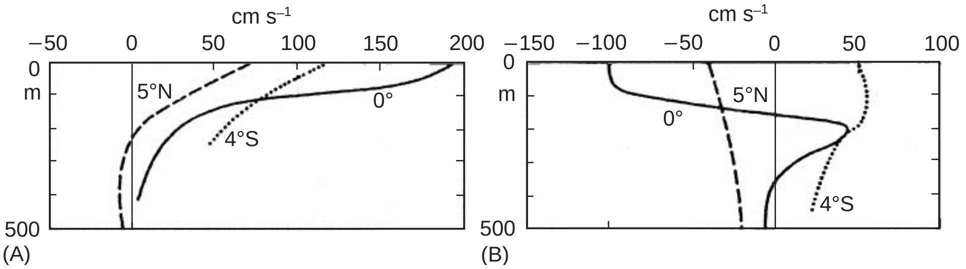

Figure 10 Current profiles for different seasons at 4°S, on the Equator, and at 5°N: (A) for summer monsoon; (B) for winter monsoon. (Reprinted from *Deep Sea Research*, 37(12), F. Schott *et al.*, 1990, The Somali Current at the equator: annual cycle of currents and transports in the upper 1000 m and connection to neighbouring latitudes, 1825–11848, copyright 1990, with permission from Elsevier Science).

Somali current that the highest variability as well as the highest current speeds in the world ocean are found.

See also

Current Systems in the Indian Ocean. Elemental Distribution: Overview. Indian Ocean Equatorial Currents. Thermohaline Circulation. Water Types and Water Masses. Wind Driven Circulation.

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SONAR SYSTEMS

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Introduction and Short History

Sonar (Sound Navigation and Ranging) systems are the primary method of imaging and communicating within the ocean. Electromagnetic energy does not propagate very far since it is attenuated by either absorption or scattering – visibility beyond 100 m is exceptional. Conversely, sound propagates very well in the ocean especially at low frequencies; consequently, sonars are by far the most important systems used by both man and marine life within the ocean for imaging and communication.

Sonars are classified as being either active or passive. In active systems an acoustic pulse, or more typically a sequence of pulses, is transmitted and a receiver processes them to form an ‘image’ or to decode a data message if operating as a communication system. The image can be as simple as the presence of a discrete echo or as complex as a visual picture. The receiver may be coincident with the transmitter – a monostatic system, or separate – a bistatic system. Both the waveform of the acoustic pulse and the beamwidths of both the transmitter and receiver are important and determine the performance of an active system. One typically associates an active sonar with the popular perception of sonar systems. Many marine mammals use active sonar for navigation and prey localization, as well as communication in ways which we are still attempting to understand. Many of the signals used by modern sonars have some of the same features as those of marine mammals.

Passive systems only receive. They sense ambient sound made by a myriad of sources in the ocean such as ships, submarines, marine mammals, volcanoes. These systems have been, and still are, especially important in anti-submarine warfare (ASW) where stealth is an important issue, and an active ping would reveal the location of the source.

The use of sound for detecting underwater objects was first introduced in a patent by Richardson in June 1912 for the 'sonic detection of icebergs,' 2 months after the sinking of the *Titanic*.[1] This was soon followed by the development of the Fessenden oscillator in 1914 which eventually led to the development of fathometers, an acoustic system for measuring the depth to the seabed. The French physicist/chemist Paul Langevin was the first to detect a submarine using sonar in 1918, motivated by the extensive damage of German U-boats. Between World Wars I and II both Britain and the US sponsored sonar research, especially on transducers. The former was conducted under the Antisubmarine Detection Investigation Committee, or ASDIC as sonar is still often referred to within the British military, and the latter was performed at the Naval Research Laboratory.

The re-emergence of the German U-boat stimulated the modern era of sonars and the physics of sound propagation in the ocean where major research programs were chartered in the USA (Columbia, Harvard, Scripps Institution of Oceanography, Woods Hole Oceanographic Institution), UK, and Russia. A very comprehensive summary was compiled by the US National Defense Research Council after World War II, which still remains a valuable reference (*see* Further Reading Section).

The development of the nuclear submarine, both as an attack boat (SSN) or as a missile carrier (SSBN) provided a major emphasis for sonar throughout the cold war. The USA, UK, Russia, and France all had substantial research programs on sonar for many applications, but ASW certainly had a major priority. The nuclear submarine could deny use of the oceans but could also unleash massive destruction with nuclear missiles. With the end of the cold war, ASW now has a lower priority; however, the submarine still remains the platform of choice for many countries since modern diesel/electric submarines operating on batteries are extremely hard to detect and localize. Undoubtedly, the most extensively used reference was compiled by Urick (1975), which is frequently referenced as a handbook for sonar engineers.

While military operations have dominated the development of sonars, they are now used extensively for both scientific and commercial applications. The use of fathometers and closely related seismic methods provided much of the important data validating plate tectonics. There is also a lot of overlap between geophysical exploration for hydrocarbons and modern sonars. High resolution and multibeam systems are extensively used for charting the seabed and its sub-bottom characteristics, fish finding, current measurements exploiting Doppler, as well as archaeological investigations.

