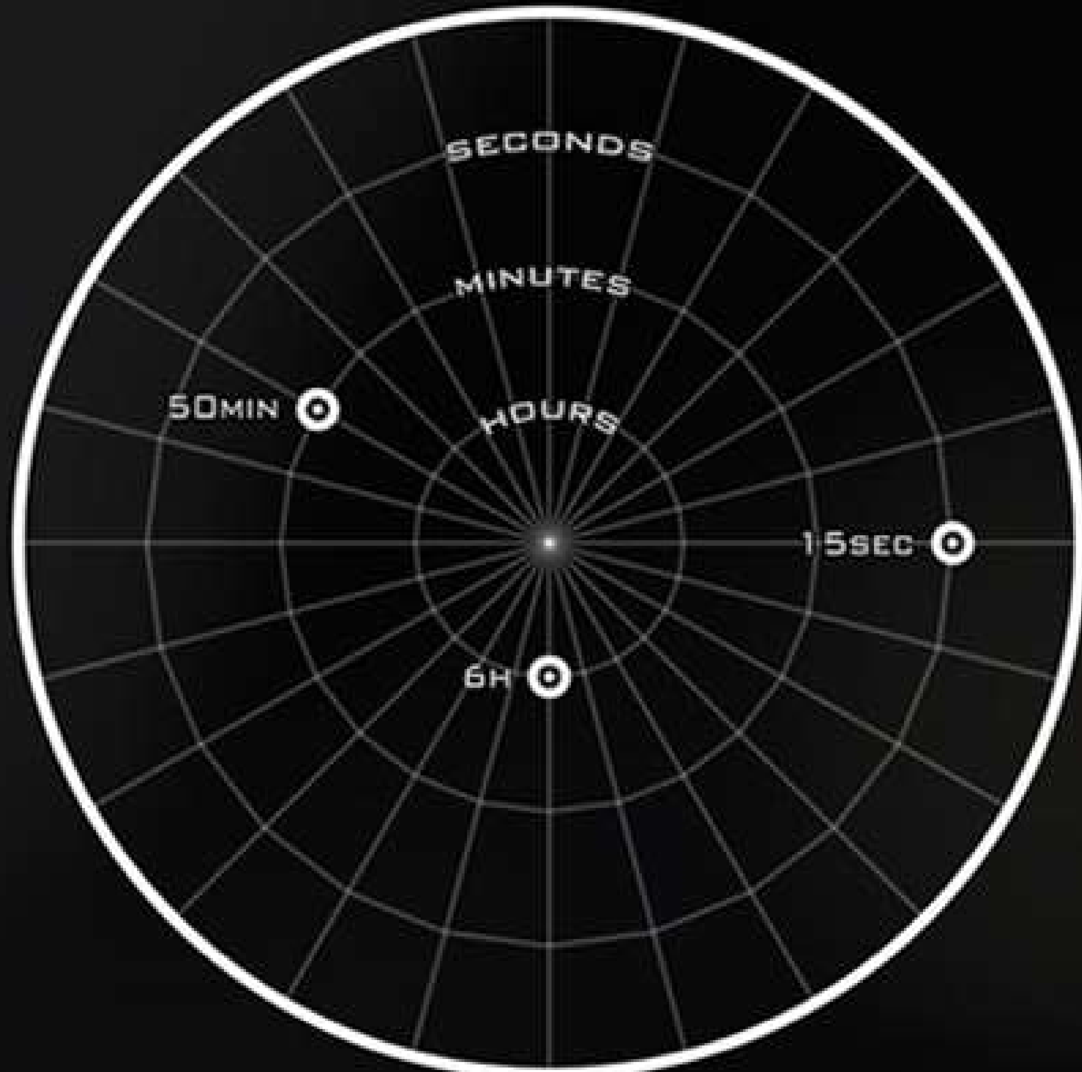
# Handbook of
# Navigational Equipments and Technology

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First Edition, 2012

ISBN 978-81-323-1481-3

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*Published by:*
**College Publishing House**
4735/22 Prakashdeep Bldg,
Ansari Road, Darya Ganj,
Delhi - 110002
Email: info@wtbooks.com

# Table of Contents



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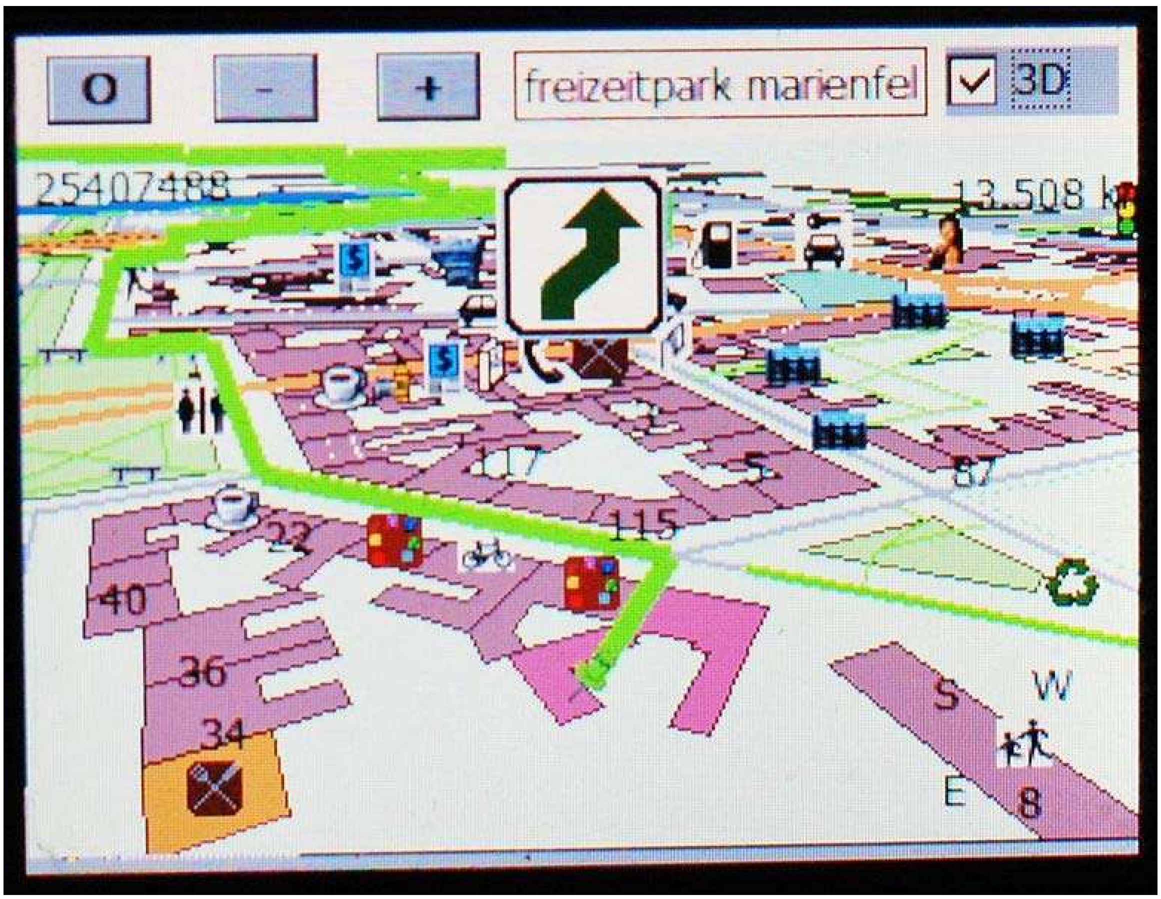
## Chapter 1

# GPS Navigation Device




Bicycle navigation with Gosmore, an open source routing software, on a personal navigation assistant with free map data from OpenStreetMap.

A **GPS navigation device** is any device that receives Global Positioning System (GPS) signals for the purpose of determining the device's current location on Earth. GPS devices provide latitude and longitude information, and some may also calculate altitude, although this is not considered sufficiently accurate or continuously available enough (due to the possibility of signal blockage and other factors) to rely on exclusively to pilot aircraft. GPS devices are used in military, aviation, marine and consumer product applications.

GPS devices may also have additional capabilities such as:

- containing maps, which may be displayed in human readable format via text or in a graphical format
- providing suggested directions to a human in charge of a vehicle or vessel via text or speech
- providing directions directly to an autonomous vehicle such as a robotic probe
- providing information on traffic conditions (either via historical or real time data) and suggesting alternative directions
- providing information on nearby amenities such as restaurants, fueling stations, etc.

In other words, all GPS devices can answer the question "Where am I?", and may also be able to answer:

- which roads or paths are available to me now?
- which roads or paths should I take in order to get my desired destination?
- if some roads are usually busy at this time or are busy right now, what would be a better route to take?
- where can I get something to eat nearby or where can I get fuel for my vehicle?

## *Consumer applications*

Consumer GPS navigation devices include:

- Dedicated GPS navigation devices
- GPS modules that need to be connected to a computer to be used
- GPS loggers that record trip information for download. Such GPS tracking is useful for trailblazing, mapping by hikers and cyclists, and the production of geocoded photographs.
- Converged devices, including GPS Phones and GPS cameras, in which GPS is a feature rather than the main purpose of the device. Those devices may be assisted GPS or standalone (not network dependent) or both.

## Dedicated GPS navigation devices


A variety of hand-held receivers

A taxi equipped with GPS navigation system

Dedicated devices have various degrees of mobility. *Hand-held*, *outdoor*, or *sport* receivers have replaceable batteries that can run them for several hours, making them suitable for hiking, bicycle touring and other activities far from an electric power source. Their screens are small, and some do not show color, in part to save power. Cases are rugged and some are water resistant.

Other receivers, often called *mobile* are intended primarily for use in a car, but have a small rechargeable internal battery that can power them for an hour or two away from the car. Special purpose devices for use in a car may be permanently installed and depend entirely on the automotive electrical system.

The pre-installed embedded software of early receivers did not display maps; 21st century ones commonly show interactive street maps (of certain regions) that may also show points of interest, route information and step-by-step routing directions, often in spoken form with a feature called "text to speech".

Manufacturers include:

- Navman products
- TomTom products
- Garmin products
- Mio products

- Navigon products
- Magellan Navigation consumer products
- TeleType products

## Mobile phones with GPS capability

Due in part to regulations encouraging mobile phone tracking, including E911, the majority of GPS receivers are built into mobile telephones, with varying degrees of coverage and user accessibility. Commercial navigation software is available for most 21st century smartphones as well as some Java-enabled phones that allows them to use an internal or external GPS receiver (in the latter case, connecting via serial or Bluetooth). Some phones with GPS capability work by assisted GPS (A-GPS) only, and do not function when out of range of their carrier's cell towers. Others can navigate worldwide with satellite GPS signals as a dedicated portable GPS receiver does, upgrading their operation to A-GPS mode when in range. Still others have a hybrid positioning system that can use other signals when GPS signals are inadequate.

More bespoke solutions also exist for smartphones with inbuilt GPS capabilities. Some such phones can use tethering to double as a wireless modem for a laptop, while allowing GPS-navigation/localisation as well. One such example is marketed by Verizon Wireless in the United States, and is called VZ Navigator. The system uses gpsOne technology to determine the location, and then uses the mobile phone's data connection to download maps and calculate navigational routes. Other products including iPhone are used to provide similar services. Nokia gives Ovi Maps free on its smartphones and maps can be preloaded. According to market research from the independent analyst firm Berg Insight, the sales of GPS-enabled GSM/WCDMA handsets was 150 million units in 2009. while only 40 million separate GPS receivers were sold.

GPS navigation applications for mobile phones include Waze.

## Laptop PC GPS

Various software companies have made available GPS road navigation software programs for in-vehicle use on laptop computers. Benefits of GPS on a laptop include larger map overview, ability to use the keyboard to control GPS functions, and some GPS software for laptops offers advanced trip-planning features not available on other platforms. Laptop computers allow for other uses beside GPS.

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## GPS modules


A modern SiRFstarIII chip based 20-channel GPS receiver with WAAS/EGNOS support

Other GPS devices need to be connected to a computer in order to work. This computer can be a home computer, laptop or even a PDAs, or smartphones. Depending on the type of computer and available connectors, connections can be made through a serial or USB cable, as well as Bluetooth, CompactFlash, SD, PCMCIA and the newer ExpressCard. Some PCMCIA/ExpressCard GPS units also include a wireless modem. Devices usually do not come with preinstalled GPS navigation software, thus once purchased the user must install or write their own navigation software. As the user can choose which navigation software to use, it can be better matched to their personal taste. It is very common for a PC-based GPS receiver to come bundled with a navigation software suite. Also, GPS modules are significantly cheaper than complete stand-alone systems (around 50-100 €). The software may include maps only for a particular region, or the entire world (if software such as Google Maps, Networks in Motion's AtlasBook mobile navigation platform, etc. is used).

Some hobbyists have also made some GPS devices and open-sourced the plans. An example is the Elektor GPS units. These are based around a SirFStar 3 chip and are comparable to their commercial counterparts.

### *Commercial aviation*

Commercial aviation applications include GPS devices that calculate location and feed that information to large multi-input navigational computers for autopilot, course information and correction displays to the pilots, and course tracking and recording devices.

### *Military*

Military applications include devices similar to consumer sport products for foot soldiers (commanders and regular soldiers), small vehicles and ships, and devices similar to commercial aviation applications for aircraft and missiles. Examples are the US military's **Commander's Digital Assistant** and the **Soldier Digital Assistant**.

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# Chapter 2

# 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.

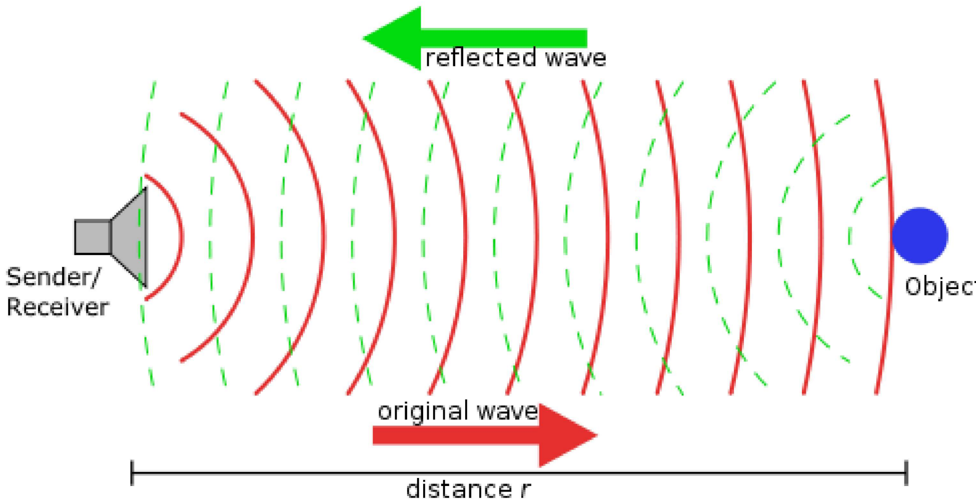
### Countermeasures

*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*.

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## 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.

- 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.

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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.

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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.

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### 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.

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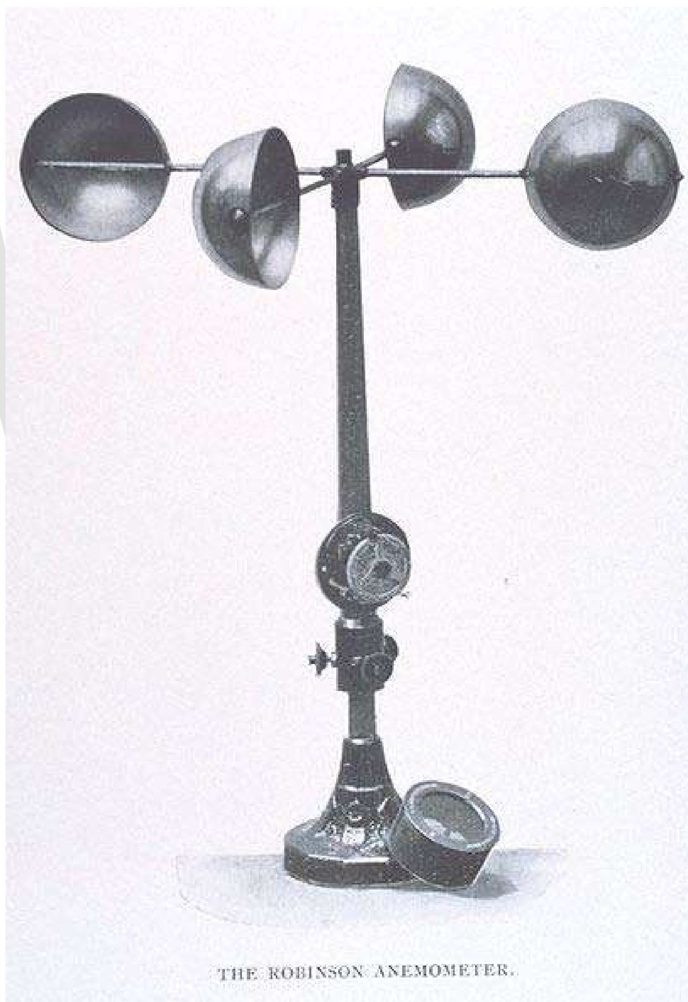
# Chapter 3

# Anemometer




A hemispherical cup anemometer of the type invented in 1846 by John Thomas Romney Robinson

Cup-type anemometer with vertical axis, a sensor on a remote meteorological station deployed on Skagit Bay, Washington July–August, 2009.

An **anemometer** is a device for measuring wind speed, and is a common weather station instrument. The term is derived from the Greek word *anemos*, meaning wind. The first known description of an anemometer was given by Leon Battista Alberti around 1450. They are also very easy to make as a project.

Anemometers can be divided into two classes: those that measure the wind's speed, and those that measure the wind's pressure; but as there is a close connection between the pressure and the speed, an anemometer designed for one will give information about both.

## *Velocity anemometers*

### Cup anemometers

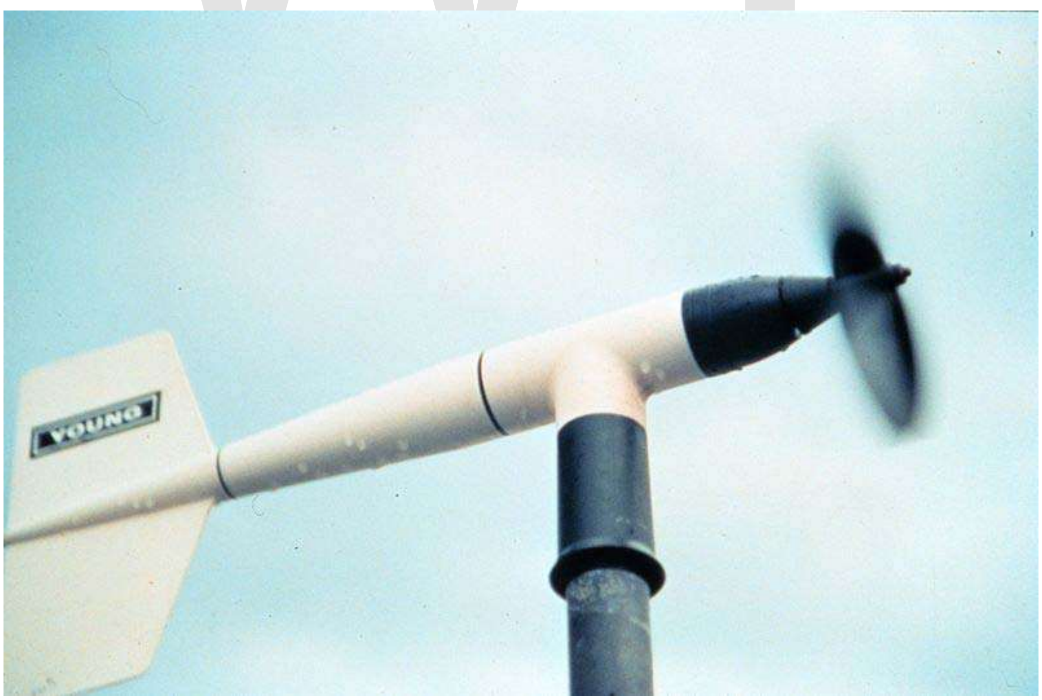
A simple type of anemometer, invented (1846) by Dr. John Thomas Romney Robinson, of Armagh Observatory. It consisted of four hemispherical cups each mounted on one end of four horizontal arms, which in turn were mounted at equal angles to each other on a vertical shaft. The air flow past the cups in any horizontal direction turned the cups in a manner that was proportional to the wind speed. Therefore, counting the turns of the cups over a set time period produced the average wind speed for a wide range of speeds. On an anemometer with four cups it is easy to see that since the cups are arranged symmetrically on the end of the arms, the wind always has the hollow of one cup presented to it and is blowing on the back of the cup on the opposite end of the cross.

When Robinson first designed his anemometer, he asserted that the cups moved one-third of the speed of the wind, unaffected by the cup size or arm length. This was apparently confirmed by some early independent experiments, but it was incorrect. Instead, the ratio of the speed of the wind and that of the cups, the anemometer factor, depends on the dimensions of the cups and arms, and may have a value between two and a little over three. Every experiment involving an anemometer had to be repeated.

The three cup anemometer developed by the Canadian John Patterson in 1926 and subsequent cup improvements by Brevoort & Joiner of the USA in 1935 led to a cupwheel design which was linear and had an error of less than 3% up to 60 mph (97 km/h). Patterson found that each cup produced maximum torque when it was at 45 degrees to the wind flow. The three cup anemometer also had a more constant torque and responded more quickly to gusts than the four cup anemometer.

The three cup anemometer was further modified by the Australian Derek Weston in 1991 to measure both wind direction and wind speed. Weston added a tag to one cup, which causes the cupwheel speed to increase and decrease as the tag moves alternately with and against the wind. Wind direction is calculated from these cyclical changes in cupwheel speed, while wind speed is as usual determined from the average cupwheel speed.

Three cup anemometers are currently used as the industry standard for wind resource assessment studies.

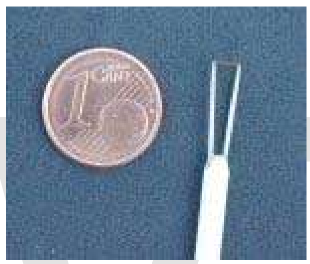


A windmill style of anemometer

## Windmill anemometers

The other forms of mechanical velocity anemometer may be described as belonging to the windmill type or propeller anemometer. In the Robinson anemometer the axis of rotation is vertical, but with this subdivision the axis of rotation must be parallel to the direction of the wind and therefore horizontal. Furthermore, since the wind varies in direction and the axis has to follow its changes, a wind vane or some other contrivance to fulfil the same purpose must be employed. An *aerovane* combines a propeller and a tail on the same axis to obtain accurate and precise wind speed and direction measurements from the same instrument. In cases where the direction of the air motion is always the same, as in the ventilating shafts of mines and buildings for instance, wind vanes, known as air meters are employed, and give most satisfactory results.

## Hot-wire anemometers



Hot-wire sensor

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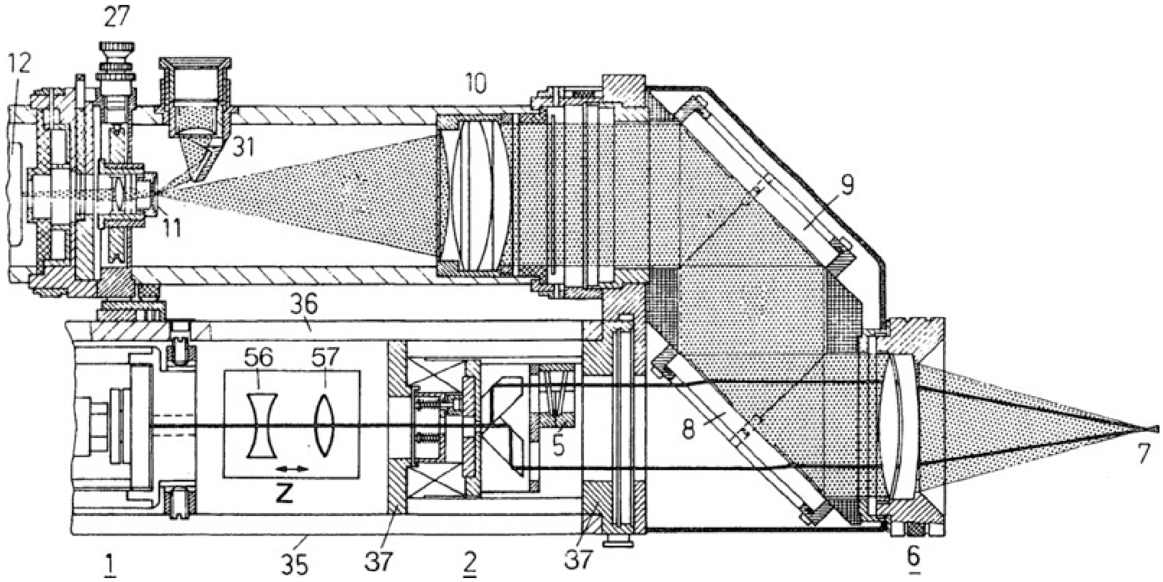
Hot wire anemometers use a very fine wire (on the order of several micrometres) electrically heated up to some temperature above the ambient. Air flowing past the wire has a cooling effect on the wire. As the electrical resistance of most metals is dependent upon the temperature of the metal (tungsten is a popular choice for hot-wires), a relationship can be obtained between the resistance of the wire and the flow speed.

Several ways of implementing this exist, and hot-wire devices can be further classified as CCA (Constant-Current Anemometer), CVA (Constant-Voltage Anemometer) and CTA (Constant-Temperature Anemometer). The voltage output from these anemometers is thus the result of some sort of circuit within the device trying to maintain the specific variable (current, voltage or temperature) constant.

Additionally, PWM (pulse-width modulation) anemometers are also used, wherein the velocity is inferred by the time length of a repeating pulse of current that brings the wire up to a specified resistance and then stops until a threshold "floor" is reached, at which time the pulse is sent again.

Hot-wire anemometers, while extremely delicate, have extremely high frequency-response and fine spatial resolution compared to other measurement methods, and as such are almost universally employed for the detailed study of turbulent flows, or any flow in which rapid velocity fluctuations are of interest.

## Laser Doppler anemometers




Drawing of a laser anemometer. The laser is emitted (1) through the front lens (6) of the anemometer and is backscattered off the air molecules (7). The backscattered radiation (dots) re-enter the device and are reflected and directed into a detector (12).

Laser Doppler anemometers use a beam of light from a laser that is divided into two beams, with one propagated out of the anemometer. Particulates (or deliberately introduced seed material) flowing along with air molecules near where the beam exits reflect, or backscatter, the light back into a detector, where it is measured relative to the original laser beam. When the particles are in great motion, they produce a Doppler shift for measuring wind speed in the laser light, which is used to calculate the speed of the particles, and therefore the air around the anemometer.

## Sonic anemometers

3D ultrasonic anemometer

Sonic anemometers, first developed in the 1970s, use ultrasonic sound waves to measure wind velocity. They measure wind speed based on the time of flight of sonic pulses between pairs of transducers. Measurements from pairs of transducers can be combined to yield a measurement of velocity in 1-, 2-, or 3-dimensional flow. The spatial resolution is given by the path length between transducers, which is typically 10 to 20 cm. Sonic anemometers can take measurements with very fine temporal resolution, 20 Hz or better, which makes them well suited for turbulence measurements. The lack of moving parts makes them appropriate for long term use in exposed automated weather stations and weather buoys where the accuracy and reliability of traditional cup-and-vane anemometers is adversely affected by salty air or large amounts of dust. Their main disadvantage is the distortion of the flow itself by the structure supporting the transducers, which requires a correction based upon wind tunnel measurements to minimize the effect. An international standard for this process, ISO 16622 *Meteorology—Sonic anemometers/thermometers—Acceptance test methods for mean wind measurements* is in general circulation. Another disadvantage is lower accuracy due to precipitation, where rain drops may vary the speed of sound.

