UNDERWATER ACOUSTIC POSITIONING

PRINCIPLES AND PROBLEMS

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Underwater acoustic navigation systems, consisting of a group of transponders placed on the sea floor and interrogating instrumentation on a ship deriving a position from the returns, offer capabilities which may under some circumstances compete favorably with the more conventional radio navigation methods. However, for the positioning of submerged vehicles, or for the development of fixed reference points below the ocean surface, underwater acoustics has no substantial competition. As marine geodesy is expanded toward the establishment of a control-point system throughout the oceans, it appears safe to predict that underwater acoustic positioning systems will play an important role.

Figure 1 shows the essential elements of a complete acoustic navigational system and the sequence of events involved in its operation. The first column lists the mobile elements which are loosely termed "shipborne equipment". The last column shows the essential parts of the transponder, which is placed on the ocean bottom or buoyed up from a mooring on the bottom. In between lies the ocean medium for the transmission back and forth of acoustic intelligence. The sequence of events for one complete cycle of data collection, as suggested by the arrows, is as follows. The interrogator transmits an acoustic impulse. This impulse is received by the transponder and recognized by its processor as demanding a reply, whereupon the transponder transmits another acoustic impulse back to the shipborne receiver. In a primitive system, the shipboard processing requires only the measurement of the total elapsed time between the transmitted and return impulse, that is, over the round-trip path, and the provision of computational or nomographic means to reduce this datum to a range. In a considerably more sophisticated system, the processor and display reduce and plot the data automatically. A still more elaborate step is the provision of a central control which, together with the processor and display, can be thought of as a special purpose computer for the automation of the entire operation.

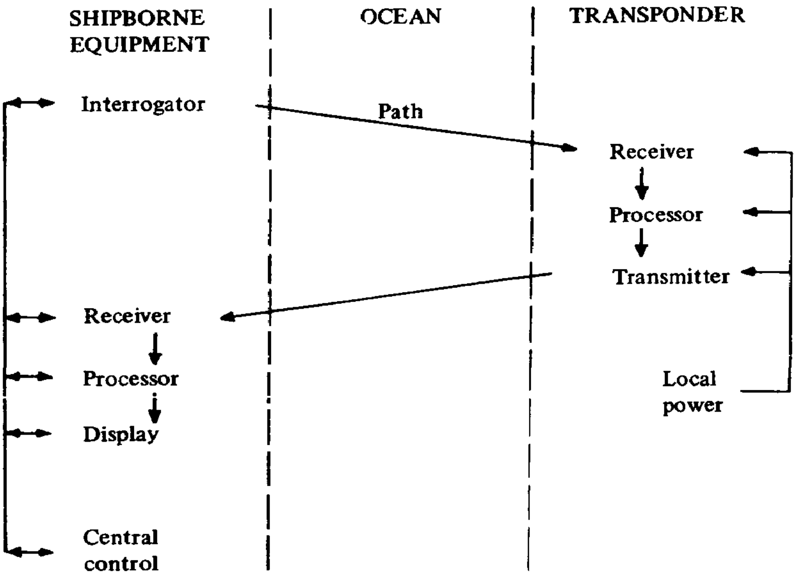

FIG. 1. — Elements of acoustic navigational system.

This paper is concerned with acoustic paths in the ocean and the effects which water properties, underwater acoustic propagation, and noise have upon the general design of useful, workable systems. While underwater positioning systems may be useful in the shallow water over continental shelves, it is in deep water, relatively remote from land, that underwater systems really come into their own and, likewise, it is in deep water that the full complexity of underwater acoustics is encountered (1). Therefore, attention is concentrated on the deep-water situation.

SYSTEM CONFIGURATIONS

In order to identify the principal acoustic paths, two different kinds of systems must be distinguished. Figure 2 shows, in schematic sectional view, what may be conveniently called the surface-to-bottom system. The shipborne interrogator and receiver can be mounted directly on the hull of the ship or they can be packaged in a vehicle that is towed at a depth of a few tens or hundreds of feet by means of a relatively short cable. While the hull-mounted arrangement is obviously more convenient, it has two serious acoustic disadvantages. First, the receiver may be overwhelmed by the

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(1) Some who work with underwater acoustics may disagree with this statement, arguing that shallow-water propagation under certain conditions exhibits more complexity, for example, where semifluid or solid strata underlie the superficial bottom and affect the propagation to a substantial extent. The author cannot contest this point but feels that, within the limited sense of path geometry within the water medium, the deep-water situation can display the wider range of effects, such as shadow zones, focusing, duct transmission, and other effects.

