M. A. Lawrence

Improved underwater communications

Summary

This article provides an outline of some of the factors taken into consideration when designing equipment for underwater acoustic communications. Data transmission 'through water' presents difficult problems for the communications engineer to solve, but experience gained from operating telegraph circuits over radio in poor propagation conditions has been of great value in finding solutions to acoustic transmission problems. A brief account is given on how radio transmission techniques have been modified and combined to provide effective low error rate underwater data transmission.

Mention is also made of future development where ranges of hundreds of miles may be achieved by further developing existing techniques.

Introduction

Since man first ventured below the surface of the sea, communication with the surface has been a problem and a vital factor in the execution of his tasks. The early 'hard hat' divers had only a rope with which to signal the surface, it being some time before cable communications enabled speech to be transmitted in both directions. Even now many commercial divers prefer the security of being directly connected with the surface through this simple but effective means of communication.

The need for rapid two-way communication with submarines has given rise to much development work being done and has advanced the methods available quite considerably. Cable communication is obviously out of the question, thus leaving only radio and acoustics as possible fields for investigation.

While most radio waves do not penetrate the surface of the sea and are therefore useless as a medium for underwater communication, extremely low-frequency (e.l.f) radio waves can and do penetrate sea-water and so are usable for long-range communications. Unfortunately, the size and nature of the transmitting equipment confines the use of e.l.f to land-based transmitting stations operating in a broadcast mode only, at comparatively low data rates.[1]

Using the long-range capability of e.l.f, it is possible to cover the greater part of the globe and its use to communicate instructions to remote, submerged submarines is obvious. However, for practical purposes where rapid, tactical, two-way communication is required, acoustic communication provides the only answer.

For a long time the acoustic properties of water have been used to advantage, but with a greater understanding now of the medium and the problems associated with sound propagation it has been possible to develop new 'through water' communication equipment capable of providing the rapid, reliable, two-way exchanges of data and information so essential in this present day and age.

Sea noise

On lowering a hydrophone into the sea, all manner of background noise can be heard such as the snapping of shrimps, the engine noise of ships and even the noise generated by the waves themselves.[2]

The use of discrete acoustic frequencies for transmission and reception permits rejection of unwanted noise to a certain extent, but the limiting factor in the sensitivity of any receiver is not the noise in the equipment itself, but the level of the signal above the sea noise. Most carefully designed acoustic receivers can be produced with internal noise levels many dB's below the actual sea noise.

However, some improvement may be obtained by choosing a carrier frequency best suited to the particular purpose of the equipment, but this usually means a trade-off between range and the elimination of background noise. For most practical purposes this optimum frequency lies somewhere in the band 2 to 100kHz.

The medium

The sea, bounded by acoustically reflecting surfaces, contains a multitude of layers and pockets of varying density and refractive index which play havoc with acoustic propagation. In addition to the non-homogeneous nature of the sea, there are three basic factors which affect the velocity of sound, these being water temperature, depth and salinity. The combined effect of these three variables is to bend the acoustic rays and consequently the radiation pattern of the transmitted signal is affected. In some cases direct communication in a horizontal direction is impossible and may only be achieved, if at all, by alteration of transducer depths.

The radio engineer can rely upon the r.f radiations travelling outwards at the rate of approximately 186,000 miles per second, but the acoustic engineer finds his sound radiations bending and weaving about at a velocity of anything between 4800 and 5050ft per second. The temperature of the water near the surface