Since the speed of sound varies with temperature, and is virtually stable with pressure change, sonic anomometers are also used as thermometers.

Two-dimensional (wind speed and wind direction) sonic anemometers are used in applications such as weather stations, ship navigation, wind turbines, aviation and weather buoys.

### Ping-pong ball anemometers

A common anemometer for basic use is constructed from a ping-pong ball attached to a string. When the wind blows horizontally, it presses on and moves the ball; because ping-pong balls are very lightweight, they move easily in light winds. Measuring the angle between the string-ball apparatus and the line normal to the ground gives an estimate of the wind speed.

This type of anemometer is mostly used for middle-school level instruction which most students make themselves, but a similar device was also flown on Phoenix Mars Lander .

## *Pressure anemometers*

The first designs of anemometers which measure the pressure were divided into plate and tube classes.

### Plate anemometers

These are the earliest anemometers and are simply a flat plate suspended from the top so that the wind deflects the plate. In 1450, the Italian art architect Leon Battista Alberti invented the first mechanical anemometer; in 1664 it was re-invented by Robert Hooke (who is often mistakenly considered the inventor of the first anemometer). Later versions of this form consisted of a flat plate, either square or circular, which is kept normal to the wind by a wind vane. The pressure of the wind on its face is balanced by a spring. The compression of the spring determines the actual force which the wind is exerting on the plate, and this is either read off on a suitable gauge, or on a recorder. Instruments of this kind do not respond to light winds, are inaccurate for high wind readings, and are slow at responding to variable winds. Plate anemometers have been used to trigger high wind alarms on bridges.

## Tube anemometers

Helicoid propeller anemometer incorporating a wind vane for orientation

James Lind's anemometer of 1775 consisted simply of a glass U tube containing liquid, a manometer, with one end bent in a horizontal direction to face the wind and the other vertical end remains parallel to the wind flow. Though the Lind was not the first it was the most practical and best known anemometer of this type. If the wind blows into the mouth of a tube it causes an increase of pressure on one side of the manometer. The wind over the open end of a vertical tube causes little change in pressure on the other side of the manometer. The resulting liquid change in the U tube is an indication of the wind speed. Small departures from the true direction of the wind causes large variations in the magnitude.

The highly successful metal pressure tube anemometer of William Henry Dines in 1892 utilized the same pressure difference between the open mouth of a straight tube facing the wind and a ring of small holes in a vertical tube which is closed at the upper end. Both are mounted at the same height. The pressure differences on which the action depends are very small, and special means are required to register them. The recorder consists of a float in a sealed chamber partially filled with water. The pipe from the straight tube is connected to the top of the sealed chamber and the pipe from the small tubes is directed into the bottom inside the float. Since the pressure difference determines the vertical position of the float this is a measure of the wind speed.

The great advantage of the tube anemometer lies in the fact that the exposed part can be mounted on a high pole, and requires no oiling or attention for years; and the registering part can be placed in any convenient position. Two connecting tubes are required. It might appear at first sight as though one connection would serve, but the differences in pressure on which these instruments depend are so minute, that the pressure of the air in the room where the recording part is placed has to be considered. Thus if the instrument depends on the pressure or suction effect alone, and this pressure or suction is measured against the air pressure in an ordinary room, in which the doors and windows are carefully closed and a newspaper is then burnt up the chimney, an effect may be produced equal to a wind of 10 mi/h (16 km/h); and the opening of a window in rough weather, or the opening of a door, may entirely alter the registration.

While the Dines anemometer had an error of only 1% at 10 mph (16 km/h) it did not respond very well to low winds due to the poor response of the flat plate vane required to turn the head into the wind. In 1918 an aerodynamic vane with eight times the torque of the flat plate overcame this problem.

## Effect of density on measurements

In the tube anemometer the pressure is measured, although the scale is usually graduated as a velocity scale. In cases where the density of the air is significantly different from the calibration value (as on a high mountain, or with an exceptionally low barometer) an allowance must be made. Approximately 1½% should be added to the velocity recorded by a tube anemometer for each 1000 ft (5% for each kilometer) above sea-level.

## Chapter 4

# Astrocompass and Flight Instruments

## Astrocompass


Astrocompass mk. II

An **astrocompass** is a navigational tool for determining the direction of north through the positions of various astronomical bodies.

There are certain circumstances when magnetic compasses and gyrocompasses are unreliable. The most obvious is in polar regions, where the force exerted on the needle of a magnetic compass is nearly vertical and gyrocompasses become unstable due to the rotation of the Earth. Magnetic compasses are also particularly susceptible to magnetic

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fields, such as those produced by the hulls of some metal vehicles or craft. Before the advent of electronic navigational aids such as GPS the most reliable way to ascertain north in such circumstances was through the use of an astrocompass.

## Principle of use

The Earth's axis of rotation remains, for all intents and purposes, stationary throughout the year. Thus, with knowledge of the current time and geographical position in the form of latitude and longitude, which are set on the instrument using dials, an astrocompass can be sighted on to any astronomical object with a known position to give an extremely accurate reading.

In its most basic form, the astrocompass consists of a base plate marked with the points of the compass, with a mechanism known as an equatorial drum mounted on it. On this drum is a set of adjustable sights and a scale of declination. More advanced versions may have built-in chronometers or default settings for bodies such as the Sun.

To use the compass, the base plate is first levelled with the horizon then pointed roughly to what the user believes to be north. The equatorial drum is then tilted in relation to this base according to the local latitude. The sights are then set using the local hour angle and the declination of whatever astronomical body is being used. Once all these settings have been made, the astrocompass is simply turned until the astronomical body is visible in the sights: it will then be precisely aligned to the points of the compass. Because of this procedure, an astrocompass requires its user to be in possession of a nautical almanac or similar astronomical tables, one of its chief disadvantages.

## Historical uses

Astrocompasses only became useful following the invention of the marine chronometer, without which it is almost useless for navigation. Even then, they saw only limited use, with first magnetic compasses and then gyrocompasses being preferred in almost all cases. Polar exploration was one of the fields in which the astrocompass saw the most use, for the reasons described above. They have also been used throughout history in other climes to check the accuracy of other forms of compasses: they saw use, for example, in the North African Campaign of World War 2.

GPS and other similar forms of electronic navigation aids mean that the astrocompass is now functionally obsolete anywhere except for areas very close to the poles where GPS coverage is not available and there are no current electronic navigation aids.

## Operation

The operation is as follows:

1. Getting the local time (by means of a clock)
2. Setting the latitude

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3. Setting (in the alidade) the star's LHA for that day obtained by means of tables or a computer program
4. Pointing the compass pinnula to the star (sun or moon)
5. Reading the true course on the limb

# Flight instruments

The cockpit of a Slingsby T-67 Firefly two-seat light airplane. The flight instruments are visible on the left of the instrument panel

**Flight instruments** are the instruments in the cockpit of an aircraft that provide the pilot with information about the flight situation of that aircraft, such as height, speed and altitude. The flight instruments are of particular use in conditions of poor visibility, such as in clouds, when such information is not available from visual reference outside the aircraft.

The term is sometimes used loosely as a synonym for cockpit instruments as a whole, in which context it can include engine instrument, navigational and communication equipment.

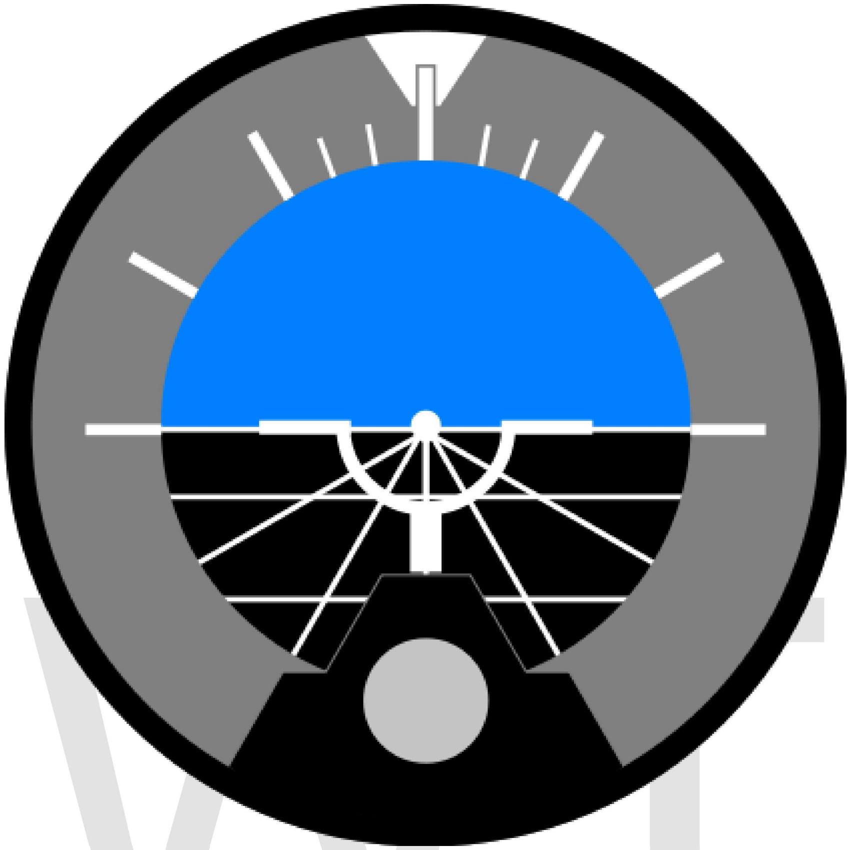
## *Flight instruments*

Most aircraft have these flight instruments:

### Altimeter


The altimeter shows the aircraft's altitude above sea-level by measuring the difference between the pressure in a stack of aneroid capsules inside the altimeter and the atmospheric pressure obtained through the static system. It is adjustable for local barometric pressure which must be set correctly to obtain accurate altitude readings. As the aircraft ascends, the capsules expand as the static pressure drops therefore causing the altimeter to indicate a higher altitude. The opposite occurs when descending.

### Attitude indicator



The attitude indicator (also known as an *artificial horizon*) shows the aircraft's attitude relative to the horizon. From this the pilot can tell whether the wings are level and if the aircraft nose is pointing above or below the horizon. This is a primary instrument for instrument flight and is also useful in conditions of poor visibility. Pilots are trained to use other instruments in combination should this instrument or its power fail.

Schempp-Hirth Janus-C glider Instrument panel equipped for "cloud flying". The turn and bank indicator is top center. The heading indicator is replaced by a GPS-driven computer with wind and glide data, driving two electronic variometer displays to the right.

**Airspeed indicator**


The airspeed indicator shows the aircraft's speed (usually in knots ) relative to the surrounding air. It works by measuring the ram-air pressure in the aircraft's pitot tube. The indicated airspeed must be corrected for air density (which varies with altitude, temperature and humidity) in order to obtain the true airspeed, and for wind conditions in order to obtain the speed over the ground.

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### Magnetic compass


The compass shows the aircraft's heading relative to magnetic north. While reliable in steady level flight it can give confusing indications when turning, climbing, descending, or accelerating due to the inclination of the Earth's magnetic field. For this reason, the heading indicator is also used for aircraft operation. For purposes of navigation it may be necessary to correct the direction indicated (which points to a magnetic pole) in order to obtain direction of true north or south (which points to the Earth's axis of rotation).

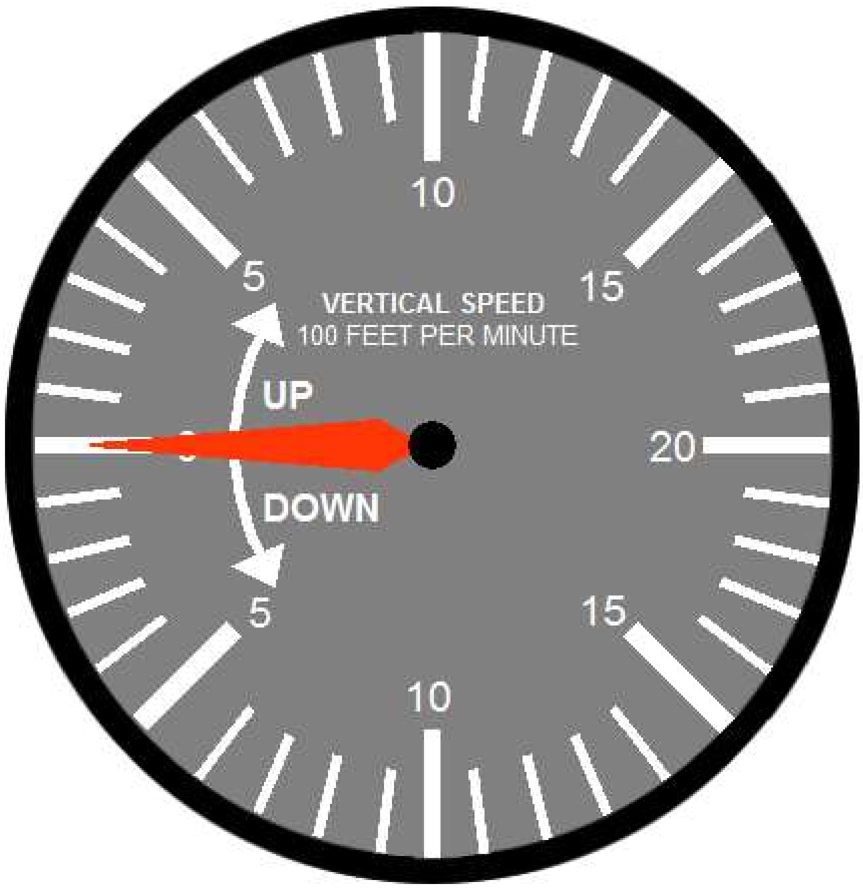
## Heading indicator


The heading indicator (also known as the directional gyro, or DG; sometimes also called the gyrocompass, though usually not in aviation applications) displays the aircraft's heading with respect to geographical north. Principle of operation is a spinning gyroscope, and is therefore subject to drift errors (called precession) which must be periodically corrected by calibrating the instrument to the magnetic compass. In many advanced aircraft (including almost all jet aircraft), the heading indicator is replaced by a Horizontal Situation Indicator (HSI) which provides the same heading information, but also assists with navigation

## Turn indicator


The turn indicator displays direction of turn and rate of turn. Internally mounted inclinometer displays 'quality' of turn, i.e. whether the turn is correctly coordinated, as opposed to an uncoordinated turn, wherein the aircraft would be in either a slip or a skid. The original turn and bank indicator was replaced in the late 1960s and early '70s by the newer turn coordinator, which is responsive to roll as well as rate of turn, the turn and bank is typically only seen in aircraft manufactured prior to that time, or in gliders manufactured in Europe.

### Vertical speed indicator




The VSI (also sometimes called a variometer). Senses changing air pressure, and displays that information to the pilot as a rate of climb or descent in feet per minute, meters per second or knots.

Additional panel instruments that may not be found in smaller aircraft include:

## Course deviation indicator


The CDI is an avionics instrument used in aircraft navigation to determine an aircraft's lateral position in relation to a track, which can be provided by a VOR or an Instrument Landing System.

This instrument can also be integrated with the heading indicator in a horizontal situation indicator.

## Radio Magnetic Indicator


An RMI is generally coupled to an *automatic direction finder* (ADF), which provides bearing for a tuned Non-directional beacon (NDB). While simple ADF displays may have only one needle, a typical RMI has two, coupled to different ADF receivers, allowing for position fixing using one instrument.

### *Layout*


Six basic instruments in a light twin-engine airplane arranged in a "basic-T". From top left: airspeed indicator, attitude indicator, altimeter, turn coordinator, heading indicator, and vertical speed indicator

Most aircraft are equipped with a standard set of **flight instruments** which give the pilot information about the aircraft's attitude, airspeed, and altitude.

### T arrangement

Most aircraft built since about 1953 have four of the **flight instruments** located in a standardized pattern called the T arrangement. The attitude indicator is in the top center, airspeed to the left, altimeter to the right and heading indicator under the attitude indicator. The other two, turn-coordinator and vertical-speed, are usually found under the airspeed and altimeter, but are given more latitude in placement. The magnetic compass will be above the instrument panel, often on the windscreen centerpost. In newer aircraft with glass cockpit instruments the layout of the displays conform to the basic T arrangement.

### Basic Six

In 1937 the Royal Air Force (RAF) chose a set of six essential flight instruments which would remain the standard panel used for flying in Instrument Meteorological Conditions (IMC) for the next 20 years. They were:

- airspeed indicator (knots)

- attitude indicator
- vertical speed indicator (rate of climb)
- altimeter
- directional gyro (compass)
- turn and bank indicator (aircraft attitude)

This panel arrangement was incorporated into every RAF aircraft, from the light Tiger Moth, to the heavy Avro Lancaster, and minimized the type-conversion difficulties associated with Blind Flying, since a pilot trained on one aircraft could quickly become accustomed to any other if the instruments were identical.

This Basic Six set, also known as a six pack, was also adopted by commercial aviation. After the Second World War the arrangement was changed to: (top row) airspeed, artificial horizon, altimeter, (bottom row) radio compass, direction indicator, vertical speed.

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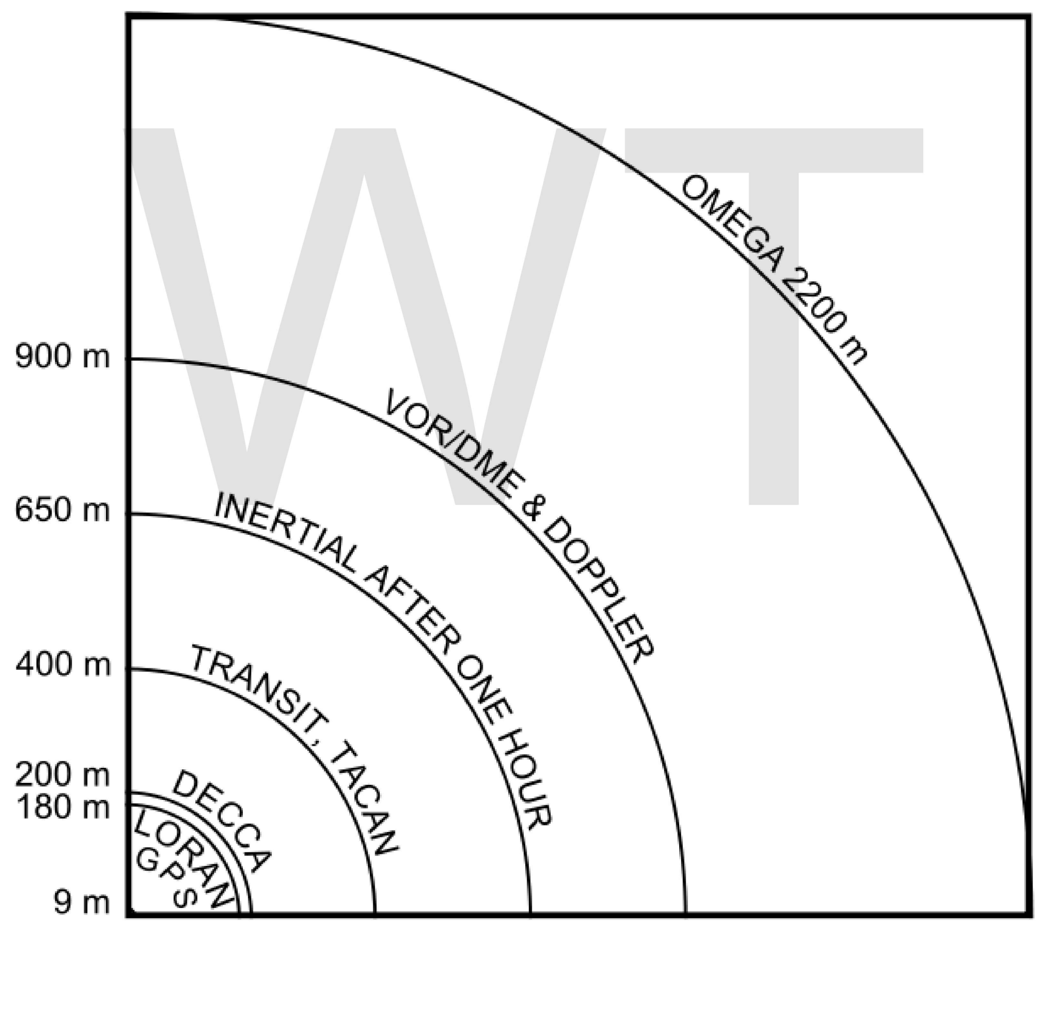
## Chapter 5

# Decca Navigator System

ACCURACY OF NAVIGATION SYSTEMS
(2-dimensional)

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Decca Navigator Mk 12

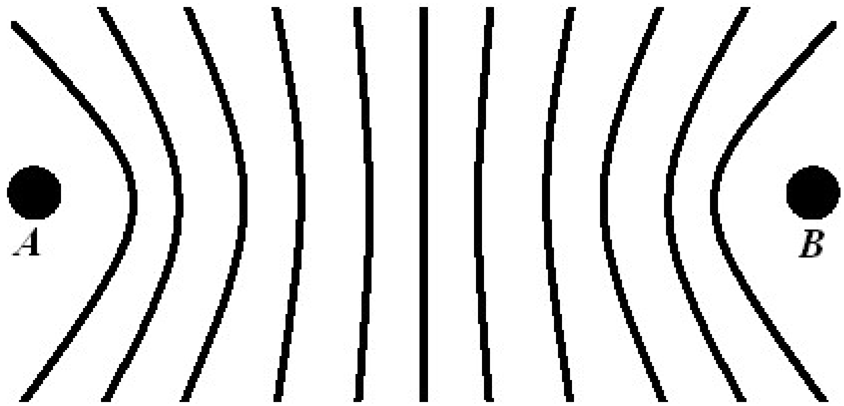
The **Decca Navigator System** was a hyperbolic low frequency radio navigation system (also known as multilateration) that was first deployed during World War II when the Allied forces needed a system which could be used to achieve accurate landings. As was the case with Loran C, its primary use was for ship navigation in coastal waters.

Fishing vessels were major post-war users, but it was also used on aircraft, including a very early (1949) application of moving-map displays. The system was deployed extensively in the North Sea and was used by helicopters operating to oil platforms. After being shut down in the spring of 2000, it has been superseded by systems such as the American GPS and the planned European GALILEO positioning system.

It was deployed in the United Kingdom after World War II and later used in many areas around the world. Decca employees used to joke that DECCA was an acronym for *Dedicated Englishmen Causing Chaos Abroad*.

## *Principles of Operation*

### Overview




*The Decca Navigator principle.*
The phase difference between the signals received from stations A (Master) and B (Slave) is constant along each hyperbolic curve. The foci of the hyperbola are at the transmitting stations, A and B.

The Decca Navigator System consisted of a number of land-based stations organised into *chains*. Each chain consisted of a Master station and three (occasionally two) Slave stations, termed Red, Green and Purple. Ideally, the Slaves would be positioned at the vertices of an equilateral triangle with the Master at the centre. The baseline length, i.e. the Master-Slave distance, was typically 60~120 nautical miles. Each station transmitted a continuous wave signal that, by comparing the phase difference of the signals from the Master and one of the Slaves, resulted in a set of hyperbolic *lines of position* called a *pattern*. As there were three Slaves there were three patterns, termed Red, Green and Purple. The patterns were drawn on nautical charts as a set of hyperbolic lines in the appropriate colour. Receivers identified which hyperbola they were on and a position could be plotted at the intersection of the hyperbola from different patterns, usually by using the pair with the angle of cut closest to orthogonal as possible.

### Detailed Principles of Operation

When two stations transmit at the same phase-locked frequency, the difference in phase between the two signals is constant along a hyperbolic path. Of course, if two stations transmit on the same frequency, it is practically impossible for the receiver to separate them; so instead of all stations transmitting at the same frequency, each chain was allocated a nominal frequency, 1f, and each station in the chain transmitted at a harmonic of this base frequency, as follows:

| Station | Harmonic | Frequency (kHz) |
|---|---|---|
| Master | 6f | 85.000 |
| Purple Slave | 5f | 70.833 |
| Red Slave | 8f | 113.333 |
| Green Slave | 9f | 127.500 |

The frequencies given are those for Chain 5B, known as the English Chain, but all chains used similar frequencies between 70 kHz and 129 kHz.

Decca receivers multiplied the signals received from the Master and each Slave by different values to arrive at a common frequency (least common multiple, LCM) for each Master/Slave pair, as follows:

| Pattern | Slave Harmonic | Slave Multiplier | Master Harmonic | Master Multiplier | Common Frequency |
|---|---|---|---|---|---|
| Purple | 5f | ×6 | 6f | ×5 | 30f |
| Red | 8f | ×3 | 6f | ×4 | 24f |
| Green | 9f | ×2 | 6f | ×3 | 18f |

It was phase comparison at this common frequency that resulted in the hyperbolic lines of position. The interval between two adjacent hyperbolas on which the signals are in phase was called a *lane*. Since the wavelength of the common frequency was small compared with the distance between the Master and Slave stations there were many possible lines of position for a given phase difference, and so a unique position could not be arrived at by this method.

Other receivers, typically for aeronautical applications, divided the transmitted frequencies down to the basic frequency (1f) for phase comparison, rather than multiplying them up to the LCM frequency.

## Lanes and Zones

Early Decca receivers were fitted with three rotating *Decometers* that indicated the phase difference for each pattern. Each Decometer drove a second indicator that counted the number of lanes traversed – each 360 degrees of phase difference was one lane traversed. In this way, assuming the point of departure was known, a more or less distinct location could be identified.

The lanes were grouped into *zones*, with 18 green, 24 red, or 30 purple lanes in each zone. This meant that on the baseline (the straight line between the Master and its Slave) the zone width was the same for all three patterns of a given chain. Typical lane and zone widths on the baseline are shown in the table below (for chain 5B):

| Lane or Zone | Width on Baseline |
|---|---|
| Purple lane | 352.1 m |
| Red lane | 440.1 m |
| Green lane | 586.8 m |
| Zones (all patterns) | 10563 m |

The lanes were numbered 0 to 23 for red, 30 to 47 for green and 50 to 79 for purple. The zones were labelled A to J, repeating after J. A Decca position coordinate could thus be written: Red I 16.30; Green D 35.80. Later receivers incorporated a microprocessor and displayed a position in latitude and longitude.

## Multipulse

*Multipulse* provided an automatic method of lane and zone identification by using the same phase comparison techniques described above on lower frequency signals.

The nominally continuous wave transmissions were in fact divided into a 20 second cycle, with each station in turn simultaneously transmitting all four Decca frequencies (5f, 6f, 8f and 9f) in a phase-coherent relationship for a brief period of 0.45 seconds each cycle. This transmission, known as Multipulse, allowed the receiver to extract the 1f frequency and so to identify which lane the receiver was in (to a resolution of a zone).

As well as transmitting the Decca frequencies of 5f, 6f, 8f and 9f, an 8.2f signal, known as Orange, was also transmitted. The beat frequency between the 8.0f (Red) and 8.2f (Orange) signals allowed a 0.2f signal to be derived and so resulted in a hyperbolic pattern in which one cycle (360°) of phase difference equates to 5 zones.

Assuming that one's position was known to this accuracy, this gave an effectively unique position.

## Range and Accuracy

During daylight ranges of around 400 nautical miles (740 km) could be obtained, reducing at night to 200 to 250 nautical miles (460 km), depending on propagation conditions.

