL + DI - (NL + DT).$$

Warfare

Modern naval warfare makes extensive use of both passive and active sonar from water-borne vessels, aircraft and fixed installations. The relative usefulness of active versus passive sonar depends on the radiated noise characteristics of the target, generally a submarine. Although in World War II active sonar was used by surface craft—submarines avoided emitting pings which revealed their presence and position—with the advent of modern signal-processing passive sonar became preferred for initial detection. Submarines were then designed for quieter operation, and active sonar is now more used. In 1987 a division of Japanese company Toshiba reportedly sold machinery to the Soviet Union that allowed it to mill submarine propeller blades so that they became radically quieter, creating a huge security issue with their newer generation of submarines.

Active sonar gives the exact bearing to a target, and sometimes the range. Active sonar works the same way as radar: a signal is emitted. The sound wave then travels in many directions from the emitting object. When it hits an object, the sound wave is then reflected in many other directions. Some of the energy will travel back to the emitting source. The echo will enable the sonar system or technician to calculate, with many factors such as the frequency, the energy of the received signal, the depth, the water temperature, the position of the reflecting object, etc. Active sonar is used when the platform commander determines that it is more important to determine the position of a possible threat submarine than it is to conceal his own position. With surface ships it

might be assumed that the threat is already tracking the ship with satellite data. Any vessel around the emitting sonar will detect the emission. Having heard the signal, it is easy to identify the sonar equipment used (usually with its frequency) and its position (with the sound wave's energy). Active sonar is similar to radar in that, while it allows detection of targets at a certain range, it also enables the emitter to be detected at a far greater range, which is undesirable.

Since active sonar reveals the presence and position of the operator, and does not allow exact classification of targets, it is used by fast (planes, helicopters) and by noisy platforms (most surface ships) but rarely by submarines. When active sonar is used by surface ships or submarines, it is typically activated very briefly at intermittent periods to minimise the risk of detection. Consequently active sonar is normally considered a backup to passive sonar. In aircraft, active sonar is used in the form of disposable sonobuoys that are dropped in the aircraft's patrol area or in the vicinity of possible enemy sonar contacts.

Passive sonar has several advantages. Most importantly, it is silent. If the target radiated noise level is high enough, it can have a greater range than active sonar, and allows the target to be identified. Since any motorized object makes some noise, it may in principle be detected, depending on the level of noise emitted and the ambient noise level in the area, as well as the technology used. To simplify, passive sonar "sees" around the ship using it. On a submarine, nose-mounted passive sonar detects in directions of about 270°, centered on the ship's alignment, the hull-mounted array of about 160° on each side, and the towed array of a full 360°. The invisible areas are due to the ship's own interference. Once a signal is detected in a certain direction (which means that something makes sound in that direction, this is called broadband detection) it is possible to zoom in and analyze the signal received (narrowband analysis). This is generally done using a Fourier transform to show the different frequencies making up the sound. Since every engine makes a specific sound, it is straightforward to identify the object. Databases of unique engine sounds are part of what is known as *acoustic intelligence* or ACINT.

Another use of passive sonar is to determine the target's trajectory. This process is called Target Motion Analysis (TMA), and the resultant "solution" is the target's range, course, and speed. TMA is done by marking from which direction the sound comes at different times, and comparing the motion with that of the operator's own ship. Changes in relative motion are analyzed using standard geometrical techniques along with some assumptions about limiting cases.

Passive sonar is stealthy and very useful. However, it requires high-tech electronic components and is costly. It is generally deployed on expensive ships in the form of arrays to enhance detection. Surface ships use it to good effect; it is even better used by submarines, and it is also used by airplanes and helicopters, mostly to a "surprise effect", since submarines can hide under thermal layers. If a submarine's commander believes he is alone, he may bring his boat closer to the surface and be easier to detect, or go deeper and faster, and thus make more sound.

Examples of sonar applications in military use are given below. Many of the civil uses given in the following section may also be applicable to naval use.

Anti-submarine warfare

Variable Depth Sonar and its winch

Until recently, ship sonars were usually with hull mounted arrays, either amidships or at the bow. It was soon found after their initial use that a means of reducing flow noise was required. The first were made of canvas on a framework, then steel ones were used. Now domes are usually made of reinforced plastic or pressurised rubber. Such sonars are primarily active in operation. An example of a conventional hull mounted sonar is the SQS-56.

Because of the problems of ship noise, towed sonars are also used. These also have the advantage of being able to be placed deeper in the water. However, there are limitations on their use in shallow water. These are called towed arrays (linear) or variable depth sonars (VDS) with 2/3D arrays. A problem is that the winches required to deploy/recover these are large and expensive. VDS sets are primarily active in operation while towed arrays are passive.

An example of a modern active/passive ship towed sonar is Sonar 2087 made by Thales Underwater Systems.

Torpedoes

Modern torpedoes are generally fitted with an active/passive sonar. This may be used to home directly on the target, but wake following torpedoes are also used. An early example of an acoustic homer was the Mark 37 torpedo.

Torpedo countermeasures can be towed or free. An early example was the German Sieglinde device while the Pillenwerfer was a chemical device. A widely used US device was the towed Nixie while MOSS submarine simulator was a free device. A modern alternative to the Nixie system is the UK Royal Navy S2170 Surface Ship Torpedo Defence system.

Mines

Mines may be fitted with a sonar to detect, localize and recognize the required target.

Mine countermeasures

Mine Countermeasure (MCM) Sonar, sometimes called "Mine and Obstacle Avoidance Sonar (MOAS)", is a specialised type of sonar used for detecting small objects. Most MCM sonars are hull mounted but a few types are VDS design. An example of a hull mounted MCM sonar is the Type 2193 while the SQQ-32 Mine-hunting sonar and Type 2093 systems are VDS designs.

Submarine navigation

Submarines rely on sonar to a greater extent than surface ships as they cannot use radar at depth. The sonar arrays may be hull mounted or towed. Information fitted on typical fits is given in Oyashio class submarine and Swiftsure class submarine.

Aircraft

Helicopters can be used for antisubmarine warfare by deploying fields of active/passive sonobuoys or can operate dipping sonar, such as the AQS-13. Fixed wing aircraft can also deploy sonobuoys and have greater endurance and capacity to deploy them. Processing from the sonobuoys or dipping sonar can be on the aircraft or on ship.

Helicopters have also been used for mine countermeasure missions using towed sonars such as the AQS-20A

AN/AQS-13 Dipping sonar deployed from an H-3 Sea King.

Underwater communications

Dedicated sonars can be fitted to ships and submarines for underwater communication.

Ocean surveillance

For many years, the United States operated a large set of passive sonar arrays at various points in the world's oceans, collectively called Sound Surveillance System (SOSUS) and later Integrated Undersea Surveillance System (IUSS). A similar system is believed to have been operated by the Soviet Union. As permanently mounted arrays in the deep ocean were utilised, they were in very quiet conditions so long ranges could be achieved. Signal processing was carried out using powerful computers ashore. With the ending of the Cold War a SOSUS array has been turned over to scientific use.

In the United States Navy, a special badge known as the Integrated Undersea Surveillance System Badge is awarded to those who have been trained and qualified in its operation.

Underwater security

Sonar can be used to detect frogmen and other scuba divers. This can be applicable around ships or at entrances to ports. Active sonar can also be used as a deterrent and/or disablement mechanism. One such device is the Cerberus system.

Hand-held sonar

Limpet Mine Imaging Sonar (LIMIS) is a hand-held or ROV-mounted imaging sonar designed for patrol divers (combat frogmen or clearance divers) to look for limpet mines in low visibility water.

The LUIS is another imaging sonar for use by a diver.

Integrated Navigation Sonar System (INSS) is a small flashlight-shaped handheld sonar for divers that displays range.

Intercept sonar

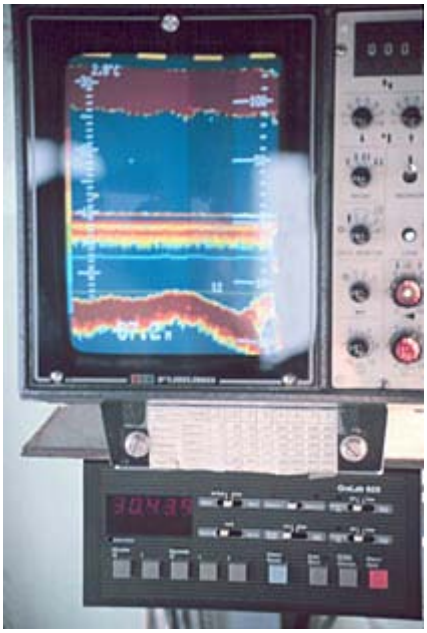
This is a sonar designed to detect and locate the transmissions from hostile active sonars. An example of this is the Type 2082 fitted on the British Vanguard class submarines.

Civilian applications

Fisheries

Fishing is an important industry that is seeing growing demand, but world catch tonnage is falling as a result of serious resource problems. The industry faces a future of continuing worldwide consolidation until a point of sustainability can be reached. However, the consolidation of the fishing fleets are driving increased demands for sophisticated fish finding electronics such as sensors, sounders and sonars. Historically, fishermen have used many different techniques to find and harvest fish. However, acoustic technology has been one of the most important driving forces behind the development of the modern commercial fisheries.

Sound waves travel differently through fish than through water because a fish's air-filled swim bladder has a different density than seawater. This density difference allows the detection of schools of fish by using reflected sound. Acoustic technology is especially well suited for underwater applications since sound travels farther and faster underwater than in air. Today, commercial fishing vessels rely almost completely on acoustic sonar and sounders to detect fish. Fishermen also use active sonar and echo sounder technology to determine water depth, bottom contour, and bottom composition.



Cabin display of a fish finder sonar

Companies such as Raymarine UK, Marport Canada, Wesmar, Furuno, Krupp, and Simrad make a variety of sonar and acoustic instruments for the deep sea commercial fishing industry. For example, net sensors take various underwater measurements and transmit the information back to a receiver onboard a vessel. Each sensor is equipped with one or more acoustic transducers depending on its specific function. Data is transmitted from the sensors using wireless acoustic telemetry and is received by a hull mounted hydrophone. The analog signals are decoded and converted by a digital acoustic receiver into data which is transmitted to a bridge computer for graphical display on a high resolution monitor.

Echo sounding

An echo-sounder sends an acoustic pulse directly downwards to the seabed and records the returned echo. The sound pulse is generated by a transducer that emits an acoustic pulse and then “listens” for the return signal. The time for the signal to return is recorded and converted to a depth measurement by calculating the speed of sound in water. As the speed of sound in water is around 1,500 metres per second, the time interval, measured in milliseconds, between the pulse being transmitted and the echo being received, allows bottom depth and targets to be measured.

The value of underwater acoustics to the fishing industry has led to the development of other acoustic instruments that operate in a similar fashion to echo-sounders but, because their function is slightly different from the initial model of the echo-sounder, have been given different terms.

Net location

The net sounder is an echo sounder with a transducer mounted on the headline of the net rather than on the bottom of the vessel. Nevertheless, to accommodate the distance from the transducer to the display unit, which is much greater than in a normal echo-sounder, several refinements have to be made. Two main types are available. The first is the cable type in which the signals are sent along a cable. In this case there has to be the provision of a cable drum on which to haul, shoot and stow the cable during the different phases of the operation. The second type is the cable less net-sounder – such as Marport's Trawl Explorer - in which the signals are sent acoustically between the net and hull mounted receiver/hydrophone on the vessel. In this case no cable drum is required but sophisticated electronics are needed at the transducer and receiver.

The display on a net sounder shows the distance of the net from the bottom (or the surface), rather than the depth of water as with the echo-sounder's hull-mounted transducer. Fixed to the headline of the net, the footrope can usually be seen which gives an indication of the net performance. Any fish passing into the net can also be seen, allowing fine adjustments to be made to catch the most fish possible. In other fisheries, where the amount of fish in the net is important, catch sensor transducers are mounted at various positions on the cod-end of the net. As the cod-end fills up these catch sensor transducers are triggered one by one and this information is transmitted acoustically to display monitors on the bridge of the vessel. The skipper can then decide when to haul the net.

Modern versions of the net sounder, using multiple element transducers, function more like a sonar than an echo sounder and show slices of the area in front of the net and not merely the vertical view that the initial net sounders used.

The sonar is an echo-sounder with a directional capability that can show fish or other objects around the vessel.good

Ship velocity measurement

Sonars have been developed for measuring a ship's velocity either relative to the water or to the bottom.

ROV and UUV

Small sonars have been fitted to Remotely Operated Vehicles (ROV) and Unmanned Underwater Vehicles (UUV) to allow their operation in murky conditions. These sonars are used for looking ahead of the vehicle. The Long-Term Mine Reconnaissance System is an UUV for MCM purposes.

Vehicle location

Sonars which act as beacons are fitted to aircraft to allow their location in the event of a crash in the sea. Short and Long Baseline sonars may be used for caring out the location, such as LBL.

Scientific applications

Biomass estimation

Detection of fish, and other marine and aquatic life, and estimation their individual sizes or total biomass using active sonar techniques. As the sound pulse travels through water it encounters objects that are of different density or acoustic characteristics than the surrounding medium, such as fish, that reflect sound back toward the sound source. These echoes provide information on fish size, location, abundance and behavior. Data is usually processed and analysed using a variety of software such as Echoview.

Wave measurement

An upward looking echo sounder mounted on the bottom or on a platform may be used to make measurements of wave height and period. From this statistics of the surface conditions at a location can be derived.

Water velocity measurement

Special short range sonars have been developed to allow measurements of water velocity.

Bottom type assessment

Sonars have been developed that can be used to characterise the sea bottom into, for example, mud, sand, and gravel. Relatively simple sonars such as echo sounders can be promoted to seafloor classification systems via add-on modules, converting echo parameters into sediment type. Different algorithms exist, but they are all based on changes in the energy or shape of the reflected sounder pings. Advanced substrate classification analysis can be achieved using calibrated (scientific) echosounders and parametric or fuzzy-logic analysis of the acoustic data (See: Acoustic Seabed Classification)

Bottom topography measurement

Side-scan sonars can be used to derive maps of the topography of an area by moving the sonar across it just above the bottom. Low frequency sonars such as GLORIA have been used for continental shelf wide surveys while high frequency sonars are used for more detailed surveys of smaller areas.

Sub-bottom profiling

Powerful low frequency echo-sounders have been developed for providing profiles of the upper layers of the ocean bottom.

Synthetic aperture sonar

Various synthetic aperture sonars have been built in the laboratory and some have entered use in mine-hunting and search systems. An explanation of their operation is given in synthetic aperture sonar.

Parametric sonar

Parametric sources use the non-linearity of water to generate the difference frequency between two high frequencies. A virtual end-fire array is formed. Such a projector has advantages of broad bandwidth, narrow beamwidth, and when fully developed and carefully measured it has no obvious sidelobes. Its major disadvantage is very low efficiency of only a few percent. P.J. Westervelt's seminal 1963 JASA paper summarizes the trends involved.

Chapter 2

Acoustic Signature and Acoustic Doppler Current Profiler

Acoustic signature

Acoustic signature is used to describe a combination of acoustic emissions of ships and submarines.

Contributing factors

The acoustic signature is made up of a number of individual elements. These include:

- Machinery noise: noise generated by a ships engines, propeller shafts, fuel pumps, air conditioning systems, etc.
- Cavitation noise: noise generated by the creation of gas bubbles by the turning of a ship's propellers.
- Hydrodynamic noise: noise generated by the movement of water displaced by the hull of a moving vessel.

These emissions depend on a hull's dimensions, the installed machinery and ship's displacement. Therefore different ship classes will have different combinations of acoustic signals that together form a unique signature.

Targeting

Hydrophones and Sonar operating in passive mode can detect acoustic signals radiated by otherwise invisible submarines, and use these signals to target attacks.

Modern naval mines and torpedoes such as the CAPTOR mine can be programmed to distinguish the acoustic signatures of different vessels, leaving friendly vessels unmolested and attacking high-value targets when faced with multiple possible targets, e.g. distinguishing an aircraft carrier from its escorts.

Countermeasures

Warship designers aim to reduce the acoustic signature of ships and submarines just as much as they aim to reduce the radar cross sections and infra-red signals. For submarines, as a prime factor in how they can be detected the reduction of the acoustic signature is a primary goal.

The acoustic signature can be reduced by

- fitting of machinery with the best possible mechanical tolerances and designed to produce a minimum of noise.
- decoupling the machinery from the hull by mounting machinery on rubber mounting blocks.
- designing propellers to reduce cavitation, this led to the development of large slow turning propellers, today there is a preference now for pump-jet propulsors over propellers.
- the fitting of anechoic tiles to the hull, however ill fitting and loose anechoic tiles can themselves be a source of noise.
- hydrodynamic efficiency to minimise the perturbation of water.
- care in minimising protrusions from the hull.

Trimaran warships

The RV Triton

For a time the Royal Navy toyed with the idea of the trimaran hulled Future Surface Combatant. These would have had a very low acoustic signature. With three blade like hulls these ships would have cut through the water with a minimum of hydrodynamic noise. Radiated mechanical noise would also be minimised by using propulsors powered by a diesel-electric power plant; with the diesels being placed in the superstructure to mechanically isolate them from the water. This project got as far as the construction of the research ship RV Triton to test the principle of a large scale trimaran design.

Acoustic Doppler Current Profiler

Head of an ADCP with the four transducers

ADCP view ahead, mounted on an oceanographic device for long term measurements in the deep sea

An **Acoustic Doppler Current Profiler** (**ADCP or ADP**) is a sonar that attempts to produce a record of water current velocities for a range of depths. They are made of ceramic materials, and contain transducers, an amplifier, a receiver, a mixer, an oscillator, a clock, a temperature sensor, a compass, a pitch and roll sensor, and computer components to save the information collected. ADCPs can be configured in many ways: side-listening, into rivers and canals for long term continuous discharge measurements, downward-listening and mounted on boats for instantaneous surveys in the ocean or rivers, and mounted on moorings, or the seabed for long term current & wave studies. They can stay underwater for years at a time, and have a battery back for an energy

source. The sonar is used for oceanography, estuary, river and stream flow measurement, and weather forecasting.

Components

Depending on the field application, an ADCP may use one or more ceramics, (or other piezo materials) for transducers, which work in water similar to directional loudspeakers in air. These transducers are aimed such that the sound pulse travels through the water in different, but known directions. As the sound energy leaves and arrives at the transducer face it is shifted in frequency, known as the Doppler effect, by the relative velocity of the water. As that sound energy is returned (echo) by scatterers in the water the sound may also be shifted in frequency if there is relative velocity of water to scatterer. Trigonometry, averaging and some critical assumptions are used to calculate the velocity of the group of echoing scatters in a volume of water. By repetitive sampling of the return echo, and by "gating" the return data in time, the ADCP can produce a "profile" of water currents over a range of depths. Phased array techniques are also used to aim the sound (acoustic) energy, allowing for economical production of smaller ADCPs to accommodate a range of frequencies from 38 kHz to several megahertz.

In addition to the transducers, an ADCP typically has an electronic amplifier, receiver, mixer, oscillator, accurate clock, temperature sensor, compass, pitch and roll sensor, analog-to-digital converters, memory, digital signal processor and instruction set. The analog-to-digital converters (ADCs) and digital signal processor (DSP) are used to sample the returning signal, determine the Doppler shift, and sample the compass and other sensors in order to calculate range and a velocity vector relative to a known orientation.

Performance

There are a number of factors that affect accuracy, resolution and profile range. Most notable are: absorption, spreading, speed of sound in water, bandwidth of the sound energy, signal strength of the transmitted pulse and echo, size of transducer, beam width (sic) of the energy pulse travelling through the water, frequency, and a host of limitations associated with the signal processing techniques and hardware, including clock/oscillator accuracy.

ADCPs can be self-contained and operate from batteries for many years under the sea or remotely in a river or stream. Some time later they are retrieved and the historical current data is transferred from the ADCP memory to a computer and displayed using a variety of graphical and text-based software to observe the water current profiles. Or ADCPs can be connected to RS232, RS422, RS485, SDI-12, USB, Ethernet, Fiber, Modbus (SCADA) connections to provide real time, "live", monitoring of their output.

