SONAR SYSTEMS FOR SEA BED IMAGING[1]

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ABSTRACT: A review of the operation and capabilities of various undersea sonar systems, including synthetic aperture sonar, the seismic profiler, and parametric sonar.

1. INTRODUCTION

Discovering the secrets of the sea has been a long-sought aim for decades, yet surprisingly few of these secrets have been revealed despite determined efforts by scientists and engineers using a variety of techniques. This paper is more concerned with the sea-bed than the sea itself because the sea-bed and the underlying sediments hold further secrets that present an even greater challenge to investigate. One way to study the sea-bed is to lower a television camera and observe it directly, but this may yield little information other than to give an idea of the topography, the presence or absence of sea life, or the location of debris such as wrecks.

If the camera is mounted on a remotely operated vehicle (ROV) or on an autonomous underwater vehicle (AUV), it is possible to cover a large area and therefore to build up a better impression of what the sea-bed looks like. The problem with a camera is that it can only be used very close to the sea-bed, which usually involves an expensive operation to place it there, and in turbid water its use is ineffective.

Another way to study the sea-bed is to deploy an underwater acoustic system, generally referred to as a sonar, an acronym for SOund Navigation And Ranging that has now crept into general usage. Many types of sonar systems have been designed for exploring and surveying the sea-bed and for identifying and characterising sediments. All of them are active systems, because they operate in both transmit and receive modes, as distinct from passive systems that only work in receive mode. They are classified here under two main categories, 'non-penetrating' and 'penetrating'. The main feature of a non-penetrating system is that all the acoustic energy incident at the sea-bed is scattered, some of which is intercepted by a receiving transducer or array. Processing the received signals can yield some kind of 'image' of the sea-bed. This may be a 'one-dimensional' depth profile, ie the topography along a particular line, or a 'two-dimensional' plan view showing the presence, shape and orientation of natural features or objects. The main feature of a penetrating system is that some of the incident energy is scattered and some is transmitted into the sea-bed to be subsequently scattered from sub-bottom interfaces or absorbed. Processing the received signals in this case is much more complicated but can lead to a 'two-dimensional' sub-bottom profile, ie a sectioned view of the sea-bed and the underlying structure. Examples of non-penetrating systems are the conventional depth sounder, side-scan sonar, sector-scan sonar (which can be mechanically or electronically scanned), 'multi-beam' phased array sonar and synthetic aperture sonar. Examples of penetrating systems are the sub-bottom profiler, seismic profiler and parametric sonar.

Even the simplest type of sonar system, a conventional echo sounder, may be used to profile the sea-bed, something that can not be done conveniently with a camera. All that is necessary is to traverse the area of interest, transmit short pulses of sound vertically downwards and detect the echoes. The 'round trip' flight time of each pulse, from the instant it is emitted to the reception of its echo, when multiplied by the average velocity of sound in the water, gives the depth at some location. Modern echo sounders, as well as displaying the instantaneous depth numerically, provide a graphical display of the sea-bed profile along the track of the vessel. Depending on the frequency of operation and its power output, the sounder may also produce echoes from under the sea-bed, but is not usually suitable for studying the nature of the underlying sediments.

More sophisticated types of sonar may be used to produce two-dimensional images of the sea-bed. These include the side-scan sonar, the sector-scan sonar and the multi-beam phased array sonar. A side-scan sonar system usually has two horizontal linear arrays of elements that are mounted in a towed body, or tow-fish, in such a way that they transmit a fan-shaped beam, narrow in the vertical plane, on each side of the towing vessel's track. According to a well-known principle of acoustics, the longer the arrays the narrower are the two beams. Generally, the axis of each beam is inclined slightly downwards so that echoes are produced from different distances, typically from almost vertically down to almost horizontal. One system that has been used for many years for long-range surveying at oceanic depths is GLORIA, which uses a carrier frequency of a few kilohertz [1]. Most side-scan sonars have a graphical display that provides a two-dimensional image of the sea-bed, showing features such as rock formations, reefs and the position and orientation of wrecks and other man-made objects. The image is essentially a 'picture' of the sea-bed but it is usually distorted and needs an experienced eye to interpret the features. At low frequencies, say less than 20 kHz, the acoustic energy can penetrate the sea-bed but because of the long wavelength and large 'footprint' the spatial resolution is poor. Smaller footprints are possible if the sonar array is mounted on a deep-towed vehicle such as TOBI [1]. By using a higher frequency,

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say 100 kHz, there is less sea-bed penetration but better resolution of detail.