The accuracy depended on:

- Width of the lanes
- Angle of cut of the hyperbolic lines of position
- Instrumental errors
- Propagation errors (e.g. Skywave)

By day these errors could range from a few meters on the baseline up to a nautical mile at the edge of coverage. At night, skywave errors were greater and on receivers without multipulse capabilities it was not unusual for the position to jump a lane, sometimes without the navigator knowing.

Although in the days of differential GPS this range and accuracy may appear poor, in its day the Decca system was one of the few, if not the only, position fixing system available to many mariners. Since the need for an accurate position is less when the vessel is further from land, the reduced accuracy at long ranges was not a great problem.

## *History*

### Origins

In 1936 William J. O'Brien, an American engineer, contracted tuberculosis which put his career on hold for a period of two years. During this period he had the idea of position fixing by means of phase comparison of continuous wave transmissions. The initial market envisaged was for aircraft and some experiments were carried out in California in 1938. However both the American Army and Navy considered the idea too complicated.

O'Brien had a friend, Harvey F. Schwarz, who was chief engineer of the Decca Record company in England, and in 1939 sent him details of the system so it could be put forward to the British military. Initially Robert Watson-Watt reviewed the system but he did not follow it up. However, in October 1941 the British Admiralty Signal Establishment (ASE) became interested in the system, which was then classified as *Admiralty Outfit QM*. O'Brien came over to the UK and conducted the first marine trials between Anglesey and the Isle of Man, at frequencies of 305/610 kHz, on 16 September 1942. These were successful and further trials were conducted in the northern Irish Sea in April 1943 at 70/130 kHz. A three-station trial was held in conjunction with a large-scale assault and landing exercise in the Moray Firth in February/March 1944.

The success of the trials and the relative ease of use and accuracy of the system resulted in Decca receiving an order for 27 *Admiralty Outfit QM* receivers. The receiver consisted of an electronics unit with two dials and was known to its operators as the "Blue Gasmeter Job". A Decca chain was set up, consisting of a master station at Chichester and slaves at Swanage and Beachy Head. A fourth, decoy, transmitter was located in the Thames Estuary as part of the deception that the invasion would be focussed on the Calais area.

Twenty-one minesweepers and other vessels were fitted with A*dmiralty Outfit QM* and on 5 June 1944 they used it to accurately navigate across the English Channel and to sweep the minefields in the planned areas. The swept areas were marked with buoys in preparation for the Normandy Landings.

After the initial ship tests, Decca conducted tests in cars, driving in the Kingston By-Pass area to verify receiver accuracy. In the car installation, it was found possible to navigate within an individual traffic lane. The company entertained high hopes that the system could be used in aircraft, to permit much more precise navigation in the critical airspace around airports and urban centers where traffic density was highest.

## Deployment

After the end of World War II the Decca Navigator Co. Ltd. was formed (1945) and the system expanded rapidly, particularly in areas of British influence; at its peak it was deployed in many of the world's major shipping areas. More than 15,000 receiving sets were in use aboard ships in 1970. There were 4 chains around England, 1 in Ireland and 2 in Scotland, 12 in Scandinavia (5 each in Norway and Sweden and 1 each in Denmark and Finland), a further 4 elsewhere in northern Europe and 2 in Spain. In the late 1950s an experimental Decca chain was set up in the United States, in the New York area, to be used for navigating the Vertol 107 helicopters of New York Airways. These helicopters were operating from the principal local airports—John F. Kennedy Airport on Long Island, Newark Airport in New Jersey, LaGuardia Airport in the Borough of Queens, nearer to Manhattan, and a site on the top of the (then) PanAm Building on Park Avenue. Use of Decca was essential because its signals could be received down to sea level, were not subject to the line-of-sight limitations of VOR/DME and did not suffer the slant-range errors that create problems with VOR/DME close to the transmitters. The Decca installations in the New York Airways helicopters included the unique Decca 'roller map' displays that enabled the pilot to see his or her position at a glance, a concept infeasible with VOR/DME. This chain installation was considered highly controversial at the time, for political reasons. This led to the U.S. Coast Guard, under instructions from the Treasury Department to which it reported, banning the use of Decca receivers in ships entering New York harbor for fear that the system might create a de facto standard (as it had become in other areas of the world). It also served to protect the marketing interests of the Hoffman Electronics division of ITT, a principal supplier of VOR/DME systems, that Decca might have been poised to usurp.

This situation was exacerbated by the workload problems of the Air Traffic Controllers Association (ATCA), under its executive director Francis McDermott, whose members were forced to use radar data on aircraft positions, relaying those positions by radio to the aircraft from their control locations. An example of the problem, cited by experts, was the collision of a Boeing 707 and a Lockheed Constellation over Staten Island, New York, that—according to some experts—could have been avoided if the aircraft had been Decca equipped and could not only have determined their positions more precisely but would not have suffered from the rho-theta position errors inherent in VOR/DME.

Other chains were established in Japan (6 chains); Namibia and South Africa (5 chains); India and Bangladesh (4 chains); Canada (4 chains around Newfoundland and Nova Scotia); North-West Australia (2 chains); the Persian Gulf (1 chain with stations in Qatar and the United Arab Emirates and a second chain in the north of the Gulf with stations in Iran) and the Bahamas (1 chain). Four chains were planned for Nigeria but only 2 chains were built and these did not enter into public service. Two chains in Vietnam were used during the Vietnam War for helicopter navigation, with limited success. During the Cold

War period, following WWII, the R.A.F. established a confidential chain in Germany. The Master station was in Bad Iburg near Osnabrück and there were two Slaves. The purpose of this chain was to provide accurate air navigation for the corridor between Western Germany and Berlin in the event that a mass evacuation of allied personnel may be required. In order to maintain secrecy, frequencies were changed at irregular intervals.


Decca Navigator Mk 21

## Decca, Racal, and the closedown

Decca Navigator was headquartered at New Malden, Surrey, just off the Kingston by-pass. There was a Decca School, at Brixham, Devon, where employees were sent on courses from time to time.

Racal, the UK weapons and communications company, acquired Decca in 1980. Claiming the acquisition was to acquire Decca's radar company, rather than the avionics side of the business, it sold off parts including Decca Navigator.

The monopoly on leased, not purchased, receivers by Decca generated great wealth for the company. This monopoly was later broken in the early 1980s when receivers could be purchased by users, thereby reducing the cost following the lapse of the patent on the basic system technology.


Decca receiver from the 1980s by Philips, which could be purchased instead of leased

A Danish company started manufacturing receivers for fishing boats which employed Decca's navigation charts, but users didn't pay rental for using the system.

In the ensuing court battle Decca lost the monopoly, and that signalled the beginning of the end. Income dwindled and eventually, the UK Ministry of Transport stepped in, having the lighthouse authorities take responsibility for operating the system in the early 1990s.

A ruling from the European Union forced the UK government to withdraw funding - for fishermen users - and started the process which eventually resulted in the system being closed down and the installations scrapped.

The Decca Navigator System provided by the General Lighthouse Authorities ceased to operate at midnight on 31 March 2000. The Irish chain provided by Bórd Iascaigh Mhara continued transmitting until 19 May 2000.

Japan holds the distinction of being the last bastion of Decca having closed down the Hokkaidō chain (9C) in March 2001. This was one year later than the UK closure. Hokkaidō was also the first Decca chain to open in Japan in the year 1967.

## *Other Applications*

A more accurate system named Hi-Fix was developed using signalling in the 1.6 MHz range. It was used for specialised applications such as precision measurements involved with oil-drilling and by the Royal Navy for detailed mapping and surveying of coasts and harbours. The Hi-Fix equipment was leased for a period with temporary chains established to provide coverage of the area required, Hi-Fix was commercialised by Racal Survey in the early 1980s. An experimental chain was installed with coverage of central London and receivers placed in London buses and other vehicles to demonstrate an early vehicle location and tracking system. Each vehicle would report its location automatically via a conventional VHF two-way radio link, the data added to a voice channel. A forerunner to a system employed by London black cabs in the 1990s using GPS and now the widespread use of GSM, 3G and Wi-Fi geolocation applications.

An interesting characteristic of the Decca VLF signal discovered on BOAC, later British Airways, test flights to Moscow, was that the carrier switching could not be detected even though the carrier could be received with sufficient strength to provide navigation. Such testing, involving civilian aircraft, is quite common and may well not be in the knowledge of a pilot.

The 'low frequency' signalling of the Decca system also permitted its use on submarines. One 'enhancement' of the Decca system was to offer the potential of keying the signal, using Morse code, to signal the onset of nuclear war. This was never optioned by the UK government. Messages were clandestinely sent, however, between Decca stations thereby bypassing international telephone calls, especially in non-UK chains.

A long range trans North Atlantic system was in operation from the mid nineteen fifties. It was called DECTRA. It utilised two stations in Newfoundland and two in Scotland. The transmissions used normal "pattern" transmitters of a much higher power than on standard DECCA frequencies. It was intended as an air navigational aid.

## *Special DECCA towers*

- Puckeridge DECCA tower
- Zeven DECCA-transmitter

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# Chapter 6

# Dynamic Positioning

Offshore Support Vessel *Toisa Perseus* with, in the background, the fifth-generation deepwater drillship *Discoverer Enterprise*, over the Thunder Horse Oil Field. Both are equipped with DP systems.

**Dynamic positioning (DP)** is a computer controlled system to automatically maintain a vessel's position and heading by using its own propellers and thrusters. Position reference sensors, combined with wind sensors, motion sensors and gyro compasses, provide information to the computer pertaining to the vessel's position and the magnitude and direction of environmental forces affecting its position. Examples of vessel types that employ DP include, but are not limited to, ships and semi-submersible Mobile Offshore Drilling Units (MODU) and Oceanographic Research Vessels.

The computer program contains a mathematical model of the vessel that includes information pertaining to the wind and current drag of the vessel and the location of the thrusters. This knowledge, combined with the sensor information, allows the computer to calculate the required steering angle and thruster output for each thruster. This allows operations at sea where mooring or anchoring is not feasible due to deep water, congestion on the sea bottom (pipelines, templates) or other problems.

Dynamic positioning may either be absolute in that the position is locked to a fixed point over the bottom, or relative to a moving object like another ship or an underwater vehicle. One may also position the ship at a favourable angle towards wind, waves and current, called weathervaning.

Dynamic positioning is utilized by much of the offshore oil industry, for example in the North Sea, Persian Gulf, Gulf of Mexico, West Africa, and off the coast of Brazil. There are currently more than 1000 DP ships.

## *History*

Dynamic positioning started in the 1960s for offshore drilling. With drilling moving into ever deeper waters, Jack-up barges could not be used any more and anchoring became less economical.

In 1961 the drillship *Cuss 1* was fitted with four steerable propellers, in an attempt to drill the first Moho well. It was possible to keep the ship in position above the well off La Jolla, California, at a depth of 948 meters.

After this, off the coast of Guadalupe, Mexico, five holes were drilled, the deepest at 183 m (601 ft) below the sea floor in 3,500 m (11,700 ft) of water, while maintaining a position within a radius of 180 meters. The ship's position was determined by radar ranging to buoys and sonar ranging from subsea beacons.

Whereas the *Cuss 1* was kept in position manually, later in the same year Shell launched the drilling ship *Eureka* that had an analogue control system interfaced with a taut wire, making it the first true DP ship.

While the first DP ships had analogue controllers and lacked redundancy, since then vast improvements have been made. Besides that, DP nowadays is not only used in the oil industry, but also on various other types of ships. In addition, DP is not limited to maintaining a fixed position any more. One of the possibilities is sailing an exact track, useful for cablelay, pipelay, survey and other tasks.

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## *Comparison between position-keeping options*

Other methods of position-keeping are the use of an anchor spread and the use of a jack-up barge. All have their own advantages and disadvantages.

**Comparison position-keeping options**

| Jack-up Barge | Anchoring | Dynamic Positioning |
|---|---|---|
| **Advantages:**<br>• No complex systems with thrusters, extra generators and controllers.<br>• No chance of running off position by system failures or blackouts.<br>• No underwater hazards from thrusters. | **Advantages:**<br>• No complex systems with thrusters, extra generators and controllers.<br>• No chance of running off position by system failures or blackouts.<br>• No underwater hazards from thrusters. | **Advantages:**<br>• Manoeuvring is excellent; it is easy to change position.<br>• No anchor handling tugs are required.<br>• Not dependent on waterdepth.<br>• Quick set-up.<br>• Not limited by obstructed seabed. |
| **Disadvantages:**<br>• No manoeuvrability once positioned.<br>• Limited to water depths of ~150 meters. | **Disadvantages:**<br>• Limited manoeuvrability once anchored.<br>• Anchor handling tugs are required.<br>• Less suitable in deep water.<br>• Time to anchor out varies between several hours to several days.<br>• Limited by obstructed seabed (pipelines, seabed). | **Disadvantages:**<br>• Complex systems with thrusters, extra generators and controllers.<br>• High initial costs of installation.<br>• High fuel costs.<br>• Chance of running off position by system failures or blackouts.<br>• Underwater hazards from thrusters for divers and ROVs.<br>• Higher maintenance of the mechanical systems. |

Although all methods have their own advantages, dynamic positioning has made many operations possible that were not feasible before.

The costs are falling due to newer and cheaper technologies and the advantages are becoming more compelling as offshore work enters ever deeper water and the environment (coral) is given more respect. With container operations, crowded ports can be made more efficient by quicker and more accurate berthing techniques. Cruise ship operations benefit from faster berthing and non-anchored "moorings" off beaches or inaccessible ports.

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## *Applications*

SBX underway

Important applications include:

- Servicing Aids to Navigation (ATON)
- Cable-laying
- Crane vessels
- Cruise ships
- Diving support vessels
- Dredging
- Drillships

- FPSOs
- Flotels
- Landing Platform Docks
- Maritime research
- Mine sweepers
- Pipe-laying ship
- Platform supply vessels
- Rockdumping
- Sea Launch
- Sea-based X-band Radar
- Shuttle tankers
- Survey ships

## *Scope*

A ship can be considered to have six degrees of freedom in its motion, i.e., it can move in any of six axes.

Three of these involve translation:

- surge (forward/astern)
- sway (starboard/port)
- heave (up/down)

and the other three rotation:

- roll (rotation about surge axis)
- pitch (rotation about sway axis)
- yaw (rotation about heave axis)

Dynamic positioning is concerned primarily with control of the ship in the horizontal plane, i.e., the three axis surge, sway and yaw.

## *Requirements*

A ship that is to be used for DP requires:

- to maintain position and heading, first of all the position and heading need to be known.
- a control computer to calculate the required control actions to maintain position and correct for position errors.
- thrust elements to apply forces to the ship as demanded by the control system.

For most applications, the position reference systems and thrust elements must be carefully considered when designing a DP ship. In particular, for good control of position in adverse weather, the thrust capability of the ship in three axes must be adequate.

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## *Reference systems*

## Position reference systems

There are several means to determine a ship's position at sea. Most traditional methods used for ships navigation are not accurate enough. For that reason, several positioning systems have been developed during the past decades. Producers of DP systems are: Kongsberg, Navis Engineering Oy, Converteam, EMI, Deep Down Marine Technologies, L3, MT-div.Chouest, Rolls Royce, Nautronix, and others. The applications and availability depends on the type of work and water depth. The most common Position reference/Measuring systems /Equipment (PRS/PME) are:

GPS satellite in orbit

- **DGPS, Differential GPS**. The position obtained by GPS is not accurate enough for use by DP. The position is improved by use of a fixed ground based reference station (differential station) that compares the GPS position to the known position of the station. The correction is sent to the DGPS receiver by long wave radio frequency. For use in DP an even higher accuracy and reliability is needed. Companies such as Fugro or C&C Technologies supply differential signals via satellite, enabling the combination of several differential stations. The advantage of DGPS is that it is almost always available. Disadvantages are degrading of the signal because of sunspots or atmospheric disturbances, blockage of satellites by cranes or structures and deterioration of the signal at high altitudes. There are also systems installed on vessels that use various different Augmentation systems, as well as combining GPS position with GLONASS.

- **Acoustics**. This system consists of one or more transponders placed on the seabed and a transducer placed in the ship's hull. The transducer sends an acoustic signal (by means of piezoelectric elements) to the transponder, which is triggered to reply. As the velocity of sound through water is known (preferably a soundprofile is taken regularly), the distance is known. Because there are many elements on the transducer, the direction of the signal from the transponder can be determined. Now the position of the ship relative to the transponder can be calculated. Disadvantages are the vulnerability to noise by thrusters or other acoustic systems. Furthermore, the use is limited in shallow waters because of ray bending that occurs when sound travels through water horizontally. Three types of HPR systems are commonly used:

  - **Ultra- or Super- Short Base Line, USBL or SSBL**. This works as described above. Because the angle to the transponder is measured, a correction needs to be made for the ship's roll and pitch. These are determined by Motion Reference Units. Because of the nature of angle measurement, the accuracy deteriorates with increasing water depth.

  - **Long Base Line, LBL**. This consists of an array of at least three transponders. The initial position of the transponders is determined by USBL and/ or by measuring the baselines between the transponders. Once that is done, only the ranges to the transponders need to be measured to determine a relative position. The position should theoretically be located at the intersection of imaginary spheres, one around each transponder, with a radius equal to the time between transmission and reception multiplied by the speed of sound through water. Because angle measurement is not necessary, the accuracy in large water depths is better than USBL.

  - **Short Baseline, SBL**. This works with an array of transducers in the ship's hull. These determine their position to a transponder, so a solution is found in the same way as with LBL. As the array is located on the ship, it needs to be corrected for roll and pitch.

- **Riser Angle Monitoring**. On drillships, riser angle monitoring can be fed into the DP system. It may be an electrical inclinometer or based on USBL, where a riser angle monitoring transponder is fitted to the riser and a remote inclinometer unit is installed on the Blow Out Preventer (BOP) and interrogated through the ship’s HPR.

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Light Taut Wire on the *HOS Achiever*

- **Light Taut Wire, LTW**. The oldest position reference system used for DP is still very accurate in relatively shallow water. A clumpweight is lowered to the seabed. By measuring the amount of wire paid out and the angle of the wire by a gimbal head, the relative position can be calculated. Care should be taken not to let the wire angle become too large to avoid dragging. For deeper water the system is less favourable, as current will curve the wire. There are however systems that counteract this with a gimbal head on the clumpweight. Horizontal LTW's are also used when operating close to a structure. Objects falling on the wire are a risk here.

- **Fanbeam** and **CyScan**. These are laser based position reference systems. They are very straightforward system, as only a small prism needs to be installed on a nearby structure or ship. Risks are the system locking on other reflecting objects and blocking of the signal. Range depends on the weather, but is typically more than 500 meters.

- **Artemis**. A radar based system. A unit is placed on a nearby structure and aimed at the unit on board the ship. The range is several kilometres. Advantage is the reliable, all-weather performance. Disadvantage is that the unit is rather heavy.
- **DARPS, Differential, Absolute and Relative Positioning System**. Commonly used on shuttle tankers while loading from a FPSO. Both will have a GPS receiver. As the errors are the same for the both of them, the signal does not need to be corrected. The position from the FPSO is transmitted to the shuttle tanker, so a range and bearing can be calculated and fed into the DP system.

- **RADius** and **RadaScan**. These are radar based system, but have no moving parts as Artemis. Another advantage is that the transponders are much smaller than the Artemis unit. The range is typically 500 – 1000 meters.

- **Inertial navigation** is used in combination with GPS (Seapath) and Hydroacoustics (HAIN).

## Heading reference systems

- **Gyrocompasses** are normally used to determine heading.

More advanced methods are:

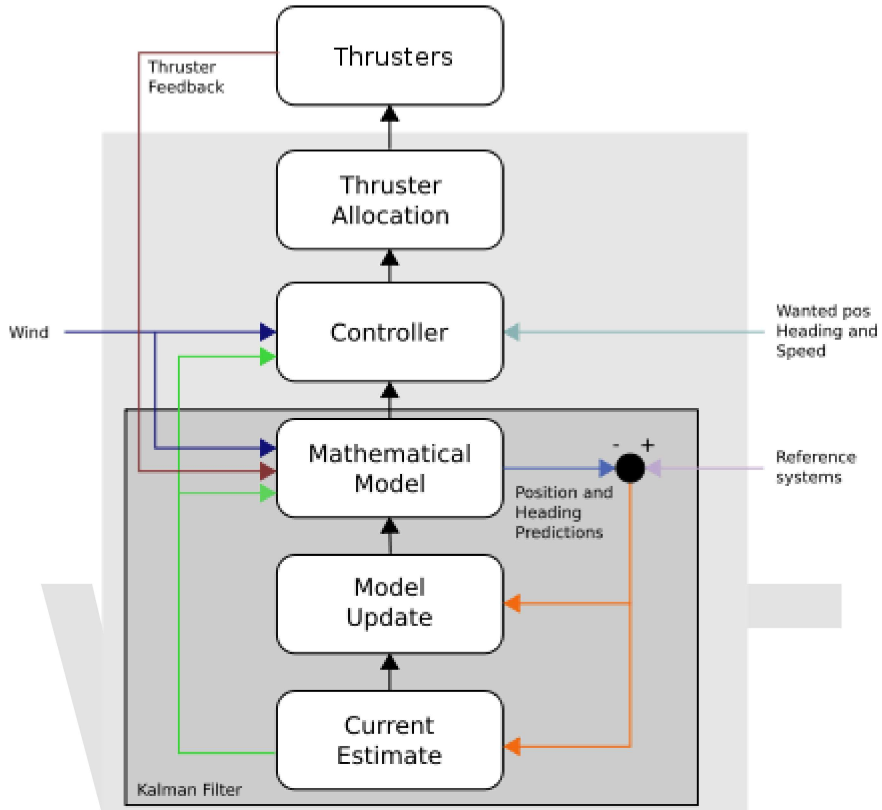
- **Ring-Laser gyroscopes**
- **Fibre optic gyroscopes**
- **Seapath**, a combination of GPS and inertial sensors.

## Reference systems

Besides position and heading, other variables are fed into the DP system through sensors:

- **Motion Reference Units, Vertical Reference Units or Vertical Reference Sensors, VRU's or MRU's or VRS's**, determine the ship's roll, pitch and heave.
- **Wind sensors** are fed into the DP system feed-forward, so the system can anticipate wind gusts before the ship is blown off position.
- **Draught sensors**, since a change of draught influences the effect of wind and current on the hull.
- Other sensors depend on the kind of ship. A pipelay ship may measure the force needed to pull on the pipe, large crane vessels will have sensors to determine the cranes position, as this changes the wind model, enabling the calculation of a more accurate model.

### *Control systems*




Block diagram of control system

In the beginning PID controllers were used and today are still used in the simpler DP systems. But modern controllers use a mathematical model of the ship that is based on a hydrodynamic and aerodynamic description concerning some of the ship's characteristics such as mass and drag. Of course, this model is not entirely correct. The ship's position and heading are fed into the system and compared with the prediction made by the model. This difference is used to update the model by using Kalman filtering technique. For this reason, the model also has input from the windsensors and feedback from the thrusters. This method even allows not having input from any PRS for some time, depending on the quality of the model and the weather.

The accuracy and precision of the different PRS's is not the same. While a DGPS has a high accuracy and precision, a USBL can have a much lower precision. For this reason, the PRS's are weighted. Based on variance a PRS receives a weight between 0 and 1.

### *Power and propulsion systems*

To maintain position azimuth thrusters (L-drive or Z-drive), azipods, bow thrusters, stern thrusters, water jets, rudders and propellers are used. DP ships are usually at least partially diesel-electric, as this allows a more flexible set-up and is better able to handle the large changes in power demand, typical for DP operations.

The set-up depends on the DP class of the ship. A Class 1 can be relatively simple, whereas the system of a Class 3 ship is quite complex.

On Class 2 and 3 ships, all computers and reference systems should be powered through a UPS.

### *Class Requirements*

Based on IMO (International Maritime Organization) publication 645 the Classification Societies have issued rules for Dynamic Positioned Ships described as Class 1, Class 2 and Class 3.

- Equipment Class 1 has no redundancy.
  Loss of position may occur in the event of a single fault.

- Equipment Class 2 has redundancy so that no single fault in an active system will cause the system to fail.
  Loss of position should not occur from a single fault of an active component or system such as generators, thruster, switchboards, remote controlled valves etc., but may occur after failure of a static component such as cables, pipes, manual valves etc.

- Equipment Class 3 which also has to withstand fire or flood in any one compartment without the system failing.
  Loss of position should not occur from any single failure including a completely burnt fire sub division or flooded watertight compartment.

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Classification Societies have their own Class notations:

| Description | IMO Equipment Class | LR Equipment Class | DnV Equipment Class | GL Equipment Class | ABS Equipment Class |
|---|---|---|---|---|---|
| Manual position control and automatic heading control under specified maximum environmental conditions | - | DP(CM) | DYNPOS-AUTS | - | - |
| Automatic and manual position and heading control under specified maximum environmental conditions | Class 1 | DP(AM) | DYNPOS-AUT | DP 1 | DPS-0, DPS-1 |
| Automatic and manual position and heading control under specified maximum environmental conditions, during and following any single fault excluding loss of a compartment. (Two independent computer systems). | Class 2 | DP(AA) | DYNPOS-AUTR | DP 2 | DPS-2 |
| Automatic and manual position and heading control under specified maximum environmental conditions, during and following any single fault including loss of a compartment due to fire or flood. (At least two independent computer systems with a separate backup system separated by A60 class division). | Class 3 | DP(AAA) | DYNPOS-AUTRO | DP 3 | DPS-3 |

## *NMD*

Where IMO leaves the decision of which Class applies to what kind of operation to the operator of the DP ship and its client, the Norwegian Maritime Directorate (NMD) has specified what Class should be used in regard to the risk of an operation. In the NMD Guidelines and Notes No. 28, enclosure A four classes are defined:

- Class 0 Operations where loss of position keeping capability is not considered to endanger human lives, or cause damage.
- Class 1 Operations where loss of position keeping capability may cause damage or pollution of small consequence.
- Class 2 Operations where loss of position keeping capability may cause personnel injury, pollution, or damage with large economic consequences.
- Class 3 Operations where loss of position keeping capability may cause fatal accidents, or severe pollution or damage with major economic consequences.

Based on this the type of ship is specified for each operation:

- Class 1 DP units with equipment class 1 should be used during operations where loss of position is not considered to endanger human lives, cause significant damage or cause more than minimal pollution.

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- Class 2 DP units with equipment class 2 should be used during operations where loss of position could cause personnel injury, pollution or damage with great economic consequences.
- Class 3 DP units with equipment class 3 should be used during operations where loss of position could cause fatal accidents, severe pollution or damage with major economic consequences.

## *Redundancy*

Redundancy is the ability to cope with a single failure without loss of position. A single failure can be, amongst others:

- Thruster failure
- Generator failure
- Powerbus failure (when generators are combined on one powerbus)
- Control computer failure
- Position reference system failure
- Reference system failure

For certain operations redundancy is not required. For instance, if a survey ship loses its DP capability, there is normally no risk of damage or injuries. These operations will normally be done in Class 1.

For other operations, such as diving and heavy lifting, there is a risk of damage or injuries. Depending on the risk, the operation is done in Class 2 or 3. This means at least three Position reference systems should be selected. This allows the principle of voting logic, so the failing PRS can be found. For this reason, there are also three DP control computers, three gyrocompasses, three MRU's and three wind sensors on Class 3 ships. If a single fault occurs that jeopardizes the redundancy, i.e., failing of a thruster, generator or a PRS, and this cannot be resolved immediately, the operation should be abandoned as quickly as possible.