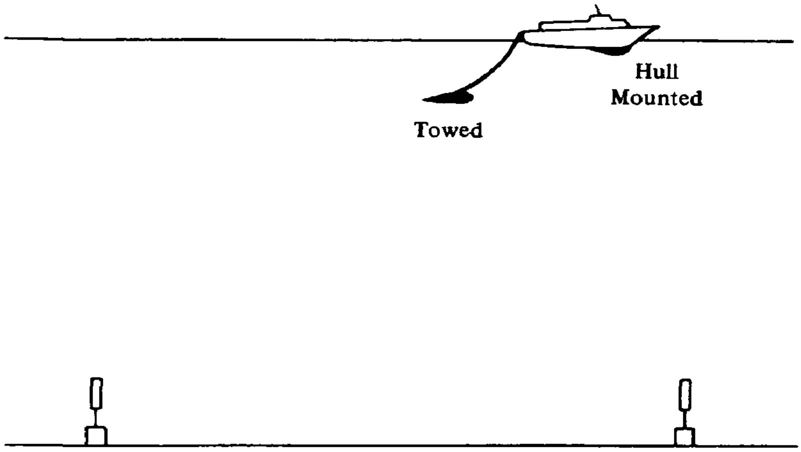

FIG. 2. — Surface-to-bottom system showing hull-mounted and shallow-towed interrogator-receiver units.

ship's noise. Second, the performance generally will be more reliable and predictable if both interrogator and receiver are operated at sufficient depth to avoid a variety of fluctuation effects near the surface. Hardware and techniques are now available for towing a vehicle at speeds up to 15 knots at shallow depths. Hence the need for towing does not impose a major limitation on ship mobility.

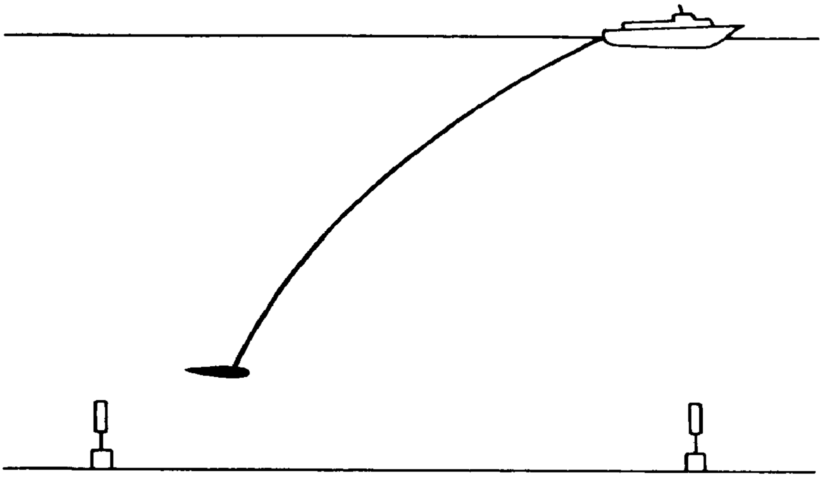

Fig. 3. — Deep-towed system.

Figure 3 shows a different system, the deep-towed vehicle, which is towed at a great depth by means of a long cable. This system is radically different from the surface-based system because the acoustic paths, which will be illustrated shortly, are substantially different and also because the position of the deep-towed vehicle cannot be related directly to the towing ship — a limitation that results from the geometry of the intervening several miles of cable which cannot be readily determined. The deep-towed system is, in fact, a system for positioning of the vehicle; and the derivation of the ship's position must be accomplished by other means as a secondary objective. Deep towing is inherently a slow maneuver. Because of the weight and drag of the long cable, speeds usually must be kept below 2 knots.