Perhaps the commonest type of scanning sonar is the mechanically-scanned version. This works on a 'ping-and-listen' principle, rather in the way a radar system operates. Most commercial systems can transmit while rotating through a sector or through a complete circle, either in the horizontal plane or inclined downwards at some angle. The echoes following each ping are processed to build up an image of the insonified area.

An electronic sector-scan sonar system usually has a wide-beam transmitting transducer or array and a narrow-beam receiving array comprising many elements. In a 300 kHz 'within-pulse' version designed and built at Loughborough University, the linear transmitting array comprises 75 elements mounted on a convex curve and the linear receiving array comprises 75 elements mounted on a flat base. Each transmitted pulse insonifies a 30° wide sector, giving rise to echoes at any angle within this sector and at any range out to a maximum determined by the pulse repetition rate of 4 Hz.

A delay is introduced between the signal arriving at element 1 at one end of the array and at element 2; the same delay is also introduced between the signal arriving at element 2 and element 3, and so on all along the array. This clearly introduces a phase difference between the signals arriving at adjacent elements and means that at any instant the receiving array is sensitive to echoes arriving from only one direction. At a later instant, when the phase difference is altered, it is sensitive to echoes from another direction. With the correct phasing, the effect is to create a sensitivity 'beam' that scans continuously through the sector of the transmit beam. In the Loughborough University system the scanning frequency is 10 kHz. The system may be used as a 'look-ahead' sonar for detecting obstacles or to look sideways for mid-water targets, but it may equally well be used to look vertically downwards to image the sea-bed.

A more complex system working along broadly similar lines is the multi-beam phased array sonar. This has two multi-element linear arrays, which for sea-bed surveying may be mounted on the bottom of the hull of a vessel. The transmitting array is mounted along the fore-aft line and generates a 'fan-shaped' beam vertically downwards; this beam is wide in the port-starboard direction and narrow in the fore-aft direction. The receiving array is mounted at right angles to the transmitting array (and generally slightly astern of it) and therefore is sensitive to echoes arriving in a fan-shaped sector that is wide in the fore-aft direction and narrow in the port-starboard direction. Instead of just one phase delay being applied to all adjacent elements across the receiving array, which makes the receiver sensitive in one direction at a time, many phase delays are applied in parallel (as many as 128 in one commercial system) so that the receiver simultaneously processes signals from all directions within the insonified sector. With this system a two-dimensional plan-view image of the sea-bed is built up pulse by pulse.

Another system of interest but one still in the research stage for use at sea is the Synthetic Aperture Sonar (SAS), which is a specialised system that allows the imaging of finer detail than is possible by most other techniques [2-4]. This example of a 'non-penetrating' type of sonar system is presented in more detail below.

The side-scan sonar, sector-scanning sonar, multi-beam phased array sonar and synthetic aperture sonar are not generally suitable for sub-sea penetration because they operate at too high a carrier frequency. Systems that may be used to characterise sub-sea sediments include the seismic profiler [5-8], the sub-bottom chirp profiler [9], the parametric sonar [10-19] and hybrids such as the 'scatterometer' [1]. The seismic system is used to profile the sea-bed on a large scale, with penetrations of hundreds of metres or more; the others are used to profile on a smaller scale, typically tens of metres at the most. In the case of the sub-bottom profiler, either a single-frequency tone or a wide-band chirp may be used. The lowest frequencies, typically 5 kHz, obviously allow the deepest penetration and can give a picture of coarse stratification, but the higher frequencies, typically up to 20 kHz, offer the best depth resolution and can therefore show finer detail. The choice of frequency usually depends on the application. To illustrate a 'penetrating' type of sonar system, a brief description of the principles of the seismic profiler is presented below, together with a more detailed description of a parametric sonar system with a steerable beam.