To have sufficient redundancy, enough generators and thrusters should be on-line so the failure of one does not result in a loss of position. This is left to the judgement of the DP operator. For Class 2 and Class 3 a Consequence Analyses should be incorporated in the system to assist the DPO in this process.

Disadvantage is that a generator can never operate at full load, resulting in less economy and fouling of the engines.

The redundancy of a DP ship should be judged by an failure mode and effects analysis (FMEA) study and proved by FMEA trials. Besides that, annual trials are done and normally DP function tests are completed prior to each project.

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## *DP Operator*

The DP operator (DPO) judges whether there is enough redundancy available at any given moment of the operation. IMO issued MSC/Circ.738 (Guidelines for dynamic positioning system (DP) operator training) on 24-06-1996. This refers to IMCA (International Marine Contractors Association) M 117 as acceptable standard.

To qualify as a DP operator the following path should be followed:

1. a DP Induction course
2. a minimum of 30 days seagoing DP familiarisation
3. a DP Advanced course
4. a minimum of 6 months watchkeeping on a DP ship
5. a statement of suitability by the master of a DP ship

When the watchkeeping is done on a Class 1 DP ship, a limited certificate will be issued; otherwise a full certificate will be issued.

The DP Training and Certification scheme is operated by The Nautical Institute (NI). The NI issue logbooks to trainees, they accredit training centres and control the issuance of certification.

With ever more DP ships and with increasing manpower demands, the position of DPO is gaining increasing prominence. This shifting landscape led to the creation of The International Dynamic Positioning Operators Association (IDPOA) in 2009.

IDPOA membership is made up of certified DPO's who qualify for fellowship (fDPO), while Members (mDPO) are those with DP experience or who may already be working within the DP certification scheme.

## *IMCA*

The International Marine Contractors Association was formed in April 1995 from the amalgamation of AODC (originally the International Association of Offshore Diving Contractors), founded in 1972, and DPVOA (the Dynamic Positioning Vessel Owners Association), founded in 1990. It represents offshore, marine and underwater engineering contractors. Acergy, Allseas, Heerema Marine Contractors, Helix Energy Solutions Group, J. Ray McDermott, Saipem, Subsea 7 and Technip have representation on IMCA's Council and provide the president. Previous presidents are:

- 1995-6 - Derek Leach, Coflexip Stena Offshore
- 1997-8 - Hein Mulder, Heerema Marine Contractors
- 1999/2000 - Donald Carmichael, Coflexip Stena Offshore
- 2001-2 - John Smith, Halliburton Subsea/Subsea 7
- 2003-4 - Steve Preston, - Heerema Marine Contractors
- 2005 - Frits Janmaat, Allseas Group

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(2005 Vice-President - Knut Boe, Technip)

While it started with the collection and analysis of DP Incidents, since then it has produced publications on different subjects to improve standards for DP systems. It also works with IMO and other regulatory bodies.

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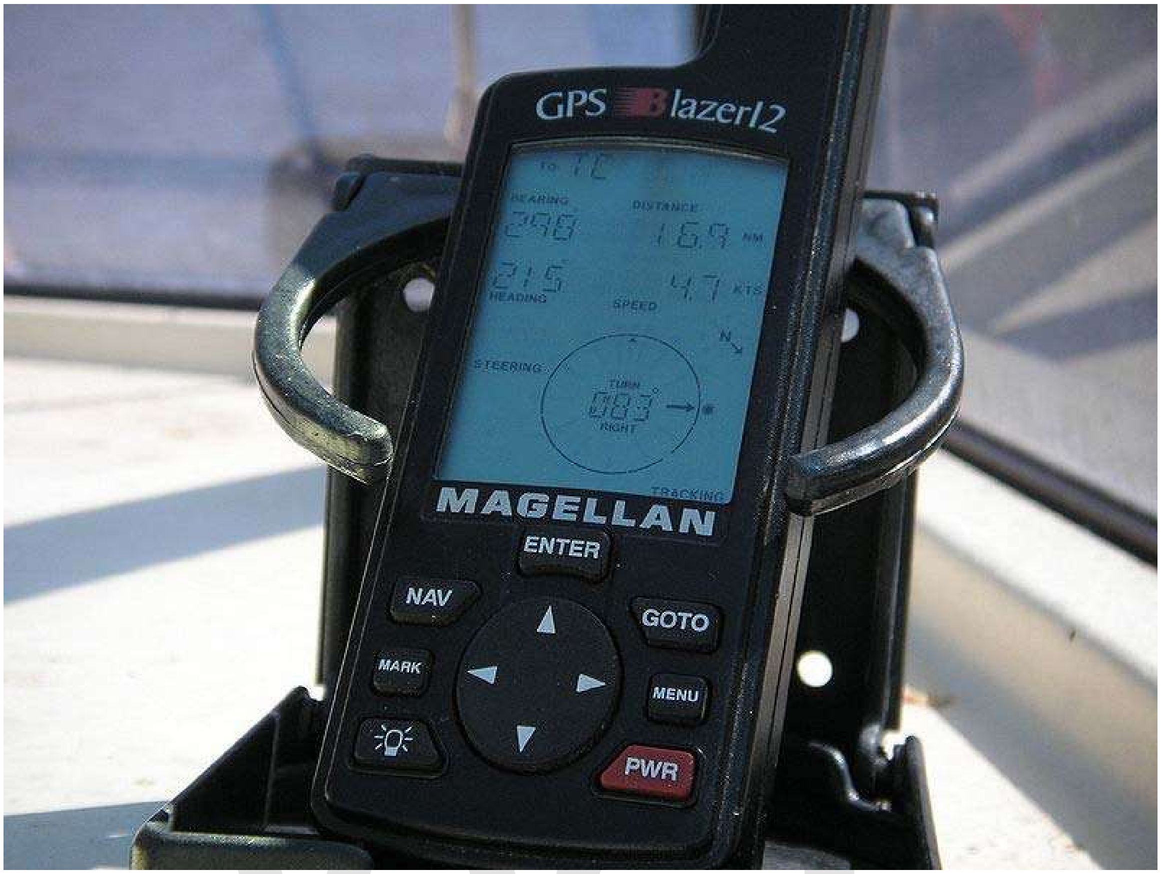
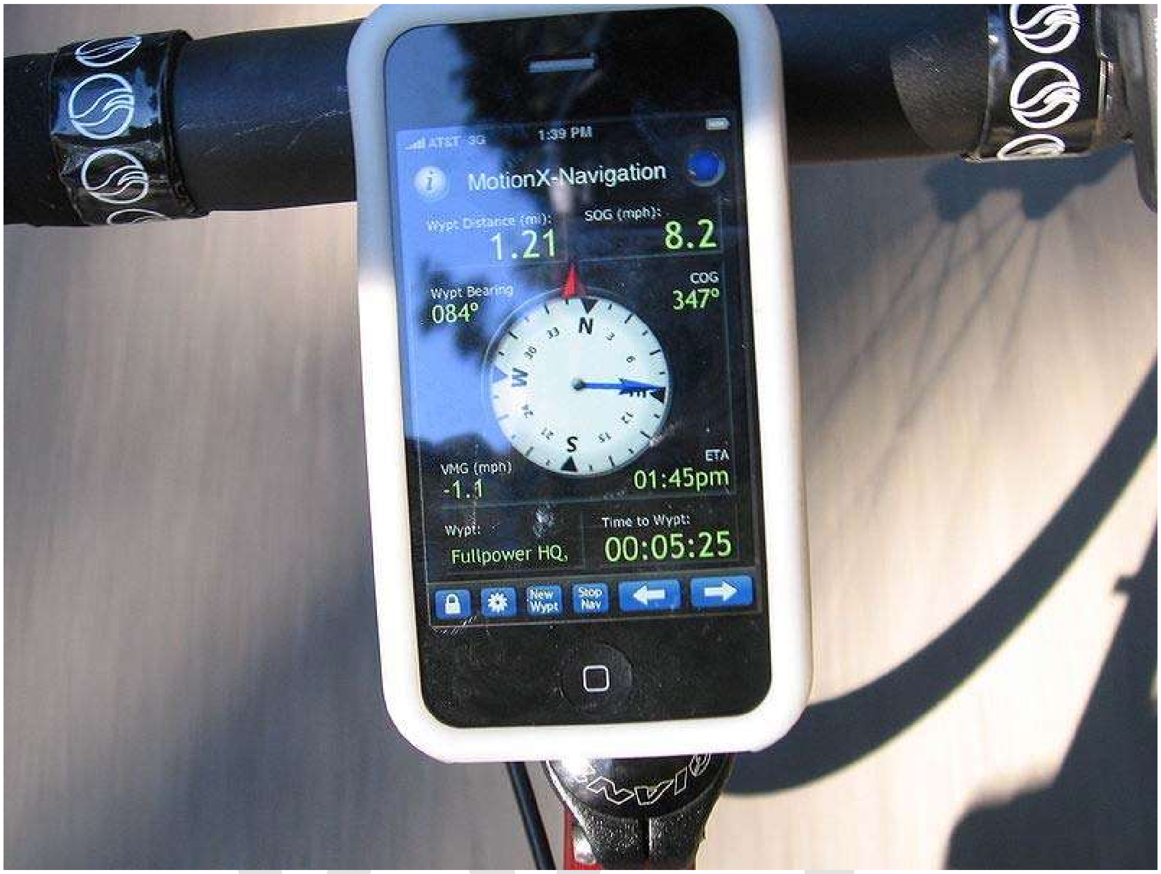
## Chapter 7

# Global Positioning System

Artist's conception of GPS Block II-F satellite in orbit




Civilian GPS receiver ("GPS navigation device") in a marine application




GPS receivers are now integrated in many mobile phones

Automotive navigation system in a taxicab

The **Global Positioning System** (**GPS**) is a space-based global navigation satellite system (GNSS) that provides reliable location and time information in all weather and at all times and anywhere on or near the Earth when and where there is an unobstructed line of sight to four or more GPS satellites. It is maintained by the United States government and is freely accessible by anyone with a GPS receiver.

The GPS project was developed in 1973 to overcome the limitations of previous navigation systems, integrating ideas from several predecessors, including a number of classified engineering design studies from the 1960s. GPS was created and realized by the U.S. Department of Defense (USDOD) and was originally run with 24 satellites. It became fully operational in 1994.

In addition to GPS, other systems are in use or under development. The Russian GLObal NAvigation Satellite System (GLONASS) was in use by the Russian military only until it was made fully available to civilians in 2007. There are also the planned Chinese Compass navigation system and the European Union's Galileo positioning system.

## *History*

The design of GPS is based partly on similar ground-based radio navigation systems, such as LORAN and the Decca Navigator developed in the early 1940s, and used during World War II. In 1956 Friedwardt Winterberg proposed a test of general relativity using accurate atomic clocks placed in orbit in artificial satellites. To achieve accuracy requirements, GPS uses principles of general relativity to correct the satellites' atomic clocks. Additional inspiration for GPS came when the Soviet Union launched the first man-made satellite, Sputnik in 1957. A team of U.S. scientists led by Dr. Richard B. Kershner were monitoring Sputnik's radio transmissions. They discovered that, because of the Doppler effect, the frequency of the signal being transmitted by Sputnik was higher as the satellite approached, and lower as it continued away from them. They realized that because they knew their exact location on the globe, they could pinpoint where the satellite was along its orbit by measuring the Doppler distortion.

The first satellite navigation system, Transit, used by the United States Navy, was first successfully tested in 1960. It used a constellation of five satellites and could provide a navigational fix approximately once per hour. In 1967, the U.S. Navy developed the Timation satellite that proved the ability to place accurate clocks in space, a technology required by GPS. In the 1970s, the ground-based Omega Navigation System, based on phase comparison of signal transmission from pairs of stations, became the first worldwide radio navigation system. Limitations of these systems drove the need for a more universal navigation solution with greater accuracy.

While there were wide needs for accurate navigation in military and civilian sectors, almost none of those were seen as justification for the billions of dollars it would cost in research, development, deployment, and operation for a constellation of navigation satellites. During the Cold War arms race, the nuclear threat to the existence of the United States was the one need that did justify this cost in the view of the United States Congress. This deterrent effect is why GPS was funded. The nuclear triad consisted of the United States Navy's submarine-launched ballistic missiles (SLBMs) along with United States Air Force (USAF) strategic bombers and intercontinental ballistic missiles (ICBMs). Considered vital to the nuclear deterrence posture, accurate determination of the SLBM launch position was a force multiplier.

Precise navigation would enable United States submarines to get an accurate fix of their positions prior to launching their SLBMs. The USAF with two-thirds of the nuclear triad also had requirements for a more accurate and reliable navigation system. The Navy and Air Force were developing their own technologies in parallel to solve what was essentially the same problem. To increase the survivability of ICBMs, there was a proposal to use mobile launch platforms so the need to fix the launch position had similarity to the SLBM situation.

In 1960, the Air Force proposed a radio-navigation system called MOSAIC (Mobile System for Accurate ICBM Control) that was essentially a 3-D LORAN. A follow-on study called Project 57 was worked in 1963 and it was "in this study that the GPS concept was born." That same year the concept was pursued as Project 621B, which had "many of the attributes that you now see in GPS" and promised increased accuracy for Air Force bombers as well as ICBMs. Updates from the Navy Transit system were too slow for the high speeds of Air Force operation. The Navy Research Laboratory continued advancements with their Timation (Time Navigation) satellites, first launched in 1967, and with the third one in 1974 carrying the first atomic clock into orbit.

With these parallel developments in the 1960s, it was realized that a superior system could be developed by synthesizing the best technologies from 621B, Transit, Timation, and SECOR in a multi-service program.

During Labor Day weekend in 1973, a meeting of about 12 military officers at the Pentagon discussed the creation of a *Defense Navigation Satellite System (DNSS)*. It was at this meeting that "the real synthesis that became GPS was created." Later that year, the DNSS program was named *Navstar*. With the individual satellites being associated with the name Navstar (as with the predecessors Transit and Timation), a more fully encompassing name was used to identify the constellation of Navstar satellites, *Navstar-GPS*, which was later shortened simply to GPS.

After Korean Air Lines Flight 007, carrying 269 people, was shot down in 1983 after straying into the USSR's prohibited airspace, in the vicinity of Sakhalin and Moneron Islands, President Ronald Reagan issued a directive making GPS freely available for civilian use, once it was sufficiently developed, as a common good. The first satellite was launched in 1989, and the 24th satellite was launched in 1994.

Initially, the highest quality signal was reserved for military use, and the signal available for civilian use was intentionally degraded ("Selective Availability", SA). This changed with United States President Bill Clinton ordering Selective Availability turned off at midnight May 1, 2000, improving the precision of civilian GPS from 100 meters (about 300 feet) to 20 meters (about 65 feet). The United States military by then had the ability to deny GPS service to potential adversaries on a regional basis.

GPS is owned and operated by the United States Government as a national resource. Department of Defense (USDOD) is the steward of GPS. *Interagency GPS Executive Board (IGEB)* oversaw GPS policy matters from 1996 to 2004. After that the *National Space-Based Positioning, Navigation and Timing Executive Committee* was established by presidential directive in 2004 to advise and coordinate federal departments and agencies on matters concerning the GPS and related systems. The executive committee is chaired jointly by the deputy secretaries of defense and transportation. Its membership includes equivalent-level officials from the departments of state, commerce, and homeland security, the joint chiefs of staff, and NASA. Components of the executive office of the president participate as observers to the executive committee, and the FCC chairman participates as a liaison.

USDOD is required by law to "maintain a Standard Positioning Service (as defined in the federal radio navigation plan and the standard positioning service signal specification) that will be available on a continuous, worldwide basis," and "develop measures to prevent hostile use of GPS and its augmentations without unduly disrupting or degrading civilian uses."

## Timeline and modernization

Summary of satellites

| Block | Launch Period | Satellite launches | | | | Currently in orbit and healthy |
|---|---|---|---|---|---|---|
| | | Suc-cess | Fail-ure | In prep-aration | Plan-ned | |
| **I** | 1978–1985 | 10 | 1 | 0 | 0 | 0 |
| **II** | 1989–1990 | 9 | 0 | 0 | 0 | 0 |
| **IIA** | 1990–1997 | 19 | 0 | 0 | 0 | 10 |
| **IIR** | 1997–2004 | 12 | 1 | 0 | 0 | 12 |
| **IIR-M** | 2005–2009 | 8 | 0 | 0 | 0 | 7 |
| **IIF** | 2010–2011 | 1 | 0 | 11 | 0 | 1 |
| **IIIA** | 2014–? | 0 | 0 | 0 | 12 | 0 |
| **IIIB** | Theoretical | 0 | 0 | 0 | 8 | 0 |
| **IIIC** | Theoretical | 0 | 0 | 0 | 16 | 0 |
| **Total** | | 59 | 2 | 11 | 36 | 30 |

(Last update: 24 May 2010)

PRN 01 from Block IIR-M is unhealthy
PRN 25 from Block IIA is unhealthy
PRN 32 from Block IIA is unhealthy

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- In 1972, the USAF Central Inertial Guidance Test Facility (Holloman AFB), conducted developmental flight tests of two prototype GPS receivers over White Sands Missile Range, using ground-based pseudo-satellites.
- In 1978, the first experimental Block-I GPS satellite was launched.
- In 1983, after Soviet interceptor aircraft shot down the civilian airliner KAL 007 that strayed into prohibited airspace because of navigational errors, killing all 269 people on board, U.S. President Ronald Reagan announced that GPS would be made available for civilian uses once it was completed.
- By 1985, ten more experimental Block-I satellites had been launched to validate the concept.
- On February 14, 1989, the first modern Block-II satellite was launched.
- The Gulf War from 1990 to 1991, was the first conflict where GPS was widely used.
- In 1992, the 2nd Space Wing, which originally managed the system, was de-activated and replaced by the 50th Space Wing.
- By December 1993, GPS achieved initial operational capability (IOC), indicating a full constellation (24 satellites) was available and providing the Standard Positioning Service (SPS).
- Full Operational Capability (FOC) was declared by Air Force Space Command (AFSPC) in April 1995, signifying full availability of the military's secure Precise Positioning Service (PPS).
- In 1996, recognizing the importance of GPS to civilian users as well as military users, U.S. President Bill Clinton issued a policy directive declaring GPS to be a dual-use system and establishing an Interagency GPS Executive Board to manage it as a national asset.
- In 1998, United States Vice President Al Gore announced plans to upgrade GPS with two new civilian signals for enhanced user accuracy and reliability, particularly with respect to aviation safety and in 2000 the United States Congress authorized the effort, referring to it as *GPS III*.
- In 1998, GPS technology was inducted into the Space Foundation Space Technology Hall of Fame.
- On May 2, 2000 "Selective Availability" was discontinued as a result of the 1996 executive order, allowing users to receive a non-degraded signal globally.
- In 2004, the United States Government signed an agreement with the European Community establishing cooperation related to GPS and Europe's planned Galileo system.
- In 2004, United States President George W. Bush updated the national policy and replaced the executive board with the National Executive Committee for Space-Based Positioning, Navigation, and Timing.
- November 2004, QUALCOMM announced successful tests of assisted GPS for mobile phones.
- In 2005, the first modernized GPS satellite was launched and began transmitting a second civilian signal (L2C) for enhanced user performance.
- On September 14, 2007, the aging mainframe-based Ground Segment Control System was transferred to the new Architecture Evolution Plan.

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- On May 19, 2009, the United States Government Accountability Office issued a report warning that some GPS satellites could fail as soon as 2010.
- On May 21, 2009, the Air Force Space Command allayed fears of GPS failure saying "There's only a small risk we will not continue to exceed our performance standard."
- On January 11, 2010, an update of ground control systems caused a software incompatibility with 8000 to 10000 military receivers manufactured by a division of Trimble Navigation Limited of Sunnyvale, Calif.
- The most recent launch was on May 28, 2010. The oldest GPS satellite still in operation was launched on November 26, 1990, and became operational on December 10, 1990.

## Awards

On February 10, 1993, the National Aeronautic Association selected the GPS Team as winners of the 1992 Robert J. Collier Trophy, the nation's most prestigious aviation award. This team combines researchers from the Naval Research Laboratory, the USAF, the Aerospace Corporation, Rockwell International Corporation, and IBM Federal Systems Company. The citation honors them "for the most significant development for safe and efficient navigation and surveillance of air and spacecraft since the introduction of radio navigation 50 years ago."

Two GPS developers received the National Academy of Engineering Charles Stark Draper Prize for 2003:

- Ivan Getting, emeritus president of The Aerospace Corporation and an engineer at the Massachusetts Institute of Technology, established the basis for GPS, improving on the World War II land-based radio system called LORAN (*Lo*ng-range *R*adio *A*id to *N*avigation).
- Bradford Parkinson, professor of aeronautics and astronautics at Stanford University, conceived the present satellite-based system in the early 1960s and developed it in conjunction with the U.S. Air Force. Parkinson served twenty-one years in the Air Force, from 1957 to 1978, and retired with the rank of colonel.

GPS developer Roger L. Easton received the National Medal of Technology on February 13, 2006.

Francis X. Kane (Col. USAF, ret.) was inducted into the U.S. Air Force Space and Missile Pioneers Hall of Fame at Lackland A.F.B., San Antonio, Texas, March 2, 2010 for his role in space technology development and the engineering design concept of GPS conducted as part of Project 621B.

## *Basic concept of GPS*

A GPS receiver calculates its position by precisely timing the signals sent by GPS satellites high above the Earth. Each satellite continually transmits messages that include

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- the time the message was transmitted
- precise orbital information (the ephemeris)
- the general system health and rough orbits of all GPS satellites (the almanac).

The receiver uses the messages it receives to determine the transit time of each message and computes the distance to each satellite. These distances along with the satellites' locations are used with the possible aid of trilateration, depending on which algorithm is used, to compute the position of the receiver. This position is then displayed, perhaps with a moving map display or latitude and longitude; elevation information may be included. Many GPS units show derived information such as direction and speed, calculated from position changes.

Three satellites might seem enough to solve for position since space has three dimensions and a position near the Earth's surface can be assumed. However, even a very small clock error multiplied by the very large speed of light — the speed at which satellite signals propagate — results in a large positional error. Therefore receivers use four or more satellites to solve for the receiver's location and time. The very accurately computed time is effectively hidden by most GPS applications, which use only the location. A few specialized GPS applications do however use the time; these include time transfer, traffic signal timing, and synchronization of cell phone base stations.

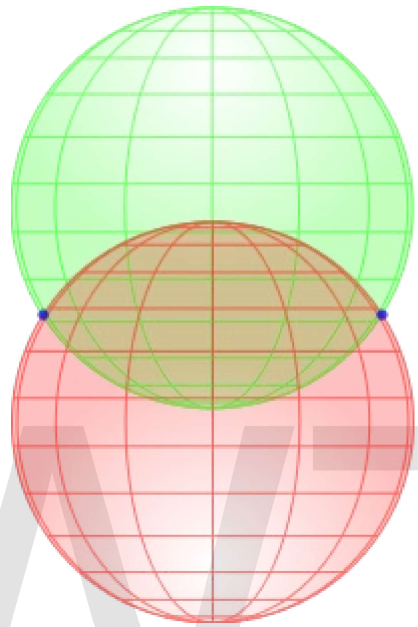
Although four satellites are required for normal operation, fewer apply in special cases. If one variable is already known, a receiver can determine its position using only three satellites. For example, a ship or aircraft may have known elevation. Some GPS receivers may use additional clues or assumptions (such as reusing the last known altitude, dead reckoning, inertial navigation, or including information from the vehicle computer) to give a less accurate (degraded) position when fewer than four satellites are visible.

## Position calculation introduction

To provide an introductory description of how a GPS receiver works, error effects are deferred to a later section. Using messages received from a minimum of four visible satellites, a GPS receiver is able to determine the times sent and then the satellite positions corresponding to these times sent. The x, y, and z components of position, and the time sent, are designated as $[x_i, y_i, z_i, t_i]$where the subscript *i* is the satellite number and has the value 1, 2, 3, or 4. Knowing the indicated, or uncorrected, time the message was received $t_{\text{r, uncorr}}$, the GPS receiver can compute the uncorrected transit time of the message as $(t_{\text{r, uncorr}} - t_i)$. Assuming the message traveled at the speed of light, *c*, the uncorrected distance traveled or pseudorange, $p_i$can be computed as $(t_{\text{r, uncorr}} - t_i)c$.

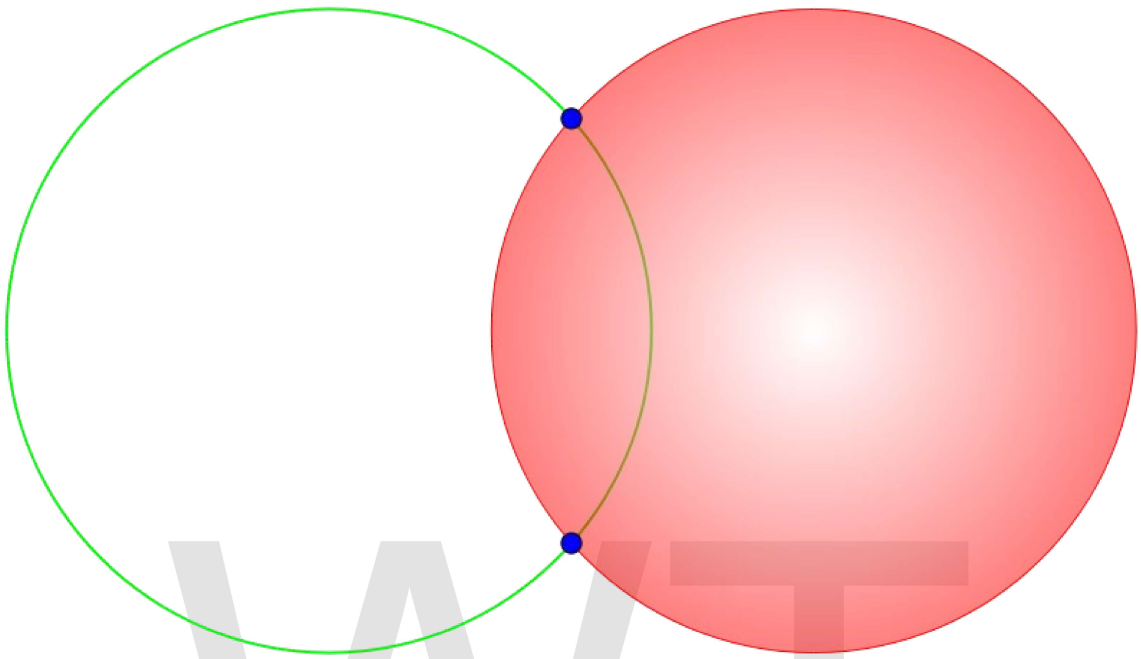
A satellite's position and pseudorange define a sphere, centered on the satellite, with radius equal to the pseudorange. The position of the receiver is somewhere on the surface of this sphere. Thus with four satellites, the indicated position of the GPS receiver is at or near the intersection of the surfaces of four spheres. In the ideal case of no errors, the GPS receiver would be at a precise intersection of the four surfaces.

If the surfaces of two spheres intersect at more than one point, they intersect in a circle. The trilateration shows this mathematically. A figure, *Two Sphere Surfaces Intersecting in a Circle*, is shown below. Two points where the surfaces of the spheres intersect are clearly shown in the figure. The distance between these two points is the diameter of the circle of intersection.



Two sphere surfaces intersecting in a circle

The intersection of a third spherical surface with the first two will be its intersection with that circle; in most cases of practical interest, this means they intersect at two points. Another figure, *Surface of Sphere Intersecting a Circle (not a solid disk) at Two Points*, illustrates the intersection. The two intersections are marked with dots. Again the trilateration clearly shows this mathematically.