ACOUSTIC PATHS AND TRAVEL TIMES

The acoustic paths which are important in the shallow-towed and deep-towed configurations are determined by the variation of sound velocity with depth. Figure 4 shows sound velocity profiles for two extreme conditions in the North Atlantic Ocean (2). During the winter season in northern latitudes, the water is cold and nearly isothermal from surface to bottom. In this case, the velocity increases monotonically with increasing depth due to the hydrostatic pressure effect. This velocity profile is labeled "northern winter" in figure 4.

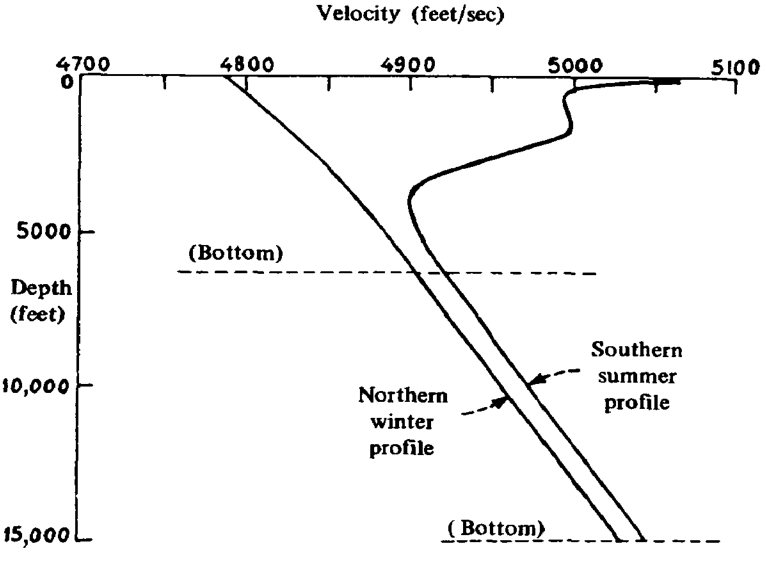

FIG. 4. — Sound velocity profiles for two extreme conditions in the North Atlantic Ocean.

In sharp contrast, in more southern latitudes, particularly in summer, the water temperature is high at the surface and decreases slowly with increasing depth, becoming isothermal only below a few thousand feet. Sound velocity in sea water is higher at elevated temperatures, and this thermal effect is greater than the hydrostatic pressure effect in the uppermost water layers. Therefore, in the case of southern summer conditions in figure 4, the sound velocity decreases from a surface value to a pronounced

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(2) In the North Pacific Ocean, qualitatively similar profiles are observed, although there are detailed differences, particularly in the depth of the sound channel axis. Data from the North Atlantic Ocean are used for specific illustration, in this paper, but the general phenomena are characteristic of other comparable oceanic areas.

minimum at about 4000 feet, the "sound channel axis", and then increases with increasing depth similar to the northern winter profile. Local conditions of currents and stratification can introduce one or two weak subsidiary minimums near the surface.

The total variation in sound velocity from surface to bottom for a given sound velocity profile or between the northern winter and southern summer profiles is only a few percent. This might appear inconsequential, and indeed for very short paths it is, but over distances greater than a fraction of a mile the variable refractive index exerts a profound influence on path geometry. In the case of interest here, where the water depth is very great compared with the acoustic wave length, the ray paths can be calculated by differential application of Snell's law from point to point. In the usual case of velocity profiles, which cannot be closely approximated by simple mathematical relationships, the paths must be determined by numerical calculation. Computer science to perform such numerical calculations is now well developed. Therefore, if given an empirically determined profile, it is a routine computer operation to calculate, and even to plot, large numbers of ray paths for any desired purpose.

Typical ray paths for the surface-to-bottom system are shown schematically in figure 5. Sound waves transmitted from a shallow-water source at an oblique downward angle are refracted downward in the water region above the sound channel axis — where the velocity decreases with depth. Below the sound channel axis, the rays are refracted upward. Rays leaving the source at a sufficiently steep angle will strike the bottom. However, at one particular angle the rays will just graze the bottom and at lesser angles the rays will miss the bottom completely. If there is no sound channel axis, as in the northern winter profile, the ray will tend to be refracted upward from its source as suggested by the dashed line originating from the displaced sound source near the surface (figure 5).