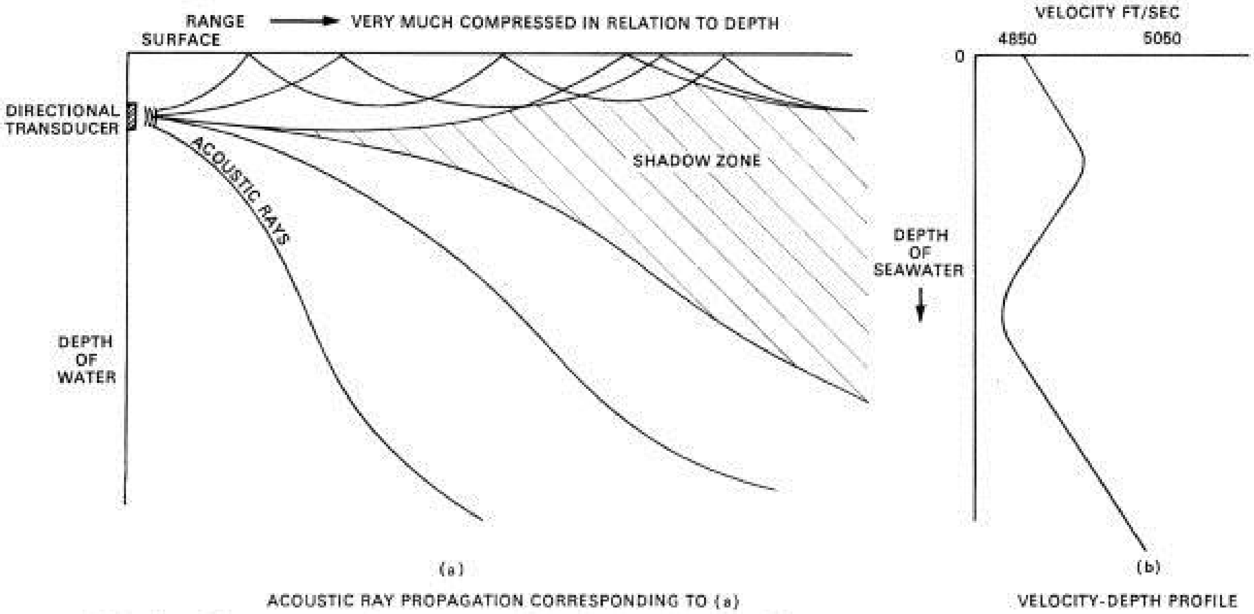

Figure 1 (a) *Acoustic ray propagation curves and* (b) *velocity – depth profile*

is the biggest single variable affecting the radiation pattern of an acoustic signal transmitted from a surface vessel.

The increase in velocity that occurs with depth is a known factor, and in conditions of constant water temperature has the effect of bending acoustic rays in an upward direction when attempts are made to transmit horizontally. Figure 1(a) shows the acoustic ray propagation curves corresponding to a typical velocity – depth profile (b) also shown in the same figure. It will be seen that under these conditions a shadow zone is created in which no direct communication is possible, this being approximately equivalent to the skip-distances experienced on h.f radio circuits.

Propagation conditions near the surface change rapidly being dependent on a number of factors, including the state of the sea, the time of day and the amount of solar heat absorbed in the water. Where a transducer is mounted on a surface vessel within this variable surface layer, prediction of propagation patterns becomes difficult and unreliable.[3]

It can also be seen that formation of sound ducts can occur and if it is possible to choose the depth at which to position the transducer, certain conditions can be used with considerable advantage. In most cases, however, it is not possible or practicable to vary the depth of the transmitting element at will, though measurement of water temperature with depth enables a calculation to be made, predicting the propagation conditions for that particular circumstance. Provided the water temperatures above the vessel are known, the submarine has a better chance of positioning itself to take advantage of the prevailing conditions.[4]

When all possible variations of sea conditions are taken into account, ranging from shallow calm tropical water to rough deep-sea conditions, the sea as an acoustic transmission medium presents some tough problems for the communication engineer to solve.

Speech transmission

The variable nature of the transmission medium and the tortuous path that a signal can take results in a considerably distorted signal being received. In addition to distortion caused by minor phase differences of the signal arriving by similar routes, more pronounced echoes can occur from bottom 'bounces' or other long propagation paths. Figure 2 shows the sort of conditions that can prevail to cause considerable distortion of the transmitted signal and possibly even complete cancellation.

