Instituto Panamericano de Ingeniería Naval
Instituto Pan-americano de Engenharía Naval
Pan-american Institute of Naval Engineering

XI CONGRESO PANAMERICANO DE INGENIERIA NAVAL,
TRANSPORTE MARITIMO E INGENIERIA PORTUARIA.

ACTIVE TOWED ARRAY SONAR (ATAS)
AND
FLEXTENSIONAL TRANSDUCERS

PAPER N° 35

ROBERT L. MALPASS
Senior Sales Executive, Underwater Systems
BRITISH AEROSPACE (DYNAMICS) LTD.
INGLATERRA

ACTIVE TOWED ARRAY SONAR (ATAS)

AND

FLEXTENSIONAL TRANSDUCERS

ROBERT L MALPASS

BOB MALPASS IS THE SENIOR SALES EXECUTIVE, UNDERWATER SYSTEMS, FOR BRITISH AEROSPACE (DYNAMICS) LIMITED. HE SERVED WITH THE ROYAL NAVY BEFORE JOINING INDUSTRY AS A SENIOR ENGINEER WITH SPERRY GYROSCOPE, LATER MOVING INTO SALES AND MARKETING, SPECIALISING IN UNDERWATER TECHNOLOGY AND EQUIPMENT.

INTRODUCTION

The objective of this Paper is to draw attention to some of the changes taking place in Underwater Warfare, with particular reference to developments in Anti-Submarine Warfare (ASW).

The submarine threat continues to grow and to dominate maritime warfare strategy. There are a large number of submarines in service worldwide, and more are in construction, both conventional diesel-electric and nuclear powered. With the introduction of new propulsion systems and modern hull cladding materials, the submarine is continuing to become quieter, faster and more difficult to detect.

Detection of submarines by surface ships is currently achieved by means of hull-mounted or variable depth sonars, which are mainly used in an active mode, or by means of towed array sonars operating in a passive mode. However, as submarine radiated noise continues to reduce, the effectiveness of the passive sonar as a means of detection becomes limited, as indicated in Figure 1.

Hull-mounted, low frequency sonar arrays are large and, because of this, planar arrays can only be fitted into large hulls, which in turn limits the number of ASW vessels. Hull-mounted sonars also suffer operational disadvantages in that they are at a fixed depth and may give poor performance under some duct and reverberation conditions. Some of the problems associated with duct conditions can be overcome by variable depth sonars which, as well as exploiting the performance advantage in differing velocity profiles, can often give improved performance in high background noise conditions. However, as shown in Figure 2, the use of anechoic coatings is reducing the effectiveness of active sonar unless lower frequencies are used.

As in the development process of most defence systems, if one area of a threat advances so too does the counter-measure. Such is the case in ASW. The technology is now moving towards the use of active low frequency sonars, operating at depths such as to reduce or avoid the effects of bathy layers.

The latest approach for surface ship application is the use of low frequency flextensional transducer elements used as an active adjunct to existing passive arrays, or, as in the case of the British Aerospace ATAS, to provide a high performance active variable depth sonar capable of being fitted to ships as small as fast attack craft of about 250 tonnes.

The first part of this Paper describes the Active Towed Array Sonar (ATAS) and Flextensional Transducers are reviewed in the second part.

ACTIVE TOWED ARRAY SONAR (ATAS)

OVERVIEW

ATAS is a hybrid of the variable depth sonar and passive towed array, and provides an active/passive towed array system which, in its current form, will operate down to 200 metres.

The system, shown in Figure 3, comprises an acoustic transmitter, receiver array, tow cables, ship-board electronics and a deck-mounted handling system. The independent acoustic transmitter is towed up to 900 metres astern of the ship, with the passive hydrophone receiver array towed a further 300 metres astern of the transmitter. At a distance of 1200 metres, the receiver array is located well away from the towing vessel and its associated noise.

Operating depth is controlled by adjusting the length of the transmitter towing cable and the towing vessel speed. The designed operational towing speed range is between 5 and 20 knots with survival to 30 knots. The characteristics are shown in Figure 4.

System objectives are:

1 To detect quiet submarines.

As the radiated noise level of submarines becomes quieter, passive detection is becoming increasingly difficult. ATAS therfore operates primarily in the active FM mode.

2 To achieve long range detection.

This is achieved through the use of a low operating frequency, together with narrow receiving beams which give a performance advantage by their ability to provide discrimination against reverberation and noise.

High transmitter power is also necessary for long range detection and is achieved by employing highly efficient flextensional transducers.

3 To enable the system to be fitted to small ships of 250 tonnes as well as to frigates and destroyers where dual systems can provide maximum advantage.

This is achieved with the unique configuration of ATAS, which employs towed array technology for the receiver, and a compact, independent transmitter.

The system is deck-mounted thereby eliminating the need for hull modification.

SYSTEM DESCRIPTION

Transmitter

The ATAS transmitter consists of a multi-element stave of flextensional transducers housed in an oil-filled, hydrodynamically stable body made of glass fibre. The unit is compact being only 1.2 metres in height with a mass of less than 200 kilograms. The transmitter is shown in Figure 5.

The transmitter is towed with the stave vertical and operates at a frequency considerably lower than current active sonars.

The acoustic energy of the ATAS transmitter is radiated omni-directionally in the horizontal plane and within a 25 degree beam angle in the vertical plane, as shown in Figure 6.

The second part of this Paper provides a more detailed technical description of the Flextensional Transducer.

Receiver

The receiver array consists of a 20 metre long oil filled flexible tube containing 32 hydrophone modules. The array is shown in Figure 7. The hydrophones are spaced at approximately half wavelength intervals and provide full 360 degree azimuth cover.

The major problem of target port-starboard ambiguity normally associated with a linear array is resolved by combining the output of a pair of elements in each hydrophone assembly to produce a cardioid beam pattern each side of the array (see Figure 8).

The port-starboard discrimination facility operates in both active and passive modes and is maintained regardless of the array roll angle.

Sensors within the array provide information on depth and heading so that the target range and bearing measurements may be corrected to allow for the physical displacement between the array and towing platform.

Shipborne Electronics

The shipborne electronics comprises two cabinets, shown in Figure 9. One cabinet contains the power supplies and the transmitter power amplifiers, whilst the second houses the signal processing, data processing and display electronics, together with the operator's console.

Beam Former

A total of 56 independent beams (28 port plus 28 starboard) are formed to give full 360 degree cover in azimuth with a 4 degree beamwidth in the broadside direction. Dolph-Tchebychev shading ensures sidelobe rejection.

Active FM Mode Processing

Correlation

In the active FM mode of operation, linear period modulation is used with replica correlation to provide good processing gain and range resolution. Interpolation between correlator outputs in adjacent beams enables a bearing resolution of 0.5 degrees to be achieved broadside.

Target Data Processing

Processed data from up to 16 successive transmissions may be overlaid on the display, each set of data having been corrected for ship movement between transmissions. This results in superposition of echoes from stationary targets such as bottom features and the development of a track history from a moving target.

Target tracking is initiated by the operator; thereafter a target is tracked automatically. Target tracks may be maintained during intervals of fading. The parameters of up to 25 tracks can be procesed and the most probable are available on a TOTE display.

Display

A single high-resolution colour monitor presentation of data is provided with operator control via a keyboard and tracker ball cursor.

The processed active data may be presented, either in a rectangular range/bearing format, or as a circular PPI (Plan Position Indicator) centred either on ship's head or due North. Whilst the range/bearing display is normally preferred for initital detections, the PPI display can be of value in shallow water, since it displays bottom features and coastlines without geometrical distortion.

The rolling ball controls a cursor square which can be placed over any point on the screen. The area enclosed by the square is enlarged and displayed separately to the right of the main display, thereby facilitating examination of short trails of echoes. Also to the right of the displays are status data and key function indicators.

Passive Mode Processing

Target Detection

Energy level is examined in each beam across a wide bandwith and normalised to reduce temporal and spatial variability in the ambient noise field.

The outputs of all beams are available for recording and a selected beam can be put on headphones or a loudspeaker to assist in target detection and classification. The output may be used in conjuction with a DEMON processor for assessment of a target's blade ratio and shaft ratio.

Display

The normalised output from each beam is displayed as a monochrome bearing/time (waterfall) display, with a long time history to enable the operator to identify weak targets.

Power Electronics

Transmitter drive is provided from modular power amplifers supplied by the ship's three-phase 440 volt supply.

Handling Equipment

A self-contained unit for deployment, recovery and stowage of the in-water system is provided and can be installed on an open deck or below a helicopter platform. The equipment incorporates a separate winch drum for the transmitter tow cable, array and array cable, with a stowage for the transmitter towed body. Control of operations is carried-out from a small console from where there is a clear view of the complete system.

The handling system can be provided on a general purpose framework which requires a deck space of approximately 2.5 metres by 2.3 metres with a deck head clearance of just under 2 metres. The System is shown in Figure 10.

In addition, the system can be packaged in a MEKO, ISO or other purpose-built container or pallet.

PERFORMANCE

The maximum detection range of an active sonar system is critically dependent upon oceanographic conditions over the propagation path, the water depth and deployment depth of the sensors. ATAS has a much lower operating frequency than conventional active sonars, therfore, absorption losses are significantly reduced and performance improved.

The most significant parameter in the sonar equation, as far as detection range is concerned, is the transmission loss, comprising the loss due to spreading and that due to absorption.

Spreading loss is likely to be anywhere between cylindrical spreading (10 logR) in the most favourable conditions to spherical spreading (20 logR) in an infinite, homogeneous volume; it will be even higher in shadow zones where insonification may be neglibile. It is the task of the sonar user to operate at the best depth to capitalise on the velocity profile and to achieve as low a spreading loss as possible, hence the requirement for a variable depth capability.

Specification of a detection range for a particular sonar is therefore impossible and it is more realistic to talk of the Figure of Merit (FOM) which indicates the acceptable one-way transmission loss for a defined level of performance.

For the purposes of this paper, we shall take a FOM of 95dB which is equivalent to the one-way spreading loss over a range of 7 kilometres in conditions of spherical spreading. This range approximates to the first convergence zone in the North Atlantic.