2. SYNTHETIC APERTURE SONAR

Synthetic Aperture Sonar is of interest because it has the potential to produce high resolution, two-dimensional images of targets by synthesising the effect of a very long phased array [2-4]. The principle of aperture synthesis consists of storing successive echoes obtained from a moving platform, in practice a tow-fish but ultimately an AUV, then synthesising the effect of a large along-track phased array by correcting the phase excursions of echoes in a given direction and summing the sequence of echoes, hence providing high along-track (cross-range) resolution.

Traditional techniques such as side-scan sonar are good enough for general surveying and for identifying wrecks but do not have sufficient resolution for displaying particular features. The main reason for this low performance is the limited aperture size available with commercial systems. Synthetic aperture techniques are well advanced in radar and known as Synthetic Aperture Radar (SAR). By comparison, only a limited amount of research has been carried out on SAS and this has highlighted the main problems that prevent the direct translation of SAR techniques. These problems are that transducer motion produces smearing of the image, and ray bending produces a bias in the apparent direction of detected objects. The solutions used to eliminate these problems in SAR are auto-focus techniques that rely on contrast enhancement, but these are of limited success with SAS because of the relatively large transducer movements encountered in practice, together with very low towing speeds, narrow bandwidth and restricted range.

The aims of recent work at Loughborough University, carried out jointly with University College London, covered four main areas: (i) the design of signal processing algorithms to compensate for transducer platform movement and ray bending; (ii) the design of algorithms for interferometric reconstruction of three-dimensional surface images; (iii) the design of algorithms for moving target tracking using SAS; and (iv) testing an experimental system in the controlled environment of a sonar test tank.

Motion compensation

The approach to the problem of motion compensation was to consider that the true signal is effectively convolved with an error function that corresponds to the true trajectory of the transducer platform. At sea, with transducers mounted on a ship or in a towed array, waves can cause gross deviations from an assumed straight line trajectory that may be several wavelengths at the transmission frequency. One solution is to measure actual platform movement and do explicit de-convolution. The preferred solution, which obviates the need for accelerometers or inertial gyroscopes, is to perform blind de-convolution based only on measurements made by the transducer array itself. Three options were considered: (i) statistical de-convolution based on Higher Order Statistics (HOS), which is applicable to motion perturbations that are fairly predictable (eg cyclic) compared with the random nature of the data field; (ii) compensation based on frequency diversity, which requires separate measurements in different bands using the same transducer and may compensate for ray bending but not for motion errors; and (iii) compensation based on spatial diversity, which can provide multiple snapshots of the same data field and also allows for adaptive tracking of errors induced by motion.

Interferometric reconstruction

The interferometric processing consists of registering two images of the same scene taken at slightly different positions, and comparing the phases of the two images on a pixel-by-pixel basis. This yields a fringe pattern, which is a function of the interferometric baseline and geometry, the wavelength and the surface topography. Provided the baseline, geometry and wavelength are known, then in principle the surface can be reconstructed from the fringe pattern to the same spatial resolution as the original images.

The main problems are: (i) the two images suffer a degree of de-correlation due to the different angles of observation and the finite signal-to-noise ratio, which causes phase noise in the fringe pattern; (ii) 'shadowing' and 'layover' cause distortion of the sonar image with respect to the true surface; and (iii) there is an ambiguity between phase and topography, and the process of reconstructing the topography unambiguously ('phase unwrapping') is made more difficult in areas of rapidly varying topography and poor signal-to-noise ratio where the fringes may be closely spaced or indistinct. The approach was to simulate the imaging of arbitrary topographic scenes, taking account of the problems listed above, then to devise algorithms to reconstruct the original topography. The idea was to optimise the geometry and processing algorithms for the experimental part of the research.

