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Progress in developing sonar systems for sea bed surveys

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ABSTRACT

Many types of sonar systems have been designed for exploring and surveying the sea bed and for identifying and characterising sediments. These include the conventional depth sounder, sidescan sonar, sector-scanning sonar, synthetic aperture sonar, sub-bottom profiler, seismic profiler and parametric sonar. The features, advantages and disadvanteages of these are described and some ideas for future research are presented.

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 which present an even greater challenge to investigate. One way to study the sea bed is to lower a television camera and have a look, but this may yield little information other than to give an idea of the topography, the presence 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 the use of a camera is ineffective.

Another way to study the sea bed is to deploy some kind of underwater acoustic system, generally referred to as a *sonar* system. Even the simplest of these, 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 sea bed echoes: the "round trip" flight time of each pulse and its echo, when multiplied by the average velocity of sound, gives the depth at some location. Modern echo sounders, as well as having a digital display of the instantaneous depth, have a graphical display of the sea bed profile along the track of the vessel. Depending on the frequency of operation, 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 produces images of the sea bed. These include the side-scan sonar and the sector-scanning sonar. A side-scan sonar system has two horizontal linear arrays of elements that are usually mounted in a towed body, or *tow-fish*, in such a way that they transmit a vertical fan-shaped beam 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 of the beams is inclined slightly downwards so that as the vessel progresses, 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 in oceanic depths is *GLORIA*, which uses a carrier frequency of a few kilohertz [1]. As with the simple echo-sounder, the side-scan sonar has a graphical display that provides a two-dimensional image of the sea bed, showing features such a rock formations, reefs and the position and orientation of wrecks. 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 very 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, say 100 kHz, there is less sea bed penetration but better resolution of detail.

A sector-scanning sonar system usually has a linear array of elements, each of which is driven by a voltage waveform that is slightly out of phase with its neighbours. With the correct phasing, the effect is to generate a beam that scans continuously through a sector. The system is often 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.

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 any other technique [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 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 penetrate the deepest 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. As examples of 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.

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 towfish 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 on commercial systems. Synthetic aperture techniques are well advanced in radar and known as Synthetic Aperture Radar (SAR). By comparison, there has been only a limited amount of research 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 autofocus 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 Lougborough University, jointly with University College London, has 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; (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 which 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 deconvolution. The preferred solution, which obviates the need for accelerometers or inertial gyroscopes, is to perform blind deconvolution based only on measurements made by the transducer array itself. Three options were considered: (i) statistical deconvolution based on Higher Order Statistics (HOS), which is applicable to motion perturbations which are fairly predictable (e.g. cyclic) in comparison to 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; (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 decorrelation 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 a distortion of the sonar image with respect to the true surface; (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 programme consists of simulating the imaging of arbitrary topographic scenes, taking into account shadowing, layover and decorrelation, then devising algorithms to reconstruct the original topography. The idea was to allow the geometry and processing algorithms to be optimised for the experimental part of the research.

Imaging moving targets: This is an important problem with towed passive sonar arrays 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 was then combined with that for the platform motion compensation to define the processing required in a practical SAS system.

Tank tests: An integral part of the research is to study the operation of these algorithms 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. A new advanced SAS system has been built for use in the tank, measuring 9 m long, 5 m wide and 2 m deep. The system operates at 40 kHz and provides a maximum aperture of 4.5 m and a 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 error. The transmit pulse is generated by a versatile signal generator which can be connected to a 486 PC bus by an interface card. The system can be programmed to generate either a simple sinusoidal pulse with adjustable amplitude, frequency, pulse length and repetition rate, or more complicated signals such as a weighted pulse or a *chirp*. The transmit pulse is fed to the transmitter array by a power amplifier to ensure maxium power transfer. Use of the system allows the feasibility of generating high resolution SAS images, including 3D 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.

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 m of sediment is typically 1450 - 2200 m/s, whereas the velocity of S-waves is typically 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 an important 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 to kilometres of depth and higher frequency sources (100 Hz - 10 kHz) are used for penetration to hundreds of metres. Typical source durations are 0.1-1s. 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 the air gun and water gun. 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. 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.