Active Sonar systems

The major components of an active system are indicated in **Figure 1**. A waveform generator forms a pulse or 'ping', which is then modulated, or frequency shifted, to an operating frequency, f_o which may be as low as tens of Hertz for very long-range systems, or as high as 1 MHz, for high resolution short-range imaging sonars. Next, the signal is often 'beamformed' by an array of transducers, that focuses the signal in specific directions either by mechanically rotating the array or by introducing appropriate time delays or phase shifts. The signals are amplified and then converted from an electrical signal to a sound wave by the transmit transducers. Efficient transduction, the conversion of electric power to sound power, and even a modest amount of directivity of the transmitter requires that the transducer have dimensions on the scale of the wavelength of the operating frequency; hence, low frequency transmitters are typically large and not very efficient, whereas high frequency transmitters are smaller and very efficient.

The pinging rate, usually termed the pulse repetition frequency (PRF) is determined by the duration over which strong echos (called 'returns') from the previously transmitted pulse can be expected, so that one return does not overlap and become confused with another. With some systems with well confined response durations, several pulses may be in transit at the same time.

The ocean introduces three important components before it is detected by a receiver.

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[1] Much of this material in the history has been extracted from Beyer, 1999.

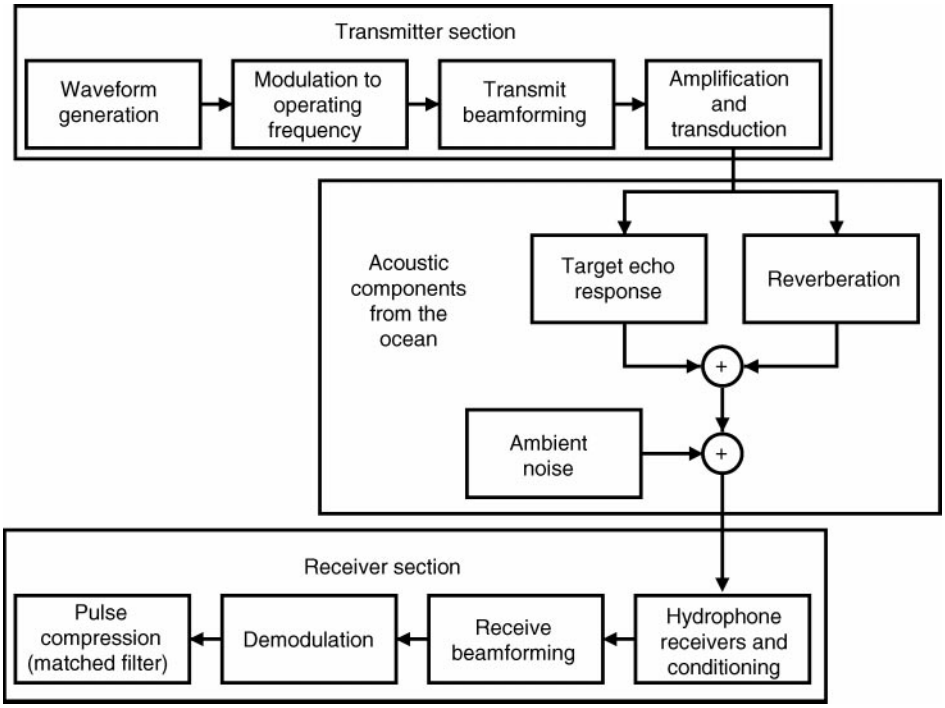

Figure 1 Active sonar system components.

- There is the desired echo from the target itself. This may be a simple echo, especially if the target is close, but it may also include many multipaths and/or modes as a result of reflections of the ocean surface and bottom as well as paths refracted completely within the ocean itself (*see* **Acoustics, Deep Ocean**).
- The ocean is filled with spurious, or unwanted reflectors which produce reverberation. The dominant source of this is the sea bottom, but the sea surface and objects (e.g. fish) can be important as well. Typically, the bottom is characterized in terms of a scattering strength per unit area insonified.
- Finally, the ocean is filled with ambient noise which is created by both natural and man-made sources. At low frequencies, 50–500 Hz, shipping tends to dominate the noise in the Northern Hemisphere, especially near shipping lanes. Wind and wave processes as well as rain can also be important. In specific areas, marine life may be a very important component.