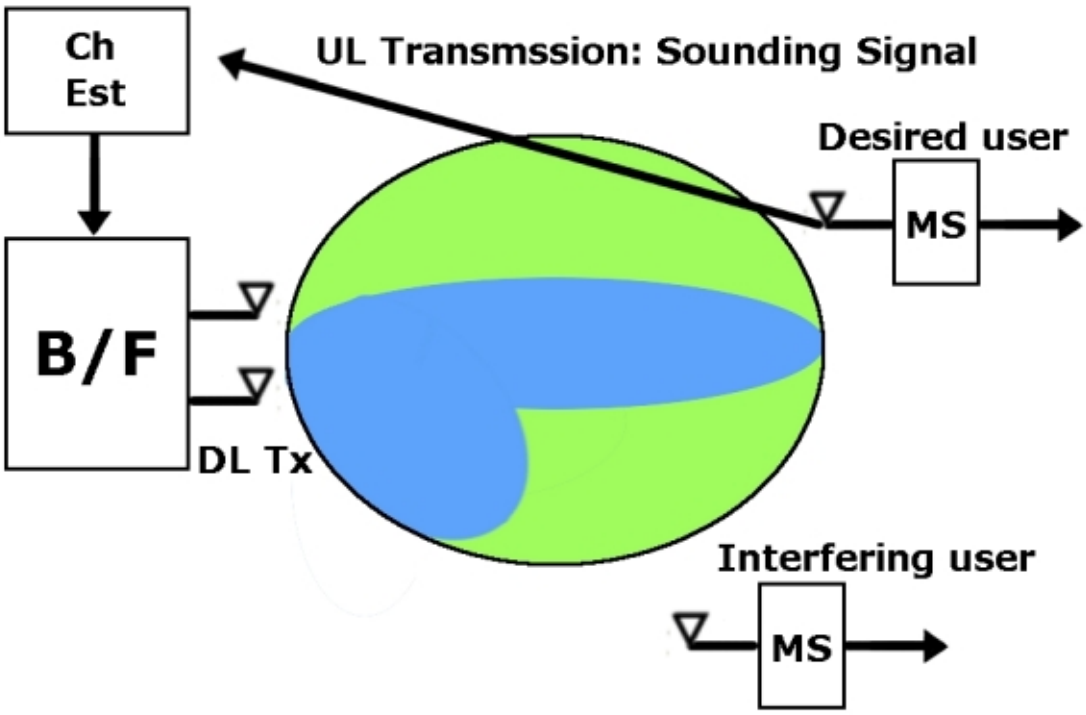
Uses

The ADCP, commercially available for about 25 years, is currently used for oceanography, estuary, river and stream flow measurement, even in weather forecasting. ADCPs are used in diverse ways, from locating underwater "tornadoes" that might damage deep water oil drilling activity, to measuring water flow through sewer pipes, or hanging up side down under an iceberg and measuring the flow of freshwater melting off the iceberg. Some harbor managers now use ADCPs to help them take advantage of tides and currents and optimize the flow of shipping in a busy port.

An ADCP can also be an acoustic **Doppler Velocity Log** (**DVL**) if it is programmed with the correct signal processing logic. The DVL bounces sound off the bottom (or a reference layer of water) and can determine the velocity vector of a subsea vehicle (or surface vessel) moving across the sea floor. This information can be combined with a starting fix, compass heading, and acceleration sensors (typically by use of a Kalman Filter) to calculate the position of the vehicle. DVLs are used to help navigate surface vessels, submarines, autonomous underwater vehicles, and ROVs for precise positioning in an environment where GPS, and other navigational aids, don't work.

Chapter 3

Beamforming



Beamforming

Beamforming is a signal processing technique used in sensor arrays for directional signal transmission or reception. This is achieved by combining elements in the array in such a way that signals at particular angle experience constructive interference and while others experience destructive interference. Beamforming can be used at both the transmit and receiver side to achieve spatially selectivity. The improvement compared with an omnidirectional reception/transmission is known as the receive/transmit gain (or loss).

Beamforming can be used for both radio or sound waves. It has found numerous applications in radar, sonar, seismology, wireless communications, radio astronomy,

speech, acoustics, and biomedicine. Adaptive beamforming is used to detect and estimate the signal-of-interest at the output of a sensor array by means of data-adaptive spatial filtering and interference rejection.

Beamforming techniques

Beamforming takes advantage of interference to change the directionality of the array. When transmitting, a beamformer controls the phase and relative amplitude of the signal at each transmitter, in order to create a pattern of constructive and destructive interference in the wavefront. When receiving, information from different sensors is combined in such a way that the expected pattern of radiation is preferentially observed.

For example in sonar, to send a sharp pulse of underwater sound towards a ship in the distance, simply transmitting that sharp pulse from every sonar projector in an array simultaneously fails because the ship will first hear the pulse from the speaker that happens to be nearest the ship, then later pulses from speakers that happen to be the further from the ship. The beamforming technique involves sending the pulse from each projector at slightly different times (the projector closest to the ship last), so that every pulse hits the ship at exactly the same time, producing the effect of a single strong pulse from a single powerful projector. The same thing can be carried out in air using loudspeakers, or in radar/radio using antennas.

In passive sonar, and in reception in active sonar, the beamforming technique involves combining delayed signals from each hydrophone at slightly different times (the hydrophone closest to the target will be combined after the longest delay), so that every signal reaches the output at exactly the same time, making one loud signal, as if the signal came from a single, very sensitive hydrophone. Receive beamforming can also be used with microphones or radar antennas.

With narrow-band systems the time delay is equivalent to a "phase shift", so in this case the array of antennas, each one shifted a slightly different amount, is called a phased array. A narrow band system, typical of radars, is one where the bandwidth is only a small fraction of the centre frequency. With wide band systems this approximation no longer holds, which is typical in sonars.

In the receive beamformer the signal from each antenna may be amplified by a different "weight." Different weighting patterns (e.g., Dolph-Chebyshev) can be used to achieve the desired sensitivity patterns. A main lobe is produced together with nulls and sidelobes. As well as controlling the main lobe width (the beam) and the sidelobe levels, the position of a null can be controlled. This is useful to ignore noise or jammers in one particular direction, while listening for events in other directions. A similar result can be obtained on transmission.

Beamforming techniques can be broadly divided into two categories:

- conventional (fixed or switched beam) beamformers
- adaptive beamformers or adaptive arrays
    - Desired signal maximization mode
    - Interference signal minimization or cancellation mode

Conventional beamformers use a fixed set of weightings and time-delays (or phasings) to combine the signals from the sensors in the array, primarily using only information about the location of the sensors in space and the wave directions of interest. In contrast, adaptive beamforming techniques generally combine this information with properties of the signals actually received by the array, typically to improve rejection of unwanted signals from other directions. This process may be carried out in either the time or the frequency domain.

As the name indicates, an adaptive beamformer is able to automatically adapt its response to different situations. Some criterion has to be set up to allow the adaption to proceed such as minimising the total noise output. Because of the variation of noise with frequency, in wide band systems it may be desirable to carry out the process in the frequency domain.

Beamforming can be computationally intensive. Sonar phased array has a data rate low enough that it can be processed in real-time in software, which is flexible enough to transmit and/or receive in several directions at once. In contrast, radar phased array has a data rate so high that it usually requires dedicated hardware processing, which is hard-wired to transmit and/or receive in only one direction at a time. However, newer field programmable gate arrays are fast enough to handle radar data in real-time, and can be quickly re-programmed like software, blurring the hardware/software distinction.

Sonar beamforming requirements

Sonar itself has many applications, such as wide-area-search-and-ranging, underwater imaging sonars such as side-scan sonar and acoustic cameras.

Sonar beamforming implementation is similar in general technique but varies significantly in detail compared to electromagnetic system beamforming implementation. Sonar applications vary from 1 Hz to as high as 2 MHz, and array elements may be few and large, or number in the hundreds yet very small. This will shift sonar beamforming design efforts significantly between demands of such system components as the "front end" (transducers, preamps and digitizers) and the actual beamformer computational hardware downstream. High frequency, focused beam, multi-element imaging-search sonars and acoustic cameras often implement fifth-order spatial processing that places strains equivalent to Aegis radar demands on the processors.

Many sonar systems, such as on torpedoes, are made up of arrays of up to 100 elements that must accomplish beamsteering over a 100 degree field of view and work in both active and passive modes.

Sonar arrays are used both actively and passively in 1, 2, and 3 dimensional arrays.

- 1 dimensional "line" arrays are usually in multi-element passive systems towed behind ships and in single or multi-element side scan sonar.
- 2 dimensional "planar" arrays are common in active/passive ship hull mounted sonars and some side-scan sonar.
- 3 dimensional spherical and cylindrical arrays are used in 'sonar domes' in the modern submarine and ships.

Sonar differs from radar in that in some applications such as wide-area-search all directions often need to be listened to, and in some applications broadcast to, simultaneously. Thus a multibeam system is needed. In a narrowband sonar receiver the phases for each beam can be manipulated entirely by signal processing software, as compared to present radar systems that use hardware to 'listen' in a single direction at a time.

Sonar also uses beamforming to compensate for the significant problem of the slower propagation speed of sound as compared to that of electromagnetic radiation. In side-look-sonars, the speed of the towing system or vehicle carrying the sonar is moving at sufficient speed to move the sonar out of the field of the returning sound "ping". In addition to focusing algorithms intended to improve reception, many side scan sonars also employ beam steering to look forward and backward to "catch" incoming pulses that would have been missed by a single sidelooking beam.

Beamforming schemes

- A conventional beamformer can be a simple beamformer also known as delay-and-sum beamformer. All the weights of the antenna elements can have equal magnitudes. The beamformer is steered to a specified direction only by selecting appropriate phases for each antenna. If the noise is uncorrelated and there are no directional interferences, the signal-to-noise ratio of a beamformer with L antennas receiving a signal of power P is $\frac{1}{\sigma_n^2} P \cdot L$, where σ_n^2 is Noise variance or Noise power.
- Null-steering beamformer
- Frequency domain beamformer

Beamforming history in cellular standards

Beamforming techniques used in cellular phone standards have advanced through the generations to make use of more complex systems to achieve higher density cells, with higher throughput.

- Passive mode: (almost) non-standardized solutions
    - Wideband Code Division Multiple Access (WCDMA) supports direction of arrival (DOA) based beamforming
- Active mode: mandatory standardized solutions
    - 2G — Transmit antenna selection as an elementary beamforming
    - 3G — WCDMA: Transmit antenna array (TxAA) beamforming
    - 3G evolution — LTE/UMB: Multiple-input multiple-output (MIMO) precoding based beamforming with partial Space-Division Multiple Access (SDMA)
    - Beyond 3G (4G, 5G, …) — More advanced beamforming solutions to support SDMA such as closed loop beamforming and multi-dimensional beamforming are expected

Chapter 4

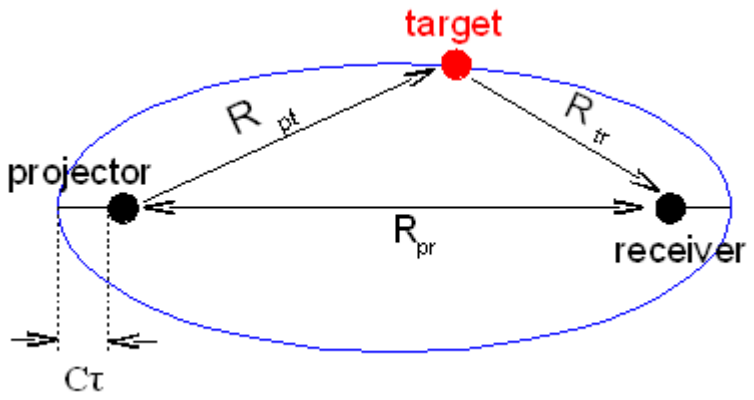
Bistatic Sonar

Most sonar systems are monostatic, in that the transmitter and receiver are in the same place. **Bistatic sonar** describes when the transmitter and receiver(s) are separated by a distance large enough to be comparable to the distance to the target.

Bistatic vs monostatic

Propagation (transmission) loss

This is a loss in sound level which happens while the sound pulse travels from projector to target and from target to receiver. There are 3 different mechanisms causing transmission loss: spherical (or cylindrical in shallow water) spreading, absorbing and scattering by ocean media inhomogeneities. Transmission loss (TL) is proportional to range, (the longer the sound travels the more the loss), and to sound frequency. In monostatic sonar the sound first travels from projector to target, then the same way back from target to receiver, so two-way loss is just 2TL, where TL is one-way loss. In bistatic sonar the total loss (in decibels) is a sum of TL_{pt} (from projector to target) and TL_{tr} (from target to receiver).

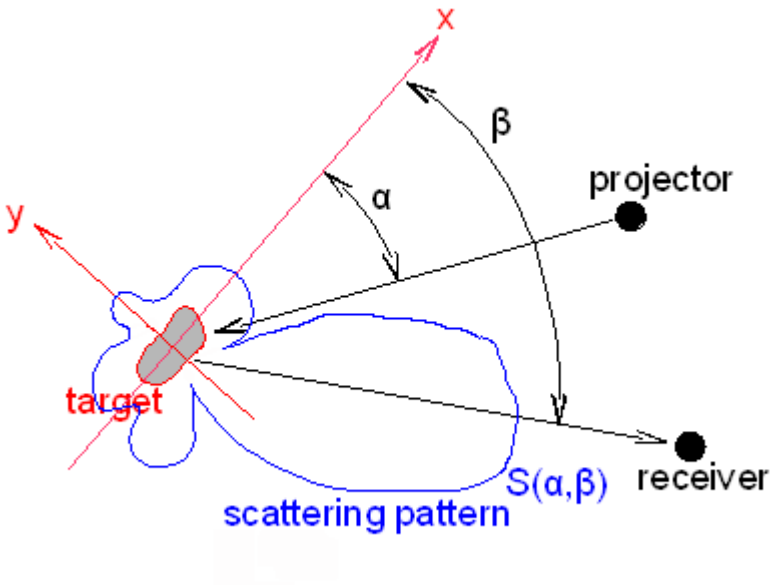


Bistatic sonar dead zone

Dead zone

In monostatic sonar, the first thing the receiver can hear is the sound of the transmitted ping. This sound level is very high, and it is impossible to detect the echo during the ping duration τ. That means targets are undetectable within the circle of Cτ/2 radius, where C is sound speed in water. This area is usually referred to as “dead zone”. If the sonar is close to the surface, bottom or both, (which may happen in shallow water), the dead zone may be greater than Cτ/2 due to a high level of reverberation.

In bistatic sonar, the travel distance from projector to target and from target to receiver is $R = R_{pt} + R_{tr}$. As the projector is separated from receiver by R_{pr} distance, first R_{pr} /C seconds after the ping starts, the receiver is just waiting. After that time, it receives direct signal from the projector (often referred to as “direct blast”,) which lasts Cτ seconds. So the sonar cannot detect targets within the ellipse R = Rpr + Cτ, as shown at the picture. High level reverberation in the projector area does not affect the dead zone.



Target scattering pattern

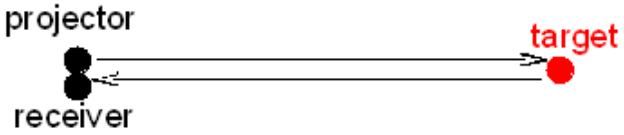
Target scattering pattern

Targets do not reflect the sound omni-directionally. The mechanism of sound reflection (or scattering by the target) is complicated, because the target is not just a rigid sphere. Scattered sound level depends on the angle β from which the target is ensonified by the projector, and it also varies with angle scattering direction α (refer to local target axes Z{x,y}). These angles are often referred to as aspects. This scattered sound level vs (α, β) function is called the scattering pattern S(α, β). Direction of maximum echo (maximum of S(α, β)) also depends on target shape and inner structure. So sometimes the best ensonifying aspect is not the same as the best receive aspect.

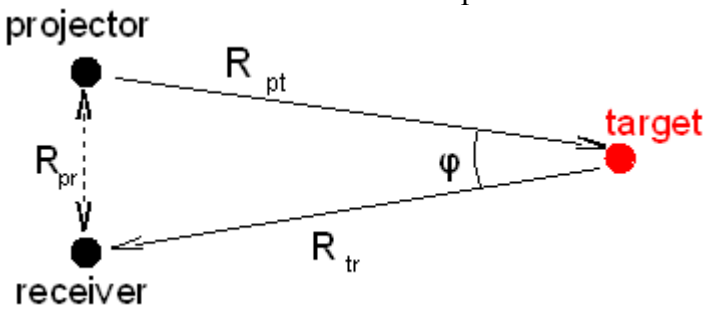
This leads to the bistatic solution. Target scattering becomes even more complicated if the target is buried (or semi-buried) into sea bottom sediments. (That happens to sea mines, waste containers, shipwrecks, etc.) In that case, the scattering mechanism is effected not by target features only, but also by sound wave interaction between the target and surrounding bottom.

Specific classes of bistatic sonars

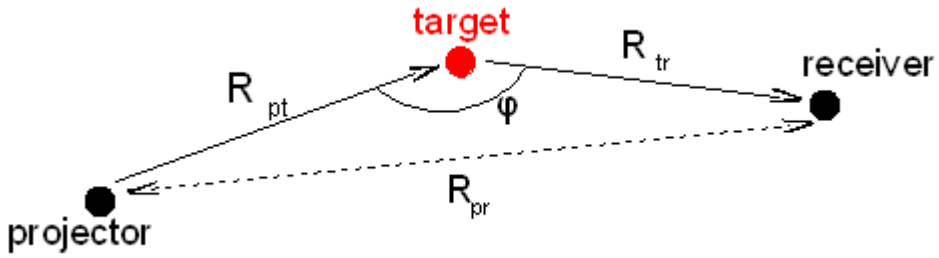
Backscattering and forward scattering



Monostatic sonar reception



Bistatic backscattering



Bistatic forward scattering

In **monostatic sonar** the receiver is listening to the echo which is reflected (scattered) right back from the target. Bistatic sonar can work in two ways: by utilizing either the target backscattering or forward scattering. **Backscattering** bistatic sonar is the sonar in which the bistatic angle φ is less than 90º. **Forward scattering** is the physical phenomena based on Babinet's principle. Forward scattering bistatic sonar is the sonar in which the bistatic angle φ is greater than 90º.

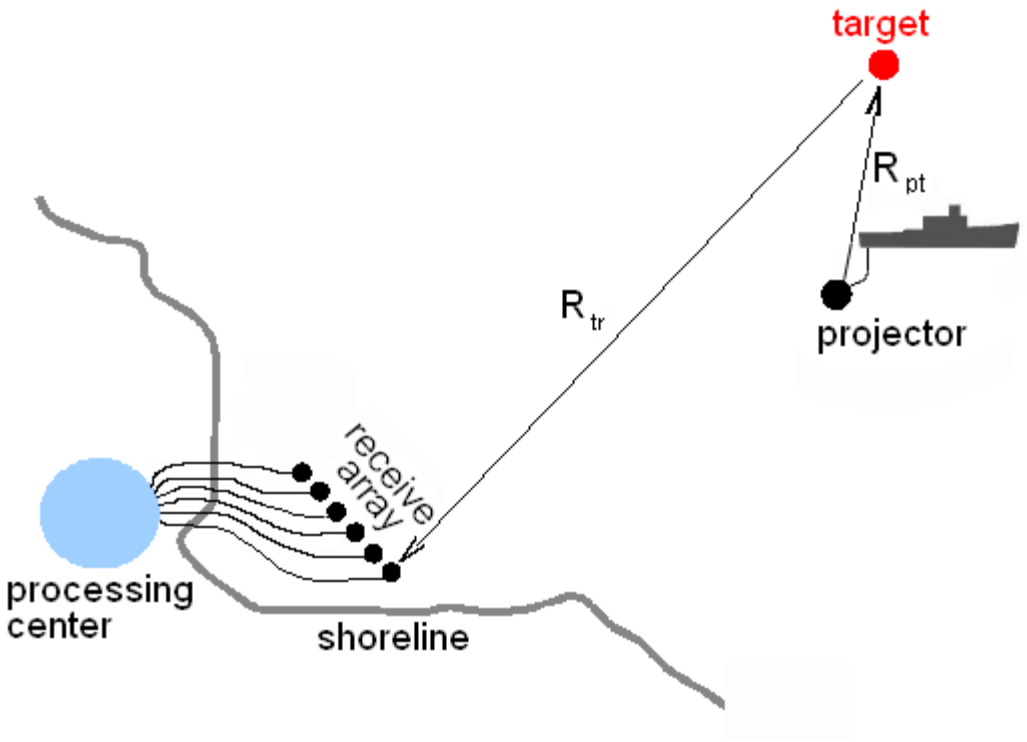
Pseudo-monostatic sonar

This is the sonar with a small bistatic angle. In other words, both the range from projector to target R_{pt} and from target to receiver R_{tr} is much greater than the distance from projector to receiver R_{pr}.