Further difficulties due to doppler shift of the signal frequency occur when the transmitter and receiver are placed in vessels which are required to maintain communication facilities even when one or both are in motion. With vessels capable of producing a closing or opening speed of 40 knots, the amount of further distortion to the signal can be 1.2 per cent.

With the inevitable amount of signal distortion that occurs in 'through water' transmission, the first prerequisite is to ensure that the transmitted signal is as distortion free as possible and the design of the transducer plays a major part in achieving this end.

In normal speech transmission there is a great deal of redundancy and should the quality of speech suffer, the human brain can reject echoes, adapt to the distortion and fill in missing information by deduction whilst in the last resort the communicator can revert to communication by spelling out each word by using a phonetic alphabet.

Data transmission

With data transmission the reception device does not have the same discretionary and intellectual powers as the human brain, and techniques of error detection and correction have to be built in to combat the mutilation and fades of the signals. Simple two-tone transmission

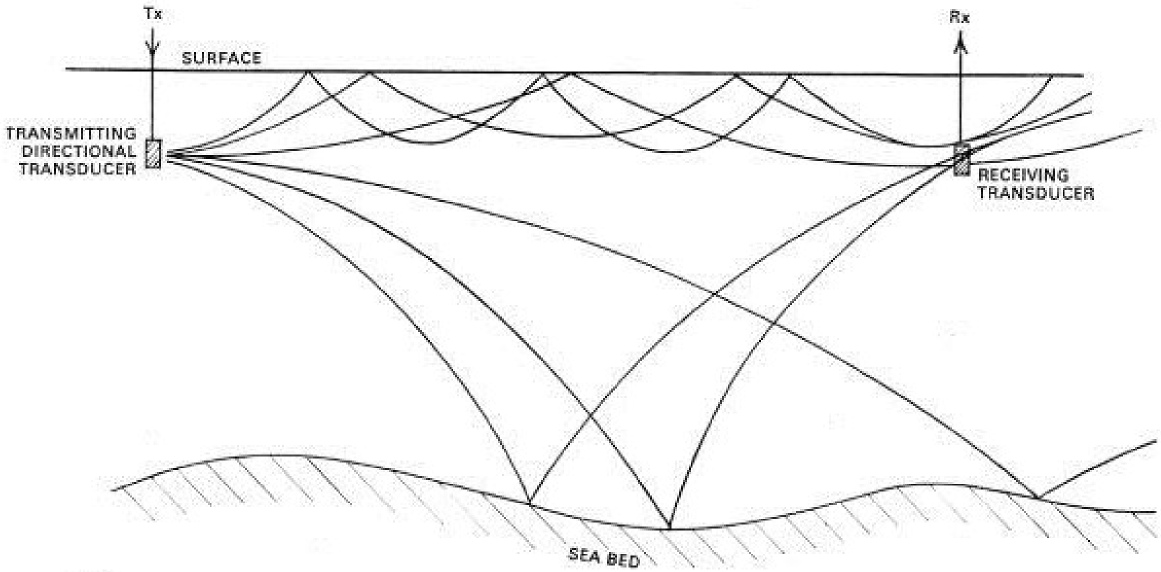

Figure 2. Acoustically transmitted signal showing multipath effect

of data can work under ideal conditions, but in practice these ideal conditions seldom exist.

An example of the severe nature of distortion that can occur is shown in figure 3. The transmitted signal is in two-tone form composed of random mark-space telegraph transmission. The recording shows the received rectified signal which is almost unrecognizable as square wave forms except for four equal mark-space at the beginning of the trace.

Obviously the transmission of digital data presents a greater problem than speech, and looking to radio there are no techniques which, on their own, go any way towards solving the problems experienced in underwater communications. With the advent of micro-circuitry and large-scale integration, it is now possible to use a number of error-prevention and detection techniques in combination where previously the cost would have been prohibitive, to say nothing of the space required, if thermionic valves had to be used.