Operational Frequency

The total acceptable transmission loss of 95dB assumed above will comprise not only the spreading loss but also the absorption loss, given by αR where α is the absorption coefficient in dB/metre and R is the range in metres.

The absorption coefficient is proportional to the square of the operating frequency at most frequencies, but is approximately directly proportional to frequency at the frequencies which we are considering.

The total one-way transmission loss is shown as a function of range, for frequencies from 500Hz to 10kHz in Figure 11, assuming spherical spreading. The higher the frequency, the greater is the shortfall in detection range, as shown in Figure 12. This Figure also shows the necessary reduction in spreading loss (compared with spherical spreading) to restore the detection range to the required 7 kilometres.

The curves of Figure 12 illustrate the sensitivity of maximum detection range to both spreading loss and absorption loss and reinforce the requirement for variable depth operation and for an operating frequency as low as possible. The lower the frequency the greater will be the probability of achieving the required performance. Taking an arbitrary figure of 5dB as the anticipated reduction in spreading loss a maximum frequency of 2kHz is indicated.

Detection Range

The following examples compare the detection ranges of ATAS with typical hull-mounted and variable depth sonars, assuming ATAS and the variable depth sonar are deployed at the same depth.

Figure 13 shows the NE Atlantic and Mediterranean in winter, an area where typically a deep, mixed layer gives rise to a deep surface duct. The ability to deploy the sensors at depth in the duct greatly extends the insonified volume and, ATAS having a low operating frequency, shows considerably improved performance. Even larger improvements are evident in Figure 14 where a warm surface layer causes a shallow submerged duct to exist.

Performance in shallow water, reverberation limited, conditions (Figure 15), is subject to quite different considerations. Detection is not affected by reduced source level but is determined by the available signal and target data processing power.

In particular, the geographically stablised display provided by ATAS enables the identification of slow moving targets even in areas of high clutter and background noise, typical of shallow water conditions.

SUMMARY

The development by British Aerospace of low frequency flextensional tranducers has provided a major step forward in ASW and the application of active towed arrays.

The Company is now applying this technology to a range of transducers from 350Hz to 3kHz and is perfecting the design to operate in water depths of 1000 metres plus. The way forward will create a situation of 'nowhere to hide' for the predator.

FLEXTENSIONAL TRANSDUCERS

OVERVIEW

The flextensional transducer is a small, highly efficient, low frequency acoustic source which is suitable for a variety of underwater applications. The transducer design makes use of the flexing of an outer shell driven at or near the resonant frequency by piezo-electric or magnetostrictive coupling.

Using various shell materials, physical size and drive method, transducers can be designed to meet specific frequency, power handling and environmental requirements. Since the dimensions of the transducer are small compared with the acoustic wavelength, it acts as an omnidirectional source.

These novel devices therefore provide scope for new applications, including oceanographic research, tomography, military anti-submarine sonars, seabed mapping and the surveying of geological features.

DESCRIPTION

The most common form of flextensional transducer is designed for Class IV operation, and is illustrated in Figure 16.

The important dimensions are the length of the major axis and the shell thickness. The ratio of major to minor axis is typically 2.5.

Whereas the Class IV device is a simple elliptical cylinder, Classes I, II and III are solids of revolution about the various axes of the ellipse.

Examples of the four classes of flextensional transducer, which are shown in Figure 17, have been manufactured, but their performance and resonant characteristics are generally more difficult to analyse and more difficult to reproduce reliably in quantity production. The Class IV transducer also presents the simplest shape, enabling individual units to be mounted together in different configurations depending upon the particular application.

A Class IV flextensional transducer comprises an elliptical outer casing or shell, with a driver element (usually ceramic) in compression across the major axis. When a suitable alternating voltage is applied to the ceramic elements, the piezo-electric properties of the ceramic generate alternating elongations and contractions along the major axis, which in turn lead to magnified deflections of the minor axis. The mode of operation is shown in Figure 18.

It is the large volume displacement around the minor axis which permits the transducer to radiate sound efficiently at low frequencies. Electro-acoustic efficiencies are typically up to 70% and acoustic power outputs of thousands of watts are obtainable at frequencies between 300Hz and about 3500Hz as a practical upper limit.

The volume of ceramic forming the driving elements governs the amount of power and duty cycle at which the transducer can be operated, but contributes only a second order effect to the resonant frequency of the shell. The ceramic can occupy up to about 25% of the volume of the transducer.

DESIGN ASPECTS

Typical shell materials are listed in Figure 19. The most commonly used materials are aluminium and glass reinforced plastic (GRP). Steel is sometimes used, but some modern materials such as carbon fibre composites do not normally have the best properties for flextensional application.

The design criteria for any particular transducer shell will take into consideration the fundamental resonant frequency, broad or narrow band operation around that frequency, the depth of operation, any requirements for mechanical strength and ruggedness, and any special features of the environment such as temperature cycling or corrosive properties.

There are a number of possible designs of transducer to provide a given resonant frequency. From the point of view of convenience, the smallest transducer would seem the best solution. However, the best performance is obtained from larger transducers for the following reasons:

a) For a given frequency, larger size means better radiation properties, higher efficiency and wider bandwidth.

b) The larger transducer allows a greater volume of ceramic, allowing higher power handling.

c) Larger transducers with thicker walls are much stronger and therefore have greater depth capability.

The size of the transducer does not normally exceed about one third of the radiated wavelength otherwise the transducer no longer radiates omnidirectionally.

DIRECTIONAL CHARACTERISTICS

Individual flextensional transducers whose dimensions are small compared with their radiated wavelength are approximately omnidirectional in sound transmission. Figure 20 shows a radiation pattern for a typical Class IV flextensional transducer.

However, many applications require the sound radiation to be directional. This can be achieved by assembling a number of transducers as multi-dimensional arrays. Such arrays may consist of spaced elements, or continuous staves, as illustrated in Figure 21. Beam patterns are then calculated using conventional array equations.

At low frequencies the arrays have to be physically very large to obtain high directivity. The use of miniature sources does not change the physics of beamforming. To obtain useful beam patterns at 800Hz, staves up to three metres long are required!

Flextensional transducers can also be mounted side by side for beamforming. The simplest case is the cardioid transmitter. However, beam patterns can be difficult to predict as element interaction can be very large at element spacings which are small compared to the wavelength. It is also possible to excite spurious resonances in modes other than the most efficient flextensional mode.

Highly directional beamforming using complex configurations of staves and arrays of flextensional transducers has so far been little explored. The most commonly considered applications to date have employed omnidirectional transmissions in the horizontal plane.

TRANSDUCER APPLICATIONS

Flextensional transducers can be used in any application in which low frequency, high power sound transmission is required down to a few hundred Hertz, and where relatively shallow depth of operation is needed.

It would be advantageous if the transducers could be deployed to any depth, but the physical laws from which their good radiation properties are derived also militate against tolerance of hydrostatic pressure. As depth increases, the external pressure on the shell reduces the amplitude of the shell deformations upon which the efficient transfer of acoustic power into the medium depends.

This aspect of performance is the subject of continuing development and it should be possible in the near future to overcome this disadvantage by incorporating pressure compensation into transducers which are required to operate under extremes of pressure.

There are still many applications however, both civil and military, for which efficient performance at depths of three hundred metres is adequate.

MILITARY APPLICATIONS

The obvious military application is in low frequency active sonar, the development of which is becoming more and more widely accepted as the next major technological advance in submarine detection. Flextensional transducers may be used in the design of new types of acoustic sources for ships' hull mounted sonars, or in the completely new concept of an active towed array. In this latter type of sonar the transducers can, as we have seen, be built into a comparatively small towed body which is used as the transmitter either for a purpose designed receiving array of hydrophones, or as an active adjunct to the current generation of low frequency passive receive-only arrays.

Using conventional transducer technology at very low frequencies is impractical as the transmitter would be so large that towing loads and physical size would severely limit the usefulness of such a device.

There are also applications for high power, low frequency sources within sonobuoys, helicopter dipping sonars, bistatic sonars or, where any discrete sound source is required such as for underwater beacons, acoustic jammers and calibration or reference transmitters.

The high efficiency and wide bandwidth of flextensional transducers can be best used in high power sonar applications, but they can also be used as wide-band sources operating off resonance. The low frequency sensitivity reduces at around 12dB per octave, and efficiency will be low away from resonance, but the devices can be more compact and more rugged than conventional underwater loudspeakers and still have better efficiencies.

CIVIL APPLICATIONS

Civil applications could include geophysical measurement, the fishing industry and acoustic oceanography.

Frequencies obtainable are slightly higher than those from sound sources such as air guns which are used commercially, but are still sufficiently low for use in applications where sediment or sea bed penetration is required. Full control of the transmitted waveform is possible, which allows best use to be made of correlation techniques. This may provide increased resolution while still maintaining adequate propagation into the sea bed.

Suggested uses in the fishing industry have included long range fish finding sonars which may give good acoustic returns and overcome target aspect problems associated with current equipment. At the low frequency end, it has been suggested that sensitivity of some species of fish to these frequencies may make flextensional transducers useful for the construction of acoustic containment 'fences' for offshore fish farms. Such sources may also be a deterrent to mammal predators, or be used, for example, to limit access of marine life to the cooling water inlets of power stations.

Flextensional transducers have applications in acoustic oceanography wherever lower frequency operation would improve the performance of existing shallow-deployed equipment. A particular use is ocean tomography, where mesoscale thermal structures can be measured and plotted by measuring the transmission time accurately between source and receiver over a course of time. Use of lower frequency flextensional transducers would give a greater range than currently possible.

DRIVING FLEXTENSIONAL TRANSDUCERS

The method chosen to provide the driving power to the transducers is dictated by the application, as the ancillary equipment needs to be considered. The electrical characteristics of flextensional transducers are similar to those of conventional ceramic transducers, although their lower operational frequency tends to give them a higher impedance. Drive voltages for high power operation are typically 1000 to 3000 volts rms.