Imaging moving targets

This is an important problem with SAS and has so far remained unsolved. Unlike for SAR, the situation is more complicated because the target is close enough to the synthetic array, which may be several kilometres long, that it presents different Doppler shifts to different parts of the array. This complicates the aperture synthesis processing. The problem may be approached by analysis, deriving expressions for the phase history of echoes as a function of the array-target geometry and motion, and using these to define the form of processing required to estimate the target motion and image the target. This algorithm can then be combined with that for the platform motion compensation to define the processing required in a practical SAS system, but further research is needed to fully achieve this aim.

Tank experiments

An important part of the research was to apply the various algorithms mentioned above for use with an experimental system, in the controlled environment of the test tank at Loughborough University. This provides a valuable test facility for the theoretical aspects of the project. An advanced SAS system was built for use in the tank, measuring 9 m long, 5 m wide and 2 m deep. It has a carrier frequency of 40 kHz, a maximum aperture of 4.5 m and a maximum range of 8 m. The platform carrying the transmit and receive arrays can be moved under computer control by two stepper motors; a third stepper motor is used to introduce across-track motion errors.

The transmitted pulse is generated by a signal generator that can be connected to a computer bus by an interface card. The system can be programmed to generate either a sinusoidal pulse with adjustable amplitude, carrier frequency, pulse length and repetition rate, or more complicated signals such as a weighted pulse or a chirp. The transmitted pulse is fed to the transmitter array by a power amplifier to ensure maximum power transfer. The system allows the feasibility of generating high resolution SAS images, including three-dimensional images, by extracting features and training the system to identify certain objects automatically using neural networks. This is an area of research in which many problems remain unsolved.

3. SEISMIC PROFILER

Seismic profiling is a means of studying the stratification of sub-bottom layers on a large scale, that is to depths of perhaps hundreds of metres or even kilometres [5]. The applications include geological mapping, environmental studies and surveying for cable routes and pipelines. The basic requirement is a sound source with a high Source Level and a receiving array of geophones to detect reflected and scattered pressure impulses. This type of profiling is attributable to the fact that sound waves propagate with little attenuation in media with elastic properties. Any abrupt changes of acoustic impedance causes refraction and reflection and the generation of compressional and shear waves, referred to as P-waves and S-waves respectively. Measurements of the arrival times of the detected acoustic signals are used to work out the sub-bottom geological structure [6].

The velocity of P-waves in the top 50 metres of sediment is typically 1450-2200 m/s, whereas the velocity of S-waves is much lower, between about 10 m/s and 400 m/s. Much of the information on sediment structure comes from the timed returns of reflected and refracted P-waves. There is usually a good correlation between shear velocity and shear strength, an important parameter in geophysical studies, especially for applications such as the construction of oil and gas production rigs where sea-bed stability is a vital factor. In some places, sediments are too soft to be sheared so no shear wave data can be obtained. The commonest method of determining shear strength is to take a core from the sea-bed and make measurements in the laboratory but by removing the sample there may be some change in the sediment properties; this is why an in-situ method is preferred [7].

One way this problem has been addressed is to study interface waves, such as Rayleigh, Stoneley and Scholte waves, which propagate along the water/sea-bed interface [8]. The idea is that since the velocity of such boundary waves is linked with the shear wave velocity of the top sea-bed sediment, information about the shear strength of the sea-bed can be obtained without disturbance. By contrast, there seems to be little dependence on the state of gas saturation in sediments, such as those found in the Arkona Basin in the Baltic Sea.

Low frequency seismic sources (20–200 Hz) are used for penetration sediments to depths of the order of kilometres, while higher frequency sources (100 Hz–10 kHz) are used for penetration to depths of hundreds of metres. Typical source durations are 0.1–1s and sources include boomers and sparkers, which are omni-directional transducers that can generate stable pressure signals.

Other sources include explosives and mechanical devices such as air guns and water guns. The array of geophones is either towed behind a vessel or from a sledge that is itself towed along the sea-bed by the vessel. In one system, the sledge stops briefly for each measurement while the vessel steams at a constant speed*. The array is normally in the form of a streamer comprising many geophones in an oil-filled plastic tube that is transparent to sound. A problem with such an array is that it is subject to noise from flow, turbulence, bubbles, waves and ship noise.