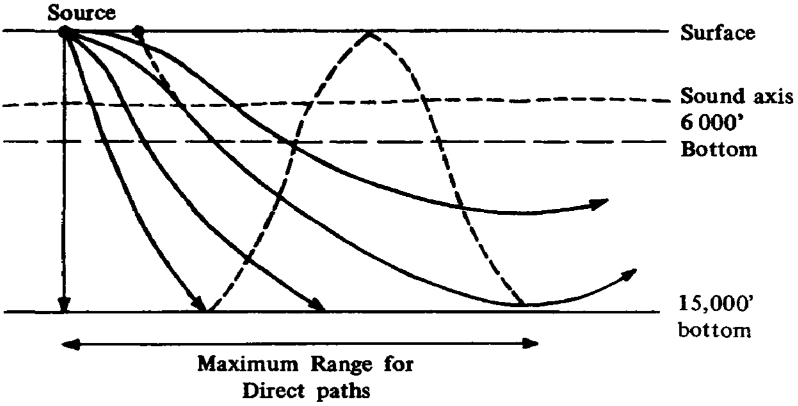

FIG. 5. — Ray paths for surface-to-bottom system.

For any source-receiver configuration, there is usually a multiplicity of paths along which sound energy can be propagated. Except for the rather special case of sources and receivers positioned near the sound channel axis, there is only one direct path which involves no reflections at the surface and bottom boundaries. In figure 5, a bottom-reflected and surface-reflected ray is shown arriving at the point where the direct ray just misses the bottom. It also is possible for other rays, with a larger number of surface and bottom reflections, to arrive at this same point. There are at least three good reasons why these boundary-reflected rays generally are not suitable for a navigational system. (1) The reflection tends to be somewhat diffuse, that is, there is a loss of precision in timing the reflected rays. (2) The reflected rays are less reliable because the reflection coefficient from rough surfaces may be erratic. (3) It is difficult to determine the geometry of reflected rays because bottom reflections may take place from undetermined points on an irregular bottom. For these reasons, acoustic positioning systems usually employ only the direct paths.

In figures 4 and 5, flat ocean floors at depths of 6000 feet (1000 fathoms, approximately 1 nautical mile) (3) and 15 000 feet (2500 fathoms, approximately 2.5 nautical miles) are indicated as typifying sensible extremes of water depth in the deep portions of the Atlantic Ocean. These two depths and the extreme velocity profiles represented in figure 4 were used for numerical calculations of ray paths. The results provide a quantitative perspective of the extremes within which the phenomena of deep water acoustic propagation will lie (4).

For the direct surface-to-bottom paths, figure 6 shows the computed one-way travel time versus the horizontal range, that is, the projection on the surface or bottom of the curved slant ray path. One curve in figure 6 corresponds to a 6000-foot water depth, the other to a 15 000-foot water depth. At the scale size of this graph, the curves for northern winter and southern summer conditions are so nearly coincident as to be indistinguishable from each other (5). There are, however, differences in the maximum range of the direct paths, as noted on the figure, for the two different sound velocity profiles (6). For short ranges, where one end point of the path is nearly overhead with respect to the other, the graphs are naturally curved, but it is interesting to note that over most of the range

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(3) For the most part, English units are used in this paper, not for lack of sympathy with the metric system, but simply because water depths on most existing charts are expressed in feet or fathoms and horizontal distances are still measured in feet, yards, or nautical miles in a great proportion of marine work.

(4) It must be emphasized that the northern winter and the southern summer sound velocity profiles for the North Atlantic are extreme conditions. At any one place, the seasonal fluctuations in profile are not nearly as great as from one of these extremes to the other. In the most northern latitudes, summer insolation may create a shallow sound channel; and conversely, to the south, the near-surface velocities may be reduced perceptibly in winter. These are, nevertheless, distinctly smaller effects than those related to large changes in latitude.

(5) The path geometries, however, are distinctly different in the two cases. To reach a given point on the bottom and hence to attain a given horizontal range, a ray must leave the source at a steeper angle in the northern winter case than in the southern summer case. A given point on either of the curves in figure 6, therefore, corresponds to substantially different paths that reach the same point on the bottom in almost exactly the same travel time.