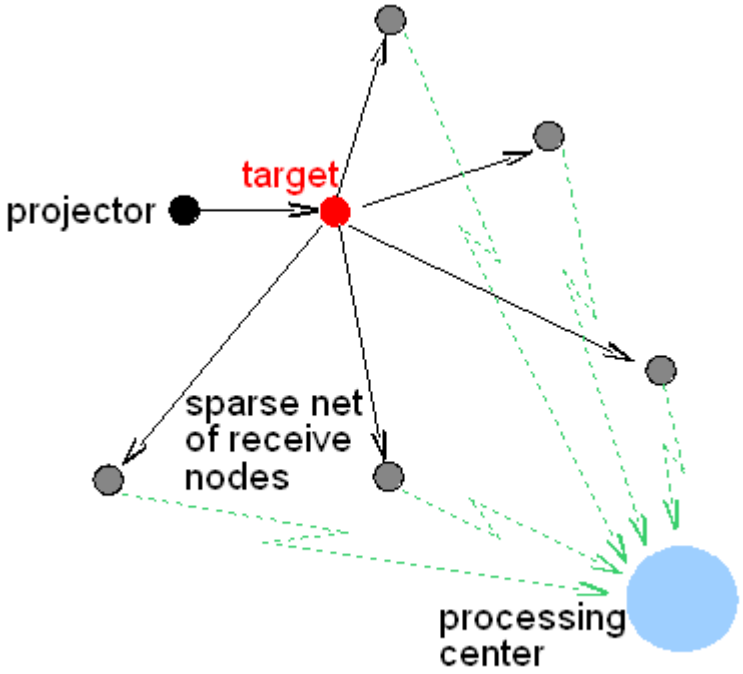
Multistatic sonar

This is the multi-node system with more than one projector, receiver or both.

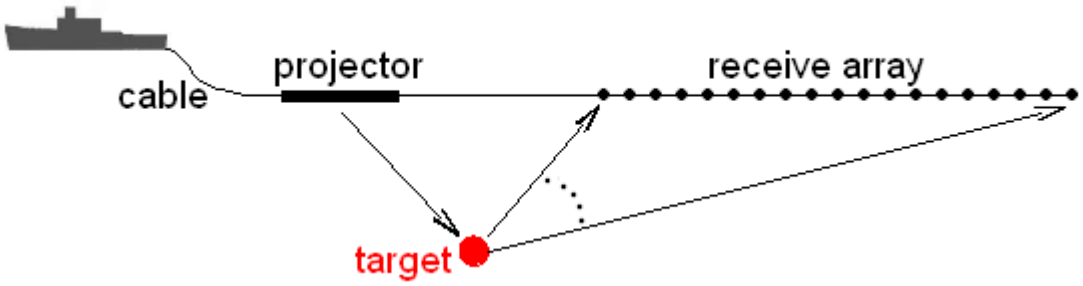
Applications



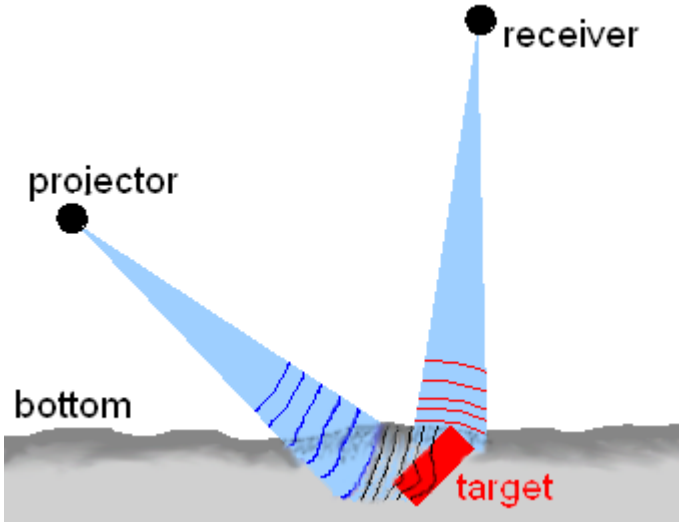
Long range surveillance



A net of receivers with a single projector



Low frequency towed sonar



Buried objects detection

Long range surveillance

For coastal surveillance, a large receive array of hydrophones is usually deployed close to the shore and connected with cables to a land-based processing center. To enable long range target detection (far away from the shore), one can use a powerful mobile projector, deployable from the ship. A system of this kind exploits the idea of "bringing the projector closer to area of interest and getting the transmission loss down".

Large area surveillance with a single projector and a net of receivers

A system of this type is multistatic. It exploits the idea of "cover the area of interest with a sparse net of receivers and ensonify the whole area with a powerful projector". Receive nodes may be sonobuoys (with radio communication link to a processing center) or autonomous underwater vehicles (AUVs) with an acoustic communication link. The example is GOATS project, using AUVs as receive nodes.

Low frequency towed sonar

The lower the frequency, the less the transmission loss absorbing and scattering components. On the other hand, the lower the frequency, the larger the size of directional projector and receive array. So the ship-deployable long range sonar is a low frequency bistatic towed array sonar with spatially separated projector and receive array. The example is LFATS towed sonar.

Buried object detection

To detect a buried object, the transmit ping must penetrate into the bottom. That requires a powerful and highly directional projector. Next, a directional receiver should be placed at the point where the "target + surrounding bottom" reflection is the best. This is a bistatic system. The example is SITAR project, developed to find objects like toxic waste containers and mines.

The principal advantages of bistatic and multistatic sonar include:

- Lower procurement and maintenance costs (if using a third party's transmitter)
- Operation without a frequency clearance (if using a third party's transmitter)
- Covert operation of the receiver
- Increased resilience to electronic countermeasures as waveform being used and receiver location are potentially unknown
- Possible enhanced radar cross section of the target due to geometrical effects

The principal disadvantages of bistatic and multistatic sonar include:

- System complexity
- Costs of providing communication between sites
- Lack of control over transmitter (if exploiting a third party transmitter)

- Harder to deploy
- Reduced low-level coverage due to the need for line-of-sight from several locations

Chapter 5

Fessenden Oscillator, Bistatic Range and Long Base Line Sonar

Fessenden oscillator

A **Fessenden oscillator** is an electro-acoustic transducer invented by Reginald Fessenden starting in 1912 in association with the Submarine Signaling Company of Boston. It was the first successful sonar device . It has been supplanted by piezoelectric devices.

It was an early kind of hydrophone, using electromagnetic forces; similar in operating principle to a voice coil loudspeaker, it was adapted to work in water instead of air. It was capable of creating underwater sounds and of picking up their echo.

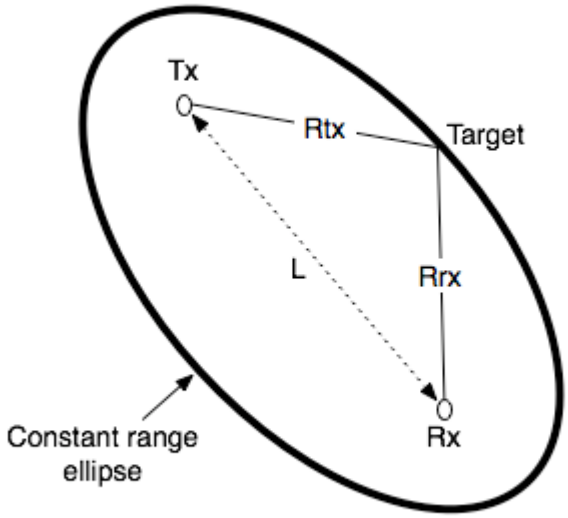
The creation of this device was motivated by a strongly-felt need to protect ships from collisions with obstacles and other ships.

Oscillator

The *oscillator* in the name referred to the fact that the device vibrated and moved water in response to a driving AC current. It was not an oscillator in the electronic sense that it generated a repetitive signal, in fact electronic oscillators did not yet exist when this device was created. Since the design of the device does not depend on a resonant response, it should not be considered a harmonic oscillator either.

Bistatic range

Bistatic range refers to the basic measurement of range made by a radar or sonar system with separated transmitter and receiver. The receiver measures the time difference of arrival of the signal from the transmitter directly, and via reflection from the target. This defines an ellipse of constant bistatic range, called an iso-range contour, on which the target lies, with foci centred on the transmitter and receiver. If the target is at range R_{rx} from the receiver and range R_{tx} from the transmitter, and the receiver and transmitter are a distance L apart, then the bistatic range is $R_{rx}+R_{tx}-L$. Motion of the target causes a rate of change of bistatic range, which results in bistatic Doppler shift.



Bistatic range geometry

Iso-range contour

Generally speaking, constant bistatic range points draw an ellipsoid with the transmitter and receiver positions as the focal points. The iso-range contours are where the ground slices the ellipsoid. When the ground is flat, this intercept forms an ellipse. Note that except when the two platforms have equal altitude, these ellipses are not centered on the specular point.

Long base line sonar

Long base line sonar, commonly referred to as **LBL**, is a method of acoustic positioning commonly used in deep water (water depth of greater than 3000 feet). A typical LBL positioning system consists of a transceiver and several beacons arranged into a structure called an array. The LBL transceiver pings each beacon and uses the 2-way travel time to calculate its position within the array. LBL positioning is much more accurate than ultra-short baseline (USBL) or SSBL surface-based positioning.

Advantages over surface tracking

In very deep water (1000m or more), acoustic positioning performed from the surface is subject to a large amount of noise and unusually long reply times due to the great distances the sound must travel. Also, a USBL system uses a single transceiver with multiple elements located close together and calculates range/bearings based on signal phase offsets. Because surface tracking may have an error radius of up to one-half percent of the water depth, 8,000 feet (2,400 m) of water can produce up to 40 feet (12 m) of error in any direction. The beacons in an LBL array are typically less than a kilometer apart, and the noise levels near the seabed in deep water are much less than near the surface, so LBL can usually resolve positions with less than a foot of error, regardless of the water depth. LBL combines range information from multiple sources. This redundancy helps to eliminate noise.

Beacon Array

Generally between 5 and 25 beacons will be placed on the seafloor. The acoustic navigator will then use a method of surface tracking such as USBL to lock in the locations of each beacon, which involves taking tens to hundreds of range/bearing measurements from different locations and averaging them to produce a final position. Once the position of each beacon is known to a high precision, the array is ready for navigation.

Underwater "smart" beacons are able to sample 2-way travel times between each other, so even a large array of smart beacons may be calibrated with only 2 or 3 known positions. The remaining beacons' positions can be resolved by ranging between beacons, reducing the time required to calibrate the array.

Tracking

Once the array has been calibrated, an underwater vehicle or diver may equip a transceiver which will take ranges (based on 2-way acoustic travel time) to each beacon in the array, and send that data to a computer located on the surface to be processed. The computer uses the ranges from these known points to calculate a final position.

Chapter 6

Geophysical MASINT

Geophysical MASINT is a branch of Measurement and Signature Intelligence (MASINT) that involves phenomena transmitted through the earth (ground, water, atmosphere) and manmade structures including emitted or reflected sounds, pressure waves, vibrations, and magnetic field or ionosphere disturbances.

According to the United States Department of Defense, MASINT is technically derived intelligence (excluding traditional imagery IMINT and signals intelligence SIGINT) that – when collected, processed, and analyzed by dedicated MASINT systems – results in intelligence that detects, tracks, identifies, or describes the signatures (distinctive characteristics) of fixed or dynamic target sources. MASINT was recognized as a formal intelligence discipline in 1986. Another way to describe MASINT is a "non-literal" discipline. It feeds on a target's unintended emissive by-products, the "trails" - the spectral, chemical or RF that an object leaves behind. These trails form distinct signatures, which can be exploited as reliable discriminators to characterize specific events or disclose hidden targets."

As with many branches of MASINT, specific techniques may overlap with the six major conceptual disciplines of MASINT defined by the Center for MASINT Studies and Research, which divides MASINT into Electro-optical, Nuclear, Geophysical, Radar, Materials, and Radiofrequency disciplines.

Military Requirements

Geophysical sensors have a long history in conventional military and commercial applications, from weather prediction for sailing, to fish finding for commercial fisheries, to nuclear test ban verification. New challenges, however, keep emerging.

First-world military forces, opposing other conventional militaries, there is an assumption that if a target can be located, it can be destroyed. As a result, concealment and deception have taken on new criticality. "Stealth" low-observability aircraft have gotten much attention, and new surface ship designs feature observability reduction. Operating in the confusing littoral environment produces a great deal of concealing interference.

Of course, submariners feel they invented low observability, and others are simply learning from them. They know that going deep or at least ultraquiet, and hiding among natural features, makes them very hard to detect.

Two families of military applications, among many, represent new challenges against which geophysical MASINT can be tried.

Deeply Buried Structures

One of the easiest ways for nations to protect weapons of mass destruction, command posts, and other critical structures is to bury them deeply, perhaps enlarging natural caves or disused mines. Deep burial is not only a means of protection against physical attack, as even without the use of nuclear weapons, there are deeply penetrating precision guided bombs that can attack them. Deep burial, with appropriate concealment during construction, is a way to avoid the opponent's knowing the buried facility's position well enough to direct precision guided weapons against it.

Finding deeply buried structures, therefore, is a critical military requirement. The usual first step in finding a deep structure is IMINT, especially using hyperspectral IMINT sensors to help eliminate concealment. "Hyperspectral images can help reveal information not obtainable through other forms of imagery intelligence such as the moisture content of soil. This data can also help distinguish camouflage netting from natural foliage." Still, a facility dug under a busy city would be extremely hard to find during construction. When the opponent knows that it is suspected that a deeply buried facility exists, there can be a variety of decoys and lures, such as buried heat sources to confuse infrared sensors, or simply digging holes and covering them, with nothing inside.

MASINT using as acoustic, seismic, and magnetic sensors would appear to have promise, but the reality of these sensors is that they must be fairly close to the target. Magnetic Anomaly Detection (MAD) is used, in antisubmarine water, for final localization before attack. The existence of the submarine is usually established through passive listening and refined with directional passive sensors and active sonar.

Once these sensors, as well as HUMINT and other sources, have failed, there is promise, for surveying large areas and deeply concealed facilities, using gravitimetric sensors. Gravity sensors are a new field, but military requirements are making it important while the technology to do it is becoming possible.

Naval Operations in Shallow Water

Especially in today's "green water" and "brown water" naval applications, navies are looking at MASINT solutions to meet new challenges of operating in littoral areas of operations. This symposium found it useful to look at five technology areas, which are interesting to contrast to the generally accepted categories of MASINT: acoustics and geology and geodesy/sediments/transport, nonacoustical detection

(biology/optics/chemistry), physical oceanography, coastal meteorology, and electromagnetic detection.

Although it is unlikely there will ever be another World War II-style opposed landing on a fortified beach, another aspect of the littoral is being able to react to opportunities for amphibious warfare. Detecting shallow-water and beach mines remains a challenge, since mine warfare is a deadly "poor man's weapon."

While initial landings from an offshore force would be from helicopters or tiltrotor aircraft, with air cushion vehicles bringing ashore larger equipment, eventually, traditional landing craft, portable causeways, or other equipment will be needed to bring heavy equipment across a beach. Shallow depth and natural underwater obstacles can block a beach as well as can shallow-water mines. Synthetic Aperture Radar (SAR), airborne laser detection and ranging (LIDAR)) and use of bioluminescence to detect wake trails around underwater obstacles all may help solve this challenge.

Moving onto and across the beach has its own challenges. Remotely operated vehicles may be able to map landing routes, and they, as well as LIDAR and multispectral imaging, may be able to detect shallow water. Once on the beach, the soil has to support heavy equipment. Techniques here include estimating soil type from multispectral imaging, or from an airdropped penetrometer that actually measures the loadbearing capacity of the surface.

Weather and Sea Intelligence MASINT

The science and art of weather prediction used the ideas of measurement and signatures to predict phenomena, long before there were any electronic sensors. Masters of sailing ships might have no more sophisticated instrument than a wetted finger raised to the wind, and the flapping of sails.

Weather information, in the normal course of military operations, has a major effect on tactics. High winds and low pressures can change artillery trajectories. High and low temperatures cause both people and equipment to require special protection. Aspects of weather, however, also can be measured and compared with signatures, to confirm or reject the findings of other sensors.

The state of the art is to fuse meteorological, oceanographic, and acoustic data in a variety of display modes. Temperature, salinity and sound speed can be displayed horizontally, vertically, or in three-dimensional perspective.

Predicting Weather based on Measurements and Signatures

While early sailors had no sensors beyond their five senses, the modern meteorologist has a wide range of geophysical and electro-optical measuring devices, operating on platforms from the bottom of the sea to deep space. Prediction based on these

measurements are based on signatures of past weather events, a deep understanding of theory, and computational models.

Weather predictions can give significant negative intelligence, when the signature of some combat system is such that it can operate only under certain weather conditions. Weather has long been an extremely critical part of modern military operations, as when the decision to land at Normandy on June 6, rather than June 5, 1944 depended on Dwight D. Eisenhower's trust in his staff weather advisor, Group Captain James Martin Stagg. It is rarely understood that something as fast as a ballistic missile reentry vehicle, or as "smart" as a precision guided munition, can still be affected by winds in the target area.

As part of Unattended Ground Sensors,. The Remote Miniature Weather Station (RMWS), from System Innovations, is an air-droppable version with a lightweight, expendable and modular system with two components: a meteorological (MET) sensor and a ceilometer (cloud ceiling height) with limited MET. The basic MET system is surface-based and measures wind speed and direction, horizontal visibility, surface atmospheric pressure, air temperature and relative humidity. The ceilometer sensor determines cloud height and discreet cloud layers. The system provides near-real-time data capable of 24-hour operation for 60 days. The RMWS can also go in with US Air Force Special Operations combat weathermen

The man-portable version, brought in by combat weathermen, has an additional function, as remote miniature ceilometer. Designed to measure multiple layer cloud ceiling heights and then send that data via satellite communications link to an operator display, the system uses a Neodinum YAG (NdYAG), 4 megawatt non-eye safe laser. According to one weatherman, "We have to watch that one," he said. "Leaving it out there basically we're worried about civilian populace going out there and playing with it—firing the laser and there goes somebody's eye. There are two different units [to RMWS]. One has the laser and one doesn't. The basic difference is the one with the laser is going to give you cloud height."

Hydrographic Sensors

Hydrographic MASINT is subtly different from weather, in that it considers factors such as water temperature and salinity, biologic activities, and other factors that have a major effect on sensors and weapons used in shallow water. ASW equipment, especially acoustic performance depends on the season the specific coastal site. Water column conditions, such as temperature, salinity, and turbidity are more variable in shallow than deep water. Water depth will influence bottom bounce conditions, as will the material of the bottom. Seasonal water column conditions (particularly summer versus winter) are inherently more variable in shallow water than in deep water.

While much attention is given to shallow waters of the littoral, other areas have unique hydrographic characteristics.

- regional areas with fresh water eddies
- open ocean salinity fronts
- near ice floes
- under ice

A submarine tactical development activity observed, "Fresh water eddies exist in many areas of the world. As we have experienced recently in the Gulf of Mexico using the Tactical Oceanographic Monitoring System (TOMS), there exist very distinct surface ducts that causes the Submarine Fleet Mission Program Library (SFMPL) sonar prediction to be unreliable. Accurate bathythermic information is paramount and a precursor for accurate sonar predictions."

Temperature and Salinity

Critical to the prediction of sound, needed by active and passive MASINT systems operating in water is knowing the temperature and salinity at specific depths. Antisubmarine aircraft, ships, and submarines can release independent sensors that measure the water temperature at various depths. The water temperature is critically important in acoustic detections, as changes in water temperature at thermoclines can act as a "barrier" or "layer" to acoustic propagation. To hunt a submarine, which is aware of water temperature, the hunter must drop acoustic sensors below the thermocline.