Surface of sphere Intersecting a circle (not a solid disk) at two points

For automobiles and other near-earth vehicles, the correct position of the GPS receiver is the intersection closest to the Earth's surface. For space vehicles, the intersection farthest from Earth may be the correct one.

The correct position for the GPS receiver is also the intersection closest to the surface of the sphere corresponding to the fourth satellite.

## Correcting a GPS receiver's clock

One of the most significant error sources is the GPS receiver's clock. Because of the very large value of the speed of light, *c*, the estimated distances from the GPS receiver to the satellites, the pseudoranges, are very sensitive to errors in the GPS receiver clock; for example an error of one microsecond (0.000 001 second) corresponds to an error of 300 metres (980 ft). This suggests that an extremely accurate and expensive clock is required for the GPS receiver to work. Because manufacturers prefer to build inexpensive GPS receivers for mass markets, the solution for this dilemma is based on the way sphere surfaces intersect in the GPS problem.

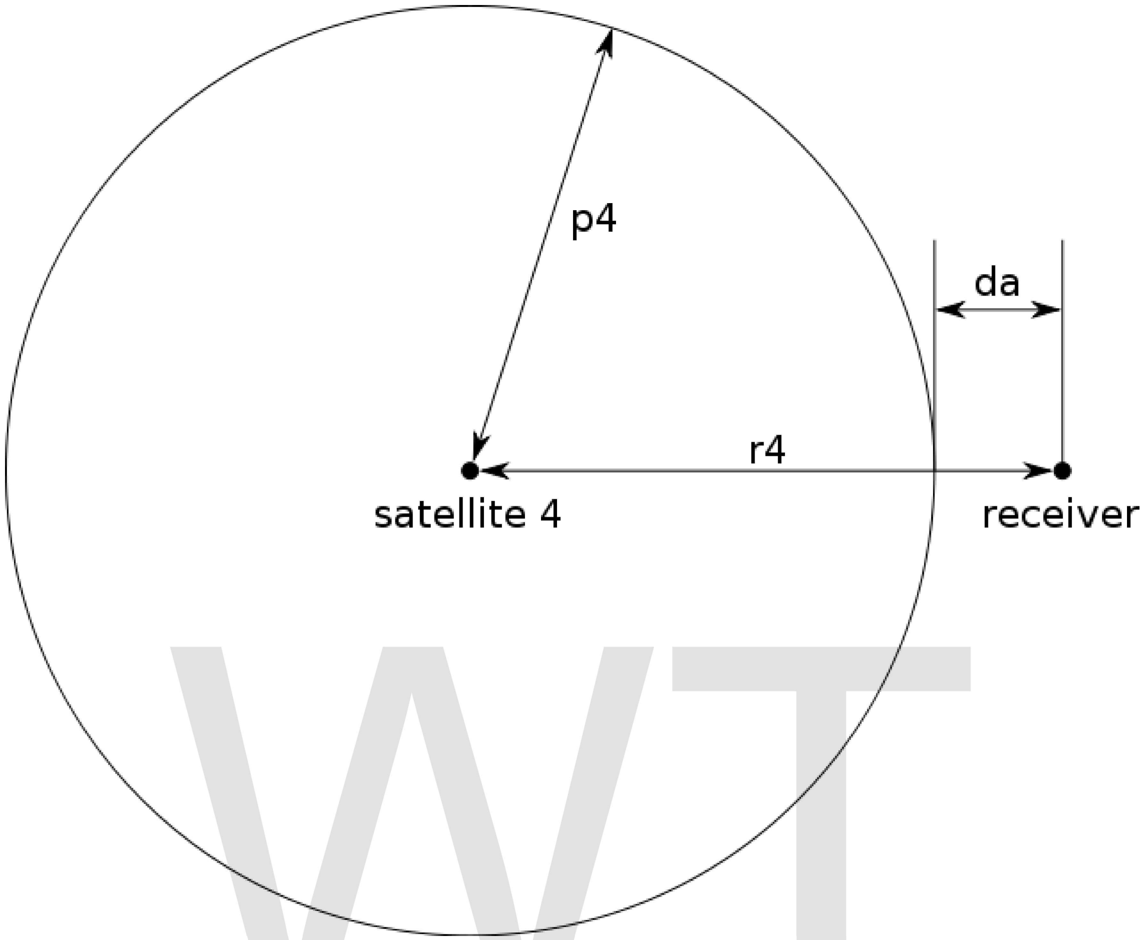



Diagram depicting satellite 4, sphere, p4, r4, and da

It is likely that the surfaces of the three spheres intersect, because the circle of intersection of the first two spheres is normally quite large, and thus the third sphere surface is likely to intersect this large circle. It is very unlikely that the surface of the sphere corresponding to the fourth satellite will intersect either of the two points of intersection of the first three, because any clock error could cause it to miss intersecting a point. However, the distance from the valid estimate of GPS receiver position to the surface of the sphere corresponding to the fourth satellite can be used to compute a clock correction. Let $r_4$ denote the distance from the valid estimate of GPS receiver position to the fourth satellite and let $p_4$ denote the pseudorange of the fourth satellite. Let $da = r_4 - p_4$. $da$ is the distance from the computed GPS receiver position to the surface of the sphere corresponding to the fourth satellite. Thus the quotient, $b_r = -da/c$, provides an estimate of

(time indicated by the receiver's on-board clock) - (correct time),

and the GPS receiver clock can be advanced if $b_r$ is positive or delayed if $b_r$ is negative. However, it should be kept in mind that a less simple function of $da$ may be needed to estimate the time error in an iterative algorithm as discussed in the Navigation equations section.

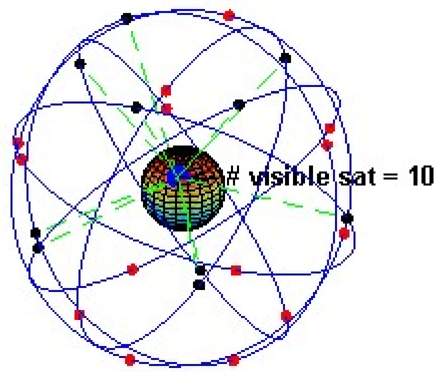
## *Structure*

The current GPS consists of three major segments. These are the space segment (SS), a control segment (CS), and a user segment (U.S.). The U.S. Air Force develops, maintains, and operates the space and control segments. GPS satellites broadcast signals from space, and each GPS receiver uses these signals to calculate its three-dimensional location (latitude, longitude, and altitude) and the current time.

The space segment is composed of 24 to 32 satellites in medium Earth orbit and also includes the payload adapters to the boosters required to launch them into orbit. The control segment is composed of a master control station, an alternate master control station, and a host of dedicated and shared ground antennas and monitor stations. The user segment is composed of hundreds of thousands of U.S. and allied military users of the secure GPS Precise Positioning Service, and tens of millions of civil, commercial, and scientific users of the Standard Positioning Service.

### Space segment

Unlaunched GPS satellite on display at the San Diego Air & Space Museum




A visual example of the GPS constellation in motion with the Earth rotating. Notice how the number of *satellites in view* from a given point on the Earth's surface, in this example at 45°N, changes with time.

The space segment (SS) is composed of the orbiting GPS satellites, or Space Vehicles (SV) in GPS parlance. The GPS design originally called for 24 SVs, eight each in three circular orbital planes, but this was modified to six planes with four satellites each. The orbital planes are centered on the Earth, not rotating with respect to the distant stars. The six planes have approximately 55° inclination (tilt relative to Earth's equator) and are separated by 60° right ascension of the ascending node (angle along the equator from a reference point to the orbit's intersection). The orbits are arranged so that at least six satellites are always within line of sight from almost everywhere on Earth's surface. The result of this objective is that the four satellites are not evenly spaced (90 degrees) apart within each orbit. In general terms, the angular difference between satellites in each orbit is 30, 105, 120, and 105 degrees apart which, of course, sum to 360 degrees.

Orbiting at an altitude of approximately 20,200 kilometers (about 12,550 miles or 10,900 nautical miles; orbital radius of approximately 26,600 km (about 16,500 mi or 14,400 NM)), each SV makes two complete orbits each sidereal day, repeating the same ground track each day. This was very helpful during development because even with only four satellites, correct alignment means all four are visible from one spot for a few hours each day. For military operations, the ground track repeat can be used to ensure good coverage in combat zones.

As of March 2008, there are 31 actively broadcasting satellites in the GPS constellation, and two older, retired from active service satellites kept in the constellation as orbital spares. The additional satellites improve the precision of GPS receiver calculations by providing redundant measurements. With the increased number of satellites, the constellation was changed to a nonuniform arrangement. Such an arrangement was shown to improve reliability and availability of the system, relative to a uniform system, when multiple satellites fail. About eight satellites are visible from any point on the ground at any one time.

## Control segment


Ground monitor station used from 1984 to 2007, on display at the Air Force Space & Missile Museum

The control segment is composed of

1. a master control station (MCS),
2. an alternate master control station,
3. four dedicated ground antennas and
4. six dedicated monitor stations

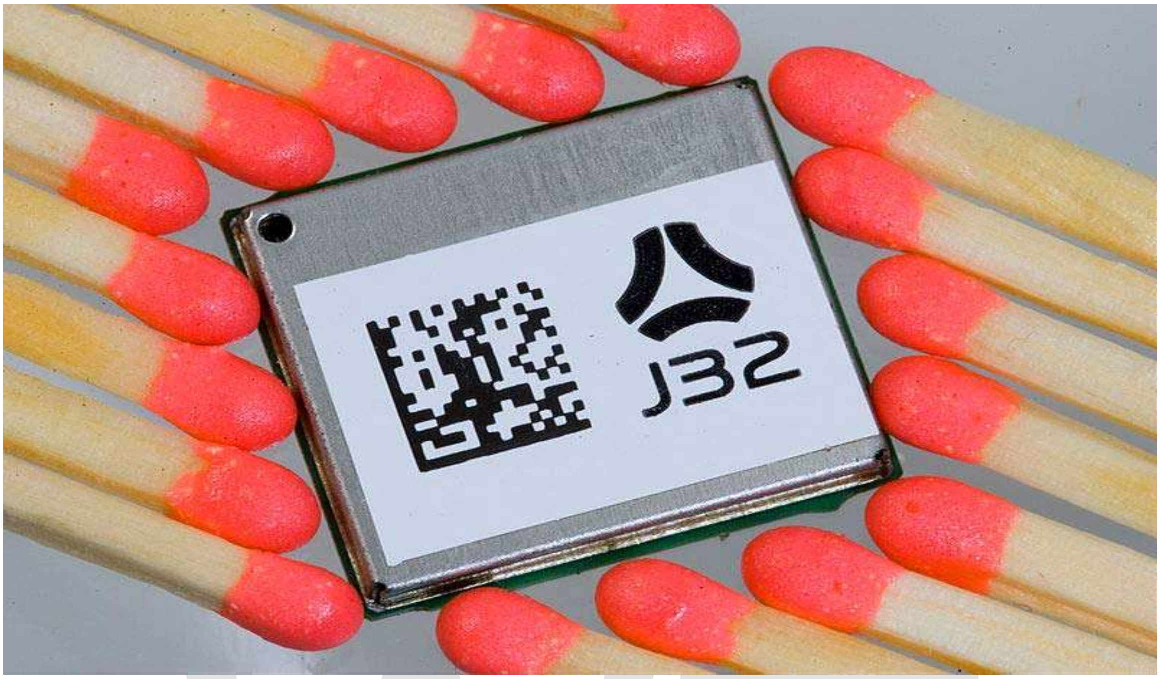
The MCS can also access U.S. Air Force Satellite Control Network (AFSCN) ground antennas (for additional command and control capability) and NGA (National Geospatial-Intelligence Agency) monitor stations. The flight paths of the satellites are tracked by dedicated U.S. Air Force monitoring stations in Hawaii, Kwajalein, Ascension Island, Diego Garcia, Colorado Springs, Colorado and Cape Canaveral, along with shared NGA monitor stations operated in England, Argentina, Ecuador, Bahrain, Australia and Washington DC. The tracking information is sent to the Air Force Space Command's MCS at Schriever Air Force Base 25 km (16 miles) ESE of Colorado Springs, which is operated by the 2nd Space Operations Squadron (2 SOPS) of the U.S. Air Force. Then 2 SOPS contacts each GPS satellite regularly with a navigational update using dedicated or shared (AFSCN) ground antennas (GPS dedicated ground antennas are located at Kwajalein, Ascension Island, Diego Garcia, and Cape Canaveral). These updates synchronize the atomic clocks on board the satellites to within a few nanoseconds of each other, and adjust the ephemeris of each satellite's internal orbital model. The updates are created by a Kalman filter that uses inputs from the ground monitoring stations, space weather information, and various other inputs.

Satellite maneuvers are not precise by GPS standards. So to change the orbit of a satellite, the satellite must be marked *unhealthy*, so receivers will not use it in their calculation. Then the maneuver can be carried out, and the resulting orbit tracked from the ground. Then the new ephemeris is uploaded and the satellite marked healthy again.

## User segment

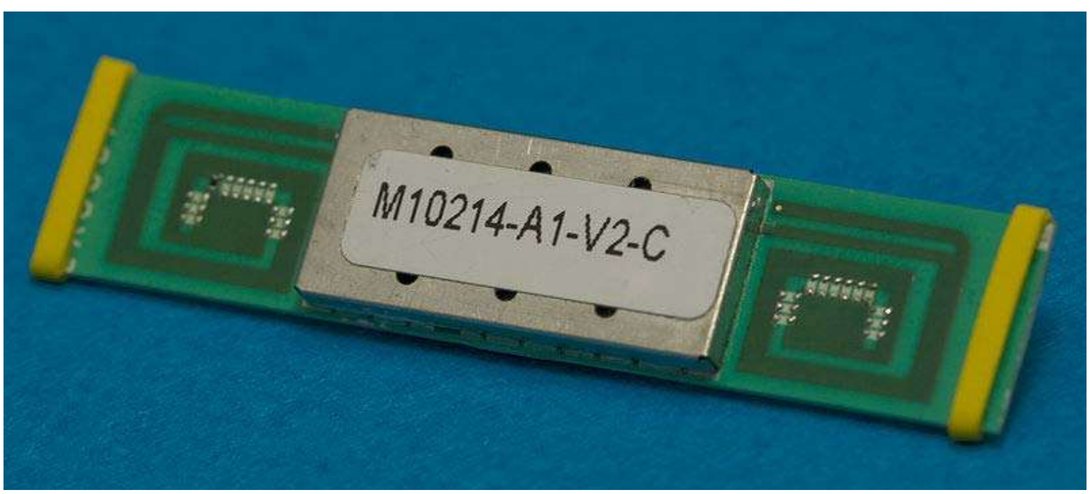

GPS receivers come in a variety of formats, from devices integrated into cars, phones, and watches, to dedicated devices such as those shown here from manufacturers Trimble, Garmin and Leica (left to right).

The user segment is composed of hundreds of thousands of U.S. and allied military users of the secure GPS Precise Positioning Service, and tens of millions of civil, commercial and scientific users of the Standard Positioning Service. In general, GPS receivers are composed of an antenna, tuned to the frequencies transmitted by the satellites, receiver-processors, and a highly stable clock (often a crystal oscillator). They may also include a display for providing location and speed information to the user. A receiver is often described by its number of channels: this signifies how many satellites it can monitor simultaneously. Originally limited to four or five, this has progressively increased over the years so that, as of 2007, receivers typically have between 12 and 20 channels.




A typical OEM GPS receiver module measuring 15×17 mm

GPS receivers may include an input for differential corrections, using the RTCM SC-104 format. This is typically in the form of an RS-232 port at 4,800 bit/s speed. Data is actually sent at a much lower rate, which limits the accuracy of the signal sent using RTCM. Receivers with internal DGPS receivers can outperform those using external RTCM data. As of 2006, even low-cost units commonly include Wide Area Augmentation System (WAAS) receivers.




A typical GPS receiver with integrated antenna

Many GPS receivers can relay position data to a PC or other device using the NMEA 0183 protocol. Although this protocol is officially defined by the National Marine

Electronics Association (NMEA), references to this protocol have been compiled from public records, allowing open source tools like gpsd to read the protocol without violating intellectual property laws. Other proprietary protocols exist as well, such as the SiRF and MTK protocols. Receivers can interface with other devices using methods including a serial connection, USB, or Bluetooth.

## *Applications*

While originally a military project, GPS is considered a *dual-use* technology, meaning it has significant military and civilian applications.

GPS has become a widely deployed and useful tool for commerce, scientific uses, tracking, and surveillance. GPS's accurate time facilitates everyday activities such as banking, mobile phone operations, and even the control of power grids by allowing well synchronized hand-off switching.

### Civilian

This antenna is mounted on the roof of a hut containing a scientific experiment needing precise timing.

Many civilian applications use one or more of GPS's three basic components: absolute location, relative movement, and time transfer.

- Cellular telephony: Clock synchronization enables time transfer, which is critical for synchronizing its spreading codes with other base stations to facilitate inter-cell handoff and support hybrid GPS/cellular position detection for mobile emergency calls and other applications. The first handsets with integrated GPS launched in the late 1990s. The U.S. Federal Communications Commission (FCC) mandated the feature in either the handset or in the towers (for use in triangulation) in 2002 so emergency services could locate 911 callers. Third-party software developers later gained access to GPS APIs from Nextel upon launch, followed by Sprint in 2006, and Verizon soon thereafter.
- Disaster relief/emergency services: Depend upon GPS for location and timing capabilities.
- Geofencing: Vehicle tracking systems, person tracking systems, and pet tracking systems use GPS to locate a vehicle, person, or pet. These devices are attached to the vehicle, person, or the pet collar. The application provides continuous tracking and mobile or Internet updates should the target leave a designated area.
- Geotagging: Applying location coordinates to digital objects such as photographs and other documents for purposes such as creating map overlays.
- GPS Aircraft Tracking
- GPS tours: Location determines what content to display; for instance, information about an approaching point of interest.
- Map-making: Both civilian and military cartographers use GPS extensively.
- Navigation: Navigators value digitally precise velocity and orientation measurements.
- Phasor measurement units: GPS enables highly accurate timestamping of power system measurements, making it possible to compute phasors.
- Recreation: For example, geocaching, geodashing, GPS drawing and waymarking.
- Surveying: Surveyors use absolute locations to make maps and determine property boundaries.
- Tectonics: GPS enables direct fault motion measurement in earthquakes.

## Restrictions on civilian use

The U.S. Government controls the export of some civilian receivers. All GPS receivers capable of functioning above 18 kilometers (11 mi) altitude and 515 metres per second (1,001 kn) are classified as munitions (weapons) for which U.S. State Department export licenses are required. These limits attempt to prevent use of a receiver in a ballistic missile. They would not prevent use in a cruise missile because their altitudes and speeds are similar to those of ordinary aircraft.

This rule applies even to otherwise purely civilian units that only receive the L1 frequency and the C/A (Clear/Acquisition) code and cannot correct for Selective Availability (SA), etc.

Disabling operation above these limits exempts the receiver from classification as a munition. Vendor interpretations differ. The rule targets operation given the combination of altitude and speed, while some receivers stop operating even when stationary. This has caused problems with some amateur radio balloon launches that regularly reach 30 kilometers (19 mi).

## Military

Attaching a GPS guidance kit to a 'dumb' bomb, March 2003

As of 2009, military applications of GPS include:

- Navigation: GPS allows soldiers to find objectives, even in the dark or in unfamiliar territory, and to coordinate troop and supply movement. In the United States armed forces, commanders use the *Commanders Digital Assistant* and lower ranks use the *Soldier Digital Assistant*.
- Target tracking: Various military weapons systems use GPS to track potential ground and air targets before flagging them as hostile. These weapon systems pass target coordinates to precision-guided munitions to allow them to engage targets accurately. Military aircraft, particularly in air-to-ground roles, use GPS to find targets (for example, gun camera video from AH-1 Cobras in Iraq show GPS co-ordinates that can be viewed with special software.)
- Missile and projectile guidance: GPS allows accurate targeting of various military weapons including ICBMs, cruise missiles and precision-guided munitions. Artillery projectiles. Embedded GPS receivers able to withstand accelerations of

12,000 *g* or about 118 km/s$^2$ have been developed for use in 155 millimeters (6.1 in) howitzers.
- Search and Rescue: Downed pilots can be located faster if their position is known.
- Reconnaissance: Patrol movement can be managed more closely.
- GPS satellites carry a set of nuclear detonation detectors consisting of an optical sensor (Y-sensor), an X-ray sensor, a dosimeter, and an electromagnetic pulse (EMP) sensor (W-sensor), that form a major portion of the United States Nuclear Detonation Detection System.

## *Communication*

The navigational signals transmitted by GPS satellites encode a variety of information including satellite positions, the state of the internal clocks, and the health of the network. These signals are transmitted on two separate carrier frequencies that are common to all satellites in the network. Two different encodings are used, a public encoding that enables lower resolution navigation, and an encrypted encoding used by the U.S. military.

### Message format

GPS message format

| **Subframes** | **Description** |
|---|---|
| 1 | Satellite clock,<br>GPS time relationship |
| 2–3 | Ephemeris<br>(precise satellite orbit) |
| 4–5 | Almanac component<br>(satellite network synopsis,<br>error correction) |

Each GPS satellite continuously broadcasts a *navigation message* at a rate of 50 bits per second. Each complete message is composed of 30-second frames, distinct groupings of 1,500 bits of information. Each frame is further subdivided into 5 subframes of length 6 seconds and with 300 bits each. Each subframe contains 10 words of 30 bits with length 0.6 seconds each. Each 30 second frame begins precisely on the minute or half minute as indicated by the atomic clock on each satellite.

The first part of the message encodes the week number and the time within the week, as well as the data about the health of the satellite. The second part of the message, the *ephemeris*, provides the precise orbit for the satellite. The last part of the message, the *almanac*, contains coarse orbit and status information for all satellites in the network as well as data related to error correction.

All satellites broadcast at the same frequencies. Signals are encoded using code division multiple access (CDMA) allowing messages from individual satellites to be distinguished from each other based on unique encodings for each satellite (that the receiver must be aware of). Two distinct types of CDMA encodings are used: the coarse/acquisition (C/A) code, which is accessible by the general public, and the precise (P) code, that is encrypted so that only the U.S. military can access it.

The ephemeris is updated every 2 hours and is generally valid for 4 hours, with provisions for updates every 6 hours or longer in non-nominal conditions. The almanac is updated typically every 24 hours. Additionally data for a few weeks following is uploaded in case of transmission updates that delay data upload.

## Satellite frequencies

GPS frequency overview

| Band | Frequency | Description |
|---|---|---|
| **L1** | 1575.42 MHz | Course-acquisition (C/A) and encrypted precision P(Y) codes, plus the L1 civilian (L1C) and military (M) codes on future Block III satellites. |
| **L2** | 1227.60 MHz | P(Y) code, plus the L2C and military codes on the Block IIR-M and newer satellites. |
| **L3** | 1381.05 MHz | Used for nuclear detonation (NUDET) detection. |
| **L4** | 1379.913 MHz | Being studied for additional ionospheric correction. |
| **L5** | 1176.45 MHz | Proposed for use as a civilian safety-of-life (SoL) signal. |

All satellites broadcast at the same two frequencies, 1.57542 GHz (L1 signal) and 1.2276 GHz (L2 signal). The satellite network uses a CDMA spread-spectrum technique where the low-bitrate message data is encoded with a high-rate pseudo-random (PRN) sequence that is different for each satellite. The receiver must be aware of the PRN codes for each satellite to reconstruct the actual message data. The C/A code, for civilian use, transmits data at 1.023 million chips per second, whereas the P code, for U.S. military use, transmits at 10.23 million chips per second. The L1 carrier is modulated by both the C/A and P codes, while the L2 carrier is only modulated by the P code. The P code can be encrypted as a so-called P(Y) code that is only available to military equipment with a proper decryption key. Both the C/A and P(Y) codes impart the precise time-of-day to the user.

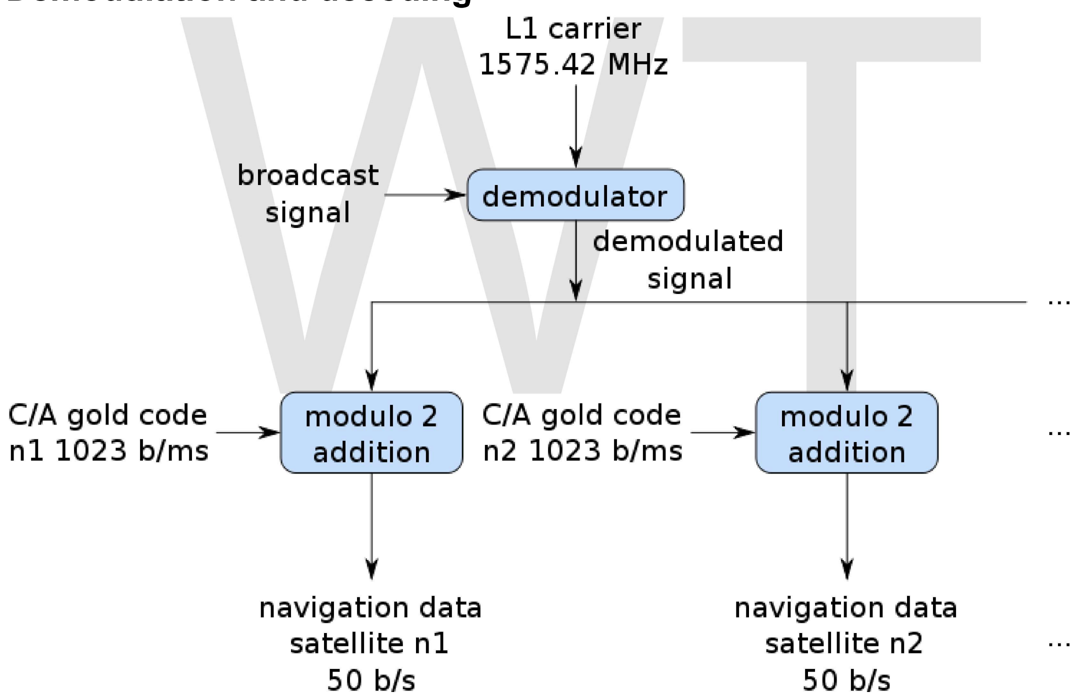
The L3 signal at a frequency of 1.38105 GHz is used by the United States Nuclear Detonation (NUDET) Detection System (USNDS) to detect, locate, and report nuclear detonations (NUDETs) in the Earth's atmosphere and near space. One usage is the enforcement of nuclear test ban treaties.

The L4 band at 1.379913 GHz is being studied for additional ionospheric correction.

The L5 frequency band at 1.17645 GHZ was added in the process of GPS modernization. This frequency falls into an internationally protected range for aeronautical navigation, promising little or no interference under all circumstances. The first Block IIF satellite that would provide this signal is set to be launched in 2009. The L5 consists of two carrier components that are in phase quadrature with each other. Each carrier component is bi-phase shift key (BPSK) modulated by a separate bit train.

A waiver has recently been granted to LightSquared to operate a terrestrial broadband service in the L1 band. There is some concern that this will seriously degrade the GPS signal for many consumer uses.

## Demodulation and decoding




Demodulating and Decoding GPS Satellite Signals using the Coarse/Acquisition Gold code.