The capacitative part of the electrical load may be cancelled out by an inductor, which may either be placed at the platform end of the transducer drive cable or mounted in a pod adjacent to the transducer. The latter method is preferred as it reduces the reactive current in the cable. The transducers typically have both electrical and mechanical Q values in the region of 3 to 6 in water.

Alternatively, the inductance may be incorporated in the driver transformer. The transformer may also be either at the platform end or adjacent to the transducer depending on the operator's preference for driving underwater cables at high current or high voltage.

Transducer efficiencies are typically 60% or more around resonance, so the amplifier chosen to work with it should preferably have a power output at least twice the rated acoustic output of the transducer. If wideband use is envisaged, a more powerful amplifier with high tolerance of capacitative loads should be used.

FUTURE DEVELOPMENTS

Current research and development of flextensional transducers is expected to lead to devices which will operate at much greater depths (targeted at 800 metres) and, with alternative drive methods, such as magnetostrictive coupling rather than piezo- electric, which will allow more flexibility in the choice of electrical power source.

The present range of flextensional transducers are now stock or production units with reproduceable characteristics covering the complete frequency range over which the transducers can operate efficiently. Such is the confidence with which British Aerospace can manufacture transducers, that units may be designed by a computer program which takes as its input specific customer requirements in terms of frequency, power, physical and environmental characteristics.

The incorporation of pressure compensation into these devices will allow their operation to be extended from a few hundred metres depth down to perhaps a few thousand metres. The use of rare earth materials and magnetostrictive drives will allow high current driving of the transducers, rather than high voltage driving as with today's piezo-electric devices. This means that the designer may opt for a device which appears as a capacitive load or an inductive load, as the application requires, and optimise the ancillary driving electronics and power source.

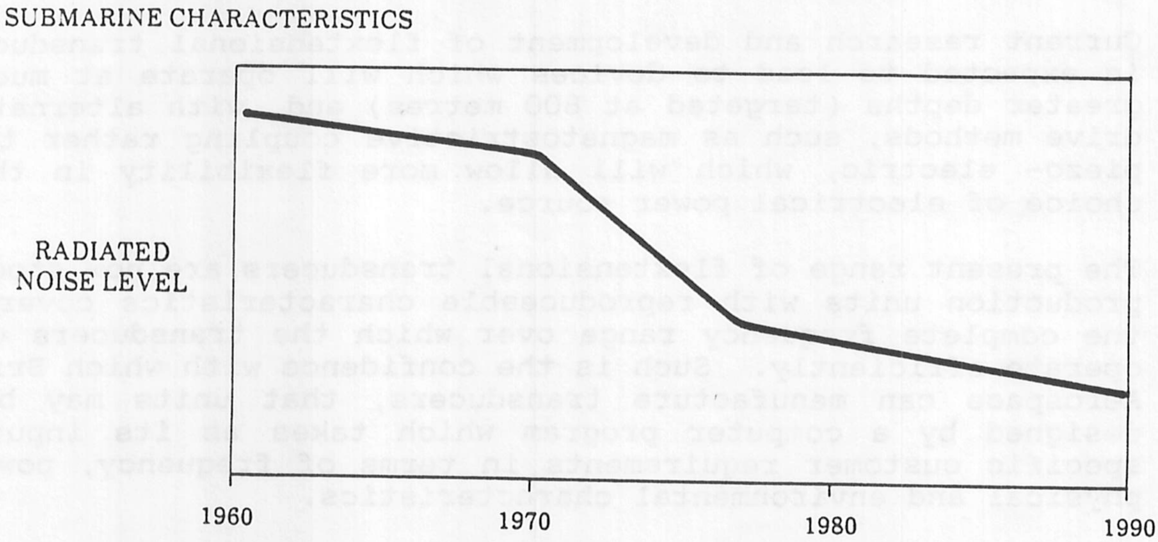
Both of these major developments will generate new applications in the civil and military fields since all aspects of performance will be improved over the present generation of devices.

SUMMARY

Flextensional transducers are compact, low frequency, high power sources which offer advantages in high efficiency and wide bandwidth at shallow operational depths.

They may be used in both civil and military applications, wherever low frequency operation can enhance the performance of existing equipment.

Standard transducer variants are available but, additionally, an individual design service can be offered. Research and development continues to provide flextensional transducers with even higher levels of performance than the existing range of units, which is available to acoustic engineers and designers in all fields of oceanology.