Water conductivity is used as a surrogate marker for salinity. The current and most recently developed software, however, does not give information on suspended material in the water or bottom characteristics, both considered critical in shallow-water operations.

The US Navy does this by dropping expendable probes, which transmit to a recorder, of 1978-1980 vintage, the AN/BQH-7 for submarines and the AN/BQH-71 for surface ships. While the redesign of the late seventies did introduce digital logic, the devices kept hard-to-maintain analog recorders, and maintainability became critical by 1995. A project was begun to extend with COTS components, to result in the AN/BQH-7/7A EC-3. In 1994-5, the maintainability of the in-service units became critical.

Variables in selecting the appropriate probe include:

- Maximum depth sounded
- Speed of launching vessel
- Resolution Vertical Distance Between Data Points (ft)
- Depth Accuracy

Biomass

Large schools of fish contain enough entrapped air to conceal the sea floor, or manmade underwater vehicles and structures. Fishfinders, developed for commercial and recreational fishing, are specialized sonars that can identify acoustic reflections between

the surface and the bottom. Variations on commercial equipment are apt to be needed, especially in littoral areas rich in marine life.

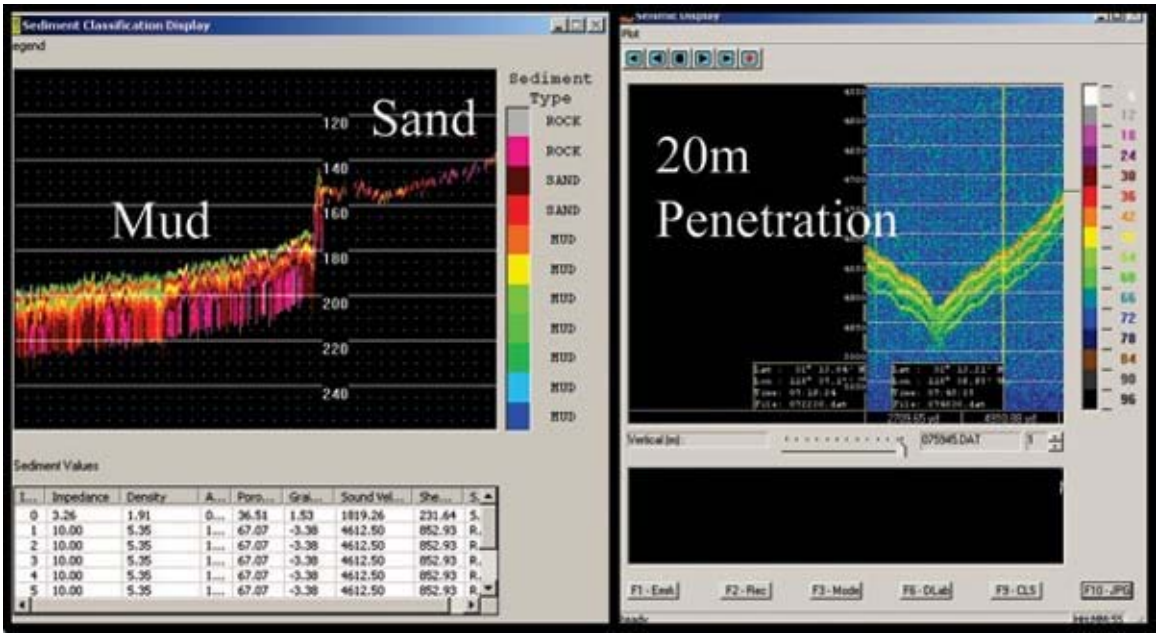
Sea Bottom Measurement

A variety of sensors can be used to characterise the sea bottom into, for example, mud, sand, and gravel. Active acoustic sensors are the most obvious, but there is potential information from gravitimetric sensors, electro-optical and radar sensors for making inferences from the water surface, etc.

Relatively simple sonars such as echo sounders can be promoted to seafloor classification systems via add-on modules, converting echo parameters into sediment type. Different algorithms exist, but they are all based on changes in the energy or shape of the reflected sounder pings.

Side-scan sonars can be used to derive maps of the topography of an area by moving the sonar across it just above the bottom. Multibeam hull-mounted sonars are not as precise as a sensor near the bottom, but both can give reasonable three-dimensional visualization.

Another approach comes from greater signal processing of existing military sensors. The US Naval Research Laboratory demonstrated both seafloor characterization, as well as subsurface characteristics of the seafloor. Sensors used, in different demonstrations, included normal incidence beams from the AM/UQN-4 surface ship depthfinder, and AN/BQN-17 submarine fathometer; backscatter from the Kongsberg EM-121 commercial multibeam sonar; AN/UQN-4 fathometers on mine countermeasures (MCM) ships, and the AN/AQS-20 mine-hunting system. These produced the "Bottom and Subsurface Characterization" graphic.



Bottom and Subsurface Characterization

Weather effects on chemical, biological, and radiological weapon propagation

One of the improvements in the Fuchs 2 reconnaissance vehicle is adding onboard weather instrumentations, including data such as wind direction and speed;, air and ground temperature; barometric pressure and humidity.

Acoustic MASINT

This includes the collection of passive or active emitted or reflected sounds, pressure waves or vibrations in the atmosphere (ACOUSTINT) or in the water (ACINT) or conducted through the ground Going well back into the Middle Ages, military engineers would listen to the ground for sounds of telltale digging under fortifications.

In modern times, acoustic sensors were first used in the air, as with artillery ranging in World War I. Passive hydrophones were used by the World War I Allies against German submarines; the UC-3, was sunk with the aid of hydrophone on 23 April 1916. Since submerged submarines cannot use radar, passive and active acoustic systems are their primary sensors. Especially for the passive sensors, the submarine acoustic sensor operators must have extensive libraries of acoustic signatures, to identify sources of sound.

In shallow water, there are sufficient challenges to conventional acoustic sensors that additional MASINT sensors may be required. Two major confounding factors are:

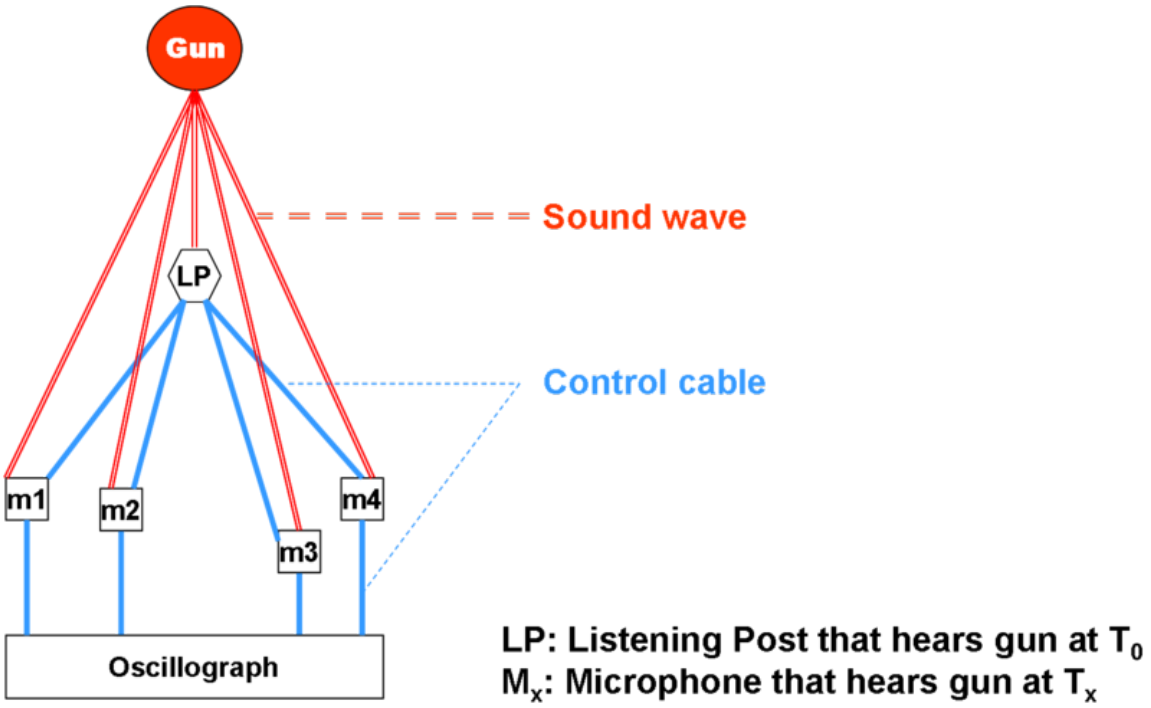
- Boundary interactions. The effects of the seafloor and the sea surface on acoustic systems in shallow water are highly complex, making range predictions difficult. Multi-path degradation affects overall figure of merit and active classification. As a result, false target identifications are frequent.
- Practical limitations. Another key issue is the range dependence of shallow water propagation and reverberation. For example, shallow water limits the depth of towed sound detection arrays, thus increasing the possibility of the system's detecting its own noise. In addition, closer ship spacing increases the potential for mutual interference effects. It is believed that nonacoustic sensors, of magnetic, optical, bioluminescent, chemical, and hydrodynamic disturbances will be necessary in shallow-water naval operations.

Counterbattery and Countersniper Location and Ranging

While now primarily of historical interest, one of the first applications of acoustic and optical MASINT was locating enemy artillery by the sound and flash of their firing, a technique pioneered by Canadian Forces under Gen. Arthur Currie, with Andrew McNaughton in a key staff role. The combination of sound ranging (i.e., acoustic MASINT) and flash ranging (i.e., before modern optoelectronics) gave information

unprecedented for the time, in both accuracy and timeliness. Enemy gun positions were located within 25 to 100 yards, with the information coming in three minutes or less.

Initial WWI Counterbattery Acoustic Systems



Sound Ranging

In the "Sound Ranging" graphic, the Listening Post, which is well forward of the microphone stations, sends an electrical signal to the microphone stations (MS) when the LP operator hears the gun's sound at time T_0. Either manually or electrically, each MS_x sends a starting pulse to an oscillograph. When the MS operator hears the sound, he stops the signal sent to the oscillograph. The oscillograph operator can then compute a time of arrival A_x, which is the difference between the T_0 and T_{Mx}. Without computer assistance, the range had to be computed manually.

The positions of the microphone stations and listening posts are precisely known. Each A_x can be graphed as a hyperbola. Where the asymptotes of the hyperbola meet is the position at which the gun is assumed to be located.

Where sound ranging is a time-of-arrival technique not dissimilar to that of modern multistatic sensors, flash ranging used theodolites to take bearings on the flash from the presurveyed flash observation post. The location of the gun was determined goniometrically, where the bearings intersected. Flash ranging, today, would be called electro-optical MASINT.

Artillery sound and flash ranging remained in use through World War II and into the postwar years, until mobile counterbattery radar, itself a MASINT radar sensor, became

available. These techniques anticipated, and then paralleled, radio direction finding in SIGINT, which first was goniometric and now, with the precision time synchronization from GPS, is often time-of-arrival.

If the observation was at night, the Canadian master gunner could compare the sound and flash, while only sound was available in daylight. The Canadian units still had to estimate wind, temperature, and barometric pressure on the trajectory to the German artillery. and manually—and quickly—compute firing orders. Optimal times were on the order of three minutes.

Modern Acoustic Artillery Locators

Artillery positions now are located primarily with counterartillery radar, such as the US AN/TPQ-37, as well as IMINT. SIGINT also may give clues to positions, both with COMINT for firing orders, and ELINT for such things as weather radar. Still, there is renewed interest in both acoustic and electro-optical systems to complement counterartillery radar.

Acoustic sensors have come a long way since World War I. Typically, the acoustic sensor is part of a combined system, in which it cues radar or electro-optical sensors of greater precision, but narrower field of view.

HALO

The UK's hostile artillery locating system (HALO) has been in service with the British Army since 2002. HALO is not as precise as radar, but especially complements the directional radars. It passively detects artillery cannon, mortars and tank guns, with 360 degree coverage and can monitor over 2,000 square kilometers. HALO has worked in urban areas, the mountains of the Balkans, and the deserts of Iraq.

The system consists of a distributed array of up to 12 acoustic pressure sensors, which can compute location data on up to 8 rounds per second, and forwarding the data to the system operator. Assuming typical sensor dispersion, three or more sensors will measure the pressure wave, and the triangulation of the system computer can match a signature and help the AN/TPQ-36 and TPQ-37 Firefinder radars, which are not omnidirectional, to focus on the correct vector.

UTAMS

Another acoustic system is the US Army Unattended Transient Acoustic MASINT Sensor (UTAMS), which detects detect mortar and rocket launches and impacts. UTAMS has three to five acoustic arrays, each with four microphones, a processor, radio link, power source, and a laptop control computer. UTAMS, which was first operational in Iraq, first tested in November 2004 at a Special Forces Operating Base (SFOB) in Iraq. UTAMS was used in conjunction with AN/TPQ-36 and AN/TPQ-37 counter-artillery radar. While UTAMS was intended principally for detecting indirect artillery fire, Special

Forces and their fire support officer learned it could pinpoint improvised explosive device (IED) explosions and small arms/rocket-propelled grenade (RPG) fires. It detected Points of Origin (POO) up to 10 kilometers from the sensor.

Analyzing the UTAMS and radar logs revealed several patterns. The opposing force was firing 60 mm mortars during observed dining hours, presumably since that gave the largest groupings of personnel and the best chance of producing heavy casualties. That would have been obvious from the impact history alone, but these MASINT sensors established a pattern of the enemy firing locations.

This allowed the US forces to move mortars into range of the firing positions, give coordinates to cannon when the mortars were otherwise committed, and to use attack helicopters as a backup to both. The opponents changed to night fires, which, again, were countered with mortar, artillery, and helicopter fires. They then moved into an urban area where US artillery was not allowed to fire, but a combination of PSYOPS leaflet drops and deliberate near misses convinced the locals not to give sanctuary to the mortar crews.

Tower-mounted UTAMS array component of UTAMS in the Rocket Launch Spotter (RLS) system

Originally for a Marine requirement in Afghanistan, UTAMS was combined with electro-optical MASINT to produce the Rocket Launch Spotter (RLS) system useful against both rockets and mortars.

In the Rocket Launch Spotter (RLS) application, each array consists of four microphones and processing equipment. Analyzing the time delays between an acoustic wavefront's interaction with each microphone in the array UTAMS provides an azimuth of origin. The azimuth from each tower is reported to the UTAMS processor at the control station, and a POO is triangulated and displayed. The UTAMS subsystem can also detect and locate the point of impact (POI), but, due to the difference between the speeds of sound

and light, it may take UTAMS as long as 30 seconds to determine the POO for a rocket launch 13 km away. In this application, the electro-optical component of RLS will detect the rocket POO earlier, while UTAMS may do better with the mortar prediction.

Passive sea-based acoustic sensors (hydrophones)

Modern hydrophones convert sound to electrical energy, which then can undergo additional signal processing, or that can be transmitted immediately to a receiving station. They may be directional or omnidirectional.

Navies use a variety of acoustic systems, especially passive, in antisubmarine warfare, both tactical and strategic. For tactical use, passive hydrophones, both on ships and airdropped sonobuoys, are used extensively in antisubmarine warfare. They can detect targets far further away than with active sonar, but generally will not have the precision location of active sonar, approximating it with a technique called Target Motion Analysis (TMA). Passive sonar has the advantage of not revealing the position of the sensor.

The Integrated Undersea Surveillance System (IUSS) consists of multiple subsystems in SOSUS, Fixed Distributed System (FDS), and the Advanced Deployable System (ADS or SURTASS). Reducing the emphasis on Cold War blue-water operations put SOSUS, with more flexible "tuna boat" sensing vessels called SURTASS being the primary blue-water long-range sensors

SURTASS used longer, more sensitive towed passive acoustic arrays than could be deployed from maneuvering vessels, such as submarines and destroyers.

USNS Able (T-AGOS-20) aft view of SURTASS equipment.

Air-dropped passive acoustic sensors

Passive sonobuoys, such as the AN/SSQ-53F, can be directional or omnidirectional and can be set to sink to a specific depth. These would be dropped from helicopters and maritime patrol aircraft such as the P-3.

Fixed underwater passive acoustic sensors

The US installed massive Fixed Surveillance System (FSS, also known as SOSUS) hydrophone arrays on the ocean floor, to track Soviet and other submarines.

Surface ship passive acoustic sensors

Purely from the standpoint of detection, towed hydrophone arrays offer a long baseline and exceptional measurement capability. Towed arrays, however, are not always feasible, because when deployed, their performance can suffer, or they can suffer outright damage, from fast speeds or radical turns. A state-of-the-art British towed array, with both passive and active capabilities, is Sonar 2087 made by Thales Underwater Systems.

Steerable sonar arrays on the hull or bow usually have a passive as well as active mode, as do variable-depth sonars

Surface ships may have warning receivers to detect hostile sonar.

Submarine passive acoustic sensors

Modern submarines have multiple passive hydrophone systems, such as a steerable array in a bow dome, fixed sensors along the sides of the submarines, and towed arrays. They also have specialized acoustic receivers, analogous to radar warning receivers, to alert the crew to the use of active sonar against their submarine.

US submarines made extensive clandestine patrols to measure the signatures of Soviet submarines and surface vessels. This acoustic MASINT mission included both routine patrols of attack submarines, and submarines sent to capture the signature of a specific vessel. US antisubmarine technicians on air, surface, and subsurface platforms had extensive libraries of vessel acoustic signatures.

Passive acoustic sensors can detect aircraft flying low over the sea.

Land-based Passive Acoustic Sensors (geophones)

Vietnam-era acoustic MASINT sensors included "Acoubuoy (36 inches long, 26 pounds) floated down by camouflaged parachute and caught in the trees, where it hung to listen. The Spikebuoy (66 inches long, 40 pounds) planted itself in the ground like a lawn dart. Only the antenna, which looked like the stalks of weeds, was left showing above ground." This was part of Operation Igloo White.

Part of the AN/GSQ-187 Improved Remote Battlefield Sensor System (I-REMBASS) is a passive acoustic sensor, which, with other MASINT sensors, detects vehicles and personnel on a battlefield. Passive acoustic sensors provide additional measurements that can be compared with signatures, and used to complement other sensors. I-REMBASS control will integrate, in approximately 2008, with the Prophet SIGINT/EW ground system.

For example, a ground search radar may not be able to differentiate between a tank and a truck moving at the same speed. Adding acoustic information, however, may quickly distinguish between them.

File:MASINT-T72-acoustic.jpg
The acoustic signature of a Russian T-72 tank shows the image is not of a dummy

Active Acoustic Sensors and Supporting Measurements

Combatant vessels, of course, made extensive use of active sonar, which is yet another acoustic MASINT sensor. Besides the obvious application in antisubmarine warfare, specialized active acoustic systems have roles in:

- Mapping the seafloor for navigation and collision avoidance. These include basic depth gauges, but quickly get into devices that do 3-dimensional underwater mapping
- Determining seafloor characteristics, for applications varying from understanding its sound-reflecting properties, to predicting the type of marine life that may be found there, to knowing when a surface is appropriate for anchoring or for using various equipment that will contact the seafloor

Various synthetic aperture sonars have been built in the laboratory and some have entered use in mine-hunting and search systems. An explanation of their operation is given in synthetic aperture sonar.

Water Surface, Fish Interference and Bottom Characterization

The water surface and bottom are reflecting and scattering boundaries. Large schools of fish, with air in their swim bladder balance apparatus, can also have a significant effect on acoustic propagation.

For many purposes, but not all naval tactical applications, the sea-air surface can be thought of as a perfect reflector. "The effects of the seafloor and the sea surface on acoustic systems in shallow water are highly complex, making range predictions difficult. Multi-path degradation affects overall figure of merit and active classification. As a result, false target identifications are frequent."

The acoustic impedance mismatch between water and the bottom is generally much less than at the surface and is more complex. It depends on the bottom material types and depth of the layers. Theories have been developed for predicting the sound propagation in the bottom in this case, for example by Biot and by Buckingham.

Water Surface

For high frequency sonars (above about 1 kHz) or when the sea is rough, some of the incident sound is scattered, and this is taken into account by assigning a reflection coefficient whose magnitude is less than one.