The relatively slow propagation time of a sonar transmitter makes automatic request for retransmission (ARQ) methods impracticable as the confirmation that a signal has been received correctly could take up to 20 seconds at a range of 10 miles.

Most methods of telegraph forward error correction (FEC) are based on the introduction of further elements or bits such that a block of information or code becomes self-checking and the equipment is designed to recognize and reject any mutilated code or character. There are a number of self-checking codes which are in everyday use on radio-telegraph circuits which can be adapted for sonar use, but on their own would not be effective. The introduction of checking elements means more information has to be transmitted in the same period or alternatively at a slower data rate. The low carrier frequencies used in sonar transmission compared with radio do not permit high data rates, particularly when long ranges are sought and although

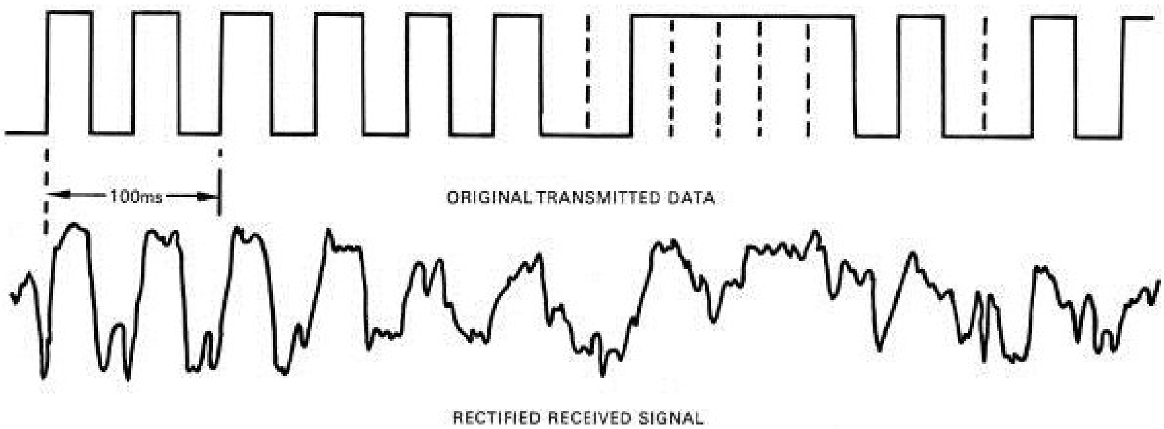

Figure 3. Sample recording of telegraph signal showing distortion after 'through-water' transmission

FEC techniques are required, any shortening of element duration must inevitably degrade the performance. The situation can, however, be remedied by converting serial information into a parallel form and transmitting a number of tones simultaneously over a longer period than the basic information period.

The technique of having the transmitter and receiver locked in synchronism after 'phasing up' yields many benefits, not least of which is that of knowing how much information has been lost and when to inspect the incoming signal to detect mark or space. Such a system requires that synchronism is maintained and constantly updated, particularly when communicating vessels are in motion.

Another problem which is more pronounced in sonar communication is that of fading, and the susceptibility of the transmission to bursts of noise that cover the whole frequency spectrum; both mean loss of signal for a period of time and occur at random intervals. Time diversity provides some protection, but the period between repetition has to be determined empirically rather than by theoretical calculation. The particular application may, in fact, require more than one repetition of the signal at irregular spacing. The penalty for adopting this technique also results in a lower data rate or a shorter element time, but the advantages gained outweigh the disadvantages.

Data transmission through water is far more demanding in terms of error protection techniques and combinations of frequency and time diversity than radio. Maintenance of synchronism, together with automatic frequency control, requires equipment more akin to a mini-computer than conventional circuitry, especially where the error rate demanded by the application must be of a low order or non-existent.