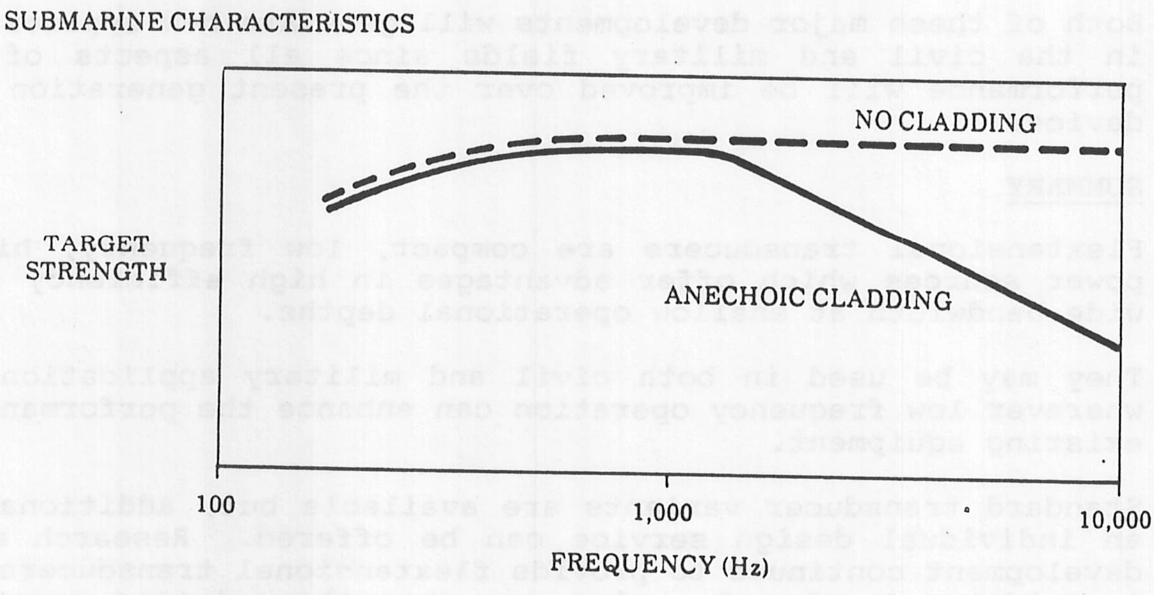


SONAR RESPONSE

LARGE APERTURE TOWED ARRAY SONARS

- IMPROVED SENSITIVITY
- LOWER OPERATING FREQUENCY

FIGURE 1 - EFFECTIVENESS OF PASSIVE SONAR



SONAR RESPONSE

LOW FREQUENCY ACTIVE SONARS

- NOVEL CONFIGURATIONS
- EFFICIENT, COMPACT ACOUSTIC SOURCE
- LARGE APERTURE ACOUSTIC RECEIVER

FIGURE 2 - EFFECTIVENESS OF ACTIVE SONAR