Rather than measuring surface effects directly from a ship, radar MASINT, in aircraft or satellites, may give better measurements. These measurements would then be transmitted to the vessel's acoustic signal processor.

Under Ice

A surface covered with ice, of course, is tremendously difference than even storm-driven water. Purely from a collision avoidance and acoustic propagation, a submarine needs to know how close it is to the bottom of ice. Less obvious is the need to know the three-dimensional structure of the ice, because submarines may need to break through it to launch missiles, to raise4 electronic masts, or to surface the boat. Three-dimensional ice information also can tell the submarine captain whether antisubmarine warfare aircraft can detect or attack the boat.

The state of the art is providing the submarine with a three-dimensional visualization of the ice above: the lowest part (ice keel) and the ice canopy. While sound will propagate differently in ice than liquid water, the ice still needs to be considered as a volume, to understand the nature of reverberations within it.

Bottom

A typical basic depth measuring device is the US AN/UQN-4A. Both the water surface and bottom are reflecting and scattering boundaries. For many purposes, but not all naval tactical applications, the sea-air surface can be thought of as a perfect reflector. In reality, there are complex interactions of water surface activity, seafloor characteristics, water temperature and salinity, and other factors that make "...range predictions difficult. Multi-path degradation affects overall figure of merit and active classification. As a result, false target identifications are frequent."

This device, however, does not give information on the characteristics of the bottom. In many respects, commercial fishing and marine scientists have equipment that is perceived as needed for shallow water operation.

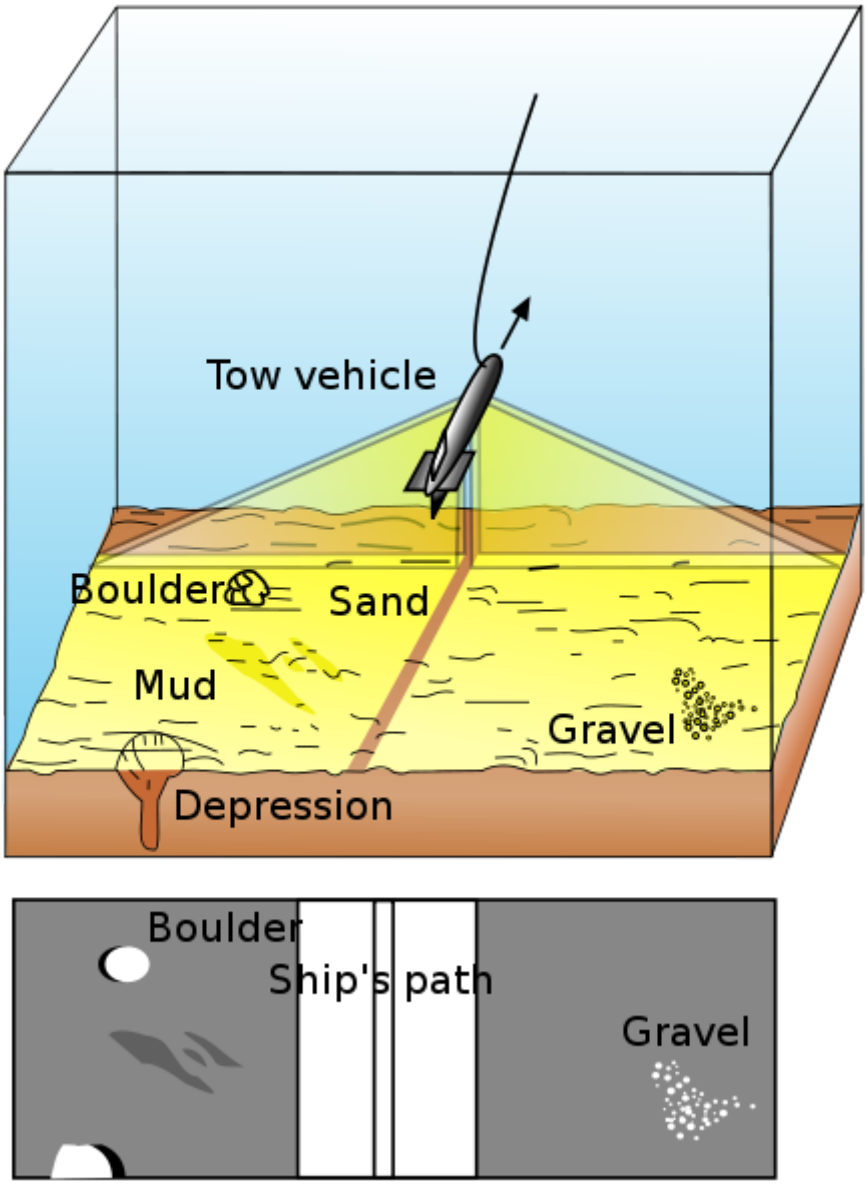


Diagram of sidescan sonar with towed probe, higher performance than multibeam ship-mounted but comparable

Biologic Effects on Sonar Reflection

A further complication is the presence of wind generated bubbles or fish close to the sea surface. . The bubbles can also form plumes that absorb some of the incident and scattered sound, and scatter some of the sound themselves. .

This problem is distinct from biologic interference caused by acoustic energy generated by marine life, such as the squeaks of porpoises and other cetaceans, and measured by acoustic receivers. The signatures of biologic sound generators need to be differentiated

from more deadly denizens of the depths. Classifying biologics is a very good example of an acoustic MASINT process.

Surface Combatants

Modern surface combatants with an ASW mission will have a variety of active systems, with a hull- or bow-mounted array, protected from water by a rubber dome; a "variable-depth" dipping sonar on a cable, and, especially on smaller vessels, a fixed acoustic generator and receiver.

Some, but not all, vessels carry passive towed arrays, or combined active-passive arrays. These depend on target noise, which, in the combined littoral environment of ultraquiet submarines in the presence of much ambient noise. Vessels that have deployed towed arrays cannot make radical course maneuvers. Especially when active capabilities are included, the array can be treated as a bistatic or multistatic sensor, and act as a synthetic aperture sonar (SAS)

For ships that cooperate with aircraft, they will need a data link to sonobuoys and a sonobuoy signal processor, unless the aircraft has extensive processing capability and can send information that can be accepted directly by tactical computers and displays.

Signal processors not only analyze the signals, but constantly track propagation conditions. The former is usually considered part of a particular sonar, but the US Navy has a separate propagation predictor called the AN/UYQ-25B(V) Sonar *in situ* Mode Assessment System (SIMAS)

Echo Tracker Classifiers (ETC) are adjuncts, with a clear MASINT flavor, to existing surface ship sonars . ETC is an application of synthetic aperture sonar (SAS). SAS is already used for minehunting, but could help existing surface combatants, as well as future vessels and unmanned surface vehicles (USV), detect threats, such as very silent air-independent propulsion non-nuclear submarines, outside torpedo range. Torpedo range, especially in shallow water, is considered anything greater than 10 nmi.

Conventional active sonar may be more effective than towed arrays, but the small size of modern littoral submarines makes them difficult threats. Highly variable bottom paths, biologics, and other factors complicate sonar detection. If the target is slow-moving or waiting on the bottom, they have little or no Doppler effect, which current sonars use to recognize threats.

Continual active tracking measurement of all acoustically detected objects, with recognition of signatures as deviations from ambient noise, still gives a high false alarm rate (FAR) with conventional sonar. SAS processing, however, improves the resolution, especially of azimuth measurements, by assembling the data from multiple pings into a synthetic beam that gives the effect of a far larger receiver.

MASINT-oriented SAS measures shape characteristics and eliminates acoustically detected objects that do not conform to the signature of threats. Shape recognition is only one of the parts of the signature, which include course and Doppler when available.

Air-Dropped Active Sonobuoys

Active sonobuoys, containing a sonar transmitter and receiver, can be dropped from fixed-wing maritime patrol aircraft (e.g., P-3, Nimrod, Chinese Y-8, Russian and Indian Bear ASW variants), antisubmarine helicopters, and carrier-based antisubmarine aircraft (e.g., S-3). While there have been some efforts to use other aircraft simply as carriers of sonobuoys, the general assumption is that the sonobuoy-carrying aircraft can issue commands to the sonobuoys and receive, and to some extent process, their signals.

The Directional Hydrophone Command Activated Sonobuoy system (DICASS) both generate sound and listen for it. A typical modern active sonobuoy, such as the AN/SSQ 963D, generates multiple acoustic frequencies . Other active sonobuoys, such as the AN/SSQ 110B, generate small explosions as acoustic energy sources.

Airborne Dipping Sonar

Antisubmarine helicopters can carry a "dipping" sonar head at the end of a cable, which the helicopter can raise from or lower into the water. The helicopter would typically dip the sonar when trying to localize a target submarine, usually in cooperation with other ASW platforms or with sonobuoys. Typically, the helicopter would raise the head after dropping an ASW weapon, to avoid damaging the sensitive receiver. Not all variants of the same basic helicopter, even assigned to ASW, carry dipping sonar; some may trade the weight of the sonar for more sonobuoy or weapon capacity.

AN/AQS-13 Dipping sonar deployed from an H-3 Sea King used by numerous countries and produced in Italy, Japan, and the United Kingdom

The EH101 helicopter, used by a number of nations, has a variety of dipping sonars. The (British) Royal Navy version has Ferranti/Thomson-CSF sonar, while the Italian version uses the HELRAS. Russian Ka-25 helicopters carry dipping sonar, as does the US LAMPS SH-60 helicopter, which carries a "dipping" AQS-13F sonar, plus AN/SQQ-28(V)10 sonar signal processing for active sonobuoys it drops.

Surveillance Vessel Low-Frequency Active

Newer Low-Frequency Active (LFA) systems are controversial, as their very high sound pressures may be hazardous to whales and other marine life . A decision has been made to employ LFA on SURTASS vessels, after an environmental impact statement that indicated, if LFA is used with decreased power levels in certain high-risk areas for marine life, it would be safe when employed from a moving ship. The ship motion, and the variability of the LFA signal, would limit the exposure to individual sea animals. LFA operates in the low-frequency (LF) acoustic band of 100–500 Hz. It has an active component, the LFA proper, and the passive SURTASS hydrophone array. "The active component of the system, LFA, is a set of 18 LF acoustic transmitting source elements (called projectors) suspended by cable from underneath an oceanographic surveillance vessel, such as the Research Vessel (R/V) Cory Chouest, USNS Impeccable (T-AGOS 23), and the Victorious class (TAGOS 19 class).

"The source level of an individual projector is 215 dB. These projectors produce the active sonar signal or “ping.” A "ping," or transmission, can last between 6 and 100 seconds. The time between transmissions is typically 6 to 15 minutes with an average transmission of 60 seconds. Average duty cycle (ratio of sound “on” time to total time) is less than 20 percent. The typical duty cycle, based on historical LFA operational parameters (2003 to 2007), is normally 7.5 to 10 percent."

This signal "...is not a continuous tone, but rather a transmission of waveforms that vary in frequency and duration. The duration of each continuous frequency sound transmission is normally 10 seconds or less. The signals are loud at the source, but levels diminish rapidly over the first kilometer."

Submarine Active Acoustic Sensors

The primary tactical active sonar of a submarine is usually in the bow, covered with a protective dome. Submarines for blue-water operations used active systems such as the AN/SQS-26 and AN/SQS-53 have been developed but were generally designed for convergence zone and single bottom bounce environments.

Submarines that operate in the Arctic also have specialized sonar for under-ice operation; think of an upside-down fathometer.

Submarines also may have minehunting sonar. Using measurements to differentiate between biologic signatures and signatures of objects that will permanently sink the submarine is as critical a MASINT application as could be imagined.

Active Acoustic Sensors for Minehunting

Sonars optimized to detect objects of the size and shapes of mines can be carried by submarines, remotely operated vehicles, surface vessels (often on a boom or cable) and specialized helicopters.

The classic emphasis on minesweeping, and detonating the mine released from its tether using gunfire, has been replaced with the AN/SLQ-48(V)2 mine neutralization system (MNS)AN/SLQ-48 - (remotely operated) Mine Neutralization Vehicle. This works well for rendering save mines in deep water, by placing explosive charges on the mine and/or its tether. The AN/SLQ-48 is not well suited to the neutralization of shallow-water mines. The vehicle tends to be underpowered and may leave on the bottom a mine that looks like a mine to any subsequent sonar search and an explosive charge subject to later detonation under proper impact conditions.

There is mine-hunting sonar, as well as (electro-optical) television on the ROV, and AN/SQQ-32 minehunting sonar on the ship.

Acoustic sensing of large explosions

An assortment of time-synchronized sensors can characterize conventional or nuclear explosions. One pilot study, the Active Radio Interferometer for Explosion Surveillance (ARIES). This technique implements an operational system for monitoring ionospheric pressure waves resulting from surface or atmospheric nuclear or chemical explosives. Explosions produce pressure waves that can be detected by measuring phase variations between signals generated by ground stations along two different paths to a satellite. This is a very modernized version, on a larger scale, of World War I sound ranging.

As can many sensors, ARIES can be used for additional purposes. Collaborations are being pursued with the Space Forecast Center to use ARIES data for total electron content measures on a global scale, and with the meteorology/global environment community to monitor global climate change (via tropospheric water vapor content measurements), and by the general ionospheric physics community to study travelling ionospheric disturbances.

Sensors relatively close to a nuclear event, or a high-explosive test simulating a nuclear event, can detect, using acoustic methods, the pressure produced by the blast. These include infrasound microbarographs (acoustic pressure sensors) that detect very low-frequency sound waves in the atmosphere produced by natural and man-made events.

Closely related to the microbarographs, but detecting pressure waves in water, are hydro-acoustic sensors, both underwater microphones and specialized seismic sensors that detect the motion of islands.

Seismic MASINT

US Army Field Manual 2-0 defines seismic intelligence as "The passive collection and measurement of seismic waves or vibrations in the earth surface." One strategic application of seismic intelligence makes use of the science of seismology to locate and characterize nuclear testing, especially underground testing. Seismic sensors also can characterize large conventional explosions that are used in testing the high-explosive components of nuclear weapons. Seismic intelligence also can help locate such things as large underground construction projects.

Since many areas of the world have a great deal of natural seismic activity, seismic MASINT is one of the emphatic arguments that there must be a long-term commitment to measuring, even during peacetime, so that the signatures of natural behavior is known before it is necessary to search for variations from signatures.

Strategic Seismic MASINT

For nuclear test detection, seismic intelligence is limited by the "threshold principle" coined in 1960 by George Kistiakowsky, which recognized that while detection

technology would continue to improve, there would be a threshold below which small explosions could not be detected.

Tactical Seismic MASINT

The most common sensor in the Vietnam-era "McNamara Line" of remote sensors was the ADSID (Air-Delivered Seismic Intrusion Detector) sensed earth motion to detect people and vehicles. It resembled the Spikebuoy, except it was smaller and lighter (31 inches long, 25 pounds). The challenge for the seismic sensors (and for the analysts) was not so much in detecting the people and the trucks as it was in separating out the false alarms generated by wind, thunder, rain, earth tremors, and animals—especially frogs."

Vibration MASINT

This subdiscipline is also called **piezoelectric MASINT** after the sensor most often used to sense vibration, but vibration detectors need not be piezoelectric. Note that some discussions treat seismic and vibration sensors as a subset of acoustic MASINT. Other possible detectors could be moving coil or surface acoustic wave. . Vibration, as a form of geophysical energy to be sensed, has similarities to acoustic and seismic MASINT, but also has distinct differences that make it useful, especially in unattended ground sensors (UGS). In the UGS application, one advantage of a piezoelectric sensor is that it generates electricity when triggered, rather than consuming electricity, an important consideration for remote sensors whose lifetime may be determined by their battery capacity.

While acoustic signals at sea travel through water, on land, they can be assumed to come through the air. Vibration, however, is conducted through a solid medium on land. It has a higher frequency than is typical of seismic conducted signals.

A typical detector, the Thales MA2772 vibration is a piezoelectric cable, shallowly buried below the ground surface, and extended for 750 meters. Two variants are available, a high-sensitivity version for personnel detection, and lower-sensitivity version to detect vehicles. Using two or more sensors will determine the direction of travel, from the sequence in which the sensors trigger.

In addition to being buried, piezoelectric vibration detectors, in a cable form factor, also are used as part of high-security fencing. They can be embedded in walls or other structures that need protection.

Magnetic MASINT

A magnetometer is a scientific instrument used to measure the strength and/or direction of the magnetic field in the vicinity of the instrument. The measurements they make can be compared to signatures of vehicles on land, submarines underwater, and atmospheric radio propagation conditions. They come in two basic types:

- **scalar magnetometers** measure the total strength of the magnetic field to which they are subjected, and
- **vector magnetometers** have the capability to measure the component of the magnetic field in a particular direction.

Earth's magnetism varies from place to place and differences in the Earth's magnetic field (the magnetosphere) can be caused by two things:

- the differing nature of rocks
- the interaction between charged particles from the sun and the magnetosphere

Metal detectors use electromagnetic induction to detect metal. They can also determine the changes in existing magnetic fields caused by metallic objects.

Indicating Loops for detecting Submarines

One of the first means for detecting submerged submarines, first installed by the Royal Navy in 1914, was the effect of their passage over an anti-submarine indicator loop on the bottom of a body of water. A metal object passing over it, such as a submarine, will, even if degaussed, have enough magnetic properties to induce a current in the loop's cable. . In this case, the motion of the metal submarine across the indicating coil acts as an oscillator, producing electrical current.

MAD

A **magnetic anomaly detector** (MAD) is an instrument used to detect minute variations in the Earth's magnetic field. The term refers specifically to magnetometers used either by military forces to detect submarines (a mass of ferromagnetic material creates a detectable disturbance in the magnetic field)Magnetic anomaly detectors were first employed to detect submarines during World War II. MAD gear was used by both Japanese and U.S. anti-submarine forces, either towed by ship or mounted in aircraft to detect shallow submerged enemy submarines. After the war, the U.S. Navy continued to develop MAD gear as a parallel development with sonar detection technologies.

To reduce interference from electrical equipment or metal in the fuselage of the aircraft, the MAD sensor is placed at the end of a boom or a towed aerodynamic device. Even so, the submarine must be very near the aircraft's position and close to the sea surface for detection of the change or anomaly. The detection range is normally related to the distance between the sensor and the submarine. The size of the submarine and its hull composition determine the detection range. MAD devices are usually mounted on aircraft

MAD rear boom on P-3C

The SH-60B Seahawk helicopter carries an orange, towed MAD array known as a ‘MAD bird’, seen on the aft fuselage.

or helicopters.

There is some misunderstanding of the mechanism of detection of submarines in water using the MAD boom system. Magnetic moment displacement is ostensibly the main disturbance, yet submarines are detectable even when oriented parallel to the Earth's magnetic field, despite construction with non-ferromagnetic hulls.

For example, the Soviet-Russian Alfa class submarine, was constructed out of titanium. This light, strong material, as well as a unique nuclear power system, allowed the submarine to break speed and depth records for operational boats. It was thought that nonferrous titanium would defeat magnetic ASW sensors, but this was not the case. to give dramatic submerged performance and protection from detection by MAD sensors, is still detectable.

Since titanium structures are detectable, MAD sensors do not directly detect deviations in the Earth's magnetic field. Instead, they may be described as long-range electric and electromagnetic field detector arrays of great sensitivity.

An electric field is set up in conductors experiencing a variation in physical environmental conditions, providing that they are contiguous and possess sufficient mass. Particularly in submarine hulls, there is a measurable temperature difference between the bottom and top of the hull producing a related salinity difference, as salinity is affected

by temperature of water. The difference in salinity creates an electric potential across the hull. An electric current then flows through the hull, between the laminae of sea-water separated by depth and temperature. The resulting dynamic electric field produces an electromagnetic field of its own, and thus even a titanium hull will be detectable on a MAD scope, as will a surface ship for the same reason.

Vehicle Detectors

The Remotely Emplaced Battlefield Surveillance System (REMBASS) is a US Army program for detecting the presence, speed, and direction of a ferrous object, such as a tank. Coupled with acoustic sensors that recognize the sound signature of a tank, it could offer high accuracy. It also collects weather information.