The sonar receiver implements operations similar to the transmitter. Hydrophones convert the acoustic signal to an electric one whereupon it usually undergoes some ‘signal conditioning’ to amplify it to an appropriate level. In modern sonars the signal is digitized, since most of the subsequent operations are more easily implemented by digital signal processors. Next, a receiver beamformer, which may be quite different from the transmitter, focuses energy arriving from specific directions for spatial imaging. This is also done either by mechanically steering the array or by introducing time delays or phase shifts (if the processing is done in the frequency domain). The signal is then usually demodulated to a low frequency band which simplifies further electronics and signal processing steps. Finally it is ‘pulse compressed,’ or ‘matched filtered,’ which is a process that maximizes energy arriving at the travel time that corresponds to the range to a target. The matched filter is simply a correlation operation which seeks the best replica of the transmitted signal among all the signal components introduced by the ocean. In the simplest form of processing a sequence of ‘pings’ is rastered, i.e. the echo time-series are displayed one after the other, to construct an image. This is typical of a sidescan sonar system. In more sophisticated systems, especially those operating at low frequencies where phase coherence can be preserved or extracted, a sequence of outputs from the pulse compression filter is processed to form images. This is typical of synthetic aperture sonars. In both types of systems display algorithms, sometimes termed ‘normalizers,’ are important for emphasizing certain features by improving contrast and controlling the dynamic range of the output.

The performance of an active sonar system is captured in the active sonar equation; while imperfect in its details, it is very useful in assessing gross performance. It is expressed in logarithmic units, or decibels which are referenced to a standard level. For a monostatic system it is:

$$SE = SL - 2*TL + TS - \max(NL, RL) + DI_t + AG_r - DT$$

where[2,3] SE, is the signal excess at the receiver output; SL, is the source level referenced to a pressure level of 1 μPa; TS, is the target strength, which is a function of aspect angle; NL, is the level of the ambient noise at a single hydrophone; RL, is the reverberation which is determined by the area insonified, the scattering strength, and the signal level; DI_t, is the directivity index of the transmitter, which is a measure of the gain compared omnidirectional radiation; AG_r, is the array gain of the receiver in the direction of the target (often this is described as a receiver); directivity index, DI_r; DT, is the direction threshold for a target to be seen on the output display (this can be a complicated function of the complexity of the environment and the sophistication of an operator); TL, is the transmission loss, i.e. the loss in signal energy as it transmits to the target and returns. If the $SE > 0$, then a target is discernible on a display.

The notation max(NL, RL) distinguishes the two important regimes for an active sonar. When $NL > RL$, the sonar is operating in a noise-limited environment; conversely, when $RL > NL$ the environment is reverberation-limited which is the case in virtually all applications.

Reverberation is the result of unwanted echoes from the sea surface, seafloor, and volume. In the simplest formulation its level for surfaces both bottom and top is usually characterized by a scattering strength per unit area, so the level is given by the product of the resolved area multiplied by the scattering strength (or sum if using a decibel formulation). Often, the Rayleigh parameter $\frac{2\pi\sigma_s}{\lambda}\sin(\phi)$ is used, where σ_s is the rms surface roughness and ϕ is the incident angle as a measure of when surface roughness becomes important, i.e. when the Rayleigh parameter is greater than 1. Similarly with volume scattering, a scattering strength per unit volume is used.

The operating frequency of a sonar is an important parameter in its design and performance. The important design issues are:

- Resolution. There are two aspects of resolution – 'cross-range' resolution and 'in range' resolution. 'Cross-range' resolution is determined by the dimensions of the transmit and receive apertures relative to the wavelength, λ, of the acoustic signal.[4] It is given by $R\lambda/L$ where R is the range and L is the transmitter and/or receiving aperture. Higher resolution requires higher operating frequencies since these result in smaller $R\lambda/L$ ratios.

'In range' resolution is determined by the bandwidth of the signal and is given approximately by $c/2W$, where W is the available bandwidth and c is the sonar speed. Since W is usually proportional to the operating frequency, f_o, one tends to try to use higher frequencies, which limits practical ranges. Also the sonar channel is often very band-limited. As a result in most sonar systems the 'in range' resolution is typically significantly smaller than the 'cross-range' resolution, so care needs to be taken in interpreting images.

- Maximum operating range. Acoustical signals can propagate over very long ranges, but there are a number of phenomena which can both enhance and attenuate the signal power. These include the geometrical spreading, the stratification of the sound speed versus depth, absorption, and scattering processes. The first two are essentially independent of frequency while the latter two have strong dependencies. **Figure 2** indicates the absorption loss in dB km^{-1} of sound at 20° and 35 apt salinity.[5] Essentially, the absorption loss factor increases quadratically with frequency. The two 'knees' in the figure relate to the onset of losses introduced by ionic relaxation phenomena. The net implication is that efforts are made to minimize the operating frequency so that it contributes < 10 dB of loss for the desired range, i.e $\alpha(f_o)R < 10$ where $\alpha(f_o)$ is attenuation per unit distance in dB.

The penalty of this, however, is a less directive signal, so it is more difficult to avoid contact with the ocean boundaries and consequent scattering

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[2] There are many versions of the sonar equation and the nomenclature differs among them (see Urick, 1975).

[3] If the system is bistatic wherein the transmitter and receiver are not colocated, then the sonar equation is significantly more complicated (Cox, 1989).

[4] The wavelength in uncomplicated media is given by $\lambda = c/f_o$, where c is the sound speed, nominally 1500 m s^{-1} and f_o is the operating frequency.