Environment

Underwater communication problems do not end with just devising suitable electronic solutions, as the very location of the equipment places limitations on the mechanical form of the design. In the case where one or both vessels are submerged, the transmitter and the receiver will be housed in some form of housing capable of withstanding the water pressures involved. The submerged vessel has the advantage that when below the surface it is reasonably stable as compared to a surface vessel, but has the disadvantage of an enclosed atmosphere. The equipment will almost certainly be subjected to pressure fluctuations, both positive and negative, and in the case of some submersibles having diver lock-out facilities, it may be subjected to very high pressures; for example at a depth of 600ft, the equalizing atmospheric pressure would be 267 p.s.i. In addition, high concentrations of oxygen can be experienced which may convert normally safe materials into extremely volatile fire hazards.

Oxy-helium atmospheres used by commercial divers also play havoc with electronic equipment, and hermetically sealed units are not found to be proof against the ingress of helium, with the result that, on returning to normal atmospheric pressure after a long period of time at high pressure, explosion of sealed units sometimes occurs. Helium also affects the design of the electronic equipment in other ways as, being some seven times more heat conductive than air, advantage is sometimes taken of this fact to facilitate the equipments cooling arrangements.

Reliability is an essential quality as accessibility is usually poor and the chances of carrying out repairs during operation are practically nil.

Equipment designed for use in high-pressure oxy-helium atmospheres is far better housed in a separate pressure vessel with special seals and entry glands, but in most pressurized applications adequate environmental testing has proved that standard methods of electronics construction may be used.

Range

As was seen earlier, the factors determining range are many. The first requirement is that direct communication should be possible under the prevailing propagation conditions. The choice of a carrier frequency is the first consideration and in general the lower the frequency the greater the range for a given power output. Unfortunately, at low frequencies the data rate is also limited, and to a certain extent range is therefore a trade-off between data rate and, as was mentioned earlier, the elimination of background noise. In figure 4 a graph of attenuation against frequency is shown which demonstrates the losses that occur at the higher frequencies.

Great benefit can be derived from using directional transducer arrays concentrating power propagation in a limited arc. The directivity of directional arrays is determined by the size of the array in relation to the wavelength, a narrower beam being obtained if the width of the array is several wavelengths wide.

Radiated power is naturally the key factor in achieving long ranges, but this needs to be coupled with the ability of the transducer to convert the power into acoustic energy without causing cavitation, i.e the creation of a vacuum at the face of the transducer. In

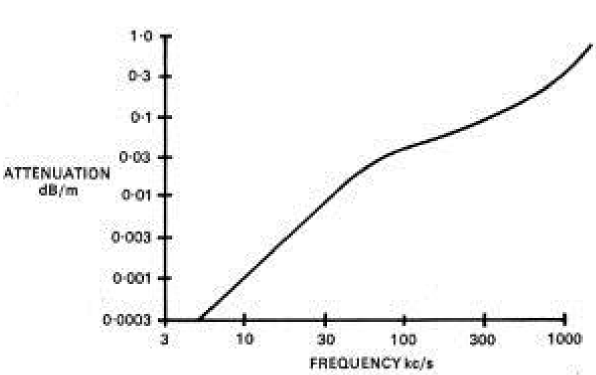

Figure 4. Attenuation coefficient at ultrasonic frequencies in sea water at 5°C.

general radiated power is limited to 0.3W/cm², and it therefore follows that there is a direct relationship between radiated power and size of transducer.

To give some idea of the ranges that can be achieved, a 10W transmitter in the 10–20kHz band will provide communication up to 2½ miles using directional transducers for both transmission and reception. With range being roughly proportional to the square root of the power output, other ranges may be calculated from these figures.

Transducers

The key to underwater communications lies in the transference of energy to and from the water. Usually communication is in simplex mode because of the long propagation times and consequently the same transducer is usually used for both transmission and reception.

Many types of electro-acoustic transducers have been developed for underwater use; they include magnetostrictive, peizoelectric electromagnetic, dielectric, electrostrictive, electrodynamic, etc. The one most commonly used in present-day designs is the electrostrictive barium titanate which provides the right level of impedance coupled with highly efficient power transference. A sectionalized barium titanate transducer which has been 'potted' to support the cut elements is shown in figure 5. A transducer in its normal state is also shown.