The Army's AN/GSQ-187 Improved Remote Battlefield Sensor System (I-REMBASS) includes both magnetic-only and combined passive infrared/magnetic intrusion detectors. The DT-561/GSQ hand emplaced MAG "sensor detects vehicles (tracked or wheeled) and personnel carrying ferrous metal. It also provides information on which to base a count of objects passing through its detection zone and reports their direction of travel relative to its location. The monitor uses two different (MAG and IR) sensors and their identification codes to determine direction of travel.

Magnetic detonators and countermeasures

Magnetic sensors, much more sophisticated than the early inductive loops, can trigger the explosion of mines or torpedoes. Early in World War II, the US tried to put magnetic torpedo exploder far beyond the limits of the technology of the time, and had to disable it, and then work on also-unreliable contact fuzing, to make torpedoes more than blunt objects than banged into hulls.

Since water is incompressible, an explosion under the keel of a vessel is far more destructive than one at the air-water interface. Torpedo and mine designers want to place the explosions in that vulnerable spot, and countermeasures designers want to hide the magnetic signature of a vessel. Signature is especially relevant here, as mines may be made selective for warships, merchant vessel unlikely to be hardened against underwater explosions, or submarines.

A basic countermeasure, started in World War II, was degaussing, but it is impossible to remove all magnetic properties.

Detecting landmines

Landmines often contain enough ferrous metal to be detectable with appropriate magnetic sensors. Sophisticated mines, however, may also sense a metal-detection oscillator, and, under preprogrammed conditions, detonate to deter demining personnel.

Foerster Minex 2FD 4.500 Metal detector used by the French army.

Not all landmines have enough metal to activate a magnetic detector. While, unfortunately, the greatest number of unmapped minefields are in parts of the world that cannot afford high technology, a variety of MASINT sensors could help demining. These would include ground-mapping radar, thermal and multispectral imaging, and perhaps synthetic aperture radar to detect disturbed soil.

Gravitimetric MASINT

While high school physics students are told that the value of gravity is 9.8 meters per second squared, they also learn Newton's equation that predicts that gravity is a function of mass. Given sufficiently sensitive instrumentation, it is possible to detect variations in gravity from the different densities of natural materials: the value of gravity will be greater on top of a granite monolith than over a sand beach. Again with sufficiently sensitive instrumentation, it should be possible to detect gravitational differences between solid rock, and rock excavated for a hidden facility.

Streland 2003 points out that the instrumentation indeed must be sensitive: variations of the force of gravity on the earth's surface are on the order of 10^6 of the average value. A practical gravitimetric detector of buried facilities would need to be able to measure "less than one one millionth of the force that caused the apple to fall on Sir Isaac Newton's head." To be practical, it would be necessary for the sensor to be able to be used while in motion, measuring the change in gravity between locations. This change over distance is called the *gravity gradient*, which can be measured with a gravity gradiometer.

Developing an operationally useful gravity gradiometer is a major technical challenge. One type, the SQUID Superconducting Quantum Interference Device gradiometer, may have adequate sensitivity, but it needs extreme cryogenic cooling, even if in space, a logistic nightmare. Another technique, far more operationally practical but lacking the necessary sensitivity, is the Gravity Recovery and Climate Experiment (GRACE) technique, currently using radar to measure the distance between pairs of satellites, whose

orbits will change based on gravity. Substituting lasers for radar will make GRACE more sensitive, but probably not sensitive enough.

A more promising technique, although still in the laboratory, is quantum gradiometry, which is an extension of atomic clock techniques, much like those in GPS. Off-the-shelf atomic clocks measure changes in atomic waves over time rather than the spatial changes measured in a quantum gravity gradiometer. One advantage of using GRACE in satellites is that measurements can be made from a number of points over time, with a resulting improvement as seen in synthetic aperture radar and sonar. Still, finding deeply buried structures of human scale is a tougher problem than the initial goals of finding mineral deposits and ocean currents.

To make this operationally feasible, there would have to be a launcher to put fairly heavy satellites into polar orbits, and as many earth stations as possible to reduce the need for large on-board storage of the large amounts of data the sensors will produce. Finally, there needs to be a way to convert the measurements into a form that can be compared against available signatures in geodetic data bases. Those data bases would need significant improvement, from measured data, to become sufficiently precise that a buried facility signature would stand out.

Chapter 7

Marine Mammals and Sonar

A Humpback whale

Active sonar, the transmission equipment used on some ships to assist with navigation, has been suggested to be detrimental to the health and livelihood of some marine animals, although the precise mechanisms for this are not well understood. Some marine animals, such as whales and dolphins, use echolocation or "biosonar" systems to locate predators and prey. It is conjectured that active sonar transmitters could confuse these animals and interfere with basic biological functions such as feeding and mating.

History

The **SOFAR channel** (short for **sound fixing and ranging channel**), or **deep sound channel** (**DSC**), is a horizontal layer of water in the ocean centered around the depth at

which the speed of sound is at a minimum. The SOFAR channel acts as a waveguide for sound, and low frequency sound waves within the channel may travel thousands of miles before dissipating. This phenomenon is an important factor in submarine warfare. The deep sound channel was discovered and described independently by Dr. Maurice Ewing, and Leonid Brekhovskikh in the 1940s.

Despite the use of the SOFAR channel in naval applications, the idea that animals might make use of this channel was not proposed until 1971. Roger Payne and Douglas Webb calculated that before ship traffic noise permeated the oceans, tones emitted by fin whales could have traveled as far as four thousand miles and still be heard against the normal background noise of the sea. Payne and Webb further determined that, on a quiet day in the pre–ship-propeller oceans, fin whale tones would only have fallen to the level of background noise after traveling thirteen thousand miles, that is, more than the diameter of the Earth.

Early confusion between fin whales and military sonar

Before extensive research on whale echolocation was completed, the low-frequency pulses emitted by some species of whales were often not correctly attributed to them. Dr Payne wrote:"Before it was shown that fin whales were the cause [of powerful sonar transmissions], no one could take seriously the idea that such regular, loud, low, and relatively pure frequency tones were coming from within the ocean, let alone from whales." This unknown sound was popularly known by navy acousticians as the *Jezebel Monster*. (*Jezebel* was narrow-band passive long-range sonar.) Some researchers believed that these sounds could be attributed to geophysical vibrations or an unknown Russian military program, and it wasn't until biologists William Schevill and William A. Watkins proved that whales possessed the biological capacity to emit sonar that the unknown sounds were correctly attributed.

Low frequency sonar

The electromagnetic spectrum has rigid definitions for "super low frequency", "extremely low frequency", "low frequency" and "medium frequency". Acoustics does not have a similar standard. The terms "low" and "mid" have roughly-defined historical meanings in sonar, because not many frequencies have been used over the decades. However, as more experimental sonars have been introduced, the terms have become muddled.

American low frequency sonar was originally introduced to the general public in a June 1961 Time magazine article, *New A.S.W. Artemis*, the low-frequency sonar used at the time, could fill a whole ocean with searching sound and spot anything sizable that was moving in the water. *Artemis* grew out of a 1951 suggestion by Harvard physicist Frederick V. Hunt (Artemis is the Ancient Greek goddess of the hunt), who convinced Navy anti-submarine experts that submarines could be detected at great distances only by unheard-of volumes of low-pitched sound. At the time, an entire *Artemis* system was envisioned to form a sort of underwater DEW (*Distant Early Warning*) line to warn the U.S. of hostile submarines. Giant, unattended transducers, powered by cables from land,

would be lowered to considerable depths where sound travels best. The Time magazine article was published during the maiden voyage of the Soviet submarine *K-19*, which was the first Soviet submarine equipped with ballistic missiles. Four days later the submarine would have the accident that gave it its nickname. The impact on marine mammals by this system was certainly not a consideration. *Artemis* never became an operational system.

Low-frequency sonar was revived in the early 1980s for military and research applications. The idea that the sound could interfere with whale biologics became widely discussed outside of research circles when Scripps Institute of Oceanography borrowed and modified a military sonar for the Heard Island Feasibility Test conducted in January and February 1991. The sonar modified for the test was an early version of SURTASS deployed in the MV *Cory Chouest*. As a result of this test a "Committee on Low-Frequency Sound and Marine Mammals" was organized by the National Research Council. Their findings were published in 1994, in *Low-Frequency Sound and Marine Mammals: Current Knowledge and Research Needs*.

Long-range transmission does not require high power. All frequencies of sound lose an average of 65dB in the first few seconds before the sound waves strike the ocean bottom. After that the acoustic energy in mid or high-frequency sound is converted into heat, primarily by the epsom salt dissolved in sea water. Very little of low frequency acoustic energy is not converted into heat, so the signal can be detected for long ranges. Fewer than five of the transducers from the low frequency active array were used in the Heard Island Feasibility Test, and the sound was detected on the opposite side of the Earth. The transducers were temporarily altered for this test to transmit sound at 50 hertz, which is lower than their normal operating frequency.

A year after the Heard Island Feasibility Test a new low-frequency active sonar was installed in the *Cory Chouest* with 18 transducers instead of 10. An environmental impact statement was prepared for that system.

Mid frequency sonar

The term *mid frequency* sonar is usually used to refer to sonars that project sound in the 3 to 4 kilohertz (kHz) range. Ever since the launch of the USS *Nautilus* (SSN-571) on 17 January 1955 the US Navy knew it was only a matter of time until the other naval powers had their own nuclear submarines. The mid-frequency sonar was developed for anti-submarine warfare against these future boats. The standard post-WWII active sonars (which were usually above 7 kHz) had an insufficient range against this new threat. Active sonar went from a piece of equipment attached to a ship, to a piece of equipment that was central to the design of a ship. They are described in the same 1961 Time magazine article by the quote "*the latest shipboard sonar weighs 30 tons and consumes 1,600 times as much power as the standard postwar sonar*". A modern system produced by Lockheed Martin since the early 1980s is the AN/SQQ-89. On June 13, 2001, Lockheed Martin announced that it had delivered its 100th AN/SQQ-89 undersea warfare system to the U.S. Navy.

There was anecdotal evidence that mid-frequency sonar could have adverse effects on whales dating back to the days of whaling. The following story is recounted in a book published in 1995:

Mid Frequency Sonar and Whaling
Source: *Among Whales* by Roger Payne (pg 258) Published 2 June 1995
Another innovation by the whalers was the use of sonar to track whales they were pursuing underwater. But there was a problem; as the boat gained on the whale, the whale started exhaling while still submerged. This produced a cloud of bubbles in the water that reflected sound better than the whale did and made a false target (akin to what a pilot does when releasing metal chaff to create a false radar echo). I suspect that this behavior by whales was simply fortuitous since exhaling while still submerged is simply a means by which a whale can reduce the time it has to remain at the surface, where surface drag will slow it down. *Whalers quickly discovered that a frequency of **three thousand hertz** seemed to panic the whales, causing them to surface much more often for air, This was a "better" use for sonar because it afforded the whalers more chances to shoot the whales. So they equipped their catcher boats with sonar at that frequency. Of course the sonar also allows the whalers to follow the whale underwater, but that is its secondary use. Its primary use is for scaring whales so that they start "panting" at the surface.*

In 1996 twelve Cuvier's beaked whales beached themselves alive along the coast of Greece while NATO (North Atlantic Treaty Organisation) was testing an active sonar with combined low and mid-range frequency transducers, according to a paper published in the journal Nature in 1998. The author established for the first time the link between atypical mass strandings of whales and the use of military sonar by concluding that *although pure coincidence cannot be excluded* there was better than a 99.3% likelihood that sonar testing caused that stranding. He noted that the whales were spread along 38.2 kilometres of coast and were separated by a mean distance of 3.5 km (sd=2.8, n=11). This spread in time and location was atypical, as usually whales mass strand at the same place and at the same time.

At the time that Dr. Frantzis wrote the article he was unaware of several important factors.

- The time correlation was much tighter than he knew. He knew about the test from a notice to mariners which only published that the test would occur over a five day period within a large area of the ocean. In fact the first time the sonar was turned on was the morning of 12 May 1996, and six whales stranded that

afternoon. The next day the sonar was turned on again and another six whales stranded that afternoon. Without knowing the coordinates of the ships he would not have realized that the ship was only about 10–15 miles offshore.

- The sonar being used in the test was an experimental research and development sonar, which was considerably smaller and less powerful than an operational sonar onboard a deployed naval vessel. Dr Frantzis believed that wide distribution of the stranded whales indicated that the cause has a large synchronous spatial extent and a sudden onset. Knowing that the sound source level was fairly low (it was only 226 dB (decibels) @ 3 kHz which is low compared to an operational sonar) would have made the damage mechanism even more puzzling.
- The experimental sonar used in the test, Towed Vertically Directive Source (TVDS) which had the dual 600 Hz and 3 kHz transducers, had been used for the first time in the Mediterranean Sea south of Sicily the year before in June 1995. Previous activated towed array sonar research using different sources on board the same ship included participation in NATO exercises "Dragon Hammer '92" and "Resolute Response '94".

Since the source level of this experimental sonar was only 226 dB @ 3 kHz re. 1 meter, at only 100 meters the received level would drop by 40 dB (to 186 dB). A NATO panel investigated the above stranding and concluded the whales were exposed to 150-160 dB re 1 μPa of low and mid-range frequency sonar. This level is about 66 dB less (more than a million times lower intensity) than the threshold for hearing damage specified by a panel of marine mammal experts.

The idea that a relatively low power sonar could cause a mass stranding of such a large number of whales was very unexpected by the scientific community. Most research had been focused on the possibility of masking signals, interference with mating calls, and similar biological functions. Deep diving marine mammals were species of concern, but very little definitive information was known. In 1995 a comprehensive book on the relation between marine mammals and noise had been published, and it did not even mention strandings.

Acoustically induced bubble formation

There was anecdotal evidence from whalers that sonar could panic whales and cause them to surface more frequently making them vulnerable to harpooning. It has also been theorized that military sonar may induce whales to panic and surface too rapidly leading to a form of decompression sickness. In general trauma caused by rapid changes of pressure is known as *barotrauma*. The idea of acoustically enhanced bubble formation was first raised by a paper published in *The Journal of the Acoustical Society of America* in 1996 and again *Nature* in 2003. It reported acute gas-bubble lesions (indicative of decompression sickness) in whales that beached shortly after the start of a military exercise off the Canary Islands in September 2002.

In the Bahamas in 2000, a sonar trial by the United States Navy of transmitters in the frequency range 3–8 kHz at a source level of 223–235 decibels re 1 μPa (scaled to a

distance of 1 m) was associated with the beaching of seventeen whales, seven of which were found dead. Environmental groups claimed that some of the beached whales were bleeding from the eyes and ears, which they considered an indication of acoustically-induced trauma. The groups allege that the resulting disorientation may have led to the stranding.

Naval sonar-linked incidents

> “ Worldwide, use of active sonar has been linked to about 50 marine mammal strandings between 1996 and 2006. In all of these occurrences, there were other contributing factors, such as unusual (steep and complex) underwater geoqraphy, limited egress routes, and a specific species of marine mammal — beaked whales — that are suspected to be more sensitive to sound than other marine mammals. ”
>
> —Rear Admiral Lawrence Rice

Date	Location	Species and Number	Naval Activity	Reference
1963-05	Gulf of Genoa, Italy	Cuvier’s beaked whale (15) stranded	Naval maneuvers	
1988-11	Canary Islands	Cuvier’s beaked whale (12+) Gervais' beaked whale (1) stranded	FLOTA 88 exercise	
1989-10	Canary Islands	Cuvier's beaked whale (15+), Gervais' beaked whale (3), Blainville's beaked whale (2) stranded	CANAREX 89 exercise	
1991-12	Canary Islands	Cuvier's beaked whale (2) stranded	SINKEX 91 exercise	
1996-05-12	Gulf of Kyparissia, Greece	Cuvier's beaked whale (12) stranded	NATO Shallow Water Acoustic Classification exercise	
1998-07	Kauai, Hawaii	beaked whale (1), sperm whale (1) stranded	RIMPAC 98 exercise	
1999-10	U.S. Virgin Islands and Puerto Rico	Cuvier’s beaked whale (4) stranded	COMPTUEX exercise	
2000-03-15	Bahamas	Cuvier’s beaked whale (9), Blainville’s beaked whale (3), beaked whale spp (2), Minke whale (2), Atlantic spotted dolphin (1) stranded	Naval MFA	
2000-05-10	Madeira Island, Portugal	Cuvier’s beaked whale (3) stranded	NATO Linked Seas 2000 and MFA	
2002-09	Canary Islands	Cuvier’s beaked whale (9), Gervais’ beaked whale (1), Blainville’s beaked whale (1), beaked whale spp. (3) stranded	Neo Tapon 2002 exercise and MFA	
2003-05	Haro Strait, Washington	Harbor porpoise (14), Dall’s porpoise (1) Orca avoidance “stampede”	U.S.S. Shoup transiting while using MFA (AN/SQS-53C)	
2004-07	Kauai, Hawaii	Melon-headed whale (~200) avoidance “stampede”	RIMPAC 04 exercise with MFA	

2004-07-22	Canary Islands	Cuvier's beaked whale (4) stranded	Majestic Eagle 04 exercise	
2005-10-25	Marion Bay, Tasmania	Long-finned pilot whales (145) stranded	Two minesweepers using active sonar	
2006-01-26	Almeira Coast, Spain	Cuvier's beaked whale (4) stranded	Royal Navy's HMS Kent using active sonar	
2008-06	Cornish coast, United Kingdom	Dolphins (26) stranded	Royal Navy sonar exercise	

Court cases

Since mid-frequency sonar has been correlated with mass cetacean strandings throughout the world's oceans, it has been singled out by some environmentalists as a focus for activism. A lawsuit filed by the Natural Resources Defense Council in Santa Monica, California on 20 October 2005 contended that the U.S. Navy has conducted sonar exercises in violation of several environmental laws, including the National Environmental Policy Act, the Marine Mammal Protection Act, and the Endangered Species Act. Mid-frequency sonar is by far the most common type of active sonar in use by the world's navies, and has been widely deployed since the 1960s.

On November 13, 2007, a United States appeals court restored a ban on the U.S. Navy's use of submarine-hunting sonar in training missions off Southern California until it adopted better safeguards for whales, dolphins and other marine mammals. On 16 January 2008, President George W. Bush exempted the US Navy from the law and argued that naval exercises are crucial to national security. On 4 February 2008, a Federal judge ruled that despite President Bush's decision to exempt it, the Navy must follow environmental laws placing strict limits on mid-frequency sonar. In a 36-page decision, U.S. District Judge Florence-Marie Cooper wrote that the Navy is not "exempted from compliance with the National Environmental Policy Act" and the court injunction creating a 12-nautical-mile (22 km) no-sonar zone off Southern California. On 29 February 2008, a three-judge federal appeals court panel upheld the lower court order requiring the Navy to take precautions during sonar training to minimize harm to marine life. The U.S. Supreme Court overturned the ruling in a 5:4 decision on 12 November 2008. However, this does not spell the end of environmentalist challenges to the Navy's sonar activities. Indeed, environmentalists have already interpreted the *NRDC v. Winter* decision as narrowly as possible given the Court's refusal to address their non-'science' claims.

Mitigation methods

Environmental impacts of the operation of active sonar are required to be carried out by US law. Procedures for minimising the impact of sonar are developed in each case where there is significant impact.

The impact of underwater sound can be reduced by limiting the sound exposure received by an animal. The maximum sound exposure level recommended by Southall et al. for

cetaceans is 215 dB re 1 μPa^2 s for hearing damage. Maximum sound pressure level for behavioural effects is dependent on context (Southall et al.).

A great deal of the legal and media conflict on this issue has to do with questions of who determines what type of mitigation is sufficient. Coastal commissions, for example, were originally thought to only have legal responsibility for beachfront property, and state waters (three miles into sea). Because active sonar is instrumental to ship defense, mitigation measures that may seem sensible to a civilian agency without any military or scientific background can have disastrous effects on training and readiness. Navies therefore often define their own mitigation requirements.

Examples of mitigation measures include:

1. not operating at nighttime
2. not operating at specific areas of the ocean that are considered sensitive
3. slow ramp-up of intensity of signal to give whales a warning
4. air cover to search for mammals
5. not operating when a mammal is known to be within a certain range
6. onboard observers from civilian groups
7. using fish-finders to look for whales in the vicinity
8. large margins of safety for exposure levels
9. not operating when dolphins are bow-riding
10. operations at less than full power
11. paid teams of veterans to investigate strandings after sonar operation.