PARAMETRIC SONAR

A parametric sonar makes use of the non-linearity of acoustic wave propagation in water [10-19]. The principle 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 additional frequencies. As the sound wave propagates, new frequencies are formed, the lowest of which is the difference frequency, $f_d = f_2 - f_1$. The generation of these signals at the *secondary* frequency along the transmitted beam gives rise to the concept of the *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/m. At primary frequencies of 20 kHz, 40 kHz and 80 kHz, the virtual array lengths are approximately 1500 m, 400 m and 100 m respectively.

A parametric sonar provides a number of advantages over its linear counterpart, but at the cost of a very low conversion efficiency and increased complexity in design. Typical conversion efficiency is of the order of 1% which depends directly on the ratio f_0:f_d, the *step-down ratio*. The low conversion efficiency dictates the use of high powers for the primary frequency signals. This means that the Source Level at the difference frequency is typically 40 dB less than that of either of the two primary frequency Source Levels for a typical step-down ratio of 10.

In the European Commission's MAST-II *REBECCA* project*, a narrow beam was needed for accurate delineation of the sea bed. As the difference frequency beamwidth is approximately that of the high frequency carriers, the beamwidth defines the dimensions of the array. For a step-down ratio of 10 (i.e. 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 x 27 matrix with approximately 0.75 λ spacing. It has an area of 20 λ x 20 λ, with a resultant -3 dB beamwidth of 3^o x 3^o 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 1m, although the maximum value measured was 241dB re 1 µPa at 1m. The array provides 13 resolvable beams, each about 3^o wide, within its phase steerable sector; since the inter-stave spacing at 75 kHz is 1.5 λ the scanned sector is $\pm 18^o$, 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 were continuous sine wave pulses, raised cosine envelope pulses, and linear frequency modulated pulses (*chirps*).

The scenario for sea trials conducted off the coast of Brittany, France is shown in Fig. 1. The array, together with other systems, was deployed at a depth of 10 m in a tow-fish specially designed and built by *IFREMER Centre de Brest*. A 40 m seismic hydrophone streamer was towed some 25 metres behind the tow-fish to detect forward-scattered signals from the seabed. The mechanical mounting arrangement, shown in Fig. 2, allowed three possible fixed angles for the transmission axis, 10^o, 15^o and 20^o with respect to vertical when the dynamic steer angle was programmed to be 0^o. When the beam was steered vertically downwards to the sea bed, the array could also be used in a *back-scatter* depth sounding mode. 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. Sensors were 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, no correction for roll is possible; but if the roll angle of the fish exceeds about 3^o the forward-scattered signals would not be detected by the hydrophone streamer so transmission for such angles is 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. With this facility, the parametric sonar system offers a new sophisticated tool to the sedimentologist which can operate near the sea surface to examine the characteristics of sediments on the continental shelf.

The hardware of the system allows the individual addressing of eight separate sections of the available memory which store the required waveforms to provide a series of phase-steered signals at 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 $\pm 18^o$, the angular separation of the beams is 4.5^o.

A further consideration is the problem of alignment of the sonar beam and the streamer when the sea bed is sloping and a number of 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, and 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.

CONCLUSIONS

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 takes cores or to disturb the sea bed directly. This was a major research theme of the European Commission's **MA**rine Science and Technology (MAST-II) programme, which was concerned with the design of new, remotely operated systems for characterising the seabed and the sub-bottom structure entirely by acoustic means. Several techniques have been presented, some for studying the sea bed (non-penetrating) and some for studying the underlying structure (penetrating). There are many variations on a theme available and there is no one 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].

* The collaborative research highlighted in this paper was carried out as part of a project called ***REBECCA: REflection from Bottom, Echo Classification and Characterisation of Acoustic propagation.*** This involved the collaboration of seven partner institutions in four countries, France,UK, Denmark and Greece. The ultimate objective is to

develop an acoustic technique such that following the propagation of a 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 teachniques that are used now. Present techniques, although advanced and sophisticated, are a long way from achieving this objective. Future applications for this technology may include dredging, material exploitation, sedimentology, propagation modelling and the detection of buried objects.

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REFERENCES

[1] Somers, M.L. 1994. The IOSDL acoustic scatterometer for sediment studies, Proc. 2nd European Conference on Underwater Acoustics, Copenhagen, pp. 497-502.

[2] Chatillon, J., Zakharia, M.E. and Bouhier, M.E. 1992. Wideband synthetic aperture sonar: advantages and limitations, Proc. 1st European Conference on Underwater Acoustics, Luxembourg, pp. 709-712.