The manufacture of the barium titanate elements of a transducer still tends to be a 'black-art' but the other factors for the successful design are known. In the first instance the transducer is designed for the particular carrier frequency the system is to use. This ensures that the stiffness of the stack in relation to the mass of the radiating head produces a natural resonance at the carrier frequency when the face is loaded with the transmission medium.

When the transducer is mounted, it is usually required that the device radiates and receives from one side only, a high ratio between the mass of the mounting compared with the vibrating element providing some rearward attentuation. The most effective way however, is to provide an elastic mismatch at the rear of the transducer such as an air gap and to see that the transducer is attached to its mounting at its vibrational centre node.

Another factor to be taken into account is the bandwidth to be covered. A speech communication system will require 2.5–3kHz bandwidth with an even response throughout the band, which means that the mechanical Q is an important design factor.

Electrical matching into transducers also presents a few problems as the transducer parameters tend to vary with changes of pressure, temperature and age of the device, but provided these are known factors and are covered in the basic design calculation, efficient power conversion can be achieved.

A multi-element directional transducer array is shown in figure 6 in which the transmitting faces of single transducers of the type shown in figure 5 may be seen.

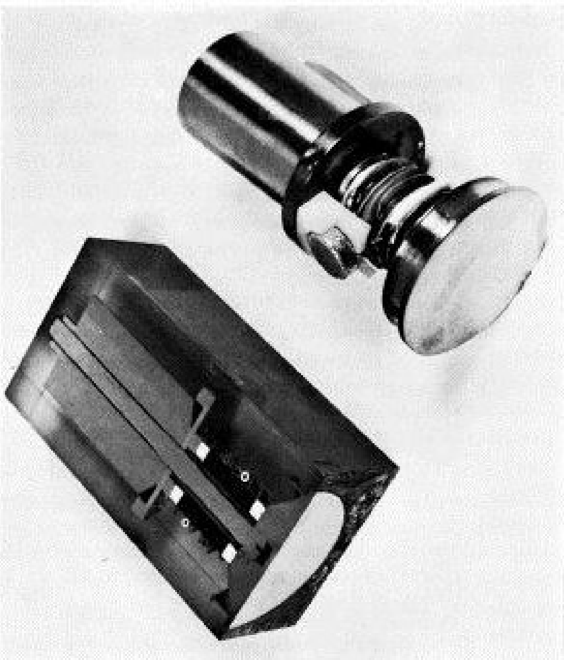

Figure 5. A typical barium titanate transducer

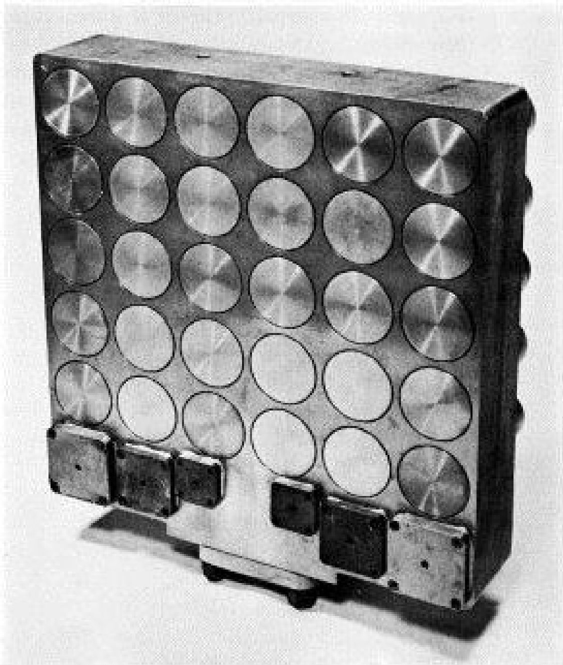

Figure 6. A typical transducer array

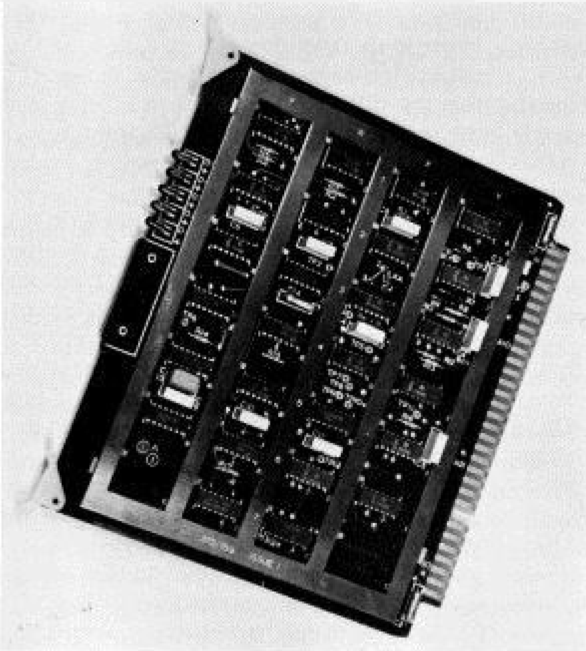

Figure 7. Example of microcircuit module for sonar 2010 equipments

Equipment design

The mode of transmission, whether it be s.s.b, d.s.b or f.m, etc. will depend upon the application and the experience of the designer, but whatever form the modulated carrier takes, the first requirement is for the signal to be processed and transferred to the transducer with a minimum of distortion over the required bandwidth. In the receiver, good automatic gain control is required capable of covering a wide range of fading and variation in signal strengths.

In the case of communication between moving vessels, allowance has also to be made for doppler shift, but in general the application of good solid-state electronic design principles is all that is required for the basic transmitter and receiver. There are no wheels to be invented and the solutions to most of the problems are already to be found in other designs.