Besides the expense of some of the mitigation measures some of them might interfere with operations. For this reason, mitigation requirements for wartime use of naval sonars can differ from either civilian mitigation requirements or from military requirements during exercises or peacetime operations. Prohibition on night time operations may be a huge waste of expensive assets. Ramping up a signal in intensity may have no impact on geophysical operations, but sonar does not work very well if you give the target submarine a warning so that he can do countermeasures. On board civilian observers are used in tuna-boat operations, and in dredging exercises, which are radically different from military operations.

Chapter 8

Scientific Echosounder and Side-Scan Sonar

Scientific echosounder

A **scientific echosounder** is a device which uses SONAR technology for the measurement of underwater physical and biological components—this device is also known as *scientific SONAR*. Applications include bathymetry, substrate classification, studies of aquatic vegetation, fish, and plankton, and differentation of water masses.

Technology

Scientific echosounder equipment is built to exacting standards and tested to be stable and reliable in the transmission and receiving of sound energy under the water. Recent advances have led to the development of the digital scientific echosounder, further enhancing the reliability and precision with which these systems operate. Modern scientific echosounders are reliable, portable, and relatively easy to use.

Data collected with a scientific echosounder can be analyzed for the presence, abundance, distribution and acoustic characteristics of such variables as: depth (bathymetry), bottom substrate class (e.g., sand, mud, rock), submersed aquatic vegetation (SAV), and water column scattering (fish and plankton). Resulting analysis can be used to generate GIS data layers for these variables.

Applications

Scientific echosounders are commonly used by International, Federal, State and Local government and management agencies, as well as private-sector consultants working for these public agencies. Academic institutions have realized and are teaching the value of sampling non-invasively with sound to enhance both the spatial coverage and objectivity of fisheries sampling. Fisheries management agencies such as the membership of ICES and the United States National Marine Fisheries Service (NMFS) commonly use

scientific sonar for stock assessment purposes, such as herring biomass assessment for resource management purposes.

More recently, the acoustic data collected has been valuable in underwater habitat assessment and classification for the variables; seabed type (e.g. rock, mud, sand) and submersed aquatic vegetation and algae - with the appropriate software.

Side-scan sonar

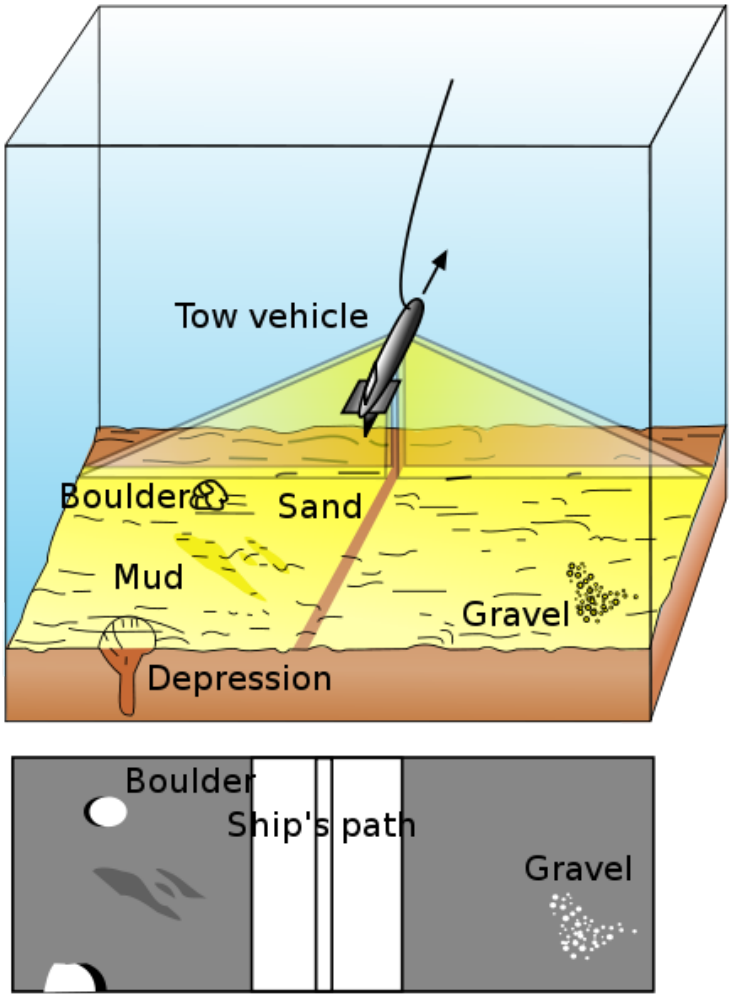
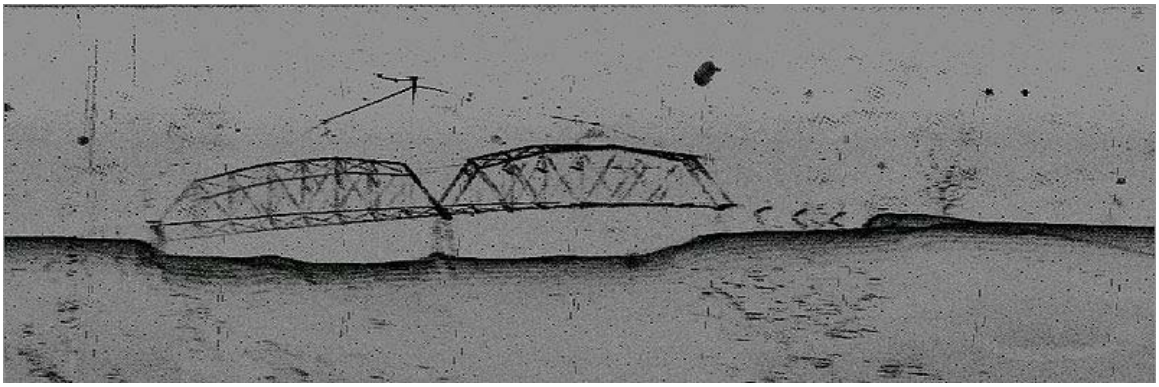


Diagram of sidescan sonar



Submerged bridge in 160 ft of fresh water seen on sidescan sonar imagery using a Humminbird 981c Side Imaging system

Side-scan sonar (also sometimes called **side scan sonar**, **sidescan sonar**, **side looking sonar**, **side-looking sonar**, **side imaging sonar**, **side-imaging sonar** and **bottom classification sonar**) is a category of sonar system that is used to efficiently create an image of large areas of the sea floor. It may be used to conduct surveys for maritime archaeology; in conjunction with seafloor samples it is able to provide an understanding of the differences in material and texture type of the seabed. Side-scan sonar imagery is also a commonly used tool to detect debris items and other obstructions on the seafloor that may be hazardous to shipping or to seafloor installations by the oil and gas industry. In addition, the status of pipelines and cables on the seafloor can be investigated using side-scan sonar. Side-scan data are frequently acquired along with bathymetric soundings and sub-bottom profiler data, thus providing a glimpse of the shallow structure of the seabed. Side-scan sonar is also used for fisheries research, dredging operations and environmental studies. It also has military applications including mine detection.

Side scan uses a sonar device that emits conical or fan-shaped pulses down toward the seafloor across a wide angle perpendicular to the path of the sensor through the water, which may be towed from a surface vessel or submarine, or mounted on the ship's hull. The intensity of the acoustic reflections from the seafloor of this fan-shaped beam is recorded in a series of cross-track slices. When stitched together along the direction of motion, these slices form an image of the sea bottom within the swath (coverage width) of the beam. The sound frequencies used in side-scan sonar usually range from 100 to 500 kHz; higher frequencies yield better resolution but less range.

The earliest side-scan sonars used a single conical-beam transducer. Next, units were made with two transducers to cover both sides. The transducers were either contained in one hull-mounted package or with two packages on either side of the vessel. Next the transducers evolved to fan-shaped beams to produce a better "sonogram" or sonar image. In order to get closer to the bottom in deep water the side-scan transducers were placed in a "towfish" and pulled by a "tow cable".

One of the inventors of side-scan sonar was German scientist, Dr. Julius Hagemann, who was brought to the US after World War II and worked at the US Navy Mine Defense

Laboratory, Panama City, FL from 1947 until his death in 1964. His work is documented in US Patent 4,197,591 which was first disclosed in Aug 1958, but remained classified by the US Navy until it was finally issued in 1980. Experimental side-scan sonar systems were made during the 1950s in laboratories including Scripps Institution of Oceanography and Hudson Laboratories and by Dr. Harold Edgerton at MIT.

Military side-scan sonars were made in the 1950s by Westinghouse. Advanced systems were later developed and built for special military purposes, such as to find H-Bombs lost at sea or to find a lost Russian submarine, at the Westinghouse facility in Annapolis up through the 1990s. This group also produced the first and only working *Angle Look Sonar* that could trace objects while looking under the vehicle.

The first commercial side-scan system was the Kelvin-Hughes "Transit Sonar", a converted echo-sounder with a single-channel, pole-mounted, fan-beam transducer introduced around 1960. In 1963 Dr. Harold Edgerton, Edward Curley, and John Yules used a conical-beam 12kHz side-scan sonar to find the sunken Vineyard Lightship in Buzzards Bay, Massachusetts. A team led by Martin Klein at Edgerton, Germeshausen & Grier (later E.G. & G., Inc.) developed the first successful towed, dual-channel commercial side-scan sonar system from 1963 to 1966. Martin Klein is generally considered to be the "father" of commercial side-scan sonar. In 1967, Edgerton used Klein's sonar to help Alexander McKee find Henry VIII's flagship *Mary Rose*. That same year Klein used the sonar to help archaeologist George Bass find a 2000-year-old ship off the coast of Turkey. In 1968 Klein founded Klein Associates, Inc.(now L-3/Klein) and continued to work on improvements including the first commercial high frequency (500 kHz) systems and the first dual-frequency side-scan sonars, and the first combined side-scan and sub-bottom profiling sonar. In 1985, Charles Mazel of Klein Associates produced the first commercial side-scan sonar training videos and the first *Side Scan Sonar Training Manual*.

For surveying large areas, the GLORIA sidescan sonar was developed by Marconi Underwater Systems for NERC. This operated at relatively low frequencies to obtain long range. It was used by the US Geological Survey and the Institute of Oceanographics in the UK to obtain images of continental shelves world-wide.

Manufacturers of higher frequency side-scan sonar systems include Lowrance, Simrad, Raytheon, Northrop Grumman (formerly Westinghouse), EdgeTech (formerly E.G. & G.), C-MAX Ltd., L-3/Klein Associates, J.W. Fishers Mfg. Inc., Imagenex Technology Corp., RESON A/S, Sonatech Inc., Benthos (the sonar formerly produced by Datasonics), WESMAR, Marine Sonic Technology, Kongsberg Maritime, Geoacoustics, EDO Corp., Ultra Electronics,Humminbird (Techsonic Industries Inc) and Deep Vision Technologies.

Up until the mid 1980s, commercial sidescan images were produced on paper records. The early paper records were produced with a sweeping plotter that burned the image into a scrolling paper record. Later plotters allowed for the simultaneous plotting of position and ship motion information onto the paper record. In the late 1980s, commercial systems using the newer, cheaper computer systems developed digital scan-converters that could

mimic more cheaply the analog scan converters used by the military systems to produce TV and computer displayed images of the scan, and store them on video tape. Now data is stored on computer hard drives.

Chapter 9

Seismic Source

An air gun seismic source (30 litre)

A **seismic source** is a device that generates controlled seismic energy used to perform both reflection and refraction seismic surveys. A seismic source can be simple, such as dynamite, or it can use more sophisticated technology, such as a specialized air gun.

Seismic sources can provide single pulses or continuous sweeps of energy that generate seismic waves, which travel through a medium such as water or layers of rocks. Some of the waves then reflect and refract and is recorded by receivers, such as geophones or hydrophones.

Seismic sources may be used to investigate shallow subsoil structure, for engineering site work, or deeper structures, usually in the search for petroleum or mineral deposits, or for scientific investigation. The returning signals from the sources are detected by geophones, laid in known locations relative to the position of the source. The recorded signals are then subjected to specialist processing and interpretation to yield comprehensible data about the subsurface.

Source model

A seismic source signal has the following characteristics:

1. generated as an impulsive source
2. band-limited
3. the generated waves are time-varying

The generalized equation that shows all above properties is:

$$s(t) = \beta e^{-\alpha t^2} \sin(2\pi f_{max} t)$$

where f_{max} is the maximum frequency component of the generated waveform.

Types of sources

Explosives

Explosives, such as dynamite, can be used as crude but effective sources of seismic energy. Generally the explosive charges are placed between 20 feet to 250 feet below ground. The charges are placed in a hole that is drilled with dedicated drilling equipment for this purpose. This type of seismic drilling is often referred to as "Shot Hole Drilling".

A common drill rig used for "Shot Hole Drilling" is the ARDCO C-1000 drill mounted on an ARDCO K 4X4 buggy. These drill rigs often use water or air in assisting the drilling.

Air gun

An **air gun** is used for marine reflection and refraction surveys. It consists of one or more pneumatic chambers that are pressurized with compressed air at pressures from 2,000 pounds per square inch to 3,000 pounds per square inch (14 to 21 MPa). The air gun array is submerged below the water surface, and is towed behind a ship. When the air gun

is fired, a solenoid is triggered, which releases air into a fire chamber which in turn causes a piston to move and thereby allowing the air to escape the main chamber and to produce a pulse of acoustic energy. Air gun arrays are built up of up to 48 individual air guns with different size chambers, the aim being to create the optimum initial shock wave with minimum reverberation of the bubble after the first shot.

Gun arrays can be fired in flip-flop mode; typically this would be 48 guns per source, which would be selected and fired alternately. Large chambers (i.e., greater than 70 cubic inches or 1.15 L) tend to give low frequency signals, and the small chambers (less than 70 cubic inches) give higher frequency signals. The air gun is made from the highest grades of corrosion resistant stainless steel.

Plasma sound source

Plasma sound source fired in small swimming pool

A **plasma sound source** (PSS), otherwise called a **spark gap sound source**, or simply a **sparker**, is a means of making very low frequency sonar pulse underwater.

For each firing, it stores electric charge in a large high-voltage bank of capacitors, and then releases all the stored energy in an arc across electrodes in the water. The underwater spark discharge produces a high-pressure plasma and vapor bubble, which expands and collapses, making a loud sound. Most of the sound produced is between 20 and 200 Hz.

The PSS has also been used for sonar. There are also plans to use PSS as a non-lethal weapon against submerged divers.

Thumper truck

A **thumper truck** (or weight-drop) truck is a vehicle mounted ground impact which can used to provide the seismic source. A heavy weight is raised by a hoist at the back of the truck and dropped, possibly about three metres, to impact (or "thump") the ground. To

augment the signal, the weight may be dropped more than once at the same spot, the signal may also be increased by thumping at several nearby places in an array whose dimensions may be chosen to enhance the seismic signal by spatial filtering.

Thumping might be less damaging to the environment than firing explosives in shot-holes, though a heavily thumped seismic line with transverse ridges every few metres might create long-lasting disturbance of the soil. An advantage of the thumper (later shared with Vibroseis), especially in politically unstable areas, was that no explosives were required.

Seismic vibrator

A Seismic vibrator, commonly known by its trademark name **Vibroseis**, propagates energy signals into the Earth over an extended period of time as opposed to the near instantaneous energy provided by impulsive sources. The data recorded in this way must be *correlated* to convert the extended source signal into an impulse. The source signal using this method was originally generated by a servo-controlled hydraulic vibrator or *shaker unit* mounted on a mobile base unit, but electro-mechanical versions have also been developed.

Vibroseis was developed by the Continental Oil Company (Conoco) during the 1950s and was a trademark until the company's patent lapsed.

Boomer sources

Boomer sound sources are used for shallow water seismic surveys, mostly for engineering survey applications. Boomers are towed in a floating sled behind a survey vessel. Similarly to the plasma source, it stores energy in capacitors, but it discharges through a flat spiral coil instead of generating a spark. A copper plate adjacent to the coil flexes away from the coil as the capacitors are discharged. This flexing is transmitted into the water as the seismic pulse.

Originally the storage capacitors were placed in a steel container (the **bang box**) on the survey vessel. The high voltages used, typically 3,000 V, required heavy cables and strong safety containers. Recently, low voltage boomers have become available. These use capacitors on the towed sled, allowing efficient energy recovery, lower voltage power supplies and lighter cables. The low voltage systems are generally easier to deploy and have fewer safety concerns.

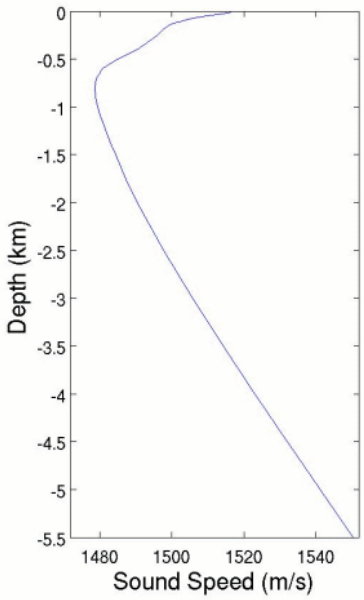
Noise sources

Correlation-based processing techniques also enable seismologists to image the interior of the Earth at multiple scales using natural (e.g., the oceanic microseism) or artificial (e.g., urban) background noise as a seismic source. For example, under ideal conditions of uniform seismic illumination, the correlation of the noise signals between two seismographs provides an estimate of the bidirectional seismic impulse response.

Chapter 10

SOFAR Channel

The **SOFAR channel** (short for **Sound Fixing and Ranging channel**), or **deep sound channel** (**DSC**), is a horizontal layer of water in the ocean at which depth the speed of sound is minimal. The SOFAR channel acts as a waveguide for sound, and low frequency sound waves within the channel may travel thousands of miles before dissipating. This phenomenon is an important factor in submarine warfare. The deep sound channel was discovered and described independently by Dr. Maurice Ewing, and Leonid Brekhovskikh in the 1940s.



Sound speed as a function of depth at a position north of Hawaii in the Pacific Ocean derived from the 2005 World Ocean Atlas. The SOFAR channel axis is at ca. 750-m depth.

The SOFAR channel is centered on the depth where the cumulative effect of temperature and water pressure (and, to a smaller extent, salinity) combine to create the region of

minimum sound speed in the water column. Pressure in the ocean increases linearly with depth, but temperature is more variable, generally falling rapidly in the main thermocline from the surface to around a thousand meters deep, then remaining almost unchanged from there to the ocean floor in the deep sea. Near the surface, the rapidly falling temperature causes a decrease in sound speed, or a negative sound speed gradient. With increasing depth, the increasing pressure causes an increase in sound speed, or a positive sound speed gradient. The depth where the sound speed is at a minimum is called the sound channel axis.

Near Bermuda, the sound channel axis occurs at a depth of around 1000 meters. In temperate waters, the axis is shallower, and at high latitudes (above about 60°N or below 60°S) it reaches the surface.

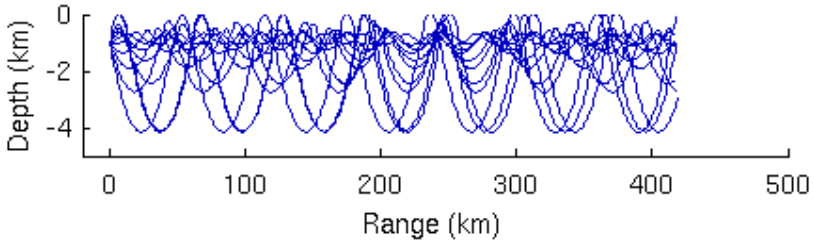
Sound propagates in the channel by refraction of sound, which makes sound travel near the depth of slowest speed. If a sound wave propagates away from this horizontal channel, the part of the wave furthest from the channel axis travels faster, so the wave turns back toward the channel axis. As a result, the sound waves trace a path that oscillates across the SOFAR channel axis. This principle is similar to long distance transmission of light in an optical fiber.

Mysterious low-frequency sounds, attributed to humpback whales and other baleen whales, are a common occurrence in the channel. Scientists believe humpback whales may dive down to this channel and "sing" to communicate with other humpback whales many kilometers away.