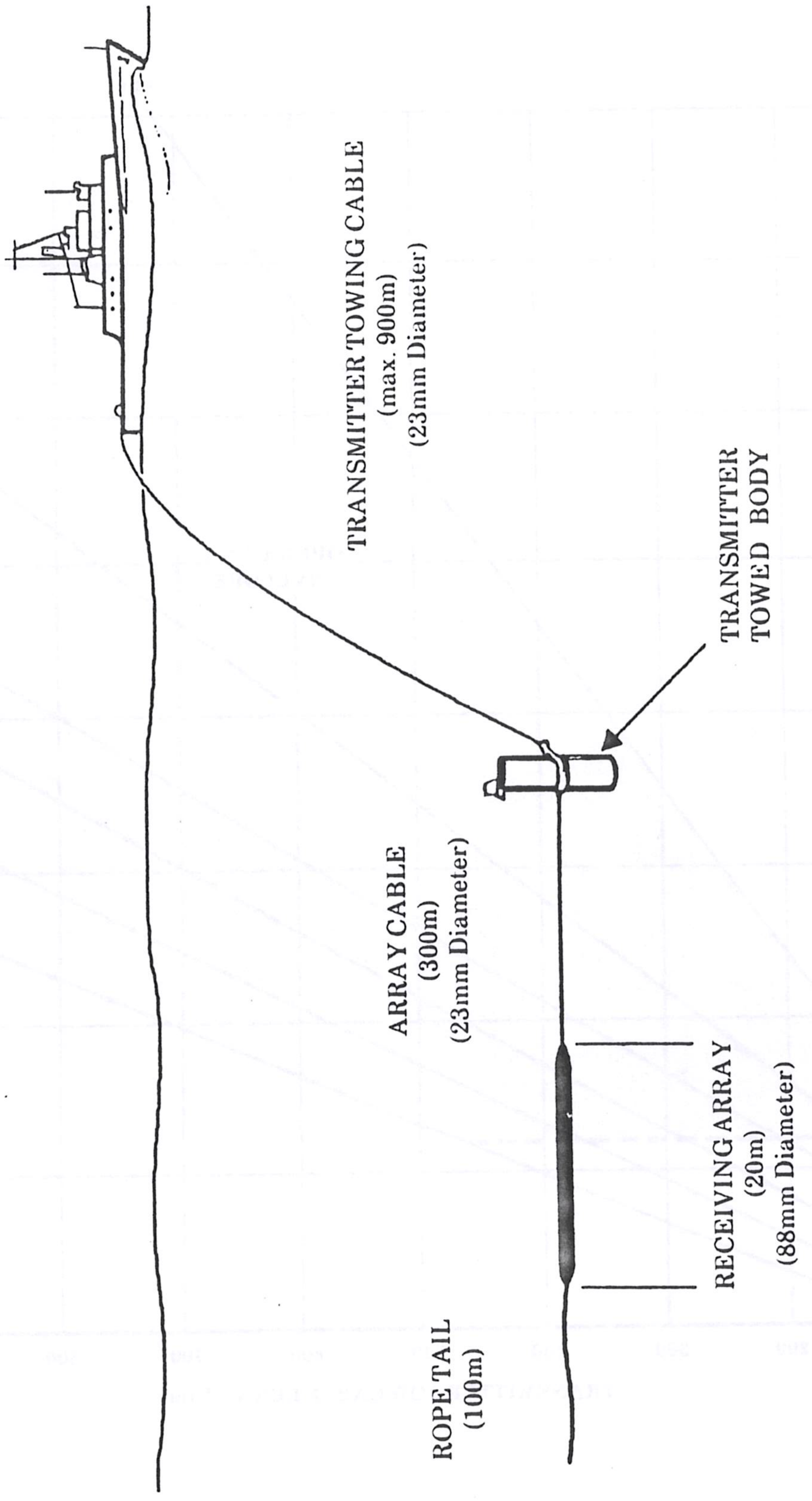


FIGURE 3 - ATAS SYSTEM CONFIGURATION

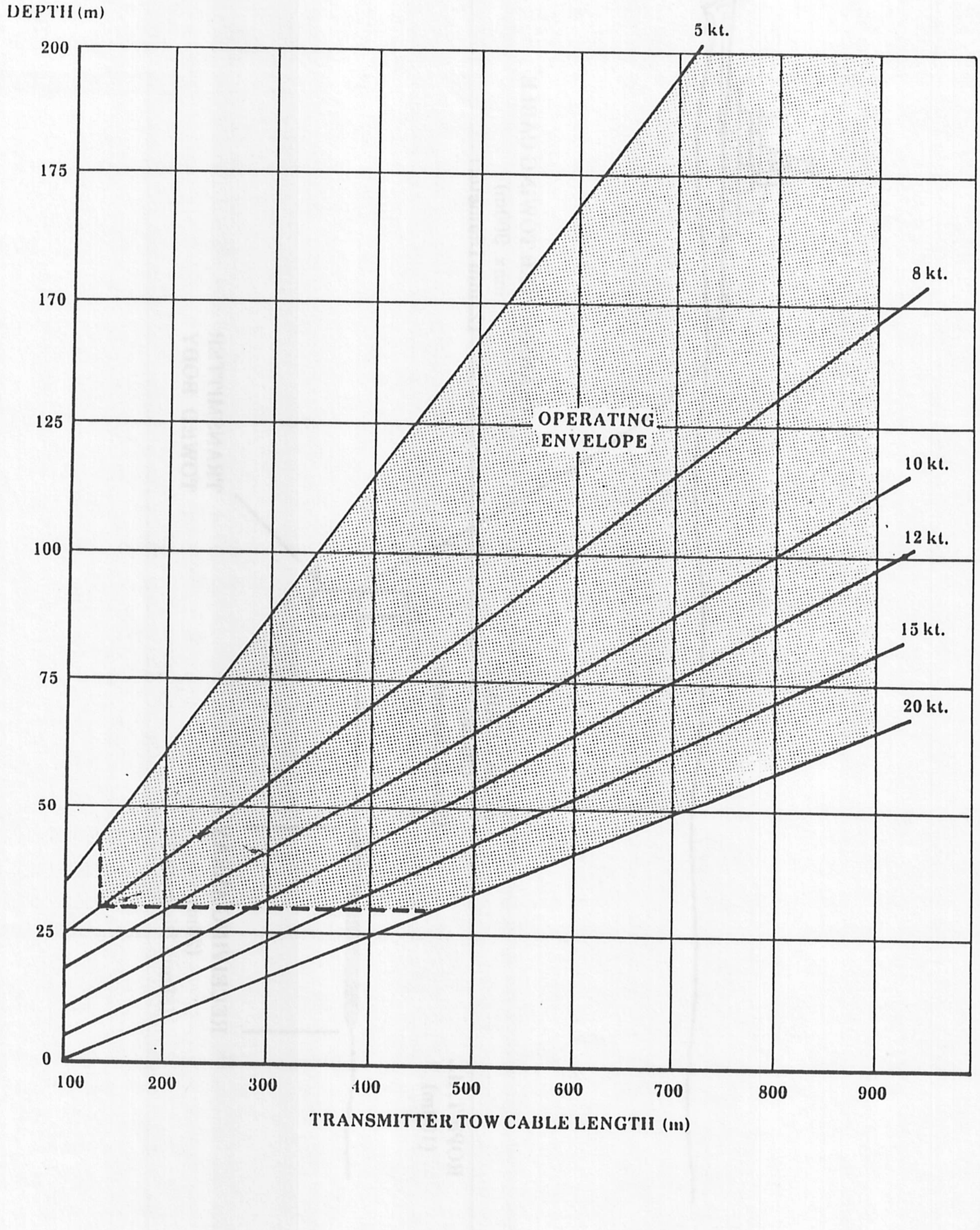


FIGURE 4 - ATAS OPERATING DEPTH v TOW CABLE LENGTH

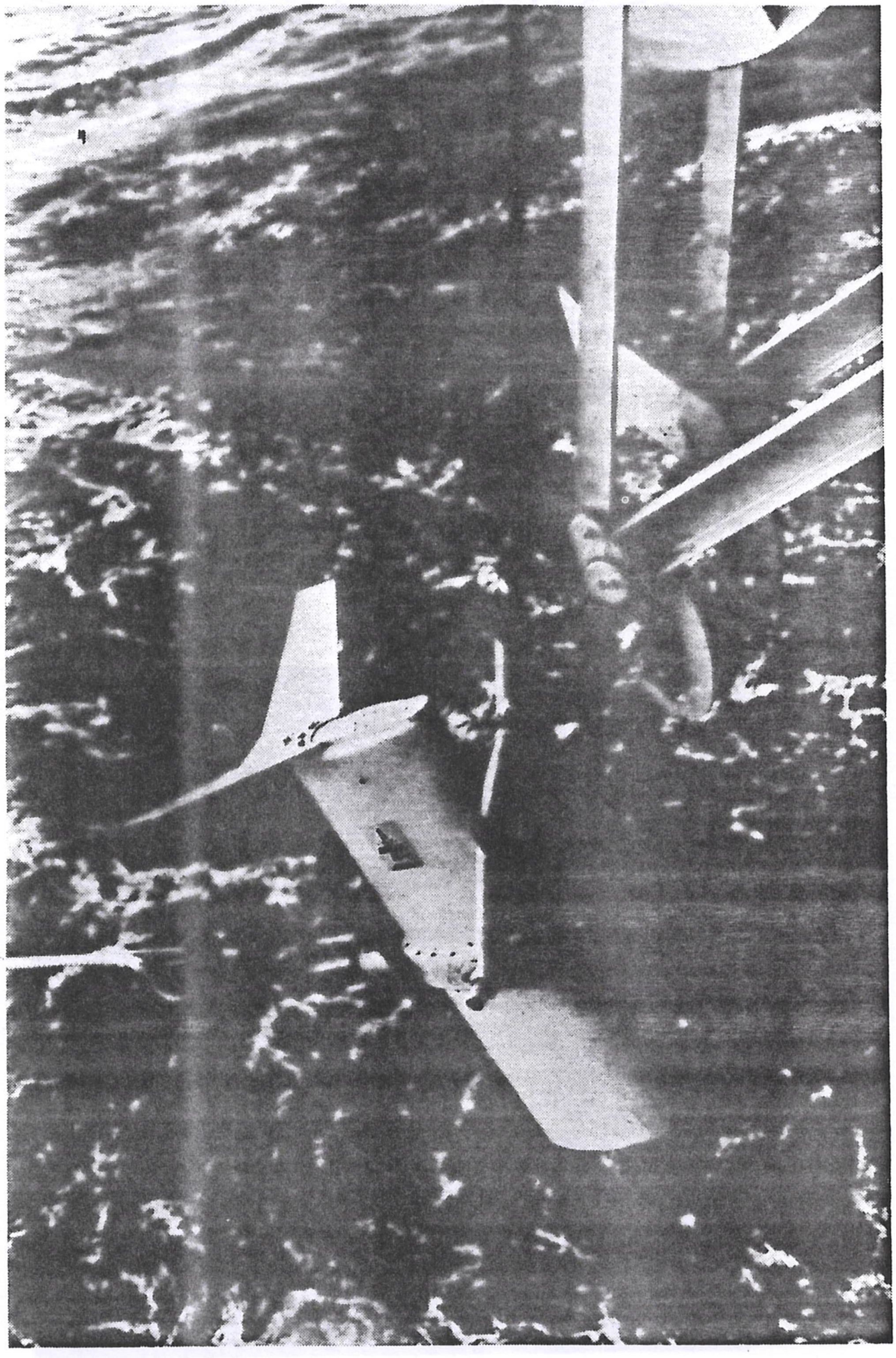
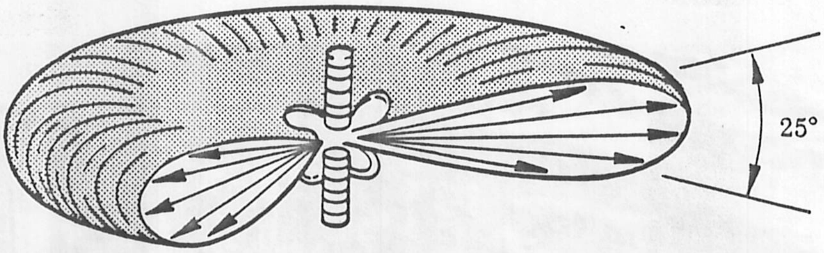


FIGURE 5 - ATAS TRANSMITTER



TRANSDUCER: 5 + 5 FLEXTENSIONAL
FREQUENCY: 3.0 kHz
WAVELENGTH: 0.5 m
HEIGHT: 1.2 m
BEAMWIDTH: 360° HORIZONTAL
25° VERTICAL