[5] db km^{-1} represents 10 log of the fractional loss in power per kilometer representing an exponential decay versus range.

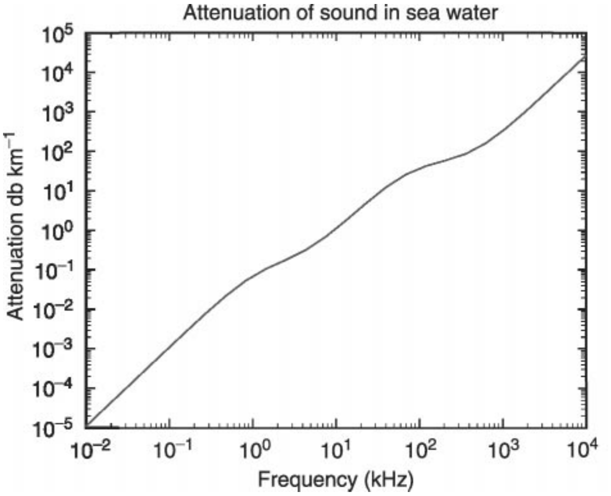

Figure 2 Attenuation of sound vs frequency.

losses, especially the bottom is shallow-water environments. As a result, the actual operating frequency of a sonar is a compromise based on the sound speed profile, the directivity of transmitter, receiver beamformers, and desired operating range and isolation.

- Target cross-section. The physics of sound reflecting from a target can be very complicated and there are few exact solutions, most of which involve long, complicated mathematical functions. In addition, the geometry of the target can introduce a significant aspect dependence. The important scaling number is $2\pi a/\lambda$ where a is a characteristic length scale presented to the incoming sound wave. Typically, if the number is less than unity, the reflected target strength depends upon the fourth power of frequency, so the target strength is quite small; this is the so-called Rayleigh region of scattering. Conversely, if this number is larger than unity, the target strength normalized by the presented area is typically between 1 and 10. There are two additional features to consider: (i) large, flat surfaces lead to large returns, often termed specular, and (ii) in a bistatic sonar, the forward scattering, essentially the shadow, is determined almost solely by the intercepted target shape, often called Babinet's principle.

The net effect is a desire for higher operating frequencies in order to stay in the Rayleigh region where there is significant target strength.

Overall high frequencies produce better resolution and higher target strengths. However, at high frequencies acoustic propagation is more complicated and absorption limits the range.

Table 1 indicates the operating frequencies of some typical active sonars.

Sonar System Components

The components in **Figure 1** all have significant impact on the performance of an active sonar. The signal processing issues are complex and there is a large sonar-related literature as well as radar where the issues are similar. The essential problem is to separate a target amidst the reverberation and ambient noise in either of two operating realms – 'noise-limited' and 'reverberation'-limited environments. In a 'noise-limited' environment the ambient background noise limits the performance of a system, so increasing the transmitter output power improves performance. A 'reverberation-limited' environment is one where the noise is composed of mostly unwanted reflections from objects other than the target, so increasing the transmitted power simply increases both the target and reverberation returns simultaneously with no net gain in signal to noise ping. Most active sonars operate in a reverberation limited environment. Effective design of an active sonar depends upon controlling reverberation through a combination of waveform design and beamforming.

Table 1 Features of some typical active sonars

Sonar system	*Operating frequency range*	*Wavelength*	*Nominal range*
Long-range, low frequency	50–500 Hz	30–3 m	1000 km
Military ASW sonars	3–4 kHz	0.5–0.75 m	100 km
Bottom-mapping echosounders	3–4 kHz	0.5–0.75 m	vertical
High-resolution fathometers	10–15 kHz	15–10 cm	vertical
Acoustic communications	10–30 kHz	15–5 cm	10 km
Sidescan sonar (long-range)	50–100 kHz	6–1.5 cm	5 km
Sidescan sonar (short range)	500–1000 kHz	3–1.5 mm	100 m
Acoustic localization nets	10–20 kHz	15–5 cm	vertical
Fish-finding sonars	25–200 kHz	6–1 cm	1–5 km
Recreational	100–250 km	15–6 mm	vertical

Waveform design There are two basic approaches to waveform design for resolving targets – 'range gating' and 'Doppler gating.' The simplest approach to 'range gating' is a short, high powered pulse. This essentially resolves every reflector and an image is constructed by successive pulses and then the returns are rastered. While this is the simplest waveform it has limitations when operating in environments with high noise and reverberation levels, since the peak power of most sonars, both man-made and marine mammal, is limited. This shortcoming can often be mitigated by exploiting bandwidth (resolution α'/β). This has led to a large literature on waveform design with the most popular being frequency modulated (FM) and coded (PRN) signals. With these signals[6] the center frequency is swept, or 'chriped' across a frequency band at the transmitter and correlated, or 'compressed' at the receiver. This class of signals is commonly used by marine mammals including whales and dolphins for target localization.