4. PARAMETRIC SONAR

A parametric sonar system makes use of the non-linearity of acoustic wave propagation in water [10-19]. The principle of operation is to drive a transducer array at two primary frequencies, f_1 and f_2, near the resonance frequency f_0 of the array, where $f_0 = (f_1+f_2)/2$, to generate new waveforms, the lowest of which is at the difference frequency, or secondary frequency, $f_d = f_2 - f_1$. The generation of this secondary frequency waveform along the transmitted beam direction gives rise to the concept of a virtual end-fire array, the effective length of which is given by $(2\alpha)^{-1}$, where α is the small signal attenuation coefficient in nepers/metre. At primary frequencies of 20 kHz, 40 kHz and 80 kHz, the virtual array lengths are approximately 1500, 400 and 100 metres respectively for transmission in sea water.

The advantage of a parametric sonar is that it can generate a sidelobe-free, narrow beam at the difference frequency, using an array that is small compared to one that would be needed to generate the same frequency directly. A further advantage is that it allows sediment penetration to depths of several metres at difference frequencies of less than 10 kHz. The disadvantage is that it operates at a very low efficiency, about 1%, a figure that depends directly on the step-down ratio $f_0{:}f_d$. The low efficiency therefore necessitates the generation of high-power primary frequency waveforms. This means that the Source Level at the difference frequency is typically 40 dB less than either of the two primary frequency Source Levels for a typical step-down ratio of 10, eg a difference frequency of 7.5 kHz from primary frequencies centred on 75 kHz. (Source Level is defined as $10 \log_{10} P_a + \mathrm{DI}$, referenced to 1 metre from the acoustic source transducer or array, where P_a is the transmitted acoustic power in watts and DI is the Directivity Index, which depends on the geometry of the source.)

In several recent European Commission projects,** a narrow beam was needed for accurate profiling of the sea-bed to characterise sediments and to detect and identify buried objects. As the difference frequency beamwidth is approximately that of the primary frequencies, the beamwidth defines the dimensions of the array. For a step-down ratio of 10 (ie $f_0{:}f_d$), the active surface area of the array need only be 1/100th of that of a conventional linear array for the same beamwidth.

This is a big advantage in terms of expense, size, weight and handling of the array at sea. The array consists of a titanium plate with 729 integral elements, resonant at 75 kHz and arranged in a 27 × 27 matrix with approximately 0.75 spacing. It has an area of $20\lambda \times 20\lambda$, with a resultant –3 dB beamwidth of 3° × 3° and a bandwidth of 6 kHz. The transmit Directivity Index is 35 dB so for an acoustic power of 10 kW the maximum predicted Source Level for a single carrier frequency is $SL_0 = 246$ dB re 1μPa at 1 m. The array provides 13 resolvable beams, each about 3° wide, within its phase-steerable sector; since the inter-stave spacing at 75 kHz is 1.5λ the scanned sector is ±18°, which allows a wide variety of incidence angles to be selected in order to apply inverse algorithms to compute sediment characteristics from measured compressional and shear wave data. The programmed signals transmitted may be continuous sine wave pulses, 'raised cosine' pulses, and linear frequency modulated pulses (chirps).

The scenario for sea trials conducted at various sites off the coast of Brittany, France is shown in Figure 1. The array, together with other systems, has been deployed at depths of 10–20 metres in a tow-fish specially designed and built by IFREMER, the French Oceanographic Institution. A 40 metre seismic hydrophone streamer is towed some 25 metres behind the tow-fish to detect forward-scattered signals from the seabed. The mechanical mounting arrangement, shown in Figure 2, allows three possible fixed angles for the transmission axis, 10°, 15° and 20° with respect to vertical, when the dynamic steer angle is programmed to be 0°. When the beam is steered vertically downwards to the sea-bed, the array may also be used in a back-scatter depth sounding mode.

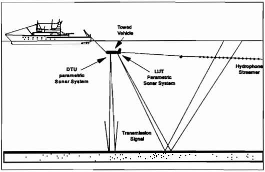

Figure 1. Deployment of a parametric sonar array and hydrophone streamer.