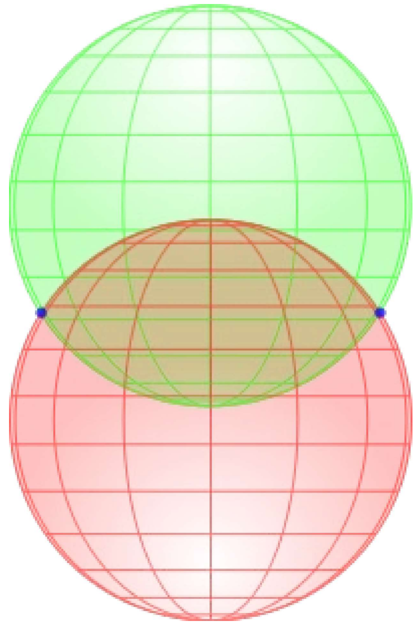
Because all of the satellite signals are modulated onto the same L1 carrier frequency, the signals must be separated after demodulation. This is done by assigning each satellite a unique binary sequence known as a Gold code. The signals are decoded after demodulation using addition of the Gold codes corresponding to the satellites monitored by the receiver.

If the almanac information has previously been acquired, the receiver picks the satellites to listen for by their PRNs, unique numbers in the range 1 through 32. If the almanac information is not in memory, the receiver enters a search mode until a lock is obtained on one of the satellites. To obtain a lock, it is necessary that there be an unobstructed line of sight from the receiver to the satellite. The receiver can then acquire the almanac and determine the satellites it should listen for. As it detects each satellite's signal, it identifies it by its distinct C/A code pattern. There can be a delay of up to 30 seconds before the first estimate of position because of the need to read the ephemeris data.

Processing of the navigation message enables the determination of the time of transmission and the satellite position at this time.

## Navigation equations

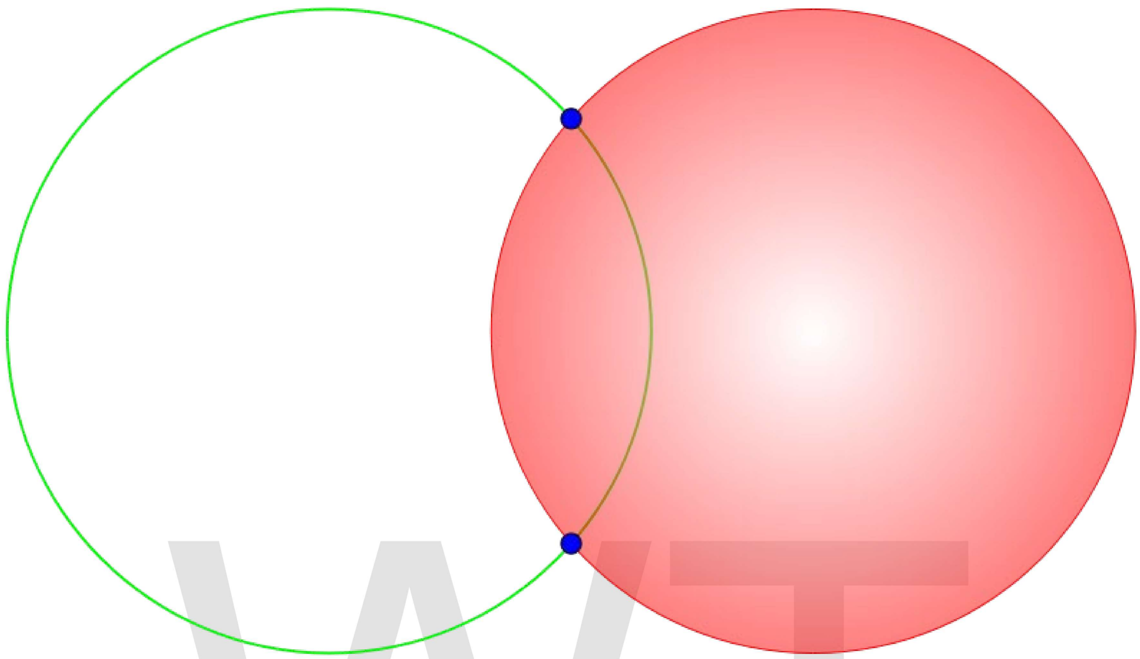
The receiver uses messages received from four satellites to determine the satellite positions and time sent. The *x, y,* and *z* components of position and the time sent are designated as $[x_i, y_i, z_i, t_i]$where the subscript *i* denotes the satellite and has the value 1, 2, 3, or 4. Knowing when the message was received $t_\mathrm{r}$, the receiver computes the message's transit time as $(t_\mathrm{r} - t_i)$. Assuming the message traveled at the speed of light (c) the distance traveled is $(t_\mathrm{r} - t_i)\, c$. Knowing the distance from receiver to satellite and the satellite's position implies that the receiver is on the surface of a sphere centered at the satellite's position. Thus the receiver is at or near the intersection of the surfaces of four spheres. In the ideal case of no errors, the receiver is at the intersection of the surfaces of four spheres. Excluding the unrealistic case (for GPS purposes) of two coincident spheres, the surfaces of two intersecting spheres is either a point (if they merely touch) or a circle as depicted in the illustration below. Two of the points where the surfaces of the spheres intersect are clearly marked on the figure. The distance between these two points is the diameter of the circle of intersection.



Two sphere surfaces intersecting in a circle

This can be seen more clearly by considering a side view of the intersecting spheres. This view would match the figure because of the symmetry of the spheres. A view from any horizontal direction would look exactly the same. Therefore the diameter as seen from all directions is the same and thus the surfaces actually do intersect in a circle. The trilateration algebraically confirms this geometric argument that the two sphere surfaces intersect in a circle.

Having found that two sphere surfaces intersect in a circle, we now consider how the intersection of the first two sphere surfaces, the circle, intersect with the third sphere. A circle and sphere surface intersect at zero, one or two points. For the GPS problem we are concerned with the case of two points of intersection. Another figure, Surface of Sphere Intersecting a Circle (not a solid disk) at Two Points, is shown below to aid in visualizing this intersection. Trilateration algebraically confirms this geometric observation. The ambiguity of two points of intersection of three sphere surfaces can be resolved by noting the point that is closest to the fourth sphere surface.



Surface of a sphere intersecting a circle (i.e., the edge of a disk) at two points

Having provided a discussion of how sphere surfaces intersect, we now formulate the equations for the case when errors are present.

Let $b$ denote the clock error or bias, the amount that the receiver's clock is off. The receiver has four unknowns, the three components of GPS receiver position and the clock bias $[x, y, z, b]$. The equation of the sphere surfaces are given by:

$$(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 = \left([t_r + b - t_i]c\right)^2,$$

$$i = 1, 2, 3, 4$$

Another useful form of these equations is in terms of *pseudoranges*, which are the approximate ranges based on the receiver clock's uncorrected time so that $p_i = (t_r - t_i)\, c$. Then the equations becomes:

$$p_i = \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2} - bc, \ i = 1, 2, 3, 4.$$

### Methods of solution of navigation equations

The navigation equations can be solved by an algebraic method, called the Bancroft Method or by numerical methods involving trilateration or multidimensional root finding.

## Bancroft's method

Bancroft's method is perhaps the most important method of solving the navigation equations because it involves an algebraic as opposed to numerical method. The method requires at least four satellites but more can be used.

## Trilateration

The receiver can use trilateration  and one dimensional numerical root finding. Trilateration is used to determine the intersection of the surfaces of three spheres. In the usual case of two intersections, the point nearest the surface of the sphere corresponding to the fourth satellite is chosen. The Earth's surface can also sometimes be used instead, especially by civilian GPS receivers, because it is illegal in the United States to track vehicles more than 60,000 feet (18,000 m) in altitude. Let da denote the signed magnitude of the vector from the receiver position to the fourth satellite (i.e. da = r4 - p4) as defined in the section, Correcting a GPS receiver's clock. da is a function of the correction because the correction changes the satellite transmission times and thus the pseudoranges. The notation, da(correction) denotes this function. The problem is to determine the correction such that

$$da\,(correction) = 0.$$

This is the familiar problem of finding the zeroes of a one dimensional non-linear function of a scalar variable. Iterative numerical methods, such as those found in the chapter on root finding in *Numerical Recipes* can solve this type of problem. One advantage of this method is that it involves one dimensional as opposed to multidimensional numerical root finding.

## Multidimensional Newton-Raphson calculations

- Alternatively, multidimensional root finding method such as Newton-Raphson method can be used. The approach is to linearize around an approximate solution, say $\left[x_{\mathrm{r}}^{(k)}, y_{\mathrm{r}}^{(k)}, z_{\mathrm{r}}^{(k)}, b_{\mathrm{r}}^{(k)}\right]$from iteration *k,* then solve four linear equations derived from the quadratic equations above to obtain $\left[x_{\mathrm{r}}^{(k+1)}, y_{\mathrm{r}}^{(k+1)}, z_{\mathrm{r}}^{(k+1)}, b_{\mathrm{r}}^{(k+1)}\right]$. The Newton-Raphson method is more rapidly convergent than other methods of numerical root finding. A disadvantage of this multidimensional root finding method as compared to single dimensional root findiing is that, "There are no good general methods for solving systems of more than one nonlinear equations."

- When more than four satellites are available, the calculation can use the four best or more than four, considering number of channels, processing capability, and geometric dilution of precision (GDOP). Using more than four is an over-determined system of equations with no unique solution, which must be solved by least-squares or a similar technique. If all visible satellites are used, the results are as good as or better than using the four best. Errors can be estimated through the residuals. With each combination of four or more satellites, a GDOP factor can be calculated, based on the relative sky directions of the satellites used. As more satellites are picked up, pseudoranges from various 4-way combinations can be processed to add more estimates to the location and clock offset. The receiver then takes the weighted average of these positions and clock offsets. After the final location and time are calculated, the location is expressed in a specific coordinate system such as latitude and longitude, using the WGS 84 geodetic datum or a country-specific system.
- Finally, results from other positioning systems such as GLONASS or the upcoming Galileo can be incorporated or used to check the result. (By design, these systems use the same frequency bands, so much of the receiver circuitry can be shared, though the decoding is different.)

## *Error sources and analysis*

Error analysis for the Global Positioning System is an important aspect for determining what errors and their magnitude are to be expected. GPS errors are affected by geometric dilution of precision and depend on signal arrival time errors, numerical errors, atmospherics effects, ephemeris erros, multipath errors and other effects.

## *Accuracy enhancement and surveying*

### Augmentation

Integrating external information into the calculation process can materially improve accuracy. Such augmentation systems are generally named or described based on how the information arrives. Some systems transmit additional error information (such as clock drift, ephemera, or ionospheric delay), others characterize prior errors, while a third group provides additional navigational or vehicle information.

Examples of augmentation systems include the Wide Area Augmentation System (WAAS), European Geostationary Navigation Overlay Service (EGNOS), Differential GPS, Inertial Navigation Systems (INS) and Assisted GPS.

### Precise monitoring

Accuracy can be improved through precise monitoring and measurement of existing GPS signals in additional or alternate ways.

The largest remaining error is usually the unpredictable delay through the ionosphere. The spacecraft broadcast ionospheric model parameters, but errors remain. This is one reason GPS spacecraft transmit on at least two frequencies, L1 and L2. Ionospheric delay is a well-defined function of frequency and the total electron content (TEC) along the path, so measuring the arrival time difference between the frequencies determines TEC and thus the precise ionospheric delay at each frequency.

Military receivers can decode the P(Y)-code transmitted on both L1 and L2. Without decryption keys, it is still possible to use a *codeless* technique to compare the P(Y) codes on L1 and L2 to gain much of the same error information. However, this technique is slow, so it is currently available only on specialized surveying equipment. In the future, additional civilian codes are expected to be transmitted on the L2 and L5 frequencies. Then all users will be able to perform dual-frequency measurements and directly compute ionospheric delay errors.

A second form of precise monitoring is called *Carrier-Phase Enhancement* (CPGPS). This corrects the error that arises because the pulse transition of the PRN is not instantaneous, and thus the correlation (satellite-receiver sequence matching) operation is imperfect. CPGPS uses the L1 carrier wave, which has a period of

$$\frac{1 \text{ sec}}{1575.42 * 10^6} = 0.63475 \text{ nanoseconds} \approx 1 \text{ nanosecond}$$

, which is about one-thousandth of the C/A Gold code bit period of

$$\frac{1 \text{ sec}}{1023 * 10^3} = 977.5 \text{ nanosecond } \approx 1000 \text{ nanosecond}$$

, to act as an additional clock signal and resolve the uncertainty. The phase difference error in the normal GPS amounts to 2–3 metres (6.6–9.8 ft) of ambiguity. CPGPS working to within 1% of perfect transition reduces this error to 3 centimeters (1.2 in) of ambiguity. By eliminating this error source, CPGPS coupled with DGPS normally realizes between 20–30 centimetres (7.9–12 in) of absolute accuracy.

*Relative Kinematic Positioning* (RKP) is a third alternative for a precise GPS-based positioning system. In this approach, determination of range signal can be resolved to a precision of less than 10 centimeters (3.9 in). This is done by resolving the number of cycles that the signal is transmitted and received by the receiver by using a combination of differential GPS (DGPS) correction data, transmitting GPS signal phase information and ambiguity resolution techniques via statistical tests—possibly with processing in real-time (real-time kinematic positioning, RTK).

## Timekeeping

### Timekeeping and leap seconds

While most clocks are synchronized to Coordinated Universal Time (UTC), the atomic clocks on the satellites are set to *GPS time*. The difference is that GPS time is not corrected to match the rotation of the Earth, so it does not contain leap seconds or other corrections that are periodically added to UTC. GPS time was set to match Coordinated Universal Time (UTC) in 1980, but has since diverged. The lack of corrections means that GPS time remains at a constant offset with International Atomic Time (TAI) (TAI - GPS = 19 seconds). Periodic corrections are performed on the on-board clocks to correct relativistic effects and keep them synchronized with ground clocks.

The GPS navigation message includes the difference between GPS time and UTC, which as of 2011 is 15 seconds because of the leap second added to UTC December 31, 2008. Receivers subtract this offset from GPS time to calculate UTC and specific timezone values. New GPS units may not show the correct UTC time until after receiving the UTC offset message. The GPS-UTC offset field can accommodate 255 leap seconds (eight bits) that, given the current period of the Earth's rotation (with one leap second introduced approximately every 18 months), should be sufficient to last until approximately the year 2300.

## Timekeeping accuracy

GPS time is accurate to about 14ns.

## Timekeeping format

As opposed to the year, month, and day format of the Gregorian calendar, the GPS date is expressed as a week number and a seconds-into-week number. The week number is transmitted as a ten-bit field in the C/A and P(Y) navigation messages, and so it becomes zero again every 1,024 weeks (19.6 years). GPS week zero started at 00:00:00 UTC (00:00:19 TAI) on January 6, 1980, and the week number became zero again for the first time at 23:59:47 UTC on August 21, 1999 (00:00:19 TAI on August 22, 1999). To determine the current Gregorian date, a GPS receiver must be provided with the approximate date (to within 3,584 days) to correctly translate the GPS date signal. To address this concern the modernized GPS navigation message uses a 13-bit field that only repeats every 8,192 weeks (157 years), thus lasting until the year 2137 (157 years after GPS week zero).

## Carrier phase tracking (surveying)

Another method that is used in surveying applications is carrier phase tracking. The period of the carrier frequency times the speed of light gives the wavelength, which is about 0.19 meters for the L1 carrier. Accuracy within 1% of wavelength in detecting the leading edge, reduces this component of pseudorange error to as little as 2 millimeters. This compares to 3 meters for the C/A code and 0.3 meters for the P code.

However, 2 millimeter accuracy requires measuring the total phase—the number of waves times the wavelength plus the fractional wavelength, which requires specially equipped receivers. This method has many surveying applications.

Triple differencing followed by numerical root finding, and a mathematical technique called least squares can estimate the position of one receiver given the position of another. First, compute the difference between satellites, then between receivers, and finally between epochs. Other orders of taking differences are equally valid. Detailed discussion of the errors is omitted.

The satellite carrier total phase can be measured with ambiguity as to the number of cycles. Let $\phi(r_i, s_j, t_k)$ denote the phase of the carrier of satellite *j* measured by receiver *i* at time $t_k$. This notation shows the meaning of the subscripts *i, j,* and *k.* The receiver (*r*), satellite (*s*), and time (*t*) come in alphabetical order as arguments of $\phi$ and to balance readability and conciseness, let $\phi_{i,j,k} = \phi(r_i, s_j, t_k)$ be a concise abbreviation. Also we define three functions, :$\Delta^r, \Delta^s, \Delta^t$, which return differences between receivers, satellites, and time points, respectively. Each function has variables with three subscripts as its arguments. These three functions are defined below. If $\alpha_{i,j,k}$ is a function of the three integer arguments, *i, j,* and *k* then it is a valid argument for the functions, :$\Delta^r, \Delta^s, \Delta^t$, with the values defined as

$$\Delta^r(\alpha_{i,j,k}) = \alpha_{i+1,j,k} - \alpha_{i,j,k},$$
$$\Delta^s(\alpha_{i,j,k}) = \alpha_{i,j+1,k} - \alpha_{i,j,k}, \text{ and}$$
$$\Delta^t(\alpha_{i,j,k}) = \alpha_{i,j,k+1} - \alpha_{i,j,k}.$$

Also if $\alpha_{i,j,k}\ and\ \beta_{l,m,n}$ are valid arguments for the three functions and *a* and *b* are constants then $(a\ \alpha_{i,j,k} + b\ \beta_{l,m,n})$ is a valid argument with values defined as

$$\Delta^r(a\ \alpha_{i,j,k} + b\ \beta_{l,m,n}) = a\ \Delta^r(\alpha_{i,j,k}) + b\ \Delta^r(\beta_{l,m,n}),$$
$$\Delta^s(a\ \alpha_{i,j,k} + b\ \beta_{l,m,n}) = a\ \Delta^s(\alpha_{i,j,k}) + b\ \Delta^s(\beta_{l,m,n}), \text{ and}$$
$$\Delta^t(a\ \alpha_{i,j,k} + b\ \beta_{l,m,n}) = a\ \Delta^t(\alpha_{i,j,k}) + b\ \Delta^t(\beta_{l,m,n}).$$

Receiver clock errors can be approximately eliminated by differencing the phases measured from satellite 1 with that from satellite 2 at the same epoch. This difference is designated as $\Delta^s(\phi_{1,1,1}) = \phi_{1,2,1} - \phi_{1,1,1}$

Double differencing computes the difference of receiver 1's satellite difference from that of receiver 2. This approximately eliminates satellite clock errors. This double difference is:

$$\Delta^r(\Delta^s(\phi_{1,1,1})) = \Delta^r(\phi_{1,2,1} - \phi_{1,1,1}) = \Delta^r(\phi_{1,2,1}) - \Delta^r(\phi_{1,1,1}) = (\phi_{2,2,1} - \phi_{1,2,1}) - (\phi_{2,1,1} - \phi_{1,1,1})$$

Triple differencing subtracts the receiver difference from time 1 from that of time 2. This eliminates the ambiguity associated with the integral number of wave lengths in carrier phase provided this ambiguity does not change with time. Thus the triple difference result eliminates practically all clock bias errors and the integer ambiguity. Atmospheric delay and satellite ephemeris errors have been significantly reduced. This triple difference is:

$$\Delta^t(\Delta^r(\Delta^s(\phi_{1,1,1})))$$

Triple difference results can be used to estimate unknown variables. For example if the position of receiver 1 is known but the position of receiver 2 unknown, it may be possible to estimate the position of receiver 2 using numerical root finding and least squares. Triple difference results for three independent time pairs quite possibly will be sufficient to solve for receiver 2's three position components. This may require the use of a numerical procedure. An approximation of receiver 2's position is required to use such a numerical method. This initial value can probably be provided from the navigation message and the intersection of sphere surfaces. Such a reasonable estimate can be key to successful multidimensional root finding. Iterating from three time pairs and a fairly good initial value produces one observed triple difference result for receiver 2's position. Processing additional time pairs can improve accuracy, overdetermining the answer with multiple solutions. Least squares can estimate an overdetermined system. Least squares determines the position of receiver 2 which best fits the observed triple difference results for receiver 2 positions under the criterion of minimizing the sum of the squares.

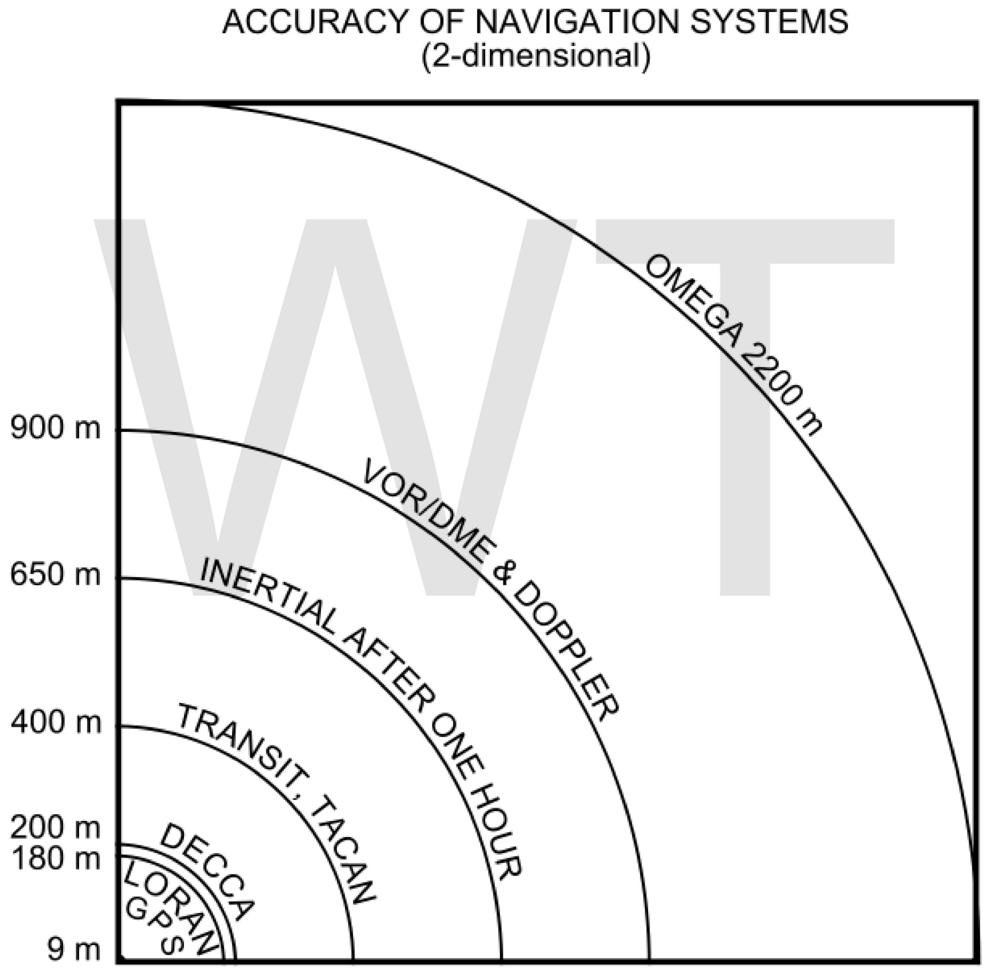
### *Other systems*

Other satellite navigation systems in use or various states of development include:

- Galileo – a global system being developed by the European Union and other partner countries, planned to be operational by 2014
- Beidou – People's Republic of China's regional system, covering Asia and the West Pacific
- COMPASS – People's Republic of China's global system, planned to be operational by 2020
- GLONASS – Russia's global navigation system
- IRNSS – India's regional navigation system, planned to be operational by 2012, covering India and Northern Indian Ocean
- QZSS – Japanese regional system covering Asia and Oceania

## Chapter 8

# Inertial Navigation System




An **inertial navigation system** (INS) is a navigation aid that uses a computer, motion sensors (accelerometers) and rotation sensors (gyroscopes) to continuously calculate via dead reckoning the position, orientation, and velocity (direction and speed of movement) of a moving object without the need for external references. It is used on vehicles such as ships, aircraft, submarines, guided missiles, and spacecraft. Other terms used to refer to inertial navigation systems or closely related devices include **inertial guidance system**, **inertial reference platform**, **inertial instrument**, and many other variations.

## *Overview*

An inertial navigation system includes at least a computer and a platform or module containing accelerometers, gyroscopes, or other motion-sensing devices. The INS is initially provided with its position and velocity from another source (a human operator, a GPS satellite receiver, etc.), and thereafter computes its own updated position and velocity by integrating information received from the motion sensors. The advantage of an INS is that it requires no external references in order to determine its position, orientation, or velocity once it has been initialized.

An INS can detect a change in its geographic position (a move east or north, for example), a change in its velocity (speed and direction of movement), and a change in its orientation (rotation about an axis). It does this by measuring the linear and angular accelerations applied to the system. Since it requires no external reference (after initialization), it is immune to jamming and deception.

Inertial-navigation systems are used in many different moving objects, including vehicles—such as aircraft, submarines, spacecraft—and guided missiles. However, their cost and complexity place constraints on the environments in which they are practical for use.

Gyroscopes measure the angular velocity of the system in the inertial reference frame. By using the original orientation of the system in the inertial reference frame as the initial condition and integrating the angular velocity, the system's current orientation is known at all times. This can be thought of as the ability of a blindfolded passenger in a car to feel the car turn left and right or tilt up and down as the car ascends or descends hills. Based on this information alone, he knows what direction the car is facing but not how fast or slow it is moving, or whether it is sliding sideways.

Accelerometers measure the linear acceleration of the system in the inertial reference frame, but in directions that can only be measured relative to the moving system (since the accelerometers are fixed to the system and rotate with the system, but are not aware of their own orientation). This can be thought of as the ability of a blindfolded passenger in a car to feel himself pressed back into his seat as the vehicle accelerates forward or pulled forward as it slows down; and feel himself pressed down into his seat as the vehicle accelerates up a hill or rise up out of his seat as the car passes over the crest of a hill and begins to descend. Based on this information alone, he knows how the vehicle is accelerating relative to itself, that is, whether it is accelerating forward, backward, left, right, up (toward the car's ceiling), or down (toward the car's floor) measured relative to the car, but not the direction relative to the Earth, since he did not know what direction the car was facing relative to the Earth when he felt the accelerations.

However, by tracking both the current angular velocity of the system and the current linear acceleration of the system measured relative to the moving system, it is possible to determine the linear acceleration of the system in the inertial reference frame. Performing integration on the inertial accelerations (using the original velocity as the initial conditions) using the correct kinematic equations yields the inertial velocities of the system, and integration again (using the original position as the initial condition) yields the inertial position. In our example, if the blindfolded passenger knew how the car was pointed and what its velocity was before he was blindfolded, and if he is able to keep track of both how the car has turned and how it has accelerated and decelerated since, he can accurately know the current orientation, position, and velocity of the car at any time.

## *Error*

All inertial navigation systems suffer from **integration drift**: small errors in the measurement of acceleration and angular velocity are integrated into progressively larger errors in velocity, which are compounded into still greater errors in position. Since the new position is calculated from the previous calculated position and the measured acceleration and angular velocity, these errors are cumulative and increase at a rate roughly proportional to the time since the initial position was input. Therefore the position must be periodically corrected by input from some other type of navigation system. The inaccuracy of a good-quality navigational system is normally less than 0.6 nautical miles per hour in position and on the order of tenths of a degree per hour in orientation.

Accordingly, inertial navigation is usually used to supplement other navigation systems, providing a higher degree of accuracy than is possible with the use of any single system. For example, if, in terrestrial use, the inertially tracked velocity is intermittently updated to zero by stopping, the position will remain precise for a much longer time, a so-called *zero velocity update*.

Control theory in general and Kalman filtering in particular, provide a theoretical framework for combining information from various sensors. One of the most common alternative sensors is a satellite navigation radio, such as GPS. By properly combining the information from an INS and the GPS system (GPS/INS), the errors in position and velocity are stable. Furthermore, INS can be used as a short-term fallback while GPS signals are unavailable, for example when a vehicle passes through a tunnel.