'Doppler gating' is based on differences in target motion. A moving target imparts a Doppler shift to the reflected signal which is proportional to operating frequency and the ratio v/c, where v is the target speed and c is the sound speed. 'Doppler gating' is particularly useful in some ASW contexts since it is difficult to keep a submarine stationary, thus a properly designed signal, one that resolves Doppler, can distinguish it against a fixed reverberant background. The ability to resolve Doppler frequency depends upon the duration of a signal, with a dependence of 1/duration, so good 'Doppler gating' waveforms are long.

There has been a lot of research on the topic of optimal waveform design. Ideally, one wants a waveform which can resolve range and Doppler simultaneously which implies long duration, and wide bandwidth. These requirements are difficult to satisfy simultaneously.

Beamforming Both the transmitter and the receiver beamformers provide spatial resolution for the sonar system. The angular resolution in degrees is approximately $\Delta\theta \approx 60\frac{\lambda}{L}$, where λ is the wavelength and L is the aperture length. Since acoustic wavelengths are large when compared with optical wavelengths, the angular resolutions tend to be large especially at low frequencies.[7] Beamformers, often termed array processors in receivers, have been an important research topic for several decades with the advent of digital signal processing which permitted increasingly more sophistication, especially in the realm of adaptive methods. One of the simplest transmit beamformers consists of a line array of transducers each radiating the same signal. The simple receiver and also a line of transducers adds all the signals together. This resolves the paths perpendicular or broadside to the array. If one wants to 'steer' the array, or resolve another direction, the array must be mechanically rotated. This method of beamforming is still used by many systems since it is quite robust. Another simple beamformer is a planar array of transducers.

Digital signal processing has led to more sophisticated array processing, especially for receivers. Beamformers which steer beams electronically by introducing delays, or phase shifts, shape beams to control sidelobes, place nulls to control strong reflectors, and reduce jamming are now practical because these features can be practical electronically rather than mechanically.

Examples of Active Sonar Images

This section describes two examples of sonars used for mapping seafloor bathymetry. In the first the sonar is carried on an unmanned underwater vehicle (UUV) close to the seafloor. The operating frequency is 675 kHz and the beam is mechanically steered from port to starboard as well as fore and aft as the UUV proceeds along its track, so the beams are steered forward and directly below the UUV (**Figure 3**). The onset time of the first echo return is the parameter of interest. It is converted to the depth of the seafloor after including the vehicle position, the direction of the beam and possibly refraction effects in the water itself. Usually straight-line acoustic propagation is assumed.

The signals are combined to generate a high resolution map of the seafloor. The processing to achieve this includes editing for spurious responses, registration of the rasters or images from successive transmission using the navigation sensors on the UUV (or more generally any vehicle) and normalization to improve the contrast so that weak features can be detected amidst strong ones.

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[6] Pseudo Random Noise (PRN) are coded signals which appear to be random noise. Well designed signals have useful mathematical constructs which led to good outputs at the output of the pulse compression, or matched filter, processor.

[7] Sonars with angular resolutions of 1° are generally considered to have high resolution. Compare this with that of the human eye with a nominal diameter of 4 mm and the wavelength of light in the visible region is 0.4 μm leading to a resolution scale of 0.1 ms.

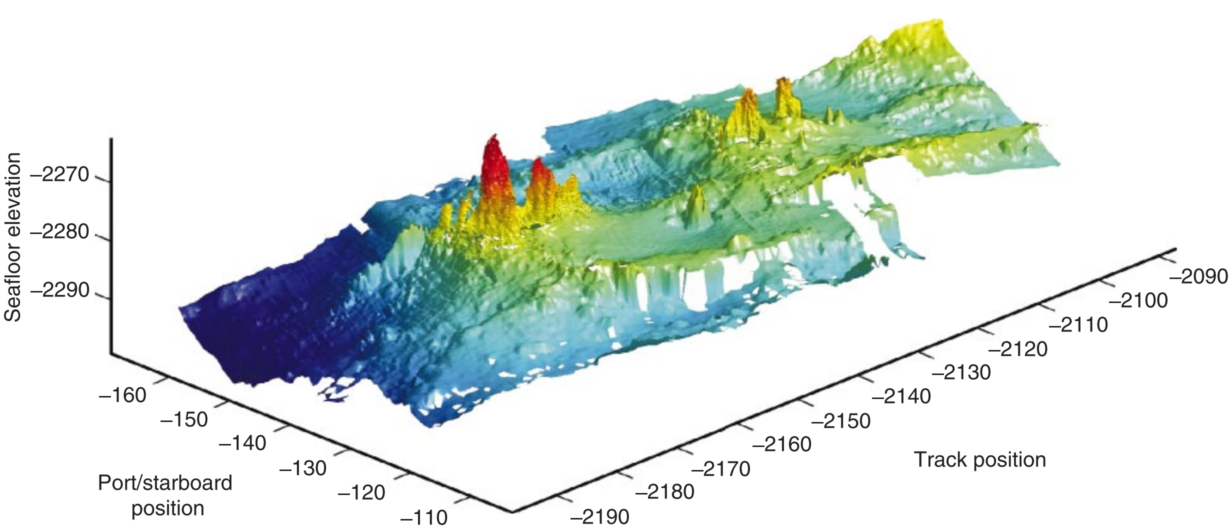

Figure 3 Image with forward-looking and down-looking sonar. (Figure courtesy of Dr Dana Yoerger, Woods Hole Oceanographic Institution.)