FIGURE 6 - ATAS TRANSMITTER BEAM PATTERN

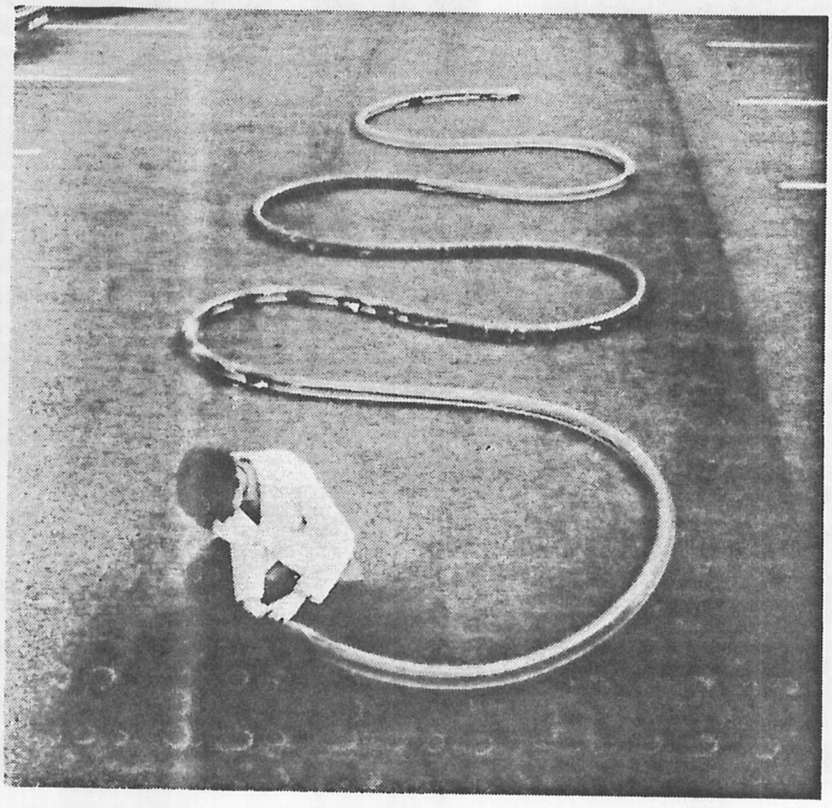


FIGURE 7 - ATAS RECEIVER ARRAY

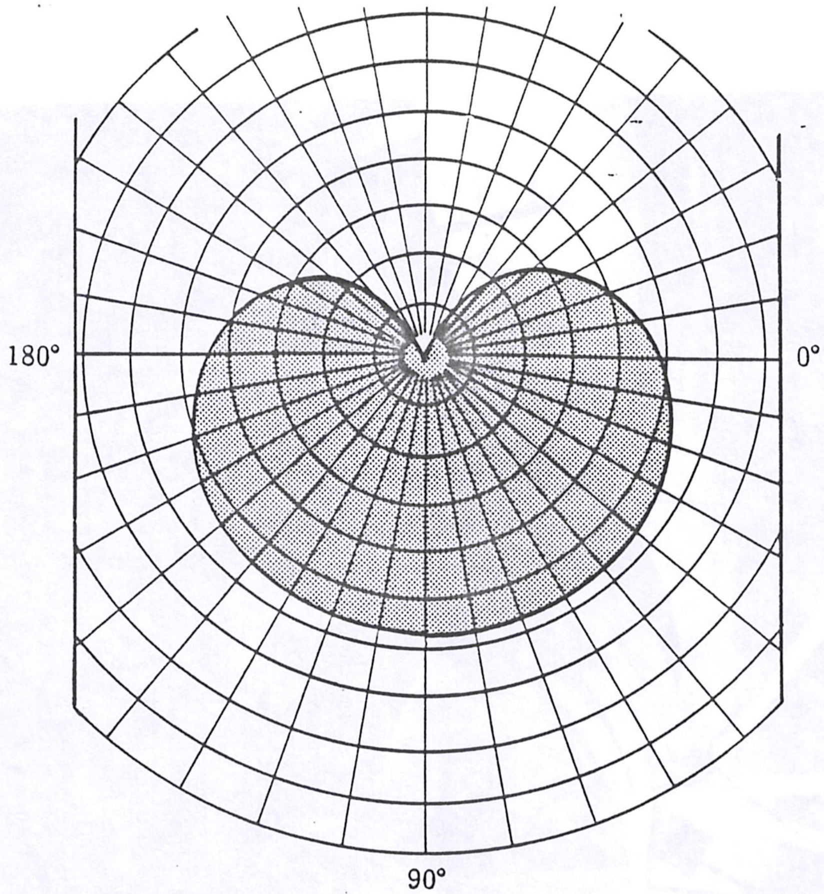


FIGURE 8 - ATAS RECEIVER CARDIOID BEAM PATTERN

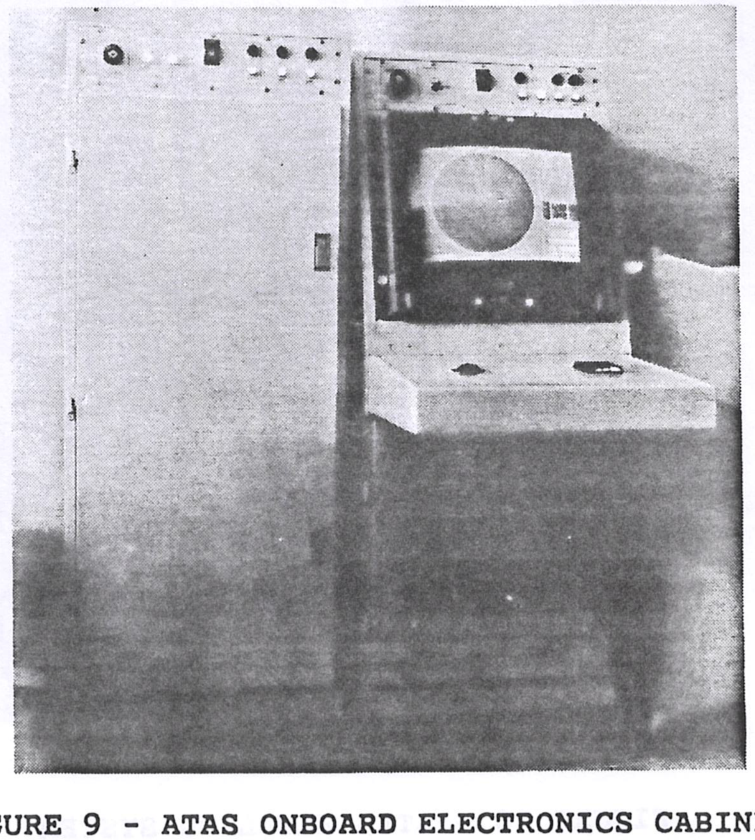


FIGURE 9 - ATAS ONBOARD ELECTRONICS CABINETS

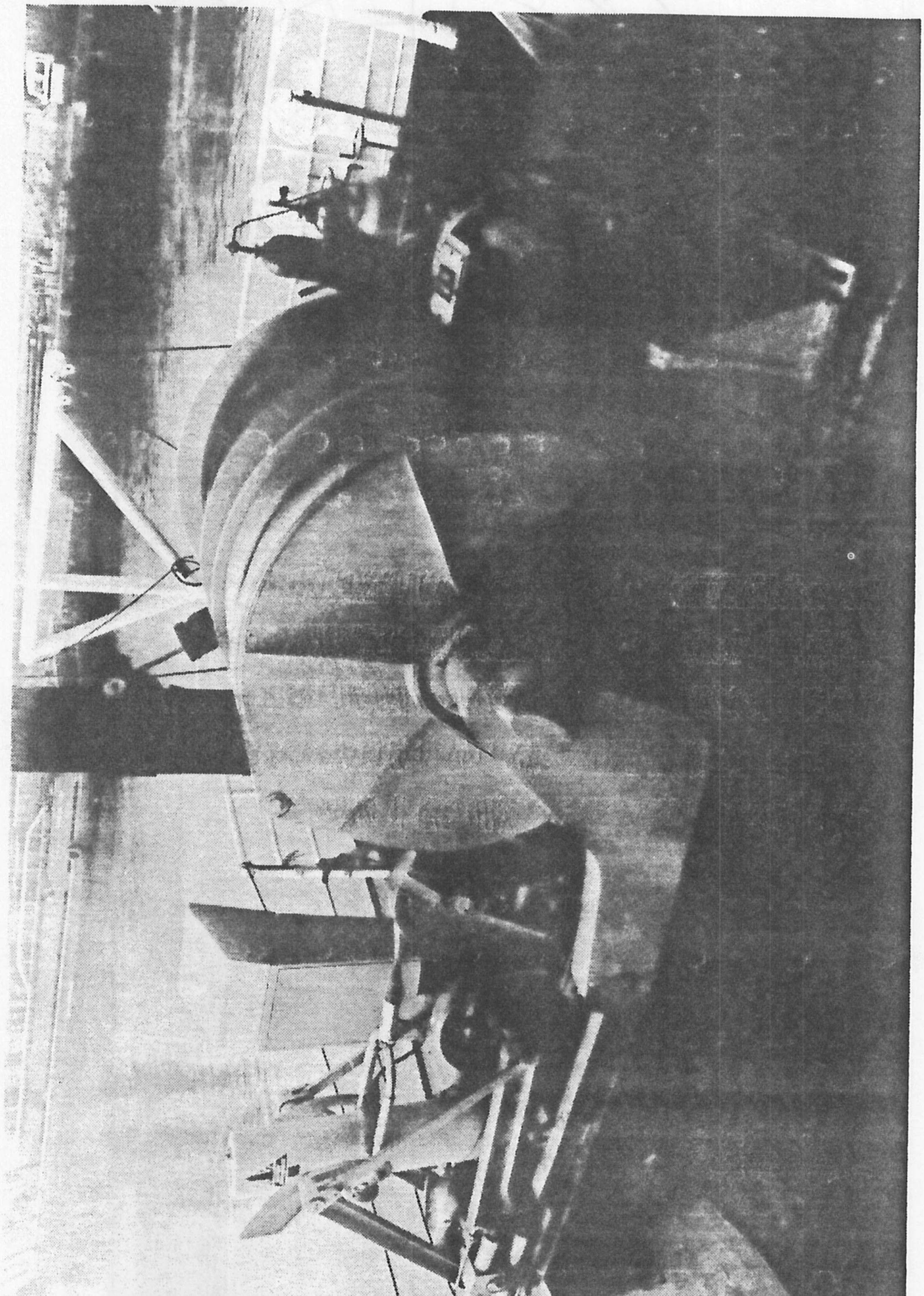


FIGURE 10 - ATAS HANDLING SYSTEM

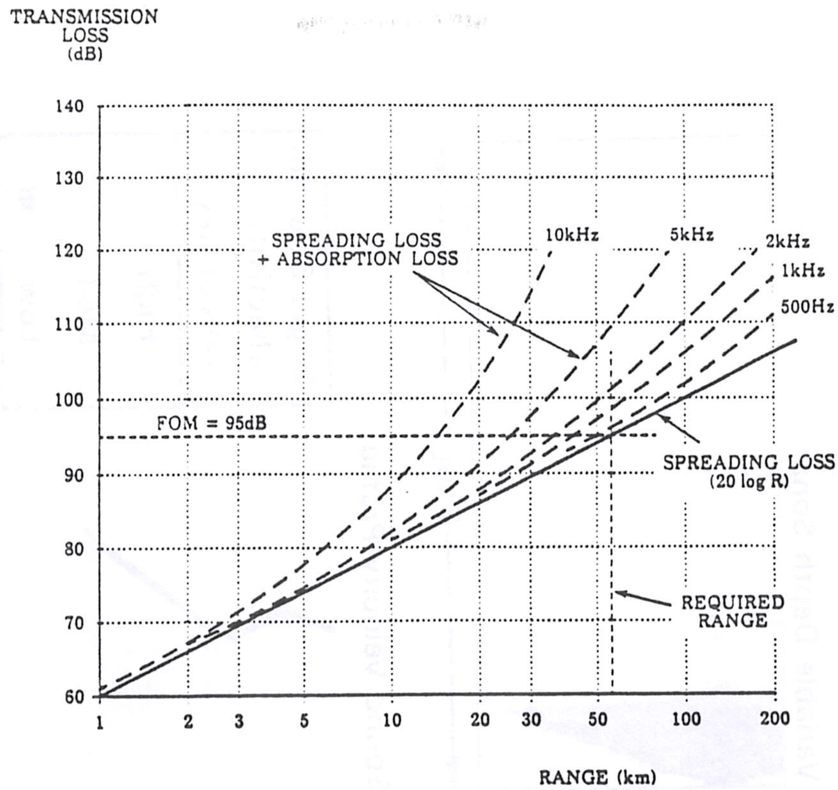


FIGURE 11 - TRANSMISSION LOSS v RANGE

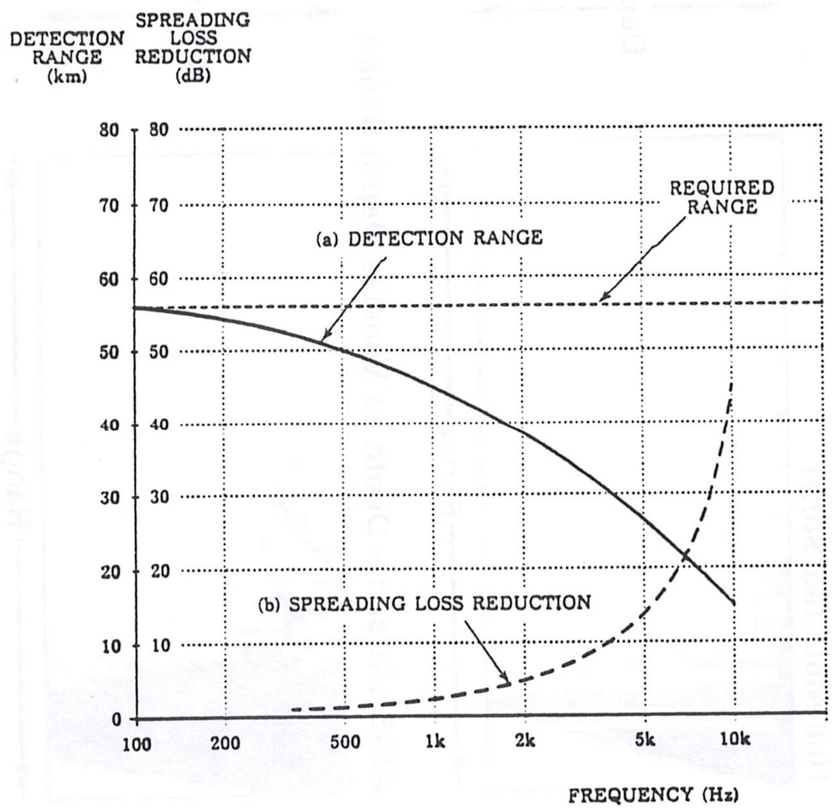


FIGURE 12 - (a) DETECTION RANGE v FREQUENCY (FOM +95dB)

(b) SPREADING LOSS REDUCTION v FREQUENCY (FOR 56km RANGE)