During World War II, Dr. Maurice Ewing suggested that dropping into the ocean a small metal sphere (called a Sofar bomb or [Sofar disc) specifically designed to implode at the SOFAR channel, could be used as a secret distress signal by downed pilots.

The novel *The Hunt for Red October* describes the use of the SOFAR channel in submarine detection.

The conjectured existence of a similar channel in the upper atmosphere, theorized by Dr. Ewing, led to Project Mogul, carried out from 1947 until late 1948.



Acoustic pulses travel great distances in the ocean because they are trapped in an acoustic "wave guide". This means that as acoustic pulses approach the surface they are turned back towards the bottom, and as they approach the ocean bottom they are turned back

towards the surface. The ocean conducts sound very efficiently, particularly sound at low frequencies, i.e., less than a few hundred Hz.

Related terms

Terminology related to The SOFAR or deep sound channel from the United States' *Navy Supplement to the DOD Dictionary of Military and Associated Terms*:

bottom limited
: A situation that exists when the ocean bottom occurs at a depth less than the critical depth. Convergence zone propagation is prevented from occurring. Deep sound channel propagation is restricted to a deep source.

conjugate depth
: For a source below the sonic layer depth, that depth below the deep sound channel axis where the sound speed equals the speed at the source depth.

convergence zone
: That region in the deep ocean where sound rays, refracted from the depths, return to the surface. They are focused at or near the surface in successive intervals. A convergence zone is a sound-transmission channel in the deep ocean [2,500 to 15,000 feet (850 to 4,500 meters)] produced by the combination of pressure and temperature changes.

cutoff frequency
: That frequency below which an acoustic signal will tend not to be trapped in a layer or duct and is a function of the depth of the layer.

critical depth
: The depth below the deep sound channel (DSC) axis at which the sound speed is the same as it is at the sonic layer depth. The critical depth is the bottom of the DSC.

deep layer
: In underwater acoustics, the layer of water between the lower edge of the main thermocline and the ocean bottom. It is characterized by a nearly constant temperature and a positive sound-speed gradient caused by pressure.

depth excess (DE)
: In underwater acoustics, 1. The difference between the bottom depth and the depth at which the sound velocity is equal to either the surface velocity when there is no layer depth, or the maximum velocity in the surface layer. 2. The difference between the depth at which the maximum near-surface sound velocity recurs and the bottom depth. It is applied to convergence zone propagation.

depth required
: In underwater acoustics, the minimum depth required for a reliable convergence zone to exist. It is 200 to 300 fathoms below the critical depth.

diffraction loss
: The loss of sound energy that occurs when sound rays traveling in a sound channel experience leakage out of the channel and thus out of the main wave front.

downslope enhancement

Acoustic energy from a source in shallow water changes from a bottom bounce path to a convergence zone or sound channel path as it travels to deeper water and is concentrated down the slope to a receiver in deep water. Also called the megaphone effect.

half channel

In underwater acoustics, an upward-refracting condition where the sound-speed gradient is positive from the surface all the way to the bottom. In a half channel, sound waves behave as if in a very thick surface duct.

limiting depth

In underwater acoustics, the depth below the deep sound channel axis where the sound speed equals the maximum near-surface sound speed.

limiting ray

In underwater acoustics, the sound ray that becomes tangent at the depth where the sound speed is at maximum; it delimits the outer boundary of direct (before reflection) sound rays.

surface duct (SD)

In underwater acoustics, a zone below the sea surface where sound rays are refracted toward the surface and then reflected. The rays alternately are refracted and reflected along the duct out to relatively long distances from the sound source.

shadow zone

In underwater acoustics, a region in which very little sound energy penetrates, depending upon the strength of the lower boundary of the surface duct. It is usually bounded by the lower boundary of the surface duct and the limiting ray. There are two shadow zones: the sea surface, beneath which a shadow is cast by the surface in the sound field of a shallow source, and the deep-sea bottom, which produces a shadow zone in the upward-refracting water above it.

sonic layer depth (SLD)

The depth of maximum near-surface sound speed above the deep sound channel.

sound channel

In underwater acoustics, that region in the water column where the sound speed first decreases to a minimum value with depth and then increases in value, due to pressure. Above the depth of minimum value, sound rays are bent downward; below the depth of minimum value, rays are bent upward, resulting in the rays being trapped in this channel and permitting their detection at great ranges from the sound source.

sound channel axis

The depth of minimum sound speed within a sound channel. Abbreviated as DSCA for the deep sound channel axis or SSCA for the secondary sound channel axis.

topographic shading

The disruption of convergence zone (CZ) or deep sound channel propagation by ocean bottom features such as seamounts, guyots, ridges, or islands. This disruption causes large shadow zones. Depth excess is destroyed for CZ propagation when a source is one-half the CZ range from such a bottom feature.

upslope enhancement

Acoustic energy from a source in deep water changes from a convergence zone or sound channel path to a bottom bounce path as the bottom shoals and is concentrated up the slope to a receiver in shallow water. Also known as the inverse megaphone effect.

vertex depth

In underwater acoustics, the depth in the water at which a refracted sound ray becomes horizontal.

Chapter 11

Surveillance Towed Array Sensor System and Towed Array Sonar

Surveillance Towed Array Sensor System

USNS *Invincible* as originally configured. Aft view of equipment for the Surveillance Towed-Array Sensor System (SURTASS), 1987.

The AN/UQQ-2 **Surveillance Towed Array Sensor System** (SURTASS) is a towed array sonar system of the United States Navy.

SURTASS began as development program in 1973 using the new research vessel Moana Wave. In 1980 SURTASS passed OPEVAL. The new Stalwart class ocean surveillance ships had the first contract awarded on 26 September 1980 and were similar to the prototype ship, the Moana Wave. Initially the SURTASS system were passive, receive only sonar systems. The array was towed miles behind the ships and were designed for long range detection of submarines.

As the passive systems were being deployed, an active adjunct known as the SURTASS Low Frequency Active (LFA) systems was designed for long range detection. The active system must be used in conjunction with the passive received system. The active component transmits an audio signal between 100 Hz and 500 Hz from an array suspended below the ship while the passive SURTASS array is towed miles behind to receive the signal after it had reflected off the submarine. The active LFA system is an updated version of the fixed low frequency surveillance system known as Project ARTEMIS. Although the Navy took steps to mitigate the environmental damage, environmental NGO's urged the Navy to prepare a public environmental impact statement. In 1996 the Navy published a notice of intent to prepare an evnvironmental impact statement. The Navy has spent over $16 million on scientific research on the effects on marine mammals and mitigation systems as well as the development of an Environmental Impact Statement.

SURTASS Twin-Line consists of either the long passive SURTASS array or the Twin-line array consisting of two shorter passive arrays towed side by side. The Twin-line Engineering Development Model was installed on USNS *Assertive*, and the first production model was installed on USNS *Bold*. Both ships are no longer serving as SURTASS units.

USNS *Able* (T-AGOS-20) aft view of SURTASS equipment.

As of 2009, SURTASS was deployed on the four T-AGOS 19 *Victorious*-class and single T-AGOS 23 *Impeccable*-class Small Waterplane Area Twin Hull (SWATH) vessels..

Low Frequency Active Sonar

- The SURTASS Low Frequency Active Sonar system, onboard *Impeccable*, commenced sea trials in late February 2004. During the spring and summer of 2004, *Impeccable* conducted five training missions in the Philippine Sea and the northwest Pacific Ocean. All LFA sonar operations included the operation of the *High Frequency / Marine Mammal Mitigation* sonar and compliance with all mitigation requirements.
- Total operational days onboard the Impeccable using the LFA array:

  (August 15, 2003 to August 15, 2004) 26.2 days with 63.0 hours of transmissions
  (August 15, 2004 to August 15, 2005) 9.4 days with 22.7 hours of transmissions
  (August 15, 2005 to August 15, 2006) 22.5 days with 39.4 hours of transmissions.

- The ship had five years of active and passive operations in the Western Pacific before the incident in the South China Sea.

SURTASS LFA sonar description

SURTASS LFA is a long-range, all-weather, sonar system that operates in the low frequency (LF) band (100–500 hertz [Hz]). There is presently two SURTASS LFA sonar systems, one each onboard the USNS *Impeccable* and *Able*, both operating in the northwestern Pacific Ocean. These systems have both passive and active components.

The active system component, LFA, is an adjunct to the passive detection system, SURTASS, and is planned for use when passive system performance proves inadequate. LFA is a set of acoustic transmitting source elements suspended by cable from underneath a ship. These elements, called projectors, are devices that produce the active sound pulse, or ping. The projectors transform electrical energy to mechanical energy that set up vibrations or pressure disturbances within the water to produce a ping.

The characteristics and operating features of LFA are:

- The source is a vertical line array (VLA) of up to 18 source projectors suspended below the vessel. LFA's transmitted sonar beam is omnidirectional (i.e., a full 360 degrees) in the horizontal (nominal depth of the LFA array center is 120 m [400 ft]), with a narrow vertical beamwidth that can be steered above or below the horizontal.
- The source frequency is between 100 and 500 Hz (the LFA system's physical design does not allow for transmissions below 100 Hz). A variety of signal types can be used, including continuous wave (CW) and frequency-modulated (FM) signals. Signal bandwidth is approximately 30 Hz.
- The source level (SL) of an individual source projector is approximately 215 decibels (dB). The sound field of the LFA array can never be higher than the SL of an individual projector.
- The typical LFA transmitted sonar signal is not a constant tone, but a transmission of various waveforms that vary in frequency and duration. A complete sequence of transmissions is referred to as a ping and lasts from 6 to 100 seconds, although the duration of each continuous frequency transmission is never longer than 10 seconds.
- Duty cycles (ratio of sound "on" time to total time) are less than 20 percent—20 percent is the maximum physical limit of the LFA system. Typical duty cycles are approximately 7.5 to 10 percent.
- The time between pings is typically from 6 to 15 minutes.

The passive, or listening, part of the system is SURTASS, which detects returning echoes from submerged objects, such as submarines, through the use of hydrophones. These devices transform mechanical energy (received acoustic sound wave) to an electrical signal that can be analyzed by the signal processing system of the sonar. The SURTASS hydrophones are mounted on a horizontal receive array that is towed behind the vessel.

The array length is 1,500 m (4,900 ft) with an operational depth of 150 to 460 m (500 to 1,500 ft). The SURTASS LFA ship must maintain a minimum speed of approximately 6 kilometers per hour (km/h) (3 knots) through the water in order to tow the hydrophone array in the horizontal plane. The return signals or echoes, which are usually below background or ambient noise level, are then processed and evaluated to identify and classify potential underwater targets.

Towed array sonar

The DUBV 43C towed array sonar of the *Lamotte-Picquet* (D 645).

A **towed array sonar** is a sonar array that is towed behind a submarine or surface ship. It is basically a long cable, up to 5 km, with hydrophones that is trailed behind the ship when deployed. The hydrophones are placed at specific distances along the cable. On the first few hundred meters near the ship's propeller there are usually none since their effectiveness would be reduced by noise, vibration and turbulence generated by the propulsion. Surface ships often have the sonar array mounted on a cable which pulls a tow vehicle behind the mother ship, or on another cable which trails from the ROV connector. By changing the ROV's depth, the sensor can be deployed in different thermal layers.

When not deployed, an Akula's towed array is stored in a teardrop shaped container mounted on top of the vertical fin

The array's hydrophones can be used to detect sound sources, but the real value of the array is that the signal processing technique of beamforming and interferometry can be used to calculate the distance and the direction of a sound source. For this, the relative positions of the hydrophones need to be known, usually only guaranteed when the cable is in a straight line, or else a GPS is used to monitor the shape of the array. Therefore, a vessel using a towed array will need to travel straight and level lest a change of course disturbs the array and reduces its effectiveness. This requirement is reduced in modern systems by sensors which constantly measure the relative positions of the array. Also it has to reduce its speed as the hydrodynamic drag might tear the cable - this can also happen if the array makes contact with the seafloor or the submarine operates astern propulsion.

Despite all those disadvantages, a towed array is useful since it offers better resolution and range compared to a hull mounted sonar and it covers the baffles, the blind spot of hull mounted sonar.

Chapter 12

Sonobuoy

Sonobuoy being loaded onto an USN P-3C Orion aircraft

A **sonobuoy** (a portmanteau of sonar and buoy) is a relatively small (typically 5 inches / 13 centimetres, in diameter and 3 ft/91 cm long) expendable sonar system that is

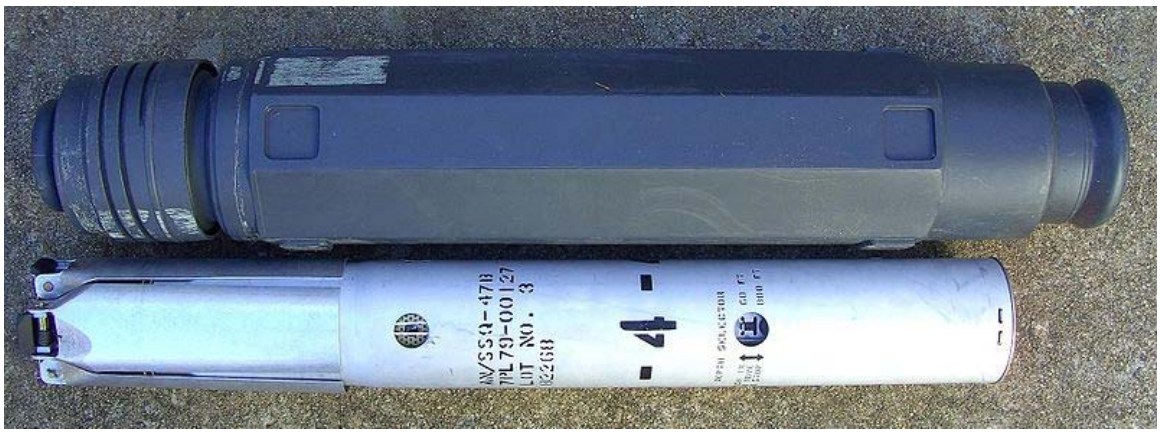
dropped/ejected from aircraft or ships conducting anti-submarine warfare or underwater acoustic research.

Theory of Operation

The buoys are ejected from aircraft in canisters and deploy upon water impact. An inflatable surface float with a radio transmitter remains on the surface for communication with the aircraft, while one or more hydrophone sensors and stabilizing equipment descend below the surface to a selected depth that is variable, depending on environmental conditions and the search pattern. The buoy relays acoustic information from its hydrophone(s) via UHF/VHF radio to operators onboard the aircraft.

History: Searching the Seas

P-3 Orion paradropping a sonobuoy.



AN/SSQ-47B active pinger ranging sonar sonobuoy (frequency #4) and shipping container (hexagonal form aids stacking.)

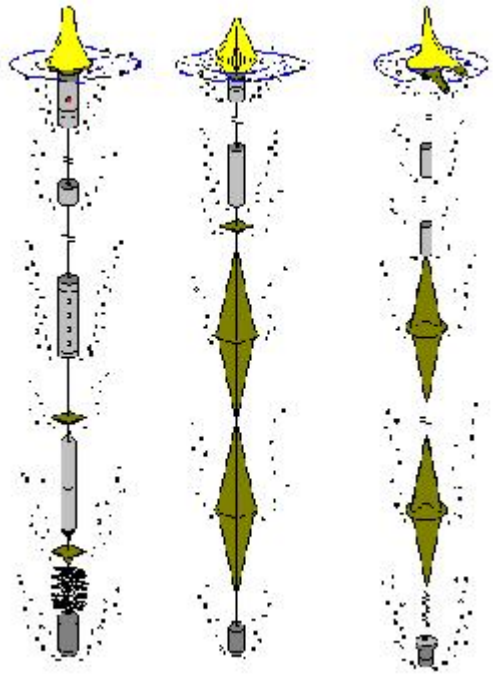
With the technological improvement of the submarine in modern warfare, the need for an effective tracking system was born. Sound Navigation And Ranging (SONAR) was originally developed by the British—who called it ASDIC—in the waning days of World War I. At the time the only way to detect submarines was by listening for them (passive sonar), or visually by chance when they were on the surface recharging their battery banks or by massive air patrols with lumbering airships and biplanes. Sonar saw extremely limited use and was mostly tested in the Atlantic Ocean with few naval officers seeing any merit in the system. With the end of WWI came the end to serious development of sonar in the US, a fact that was to be fatal in the early days of World War II. However, considerable development of ASDIC took place in the UK, including integration with a plotting table and weapon.

The ravaging wolf-packs of U-boats in WWII made the need for sonar a priority. With millions of tons of shipping being sunk in the Atlantic, there was a need to locate submarines so that they could be sunk or prevented from attacking. Sonar was installed on a number of ships along with Radio Detection and Ranging (RADAR) to detect surfaced submarines. While sonar was a primitive system, it was constantly improved.

Modern anti-submarine warfare grew from the WWII convoy and battle group movement through hostile waters. It was imperative that submarines be detected and neutralized long before the task group came within range of an attack. Aircraft-based submarine detection was the obvious solution. The maturity of radio communication and sonar technology made it possible to combine a sonar transducer, batteries, a radio transmitter and whip antenna, within a self-contained air-deployed floating (sono)buoy. The advancement in sonobuoy technology, it could be argued, eventually led to the development of entire classes of aircraft (such as the P-2 Neptune, S-2 Tracker, S-3B Viking and P-3 Orion) for anti-submarine warfare (ASW).

Early sonobuoys had limited range, limited battery life and were overwhelmed by the noise of the ocean. They first appeared towards the end of WWII where they were first used in July 1942 by RAF Coastal Command under the code name 'High Tea', the first squadron to use them operationally being No. 210 Squadron RAF, operating Sunderlands. They were also limited by the use of human ears to discriminate man-made noises from the oceanic background. However, they demonstrated that the technology was viable. With the development of better hydrophones, the transistor and miniaturization, and the realisation that very low frequency sound was important, more effective acoustic sensors followed. The sonobuoy went from being an imposing six feet tall, two feet diameter sensor to the compact suite of electronics it is today.

Concept of Operation (CONOPs)



Sonobuoy deployment procedures after impacting water.

Sonobuoys are classified into three categories: active, passive and special purpose.

- **Active sonobuoys** emit sound energy (e.g. "pings") into the water and listen for the returning echo before transmitting—usually range and bearing—information via UHF/VHF radio to a receiving ship or aircraft. The original active sonobuoys pinged continuously after deployment for a predetermined period of time. Later, Command Activated Sonobuoy System (CASS) sonobuoys allowed the aircraft to trigger pings (or buoy scuttling) via a radio link. This evolved into DICASS (Directional CASS) in which the return echo contained bearing as well as range data.
- **Passive sonobuoys** emit nothing into the water but rather listen, waiting for mechanically generated sound waves (for instance, power-plant, propeller or door-closing and other noises) from ships or submarines, or other acoustic signals of interest, to reach the hydrophone that are then transmitted via UHF/VHF radio back to a receiving ship or aircraft.
- **Special purpose sonobuoys** relay various types of oceanographic data to a ship, aircraft, or satellite. There are three types of special-purpose sonobuoys in use today. These sonobuoys are not designed for use in submarine detection or localization.
    - BT—The bathythermobuoy (BT) relay bathythermographic or salinity readings, or both, at various depths.

- SAR—The search and rescue (SAR) buoy is designed to operate as a floating RF beacon. As such, it is used to assist in marking the location of an aircraft crash site, a sunken ship, or survivors at sea.
- ATAC/DLC—Air transportable communication (ATAC) and down-link communication (DLC) buoys, such as the UQC, or "gertrude", are intended for use as a means of communication between an aircraft and a submarine, or between a ship and a submarine.

This information is indeed analysed by computers, acoustic operators and TACCOs to interpret the sonobuoy information. Any noise that a submarine makes is a potential death knell, so few submariners are communicative.

Active and/or passive sonobuoys may be laid in large fields or barriers for initial detection. Active buoys may then be used for precise location. Passive buoys may also be deployed on the surface in patterns to allow relatively precise location by triangulation. Multiple aircraft or ships monitor the pattern either passively listening or actively transmitting in order to drive the submarine into the sonar net. Sometimes the pattern takes the shape of a grid or other array formation and complex beamforming signal processing is used to transcend the capabilities of single, or limited numbers of, hydrophones.