## *History*

Inertial navigation systems were originally developed for rockets. American rocket pioneer Robert Goddard experimented with rudimentary gyroscopic systems. Dr. Goddard's systems were of great interest to contemporary German pioneers including Wernher von Braun. The systems entered more widespread use with the advent of spacecraft, guided missiles, and commercial airliners.

Early German World War II V2 guidance systems combined two gyroscopes and a lateral accelerometer with a simple analog computer to adjust the azimuth for the rocket in flight. Analog computer signals were used to drive four external rudders on the tail fins for flight control. The GN&C (Guidance, Navigation, and Control) system for V2 provided many innovations as an integrated platform with closed loop guidance. At the

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end of the war Von Braun engineered the surrender of 500 of his top rocket scientists, along with plans and test vehicles, to the Americans. They arrived at Fort Bliss, Texas in 1945 under the provisions of Operation Paperclip and were subsequently moved to Huntsville, Alabama, in 1950 where they worked for U.S. military rocket research programs.

In the early 1950s, the US government wanted to insulate itself against over dependency on the German team for military applications. Among the areas that were domestically "developed" was missile guidance. In the early 1950s the MIT Instrumentation Laboratory (later to become the Charles Stark Draper Laboratory, Inc.) was chosen by the Air Force Western Development Division to provide a self-contained guidance system backup to Convair in San Diego for the new Atlas intercontinental ballistic missile (Construction and testing were completed by Arma Division of AmBosch Arma). The technical monitor for the MIT task was a young engineer named Jim Fletcher who later served as the NASA Administrator. The Atlas guidance system was to be a combination of an on-board autonomous system, and a ground-based tracking and command system. This was the beginning of a philosophic controversy, which, in some areas, remains unresolved. The self-contained system finally prevailed in ballistic missile applications for obvious reasons. In space exploration, a mixture of the two remains.

In the summer of 1952, Dr. Richard Battin and Dr. J. Halcombe "Hal" Laning, Jr., researched computational based solutions to guidance. Dr. Laning, with the help of Phil Hankins and Charlie Werner, initiated work on MAC, an algebraic programming language for the IBM 650, which was completed by early spring of 1958. MAC became the work-horse of the MIT lab. MAC is an extremely readable language having a three-line format, vector-matrix notations and mnemonic and indexed subscripts. Today's Space Shuttle (STS) language called HAL/S, (developed by Intermetrics, Inc.) is a direct offshoot of MAC. Since the principal architect of HAL was Jim Miller, who co-authored a report on the MAC system with Hal Laning, it is probable the Space Shuttle language is named for Laning and not, as some have suggested, for the electronic star of Stanley Kubrick's *2001: A Space Odyssey"*.

Hal Laning and Richard Battin undertook the initial analytical work on the Atlas inertial guidance in 1954. Other key figures at Convair were Charlie Bossart, the Chief Engineer, and Walter Schweidetzky, head of the guidance group. Schweidetzky had worked with Wernher von Braun at Peenemuende during World War II.

The initial Delta guidance system assessed the difference in position from a reference trajectory. A velocity to be gained (VGO) calculation is made to correct the current trajectory with the objective of driving VGO to zero. The mathematics of this approach were fundamentally valid, but dropped because of the challenges in accurate inertial guidance and analog computing power. The challenges faced by the Delta efforts were overcome by the Q system of guidance. The Q system's revolution was to bind the challenges of missile guidance (and associated equations of motion) in the matrix Q. The Q matrix represents the partial derivatives of the velocity with respect to the position vector. A key feature of this approach allowed for the components of the vector cross product to be used as the basic autopilot rate signals—a technique that became known as *cross-product steering*. The Q-system was presented at the first Technical Symposium on Ballistic Missiles held at the Ramo-Wooldridge Corporation in Los Angeles on June 21 and 22, 1956. The Q system was classified information through the 1960s. Derivations of this guidance are used for today's missiles.

## Guidance in Human spaceflight

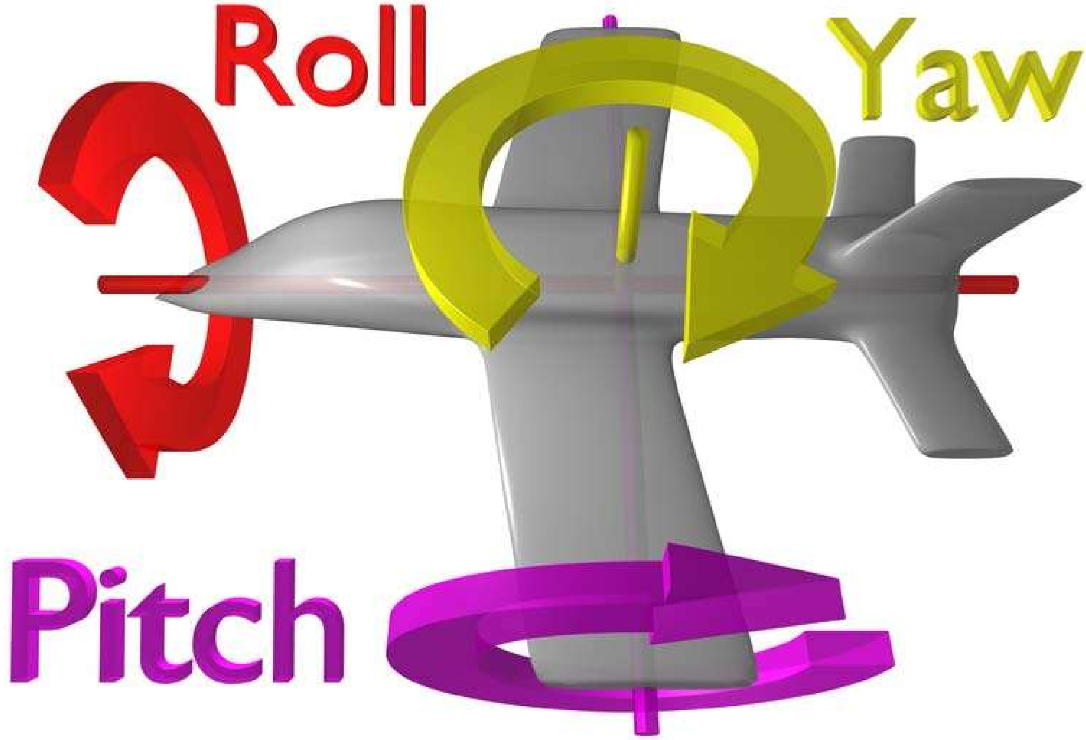
In Feb of 1961 NASA Awarded MIT a contract for preliminary design study of a guidance and navigation system for Apollo. MIT and the Delco Electronics Div. of General Motors Corp. were awarded the joint contract for design and production of the Apollo Guidance and Navigation systems for the Command Module and the Lunar Module. Delco produced the Inertial Measurement Units for these systems, Kollsman Instrument Corp. produced the Optical Systems, and the Apollo Guidance Computer was built by Raytheon under subcontract.

For the space shuttle, an open loop (no feedback) guidance is used to guide the shuttle from lift off until Solid Rocket Booster (SRB) separation. After SRB separation the primary space shuttle guidance is named PEG4 (Powered Explicit Guidance). PEG4 takes into account both the Q system and the predictor-corrector attributes of the original "Delta" System (PEG Guidance). Although many updates to the shuttle's navigation system have taken place over the last 30 years (ex. GPS in the OI-22 build), the guidance core of today's Shuttle GN&C system has evolved little. Within a manned system, there is a human interface needed for the guidance system. As Astronauts are the customer for the system, many new teams are formed that touch GN&C as it is a primary interface to "fly" the vehicle.

## Aircraft inertial guidance

One example of a popular INS for commercial aircraft was the Delco Carousel, which provided partial automation of navigation in the days before complete flight management systems became commonplace. The Carousel allowed pilots to enter a series of waypoints, and then guided the aircraft from one waypoint to the next using an INS to determine aircraft position and velocity. Boeing Corporation subcontracted the Delco Electronics Div. of General Motors to design and build the first production Carousel systems for the early models (-100, -200, and -300) models of the 747 aircraft. The 747 utilized three Carousel systems operating in concert for reliablility purposes. The Carousel system and derivatives thereof were subsequently adopted for use in many other commercial and military aircraft. The USAF C-141 was the first military aircraft to utilize the Carousel in a dual system configuration, followed by the C-5A which utilized the triple INS configuration, similar to the 747. The KC-135 fleet was fitted with a dual Carousel system that was aided by a Doppler radar.

***Inertial navigation systems in detail***



Inertial navigation unit of french IRBM S3

INSs have angular and linear accelerometers (for changes in position); some include a gyroscopic element (for maintaining an absolute angular reference).

Angular accelerometers measure how the vehicle is rotating in space. Generally, there's at least one sensor for each of the three axes: pitch (nose up and down), yaw (nose left and right) and roll (clockwise or counter-clockwise from the cockpit).

Linear accelerometers measure non-gravitational accelerations of the vehicle. Since it can move in three axes (up & down, left & right, forward & back), there is a linear accelerometer for each axis.

A computer continually calculates the vehicle's current position. First, for each of the six degrees of freedom (x,y,z and $\theta_x$, $\theta_y$ and $\theta_z$), it integrates over time the sensed acceleration, together with an estimate of gravity, to calculate the current velocity. Then it integrates the velocity to calculate the current position.

Inertial guidance is difficult without computers. The desire to use inertial guidance in the Minuteman missile and Project Apollo drove early attempts to miniaturize computers.

Inertial guidance systems are now usually combined with satellite navigation systems through a digital filtering system. The inertial system provides short term data, while the satellite system corrects accumulated errors of the inertial system.

An inertial guidance system that will operate near the surface of the earth must incorporate Schuler tuning so that its platform will continue pointing towards the center of the earth as a vehicle moves from place to place.

## *Basic schemes*

### Gimballed gyrostabilized platforms

Some systems place the linear accelerometers on a gimbaled gyrostabilized platform. The gimbals are a set of three rings, each with a pair of bearings initially at right angles. They let the platform twist about any rotational axis (or, rather, they let the platform keep the same orientation while the vehicle rotates around it). There are two gyroscopes (usually) on the platform.

Two gyroscopes are used to cancel gyroscopic precession, the tendency of a gyroscope to twist at right angles to an input force. By mounting a pair of gyroscopes (of the same rotational inertia and spinning at the same speed) at right angles the precessions are cancelled, and the platform will resist twisting.

This system allows a vehicle's roll, pitch, and yaw angles to be measured directly at the bearings of the gimbals. Relatively simple electronic circuits can be used to add up the linear accelerations, because the directions of the linear accelerometers do not change.

The big disadvantage of this scheme is that it uses many expensive precision mechanical parts. It also has moving parts that can wear out or jam, and is vulnerable to gimbal lock. The primary guidance system of the Apollo spacecraft used a three-axis gyrostabilized platform, feeding data to the Apollo Guidance Computer. Maneuvers had to be carefully planned to avoid gimbal lock.

### Fluid-suspended gyrostabilized platforms

Gimbal lock constrains maneuvering, and it would be beneficial to eliminate the slip rings and bearings of the gimbals. Therefore, some systems use fluid bearings or a flotation chamber to mount a gyrostabilized platform. These systems can have very high precisions (e.g., Advanced Inertial Reference Sphere). Like all gyrostabilized platforms, this system runs well with relatively slow, low-power computers.

The fluid bearings are pads with holes through which pressurized inert gas (such as Helium) or oil press against the spherical shell of the platform. The fluid bearings are very slippery, and the spherical platform can turn freely. There are usually four bearing pads, mounted in a tetrahedral arrangement to support the platform.

In premium systems, the angular sensors are usually specialized transformer coils made in a strip on a flexible printed circuit board. Several coil strips are mounted on great circles around the spherical shell of the gyrostabilized platform. Electronics outside the platform uses similar strip-shaped transformers to read the varying magnetic fields produced by the transformers wrapped around the spherical platform. Whenever a magnetic field changes shape, or moves, it will cut the wires of the coils on the external transformer strips. The cutting generates an electric current in the external strip-shaped coils, and electronics can measure that current to derive angles.

Cheap systems sometimes use bar codes to sense orientations, and use solar cells or a single transformer to power the platform. Some small missiles have powered the platform with light from a window or optic fibers to the motor. A research topic is to suspend the platform with pressure from exhaust gases. Data is returned to the outside world via the transformers, or sometimes LEDs communicating with external photodiodes.

## Strapdown systems

Lightweight digital computers permit the system to eliminate the gimbals, creating *strapdown* systems, so called because their sensors are simply strapped to the vehicle. This reduces the cost, eliminates gimbal lock, removes the need for some calibrations, and increases the reliability by eliminating some of the moving parts. Angular rate sensors called *rate gyros* measure how the angular velocity of the vehicle changes.

A strapdown system has a dynamic measurement range several hundred times that required by a gimbaled system. That is, it must integrate the vehicle's attitude changes in pitch, roll and yaw, as well as gross movements. Gimballed systems could usually do well with update rates of 50–60 Hz. However, strapdown systems normally update about 2000 Hz. The higher rate is needed to keep the maximum angular measurement within a practical range for real rate gyros: about 4 milliradians. Most rate gyros are now laser interferometers.

The data updating algorithms (*direction cosines* or quaternions) involved are too complex to be accurately performed except by digital electronics. However, digital computers are now so inexpensive and fast that rate gyro systems can now be practically used and mass-produced. The Apollo lunar module used a strapdown system in its backup Abort Guidance System (AGS).

Strapdown systems are nowadays commonly used in commercial and tactical applications (aircraft, missiles, etc.). However they are still not widespread in applications where superb accuracy is required (like submarine navigation or strategic ICBM guidance).

## Motion-based alignment

The orientation of a gyroscope system can sometimes also be inferred simply from its position history (e.g., GPS). This is, in particular, the case with planes and cars, where the velocity vector usually implies the orientation of the vehicle body.

For example, Honeywell's *Align in Motion* is an initialization process where the initialization occurs while the aircraft is moving, in the air or on the ground. This is accomplished using GPS and an inertial reasonableness test, thereby allowing commercial data integrity requirements to be met. This process has been FAA certified to recover pure INS performance equivalent to stationary align procedures for civilian flight times up to 18 hours. It avoids the need for gyroscope batteries on aircraft.

## Vibrating gyros

Less-expensive navigation systems, intended for use in automobiles, may use a vibrating structure gyroscope to detect changes in heading, and the odometer pickup to measure distance covered along the vehicle's track. This type of system is much less accurate than a higher-end INS, but it is adequate for the typical automobile application where GPS is the primary navigation system, and dead reckoning is only needed to fill gaps in GPS coverage when buildings or terrain block the satellite signals.

## Hemispherical Resonator Gyros (wine glass or mushroom gyros)

If a standing wave is induced in a hemispheric resonant cavity, and then the resonant cavity is rotated, the spherical harmonic standing wave rotates through an angle different than the quartz resonator structure due to the Coriolis force. The movement of the outer case with respect to the standing wave pattern is proportional to the total rotation angle and can be sensed by appropriate electronics. The system resonators are machined from quartz due to its excellent mechanical properties. The electrodes that drive and sense the standing waves are deposited directly onto separate quartz structures that surround the resonator. These gyros can operate in either a whole angle mode (which gives them nearly unlimited rate capability) or a force rebalance mode that holds the standing wave in a fixed orientation with respect to the gyro housing (which gives them much better accuracy).

This system has almost no moving parts, and is very accurate. However it is still relatively expensive due to the cost of the precision ground and polished hollow quartz hemispheres. Northrop Grumman currently manufactures Inertial Measurement Units for spacecraft that use HRGs. These IMUs have demonstrated extremely high reliability since their initial use in 1996.

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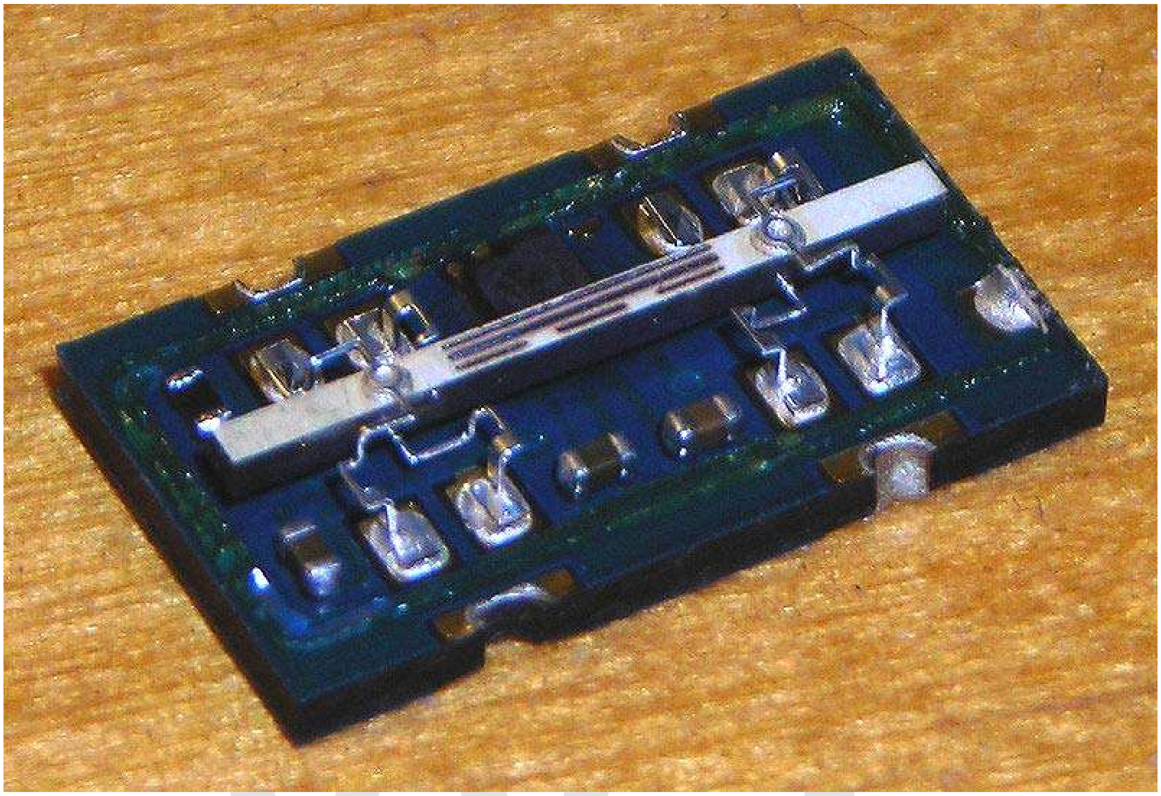
## Quartz rate sensors



The quartz rate sensor inside an E-Sky model helicopter

This system is usually integrated on a silicon chip. It has two mass-balanced quartz tuning forks, arranged "handle-to-handle" so forces cancel. Aluminum electrodes evaporated onto the forks and the underlying chip both drive and sense the motion. The system is both manufacturable and inexpensive. Since quartz is dimensionally stable, the system can be accurate.

As the forks are twisted about the axis of the handle, the vibration of the tines tends to continue in the same plane of motion. This motion has to be resisted by electrostatic forces from the electrodes under the tines. By measuring the difference in capacitance between the two tines of a fork, the system can determine the rate of angular motion.

These products include 'tuning fork gyros'. Gyro is designed as an electronically-driven tuning fork, often fabricated out of a single piece of quartz or silicon. Such gyros operate in accordance with the dynamic theory that when an angle rate is applied to a translating body, a Coriolis force is generated.

Current state of the art non-military technology (as of 2005) can build small solid state sensors that can measure human body movements. These devices have no moving parts, and weigh about 50 grams.

Solid state devices using the same physical principles are used for image stabilization in small cameras or camcorders. These can be extremely small (≈5 mm) and are built with Microelectromechanical systems (MEMS) technologies.

## MHD sensor

Sensors based on magnetohydrodynamic principles can be used to measure angular velocities.

## Laser gyros

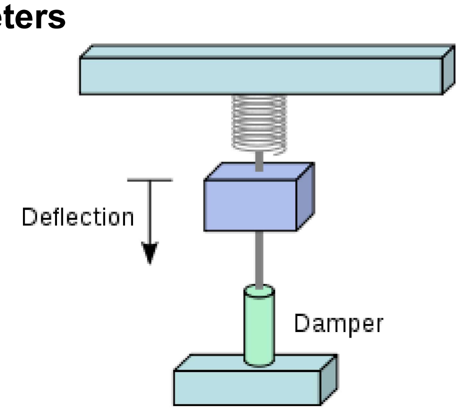
A ring laser gyro splits a beam of laser light into two beams in opposite directions through narrow tunnels in a closed optical circular path around the perimeter of a triangular block of temperature-stable Cervit glass with reflecting mirrors placed in each corner. When the gyro is rotating at some angular rate, the distance traveled by each beam becomes different—the shorter path being opposite to the rotation. The phase-shift between the two beams can be measured by an interferometer, and is proportional to the rate of rotation (Sagnac effect).

In practice, at low rotation rates the output frequency can drop to zero after the result of back scattering causing the beams to synchronise and lock together. This is known as a *lock-in*, or *laser-lock*. The result is that there is no change in the interference pattern, and therefore no measurement change.

To unlock the counter-rotating light beams, laser gyros either have independent light paths for the two directions (usually in fiber optic gyros), or the laser gyro is mounted on a piezo-electric dither motor that rapidly vibrates the laser ring back and forth about its input axis through the lock-in region to decouple the light waves.

The shaker is the most accurate, because both light beams use exactly the same path. Thus laser gyros retain moving parts, but they do not move as far.

## Pendular accelerometers



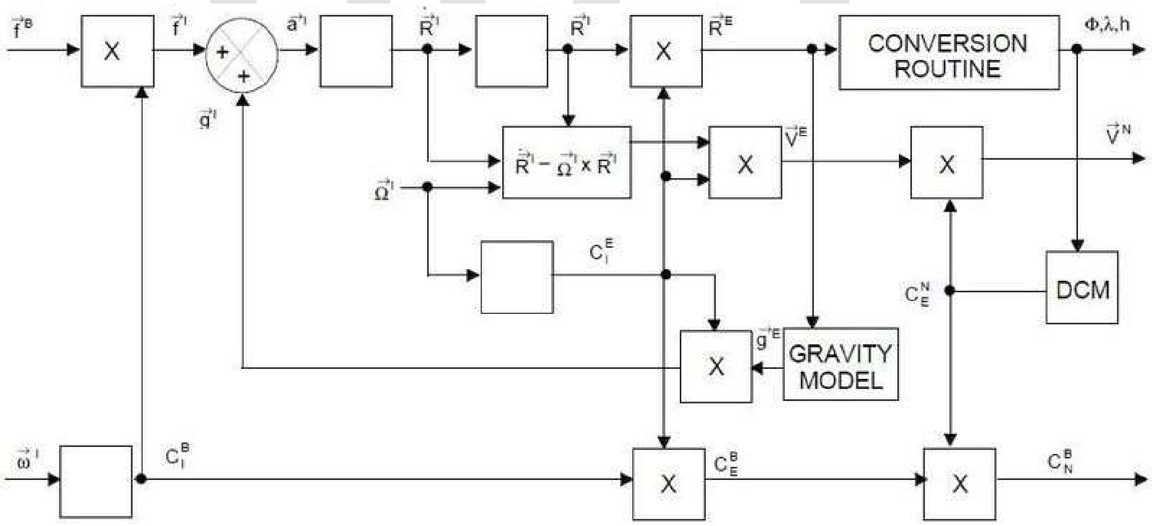

Principle of open loop accelerometer. Acceleration in the upward direction causes the mass to deflect downward.

The basic, open-loop accelerometer consists of a mass attached to a spring. The mass is constrained to move only in-line with the spring. Acceleration causes deflection of the mass and the offset distance is measured. The acceleration is derived from the values of deflection distance, mass, and the spring constant. The system must also be damped to avoid oscillation. A closed-loop accelerometer achieves higher performance by using a feedback loop to cancel the deflection, thus keeping the mass nearly stationary. Whenever the mass deflects, the feedback loop causes an electric coil to apply an equally negative force on the mass, cancelling the motion. Acceleration is derived from the amount of negative force applied. Because the mass barely moves, the non-linearities of the spring and damping system are greatly reduced. In addition, this accelerometer provides for increased bandwidth past the natural frequency of the sensing element.

Both types of accelerometers have been manufactured as integrated micromachinery on silicon chips.

## *Methodology*

In one form, the navigational system of equations acquires linear and angular measurements from the inertial and body frame, respectively and calculates the final attitude and position in the NED frame of reference.




Where: f is specific force, ω is angular rate, a is acceleration, R is position, $\dot{R}$and V are velocity, Ω is the angular velocity of the earth, g is the acceleration due to gravity, Φ,λ and h are the NED location parameters. Also, super/subscripts of E, I and B are representing variables in the Earth centered, Inertial or Body reference frame, respectively and C is a transformation of reference frames.

# Chapter 9

# 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.

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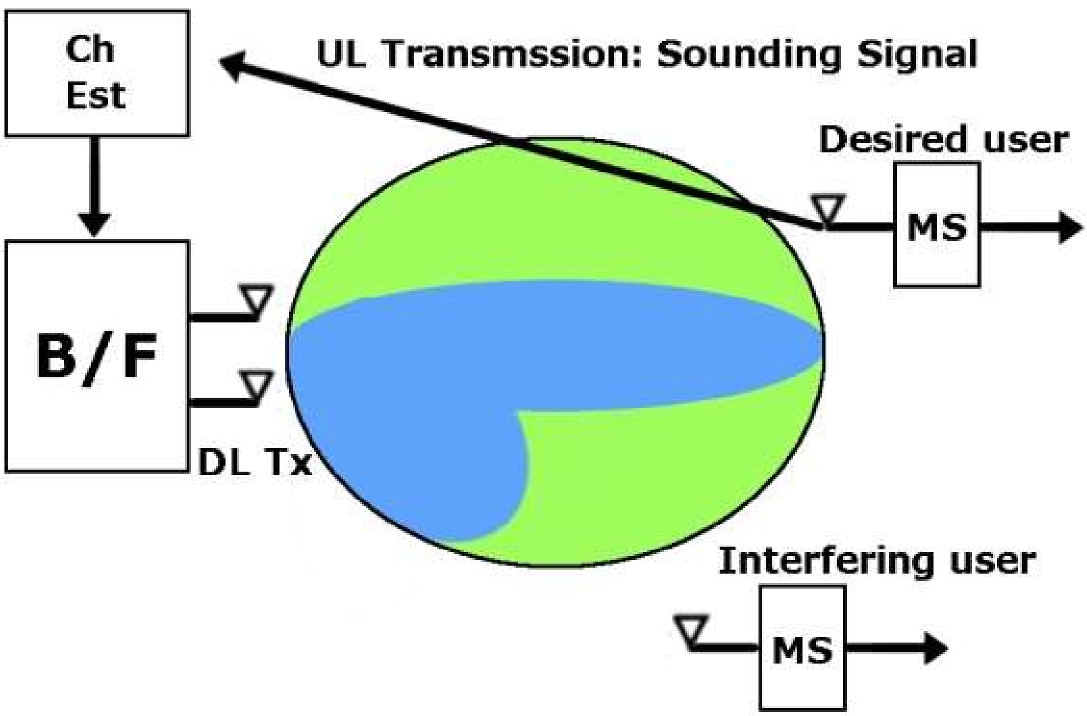
## Chapter 10

# 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 $\sigma_n^2$ 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

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# Chapter 11

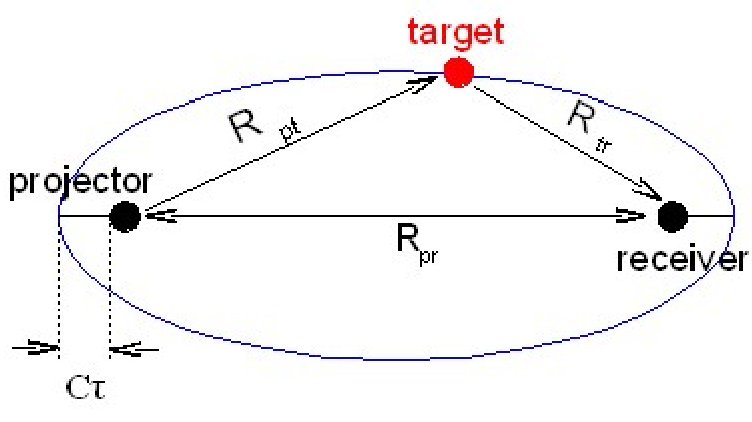
# Bistatic Sonar

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).