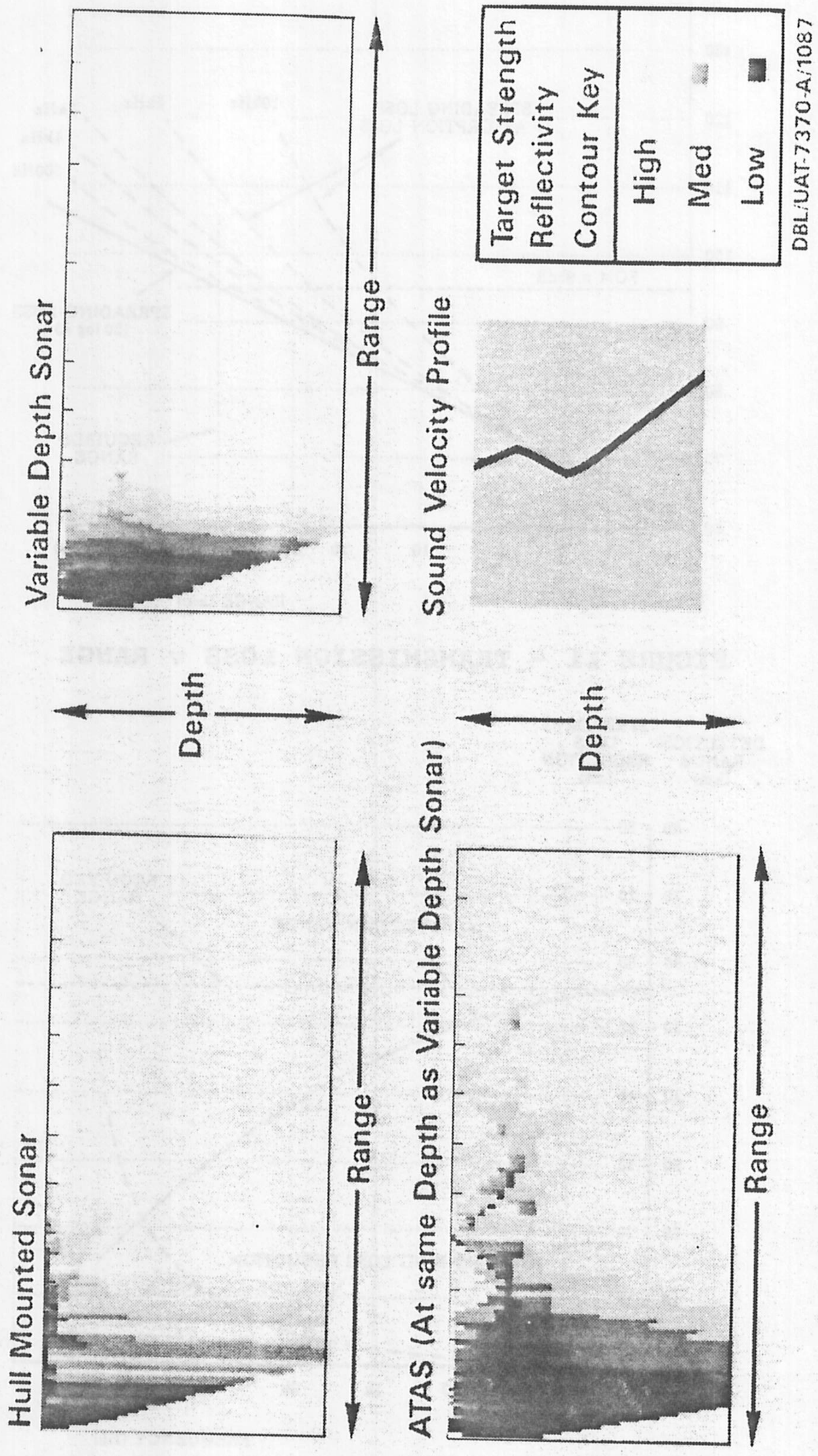


FIGURE 13 - ATAS PERFORMANCE - 1

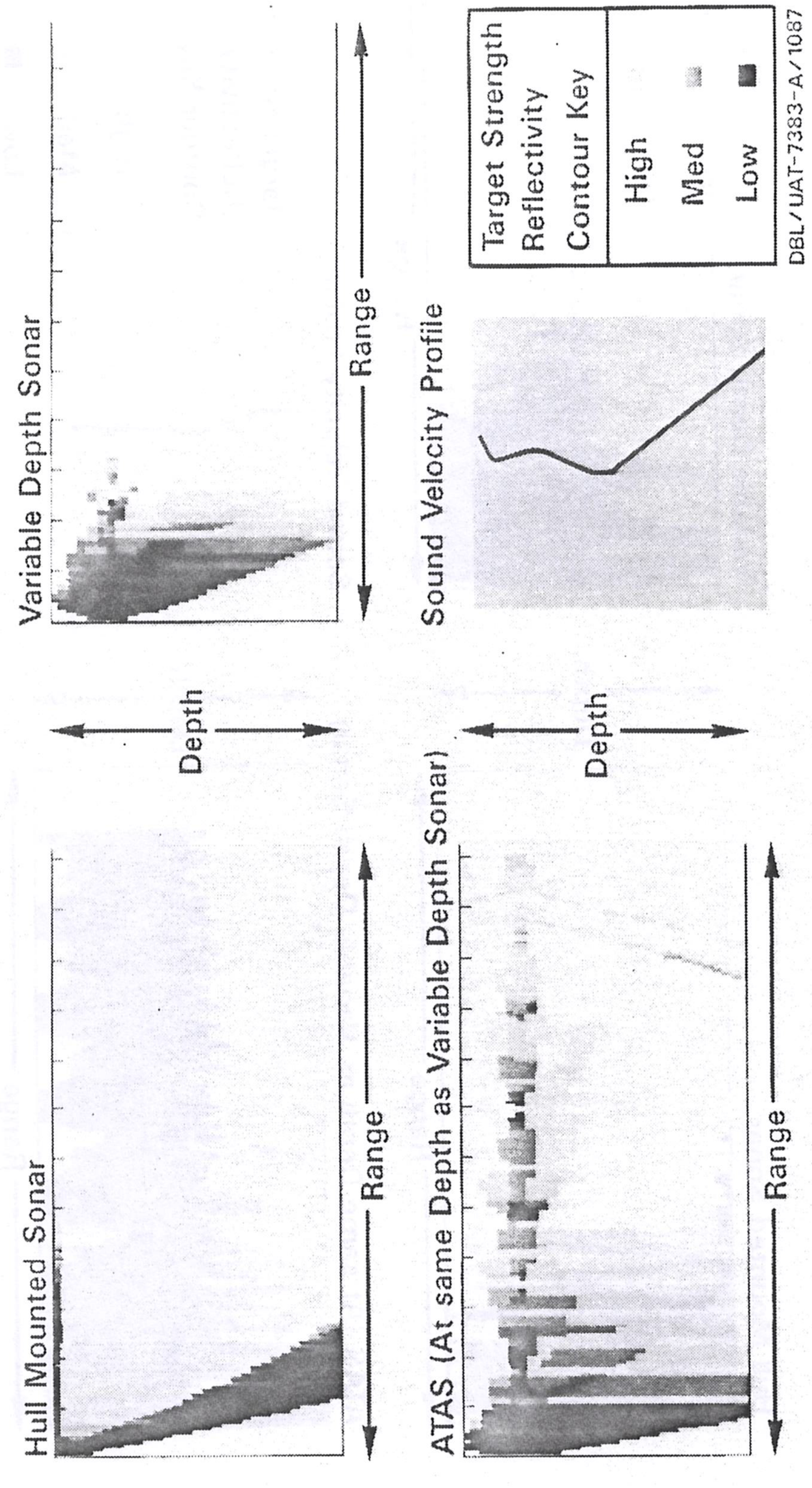


FIGURE 14 - ATAS PERFORMANCE - 2

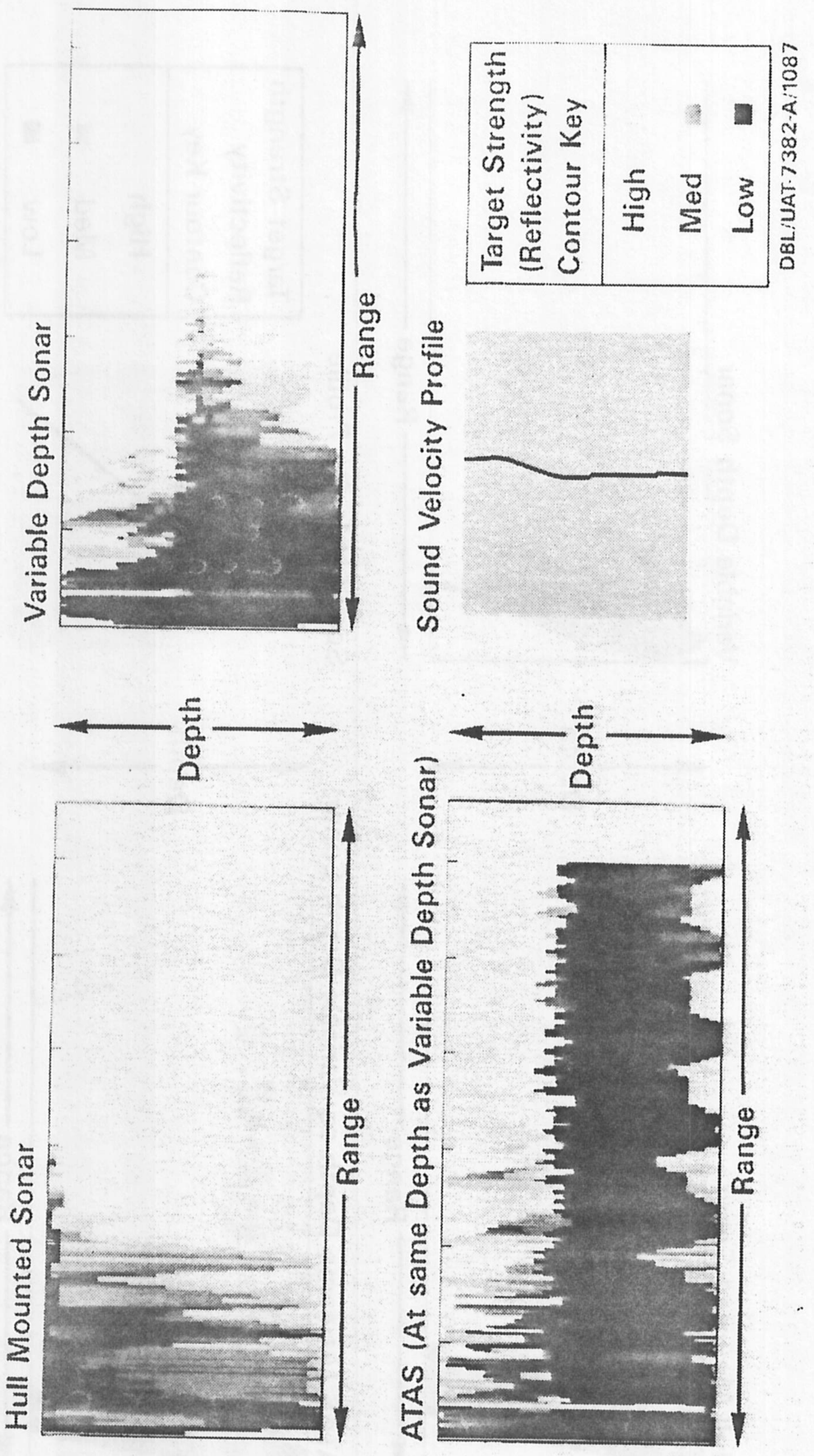


FIGURE 15 - ATAS PERFORMANCE - 3

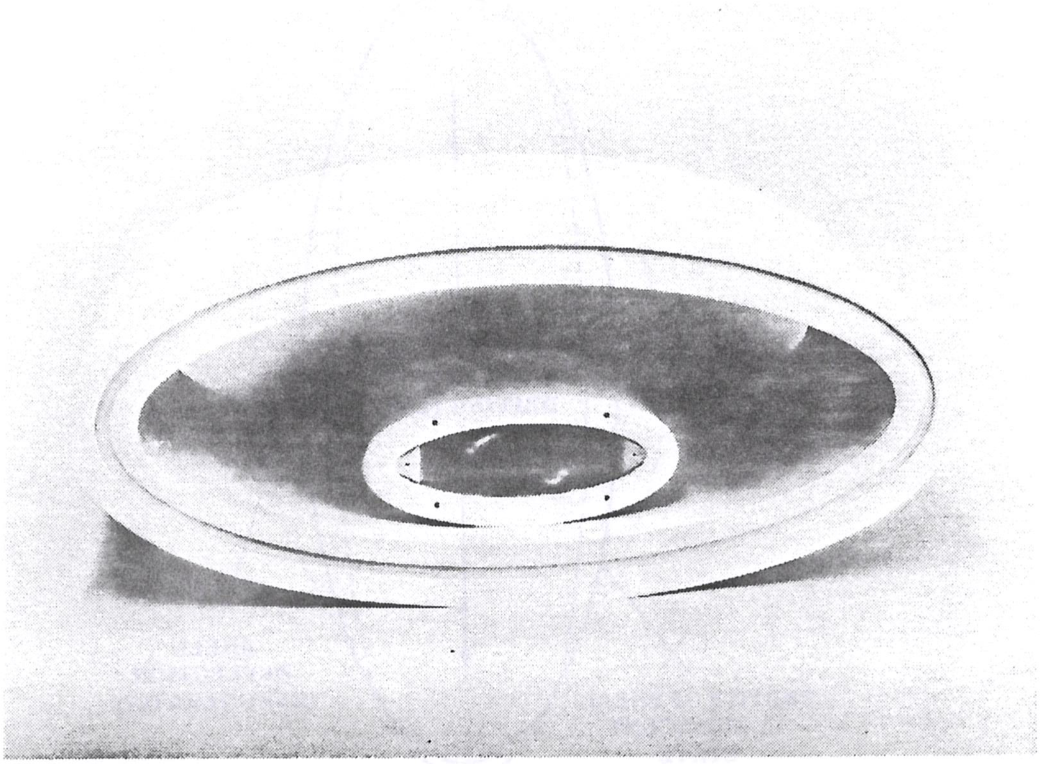


FIGURE 16 - MOST COMMON FORM OF FLEXTENSIONAL TRANSDUCER

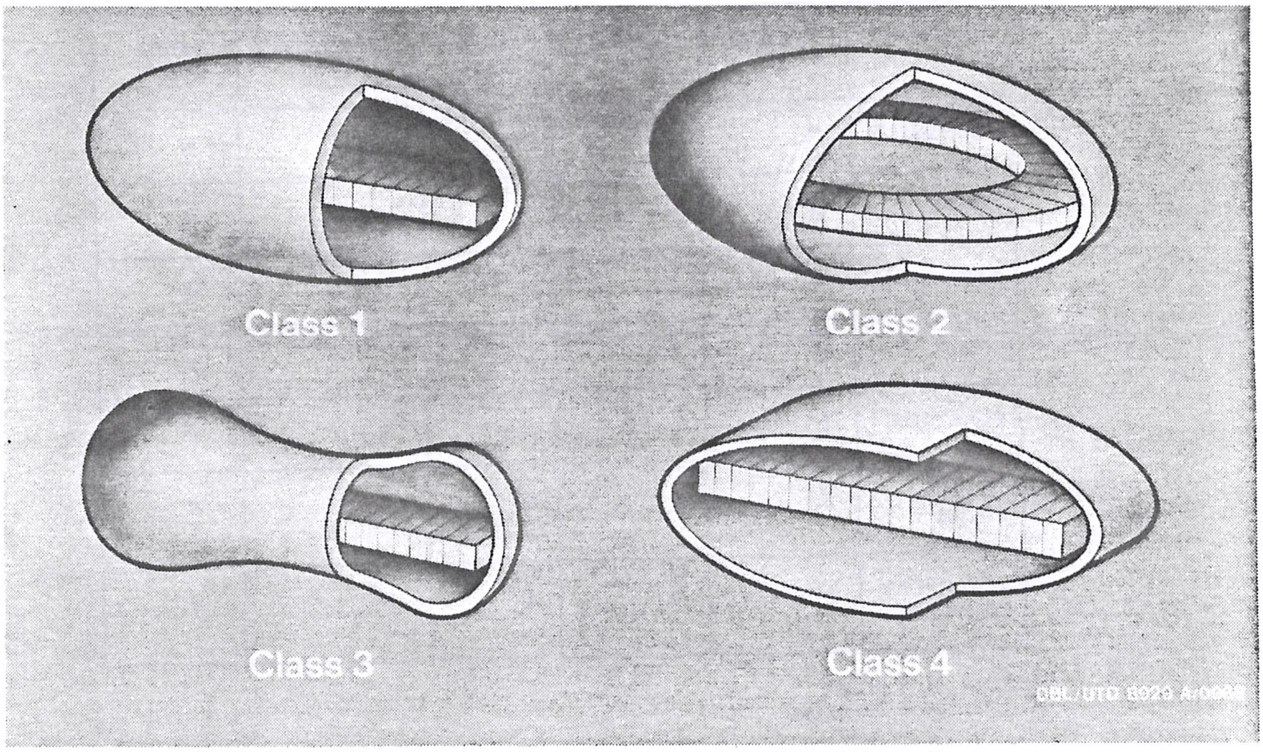


FIGURE 17 - THE FOUR CLASSES OF FLEXTENSIONAL TRANSDUCER

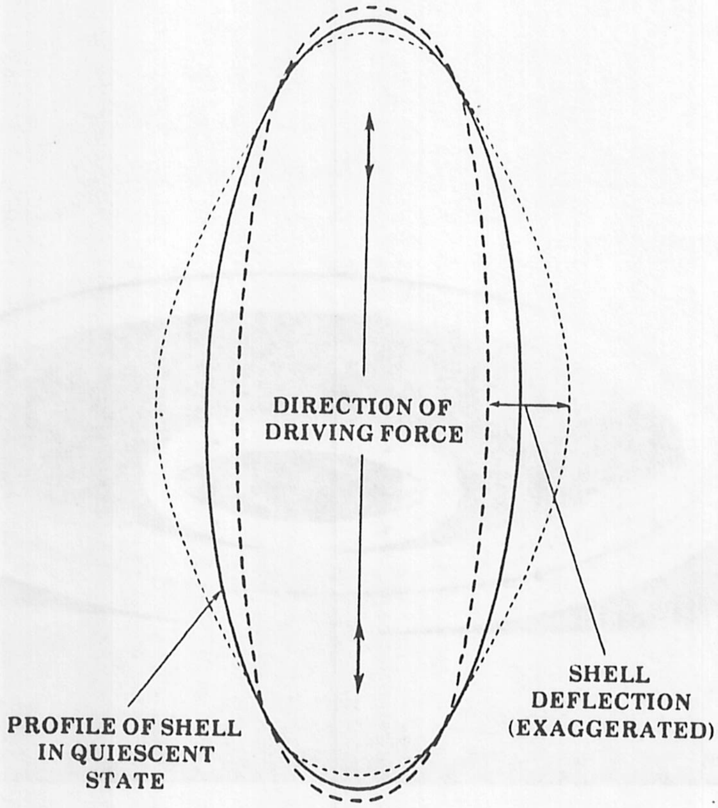


FIGURE 18 - MODE OF OPERATION OF A CLASS IV FLEXTENSIONAL TRANSDUCER