[3] Cutrona, L.J., 1975. Comparison of sonar performance achievable using synthetic aperture techniques with the performance achievable by more conventional means, J. Acoust. Soc. Am., **58**, pp. 336-348.

[4] Gough, P.T., 1986. A synthetic aperture sonar system capable of operating at high speed an in turbulent media, IEEE J. Oceanic Eng., **11**, pp. 333-339

[5] Simpkin, P.G. and Geo, P. 1993. Seismic profiling in shallow water - a novel approach, Proc. Inst. of Acoustics, **15**, pp. 279-283.

[6] Dosso, S.E. and Brooke, G.H. 1994. A high-resolution geoacoustic study in the Canadian high Arctic, Sea bed characterisation using non-linear acoustics, Proc. 2nd European Conf. on Underwater Acoustics, Copenhagen, pp. 857-862

[7] Theilen, F., Kogler, F.C., van Bocxlaer, K., de Batist, M., Missiaen, T., Ori, G.G., Ollier, G., McGee, T.M. and Brussaard, P. 1992. GISP - Geophysical In-Situ Probe, Proc. 1st European Conference on Underwater Acoustics, Luxembourg, pp. 481-484.

[8] Hovem, J.M. and Frivik, S.A., 1994, Marine geotechnical investigations using interface waves, Proc. 2nd European Conference on Underwater Acoustics, Copenhagen, pp. 869-874.

[9] Schock, S.G., LeBlanc, L.R. and Mayer, L.A. 1989, Chirp sub-bottom profiler for quantitative sediment analysis, Geophysics, **54**, pp. 445-450.

[10] Westervelt, P.J., 1957. Scattering of Sound by Sound. J. Acoust. Soc. Am., **29**, pp.199-203.

[11] Westervelt, P.J., 1963. Parametric Acoustic Arrays. J. Acoust. Soc. Am., **35**, pp. 535-537.

[12] Smith, B.V. 1971, An experimental study of a parametric end-fire array, J. Sound. Vib., **14**, pp. 7-21

[13] Konrad, W.L. and Moffett, M.B., 1977. Specialised drive waveforms for the parametric acoustic source. Proc. Oceans 77, Los Angeles, pp. 16-19.

[14] Willette, J.G., 1977. Harmonics of the difference frequency in saturation limited parametric sources. J.Acoust Soc.Am., **62**, pp. 1377-1381.

[15] Muir, T.G., Mellenbruch, L.L. and Lockwood, J.C., 1977. Reflection of finite amplitude waves in a parametric array,J.Acoust.Soc.Am., **62**, pp. 271-276.

[16] Moffett, M.B. and Mellen, R.H., 1981. Effective length of parametric acoustic sources. J.Acoust.Soc.Am., **70**, pp. 1424-1426 (and errata 71, p. 1039).

[17] Woodward, B., Cook, J.C., Goodson, A.D. and Lepper, P.A. 1994, A phase-steered parametric array for sub-bottom profiling, Proc. 6th Int. Conf. on Electronic Engineering in Oceanography, Cambridge, U.K.; IEE Conference Publication No. 394, pp.77-82

[18] Woodward, B., Goodson, A.D., Cook, J.C. and Lepper, P.A. 1994. Sea bed characterisation using non-linear acoustics, Proc. 2nd European Conf. on Underwater Acoustics, pp. 875-880.

[19] Engelbrecht, S., Pace, N.G. and Bjorno, L. 1994. The interaction of a parametric array with the seabed, Proc. 2nd European Conf. on Underwater Acoustics, pp. 893-898.

[20] Somers, M.L., 1995. Resolving the issue, a look at resolution and related topics in sonar. Man-Made Objects on the Seafloor, Discovery, Investigation and Recovery, Proceedings of Society for Underwater Technology international conference, London, 1-2 Feb, pp. 41-58, ISBN 0-906940-26-5