However, data transmission is the more difficult equipment to design and has taken several years of research and sea trials in order to test the theories and ensure that the right combination of transmission techniques have been employed. Of necessity, the receiving circuits must be analogue, but once converted into digital form for decoding and processing, the use of micrologic circuits enables many complex functions to be dealt with reliably in a small space. Figure 7 shows a printed-circuit board from an underwater digital data-processing unit, and demonstrates the simple form these complex processors take as pieces of hardware.

Enough propagation information has now been collected to permit reliable data-error detecting and correcting equipment to be designed for combating the undesirable effects within the present limits of sonar communication ranges. New techniques may be necessary when data transmission is required at ranges of several hundred miles, but these will very probably take the form of modifications to the now existing systems.

Conclusion

This brief outline of some of the factors affecting sonar communications may help to explain why the art has taken so long to develop.

Being under water is a particularly hostile environment for man, and reliable communications are therefore vital for his survival, but the medium has made this difficult to achieve.

However, it is fortunate that radio communications have had similar problems, and it has been possible to adapt the solutions already devised for radio circuits to the needs of sonar systems without too much difficulty. This applies particularly to data transmission where the experience gained in operating telegraph channels over radio circuits under poor propagation conditions has been of such great value.

The advent of microcircuits has made it possible to condense a number of modules into very small units which previously would have required a small room to house the equipment. Space in any submarine or submersible is always at a premium, and compact equipment having low power consumption is therefore essential.

Acoustic communication still has a long way to go, even though the low losses of the lower frequencies make it feasible for acoustic transmission to travel thousands of miles in deep sound channels. The data rate is of course slow with very low carrier frequencies, but in some cases this would be acceptable, particularly in military applications where simple combinations can convey a wealth of coded information. On the other hand, the losses experienced at the higher frequencies do tend to confine communications to short distances and so preserve secrecy of messages.

Whatever course future developments may take, the successful development of new theories and equipment will largely depend on the successful completion of comprehensive sea-going trials, and development engineers must be prepared to conduct a large part of their work at sea.

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Other reading on the subject

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