The second example of an active sonar is a multibeam bathymetric mapper. Most of these systems for deep water operate at a 12 kHz center frequency. The transmit beam is produced by a linear array running fore to aft along the bottom of the ship, thwartships beam, which produces a swath which resolves the seafloor along track (**Figure 4**). The receiver array is oriented port to starboard. The signals from this array are beamformed electronically, so the seafloor is resolved port to starboard within the transmitted swath, since the patch is the product of the transmit and receive beamwidth. This configuration allows two-dimensional resolution with two linear arrays instead of a full planar array. The depths from each of the multibeams are measured by combining the travel time and the ray refraction from the sound speed profile to obtain a depth. Subsequent processing edits anomalous returns and interpolates all the data to generate the contour map. Active sonar systems with additional features have been developed for special applications, but they all use the basic principles described above.

Passive Sonars

Passive sonars that only listen and do not transmit are used in a variety of applications including the military for antisubmarine warfare (ASW), tracking and classification of marine mammals, earthquake detection, and nuclear test ban monitoring.

Since the signals are passive there is no pulse compression, or matched filtering, so a passive sonar design primarily focuses upon the 'short-term' frequency wavenumber spectrum, or the directional spectrum and the power density spectrum and how it evolves in time. The data are nonstationary and inhomogeneous, but many of the processing algorithms are based upon stationary and homogeneous assumptions; hence the term 'short-term.' The performance of a passive system is characterized by the passive sonar equation:

$$SE = SL - TL - NL + AG_r - DT$$

where the terms are essentially the same as for an active sonar. In some applications the arrays are so large that the coherence of the received signal is important, and it is necessary to separate the array gain, AG_r into two terms, or:

$$AG_r = AG_{r,n} - SGD_s$$

where $AG_{r,n}$ is the array gain against the ambient noise and SGD_s is the signal gain degradation due to lack of coherence. $SGD_s = 0$ for a signal that is coherent across the entire array.

Passive Sonar Beamforming

The signals received by the sonar's hydrophone are preconditioned, which might include editing bad data channels, calibration, and filtering. They are then beamformed, either in the time domain by introducing delays to compensate for the travel time across the array, or in the frequency domain. With digital signals the former usually requires upsampling or interpolation of the data to avoid distortion.