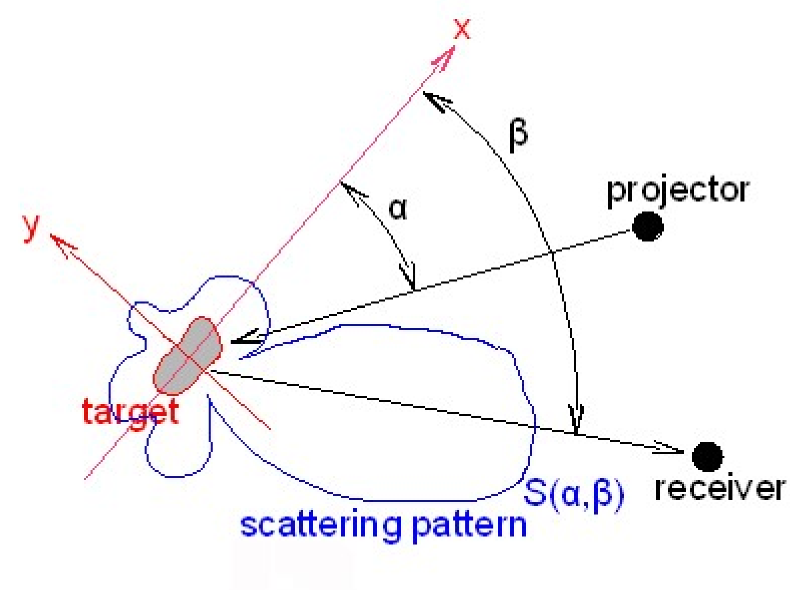



Bistatic sonar dead zone

## 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 $\tau$. That means targets are undetectable within the circle of $C\tau/2$ 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 $C\tau/2$ 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 $C\tau$ seconds. So the sonar cannot detect targets within the ellipse $R = Rpr + C\tau$, as shown at the picture. High level reverberation in the projector area does not affect the dead zone.




Target scattering pattern

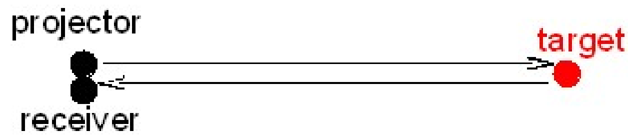
## Target scattering pattern

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 $\beta$ from which the target is ensonified by the projector, and it also varies with angle scattering direction $\alpha$ (refer to local target axes $Z\{x,y\}$). These angles are often referred to as aspects. This scattered sound level vs $(\alpha, \beta)$ function is called the scattering pattern $S(\alpha, \beta)$. Direction of maximum echo (maximum of $S(\alpha, \beta)$) also depends on target shape and inner structure. So sometimes the best ensonifying aspect is not the same as the best receive aspect.

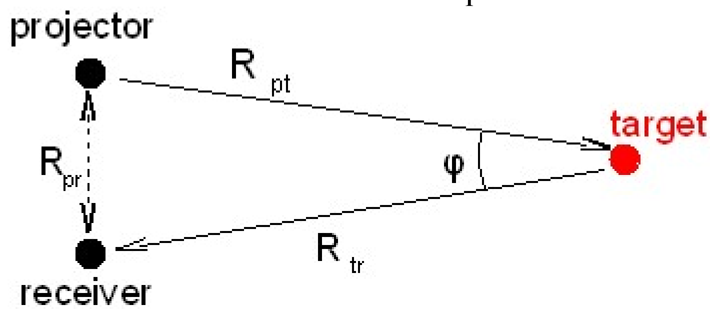
This leads to the bistatic solution. Target scattering becomes even more complicated if the target is buried (or semi-buried) into sea bottom sediments. (That happens to sea mines, waste containers, shipwrecks, etc.) In that case, the scattering mechanism is effected not by target features only, but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

## *Specific classes of bistatic sonars*

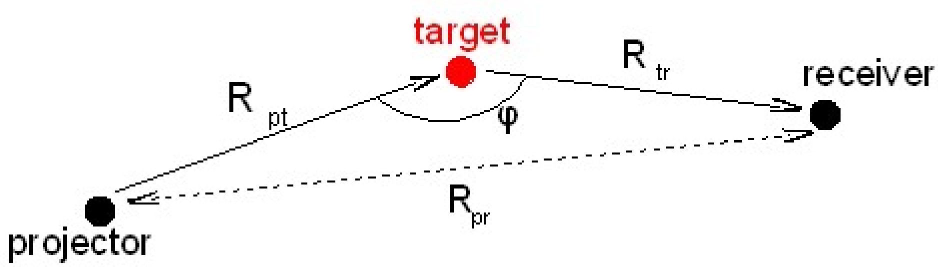
### Backscattering and forward scattering




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.

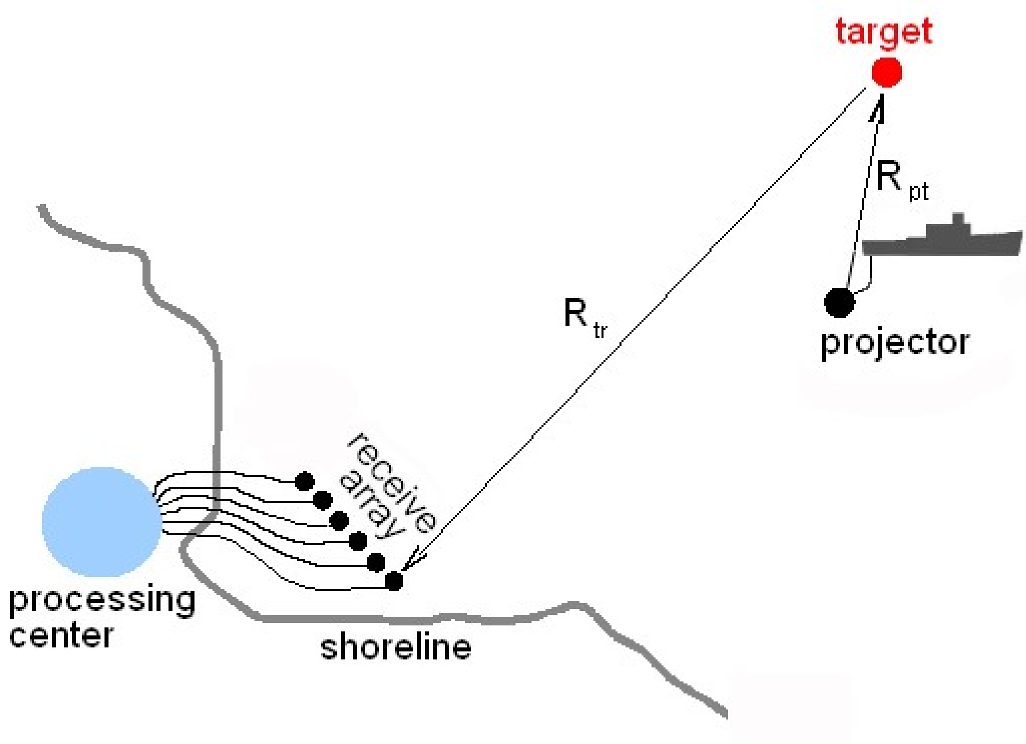
### Pseudo-monostatic sonar

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 $R_{pr}$.

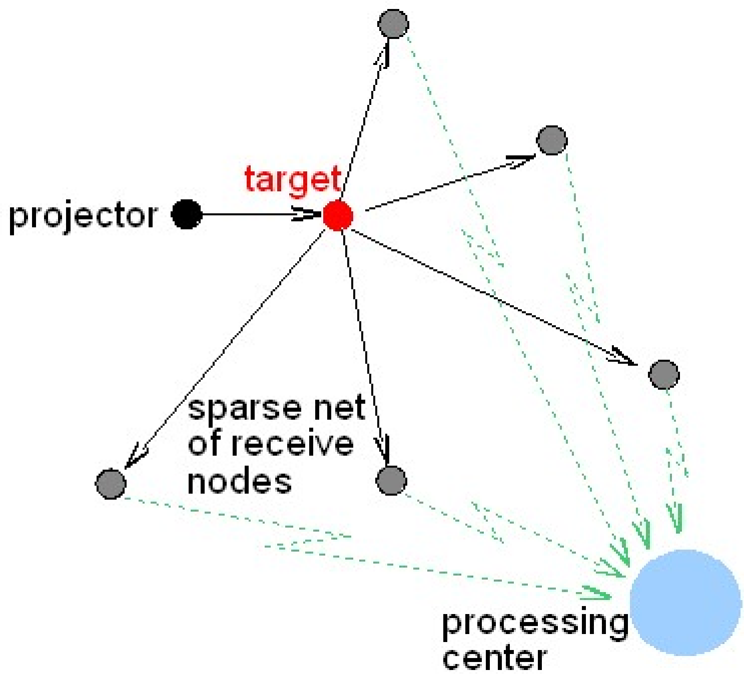
### Multistatic sonar

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

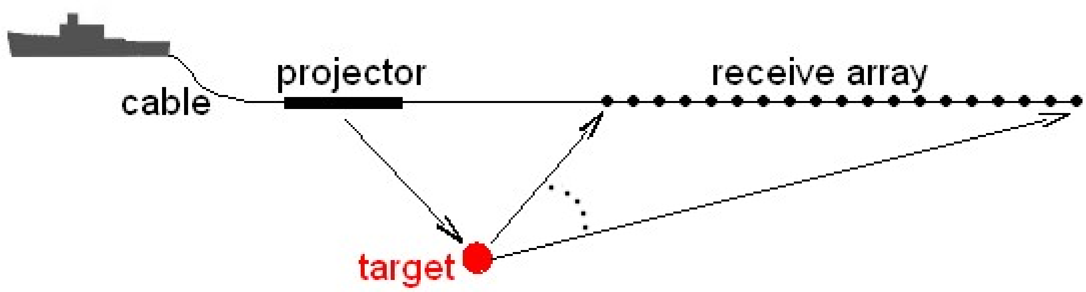
## *Applications*



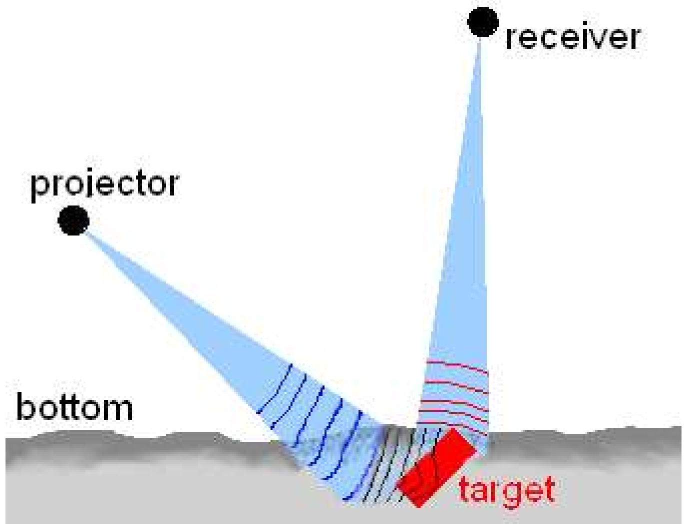

Long range surveillance




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

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## Chapter 12

# 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.

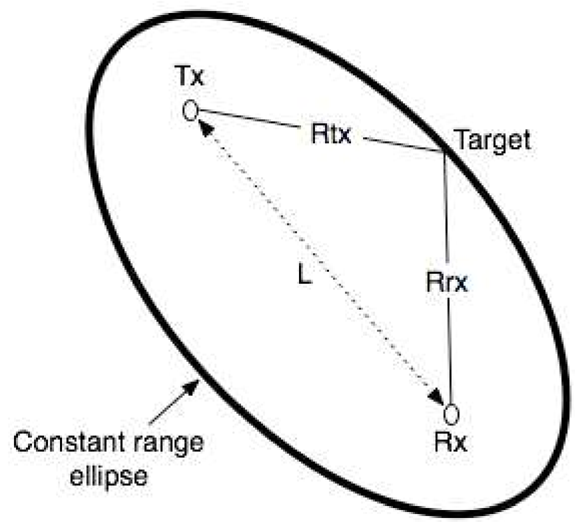
The creation of this device was motivated by a strongly-felt need to protect ships from collisions with obstacles and other ships.

### *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 13

# 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.

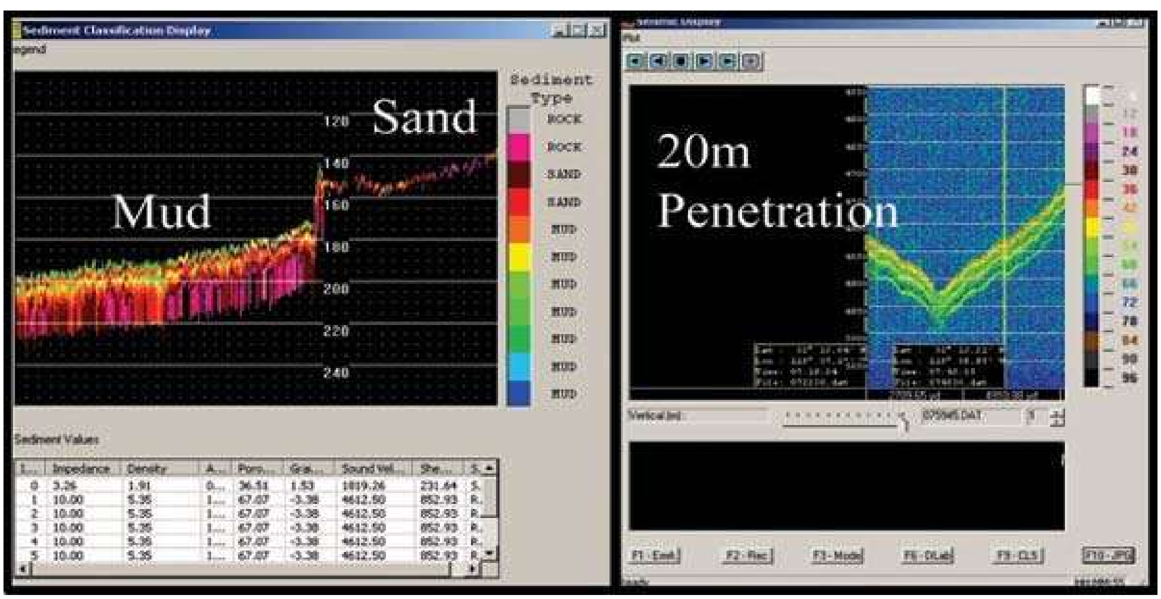
## Sea Bottom Measurement

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.

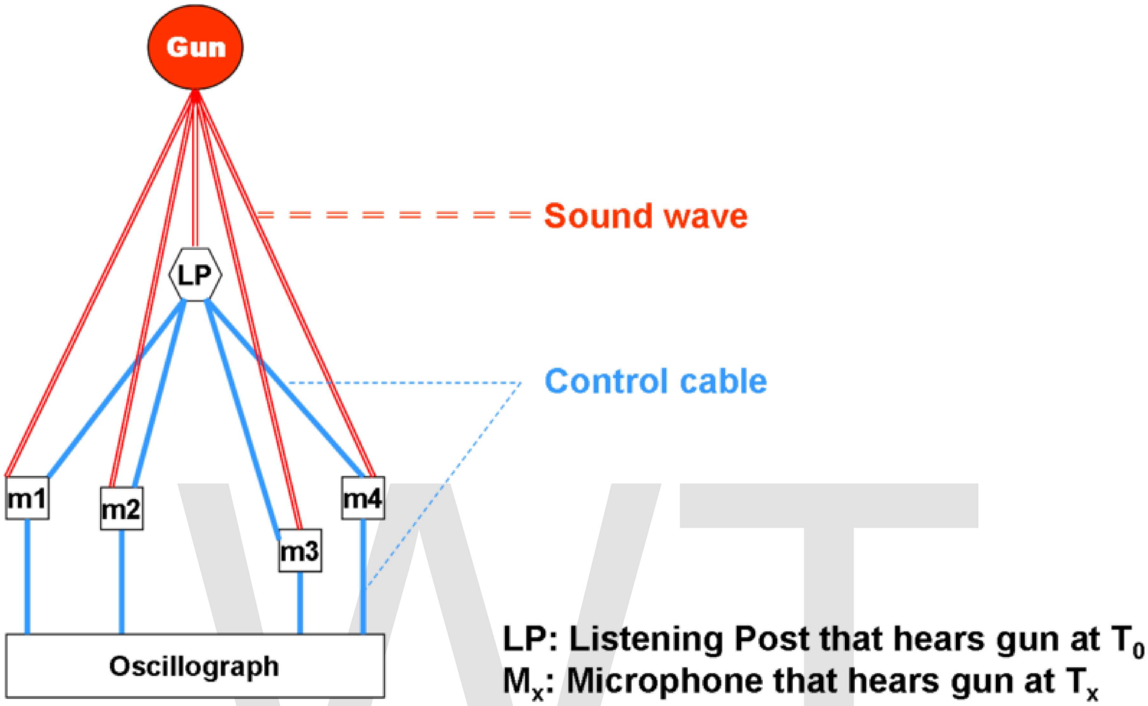
In shallow water, there are sufficient challenges to conventional acoustic sensors that additional MASINT sensors may be required. Two major confounding factors are:

- 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.

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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.

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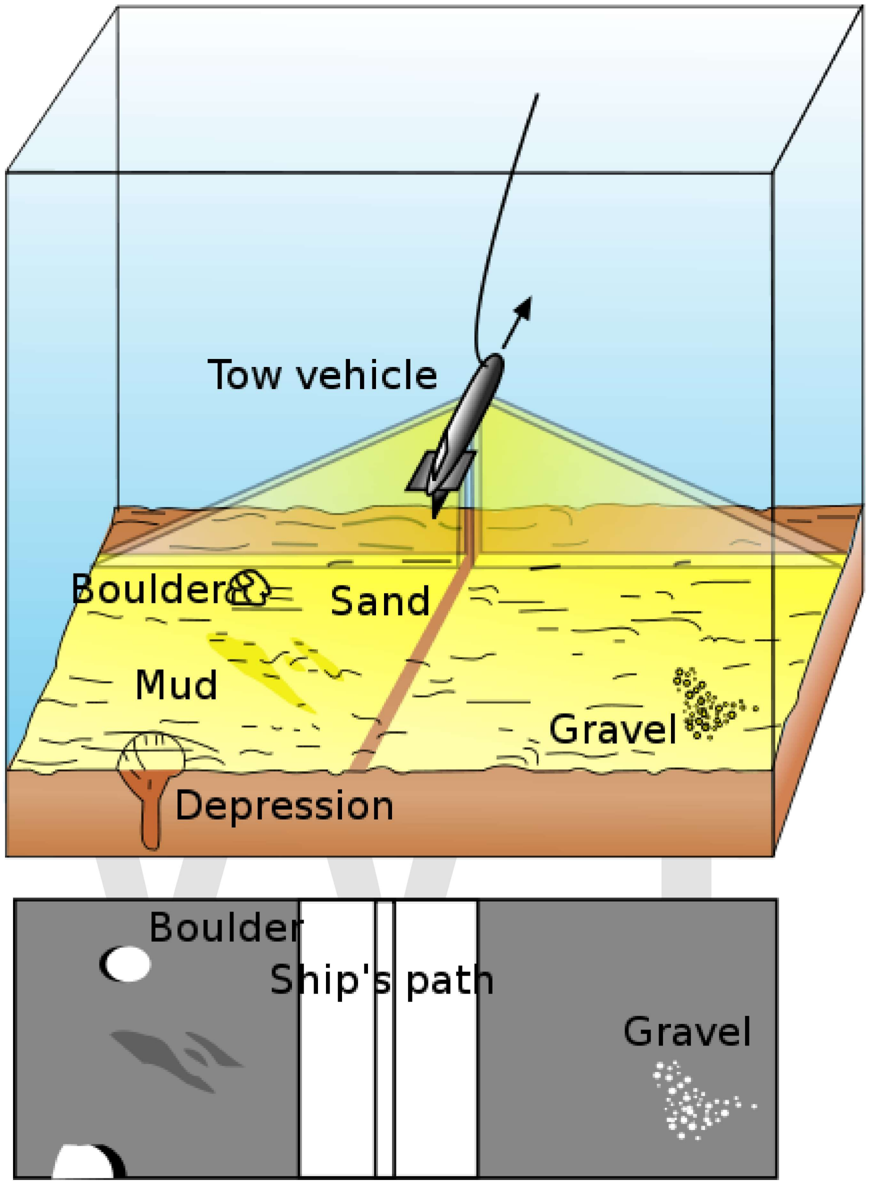


Diagram of sidescan sonar with towed probe, higher performance than multibeam ship-mounted but comparable

### *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.

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### 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:

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- **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

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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.

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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

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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.

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# Chapter 14

# 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.

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## *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.*<br><br>*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

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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

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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 |
|---|---|---|---|
| 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. | Neo Tapon 2002 exercise and MFA |

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| | | | |
|---|---|---|---|
| | | (3) stranded | |
| 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 $\mu Pa^2$ 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 15

# 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

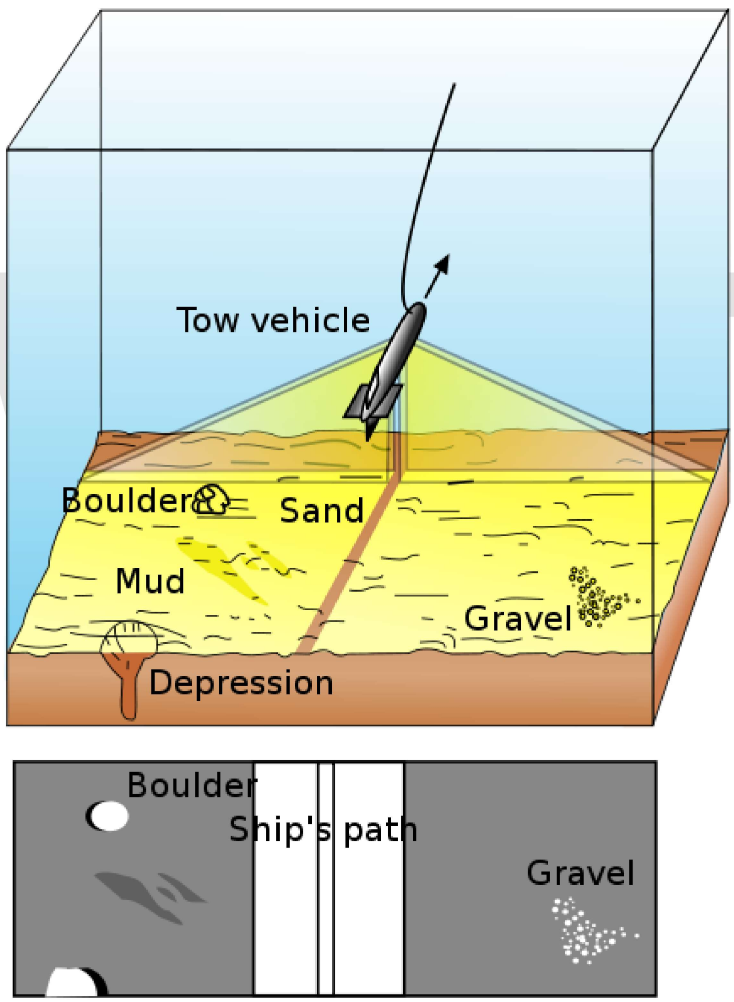
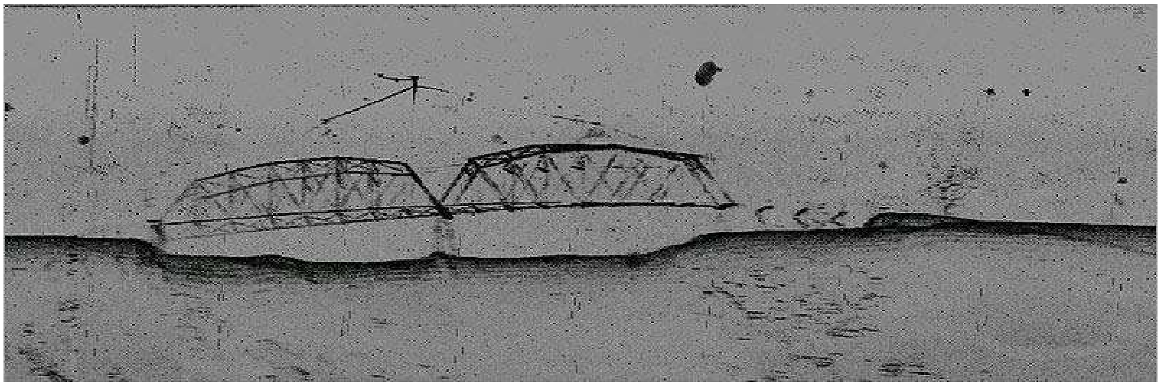



Diagram of sidescan sonar



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

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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.

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## Chapter 16

# 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.

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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.

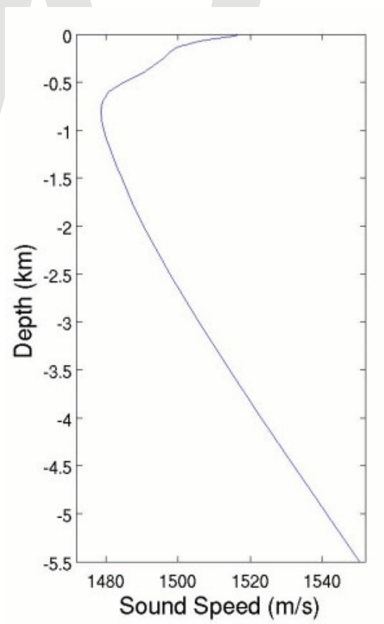
## Noise sources

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 17

# 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.

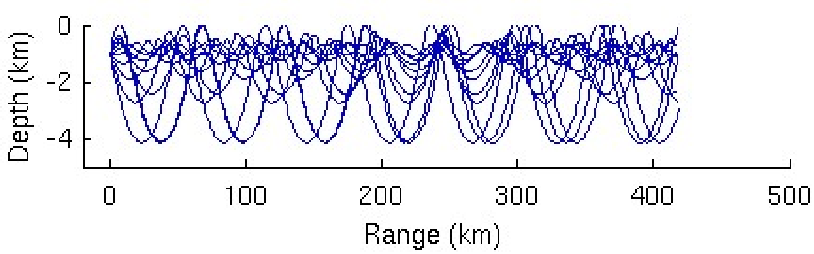
Sound propagates in the channel by refraction of sound, which makes sound travel near the depth of slowest speed. If a sound wave propagates away from this horizontal channel, the part of the wave furthest from the channel axis travels faster, so the wave turns back toward the channel axis. As a result, 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

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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

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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.

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