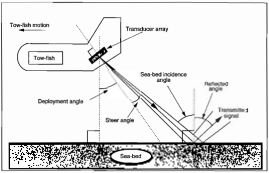

Figure 2. Configuration of electronically steered parametric array in a tow-fish.

Instabilities in the motion of the tow-fish, such as pitch, roll, yaw, heave, swell and surge, can lead to a departure from the desired sea-bed incidence angle. Any error in this angle may lead to a misalignment of the streamer with respect to the scattered signals. This in turn may produce either no data at all or data that yields spurious results when applied to the inverse algorithms that are applied to quantify the sediment parameters. Sensors are therefore attached to the array to monitor the pitch, roll and depth of the tow-fish to correct for some of the instabilities.

Since the beam cannot be steered athwartships, there is no correction for roll; but if the roll angle of the fish exceeds about 3° the forward-scattered signals would not be detected by the hydrophone streamer so transmission for such angles can be temporarily halted. For any pitching of the fish, the beam angle is dynamically adjusted so that the angle of incidence at the sea-bed remains unchanged. The hardware of the system allows the individual addressing of eight separate sections of the available memory that store the required waveforms to provide a series of phase-steered signals for a range of angles. When the sensors attached to the array detect a change of pitch, the appropriate waveform is selected and the beam is therefore steered to compensate for the movement. A series of eight signals allows near-instantaneous correction of the beam direction due to the sensed movement. With eight possible angles and a total phase steer capability of ±18°, the angular separation of the beams is 4.5°. A further consideration is the problem of alignment of the sonar beam and the streamer when the sea-bed is sloping and several methods have been studied to determine the slope. The simplest method is by depth sounding, which can be done by periodically steering a primary frequency beam vertically downwards. A more complex method is to steer two primary frequency beams at different angles, say one slightly fore of vertical and one slightly aft of vertical, then measure the time difference, which in turn allows the slope to be determined. A suitable way to do this is to correlate the envelopes of the two back-scattered signals; the two narrow beams would make the array appear like a Doppler sonar but instead of measuring a frequency difference, a time difference is measured. The method is therefore similar in principle to the operation of a correlation velocity log.

Although a parametric sonar system is fairly complex and is difficult to deploy, it allows the study of sediments remotely, since it can operate near the sea surface to examine the characteristics of sediments on the continental shelf.

5. CONCLUSIONS

Many types of sonar system have been designed for the detection of objects underwater and for the surveying or imaging of the sea-bed. There are many variations on a theme available and there is no one system or technique that is 'better' than all the others: the measurement capability or precision depends to a large extent on the application considered. Whatever the technique used it is always necessary to consider what result is expected; the resolution achievable, whether coarse or fine, is invariably of paramount importance and worth special consideration [20].

In this paper, the various sonar systems have been arbitrarily categorised as 'non-penetrating' and 'penetrating' to distinguish between types that are mainly used for imaging the sea-bed and those that are mainly used to profile sub-bottom sediments. One of the major challenges to sea-bed exploration is to find a technique or a combination of techniques to enable sediments to be identified and characterised without the need to take cores or to disturb the sea-bed directly. This has been a major research theme of the European Commission's MArine Science and Technology (MAST) programmes**. In the MAST programme research described here the broad aim has been to design new, remotely operated systems for characterising the sea-bed and the sub-bottom structure entirely by acoustic means. While the use of non-penetrating systems such as the side-scan sonar have been used routinely for decades to image the sea-bed, it remains a major challenge to determine the exact nature of the underlying sediments using penetrating systems such as the parametric sonar. The ultimate objective is to develop an acoustic technique such that following the propagation of a coded ping or a series of pings, the scattered or reflected acoustic signals may be analysed to reveal the nature of the sea-bed parameters directly without recourse to direct non-acoustic techniques that are used now. Present techniques, although advanced and sophisticated, are a long way from achieving this objective. Future applications of this technology may include dredging, material exploitation, sedimentology, propagation modelling and the detection of buried objects.

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