MATERIAL	STRENGTH	DENSITY	STIFF-NESS	FREQUENCY	BAND-WIDTH
ALUMINIUM	M	L	M	M	W
STEEL	H	H	H	M	N
TITANIUM	H	M	M	M	M
GRP	M	L	L	L	W
PLASTICS	L	L	L	L	W
CARBON FIBRE	H	L	H	H	W
AL-KEVLAR COMPOSITE	H	M	H	H	W

KEY: H = High
M = Medium
L = Low
W = Wide
N = Narrow.

FIGURE 19 - SHELL MATERIALS AND THEIR EFFECT ON FREQUENCY

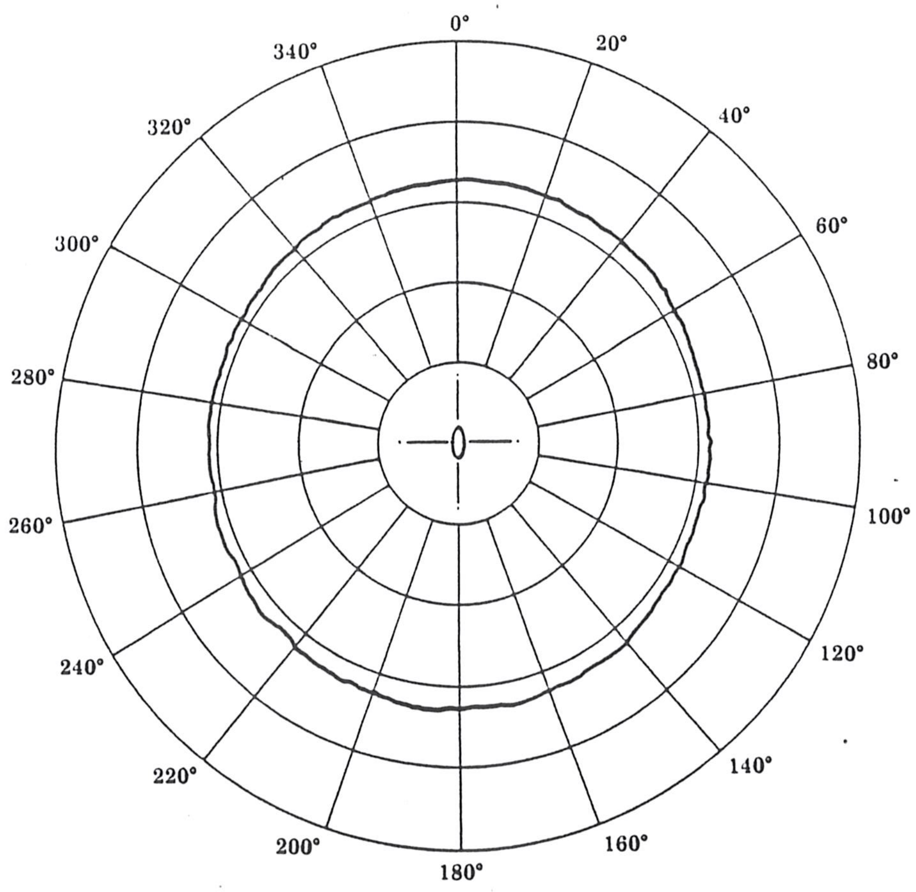


FIGURE 20 - TYPICAL CLASS IV RADIATION PATTERN

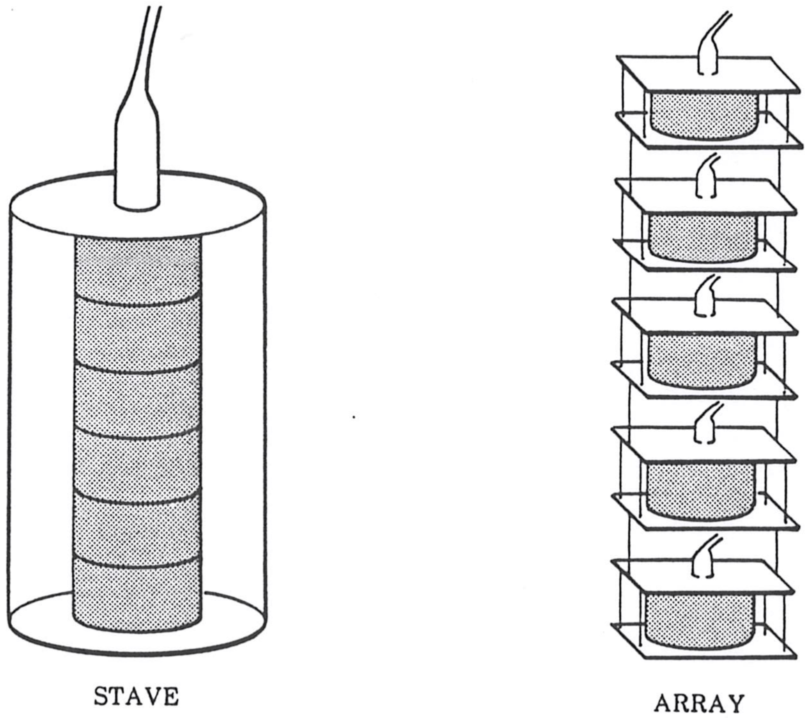


FIGURE 21 - CLASS IV FLEXTENSIONAL TRANSDUCER MOUNTINGS