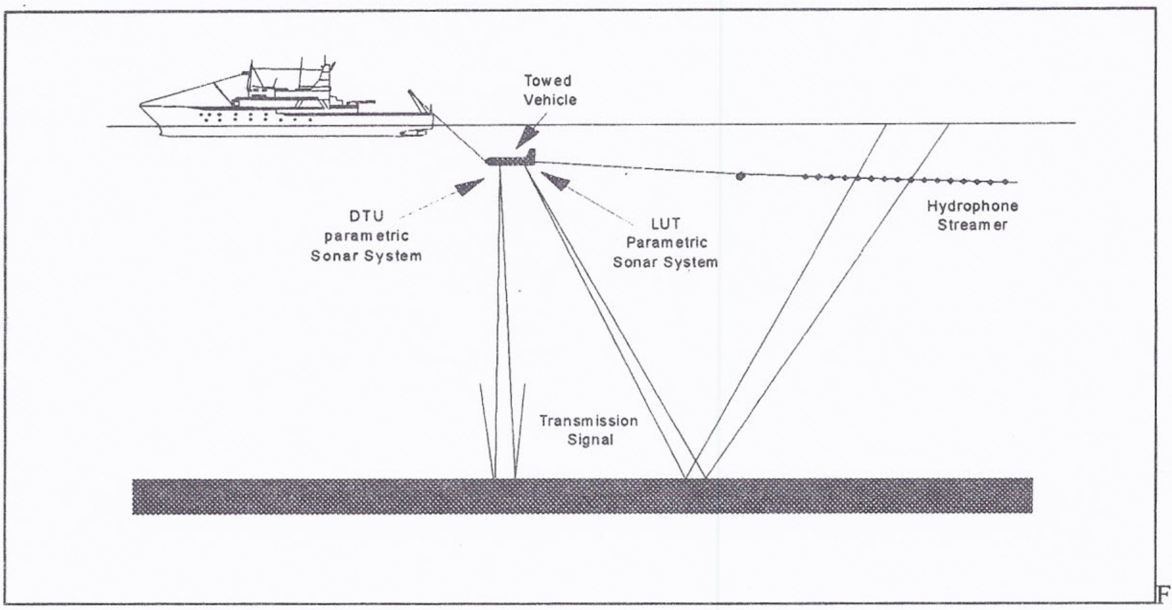

Fig. 1 Deployment of a parametric sonar array and hydrophone streamer

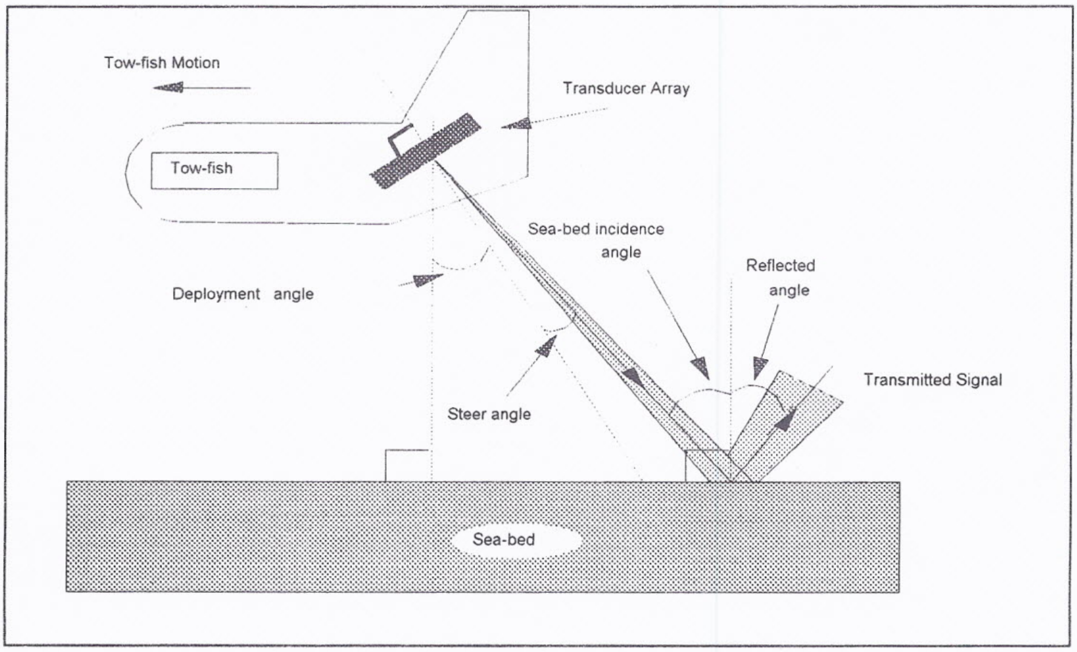

Fig. 2 Configuration of electronically steered parametric array in a tow-fish