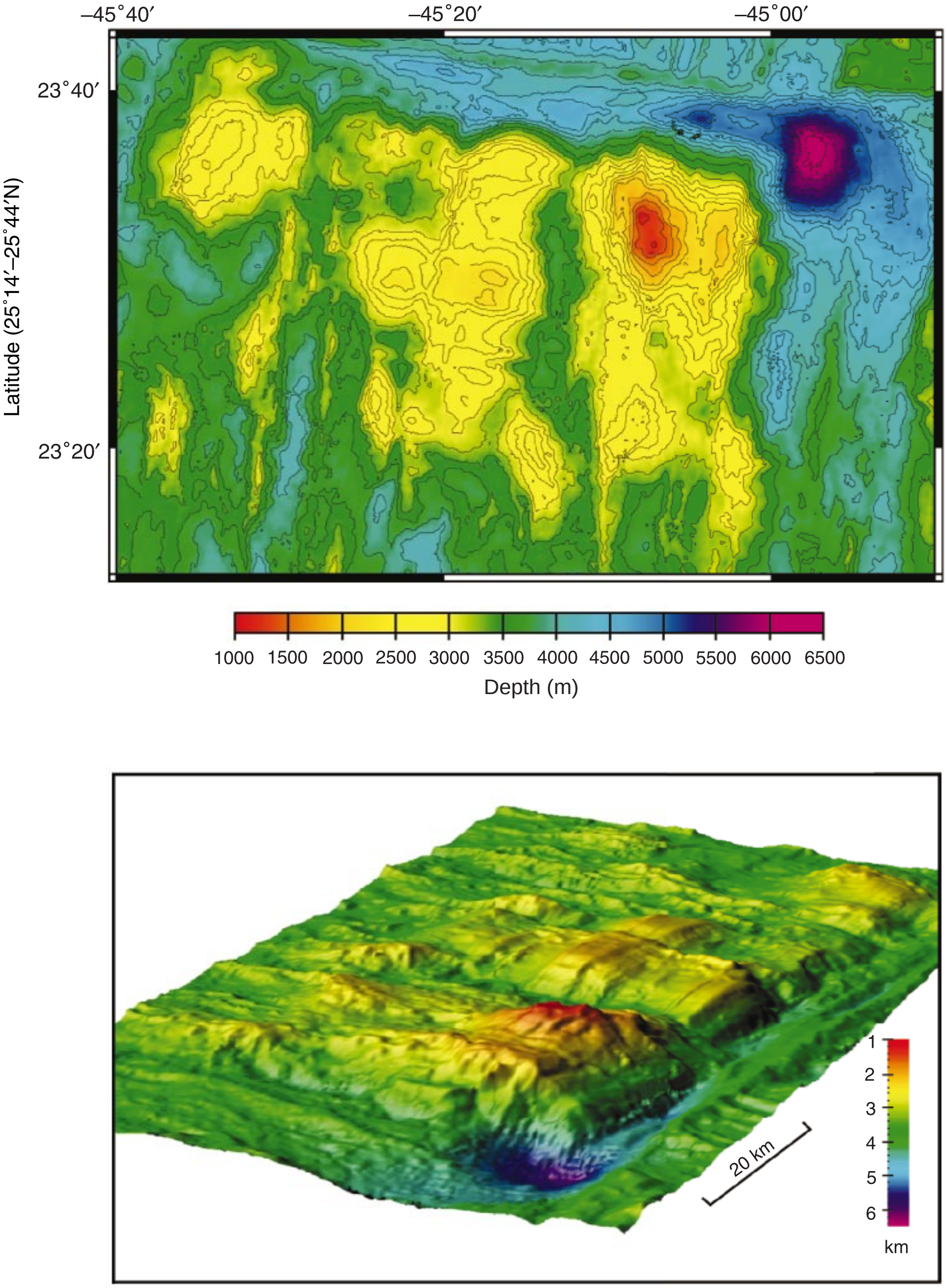

Figure 4 High resolution bathymetric map of the seafloor near the Mid-Atlantic Ridge: (A) contour map; (B) isometric projection (from top-right). (Figures courtesy of Dr Brian Tucholke, Woods Hole Oceanographic Institution.)

The latter is accomplished by FFT (fast Fourier transforms), phase shifting to compensate for the delays, and then IFFT (inverse fast Fourier transforming). Frequency domain beamforming allows simpler implementation of adaptive techniques that are useful in cases where the ambient field has many discrete components. Adaptive algorithms form beams with notches, i.e. poor response in the direction of interferers, thereby suppressing them. Many algorithms have been designed to accomplish this, but the MVDR (minimum variance distortion filter – first introduced by Capon) and related algorithms have been used most extensively in practice.

Passive Sonar Display Formats

The output of the beamformer is a time-series for each beam. In certain applications the time-series itself may be of interest, however, in most cases the

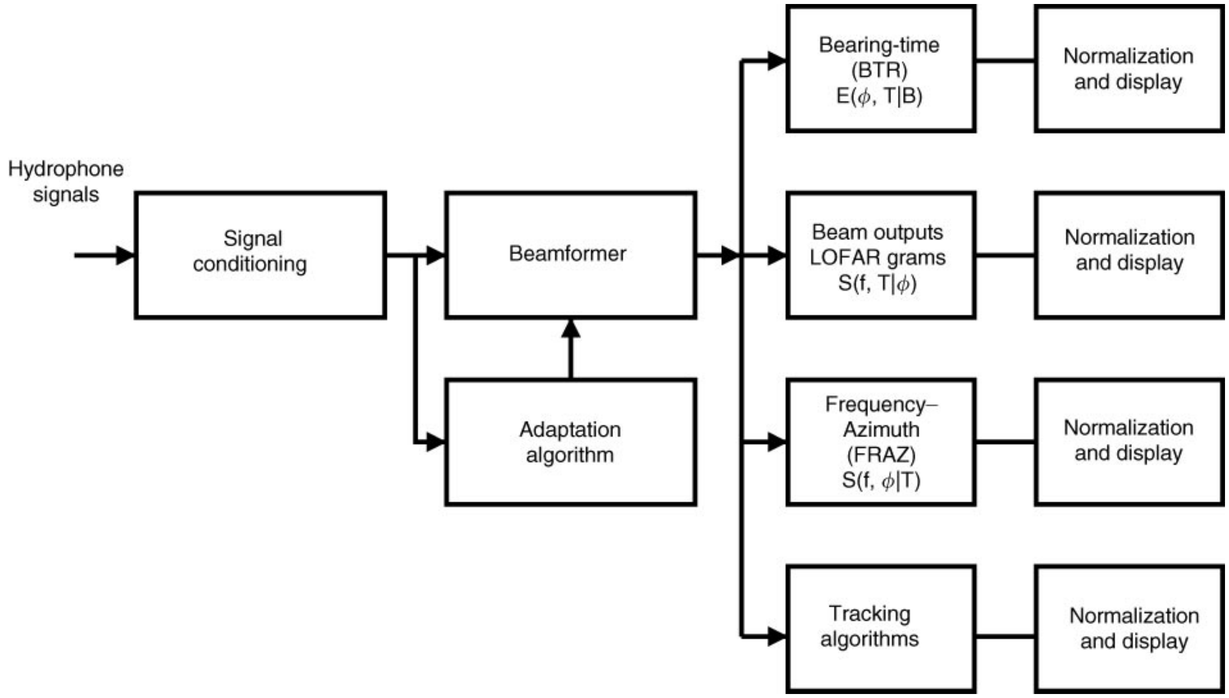

Figure 5 Passive sonar with modes of displaying output.

time-series is further processed to assist in extracting weak signals from the background noise. The parameter for signal processing schemes and display formats includes time (the epoch for data processing, T), angle (azimuth and elevation), and frequency (the spectral content of the data) (**Figure 5**).

Bearing-time Recording

Bearing time processing takes the beam outputs over a specified frequency band and plots the output versus time. Two modes of processing are often used: (i) energy detection, which forms an average of the beam outputs, or (ii) cross-correlation detection, where the array is split at the beamformer and then the two outputs are cross-correlated versus the direction. The processing is often classified according to the width of the band used, passive broadband (PBB) or passive narrowband (PNB).

The data for each time epoch are normalized to improve the contrast for signals of interest and each raster is plotted. Over a sequence of epochs, the directional components in the ambient field which are associated with shipping are observed. By maneuvering the array one can triangulate to obtain a range to each source as well.

Low Frequency Acoustic Recording and Analysis (LOFAR) grams Once a bearing or direction of interest has been determined, spectral analysis of the selected beam is used to produce a LOFAR gram, which is a plot of the signal spectrum for each analysis epoch, T, versus time. By examining the features of the LOFAR gram, such as frequency, peaks, harmonic signals, and their changes as a function of time, the source of the signal and some of its characteristics, such as speed, can be deduced. As in the case of the bearing-time display, the LOFAR gram is normalized to enhance features of interest.

FRAZ displays Frequency-azimuth, or FRAZ displays plot the spectral content as a function of frequency and azimuth for each epoch, T. Often a number of FRAZ outputs are averaged to improve signal to noise. FRAZ displays allow connection of the spectral content of a single source along a given bearing since the display contains a number of lines for each source at a given azimuth. As with the previous display, normalization algorithms to improve contrast are usually employed.

Trackers The objective of an ASW passive sonar is to detect, classify and track sources of radiating sound. Trackers are used to follow sources through direction and frequency space. There are a number of tracking algorithms build upon various signal models. Some separate the direction and frequency dimensions while others are coupled models. Since the ambient field can often have a number of sources, some targets and some interferers and since there are complicated propagation effects, the design of trackers is difficult. Most involve some form of Kalman filtering and some have integral propagation models.

Advanced beamforming

Most passive sonars are based upon a plane wave model for the ambient field components. Plane wave beamforming is robust, has several computational advantages, and is well understood. However, in many sonars this model is not adequate because the arrays are so long that wavefront curvature becomes an issue or the arrays are used vertical where acoustic propagation introduces multipaths. Advanced beamforming concepts can address these issues.

Wavefront curative becomes important when the target is in the near field of the array (usually given by the Fresnel number $2L^2/\lambda$) which is a consequence of either very long arrays or high frequencies. A quadratic approximation to the curvature is often used and the array is actually designed to focus it at specific range (rather than at infinite range which is the case for plane waves). When focused at short ranges, long-range targets are attenuated. This introduces the focal range as another parameter for displaying the sonar output.

At long ranges and low frequencies or in shallow water acoustic signals have complex multipath or multimode propagation which leads to coherent interference along a vertical array or a very long horizontal array. The appropriate array processing is to determine the full field Green's function for the signal and match the beamforming to it, a technique known as matched field processing (MFP). MFP requires knowledge of the sound speed profile along the propagation path, so its performance depends upon the accuracy of environmental data. It is a computationally intensive process, but has the powerful advantage of being able to resolve both target depth and range, as well as azimuth. MFP is an active subject of passive sonar research.

See also

Acoustic Scattering by Marine Organisms. Acoustics, Deep Ocean. Acoustics, Shallow Water.

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SOUTHERN OCEAN FISHERIES

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History

The history of harvesting living resources in the Southern Ocean goes back two centuries. Soon after South Georgia was discovered by Captain Cook, hunters arrived in search of fur seals (*Arctocephalus gazella*). Between 1801 and 1822, over 1 200 000 skins were taken there before the sealers moved on to the South Shetlands. The extent of the carnage was such as to bring the species close to extinction by the 1870s. In the early twentieth century elephant seals (*Mirounga leonina*) were harvested at South Georgia because their blubber provided higher-grade oil than that from whales. A strong management regime was instituted in 1952, which allowed the population to recover from earlier overexploitation. Elephant seals were also harvested at Macquarie Island, although there was less of a link to the whaling industry.

Whaling has been the largest fishing operation in the Southern Ocean. Initially this was shore-based but, with the introduction of floating factories in 1925, catching vessels could search much of the