(6) A point of interest is the reversal of the order of the summer and winter limits for the two different water depths. In the 15 000-foot case, as implied in figure 5, the winter ranges are reduced. However, in the 6 000-foot case, the rays which approach grazing incidence on the bottom leave the source at angles approaching the horizontal in the winter case but at angles inclined slightly upwards in the summer case. Since rays refracted upward from a shallow source will suffer a reflection at the surface, they are not direct paths. Hence the maximum direct path range under southern summer conditions is determined by a ray which just grazes the surface. This leads to a lesser range than with the northern winter profile.

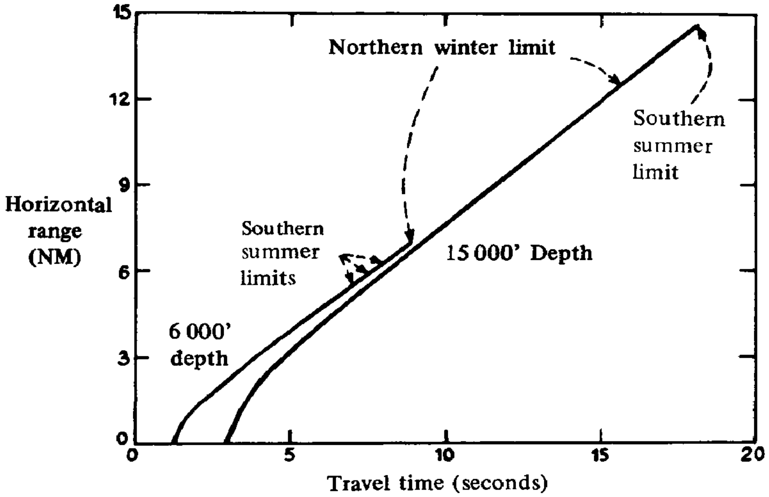

FIG. 6. — One-way travel time and horizontal range for direct ray path of surface-to-bottom system.

the relationship between horizontal range and travel time is remarkably linear (7).

An enlarged view of the small differences between the curves for the velocity profile extremes is afforded by figure 7. Here the difference in range which would be computed, for a given observed one-way travel time, is plotted as a function of range. The differences are a few hundred feet at all ranges. If an average profile is used, disregarding all changes in velocity profile with latitude and from season to season, the derived ranges will not be in error by amounts greater than about 200 feet at almost all ranges.

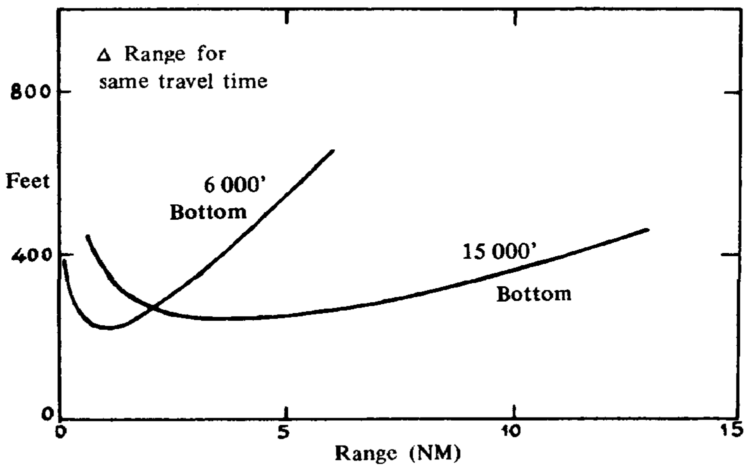

FIG. 7. — Difference in range for given observed one-way travel time plotted as a function of range.

(7) At first glance, it seems surprising indeed that the horizontal projection of a complexly curved path is related to the travel time along the path in a nearly linear way over such a wide variation of range. This behavior can be predicted, however, from analysis of the idealized case of a linear velocity profile, which can be solved in closed form. Certain gross features of the ray path are dominated by the prolonged traverse of the deeper water within which the linear profile is a good approximation. The close linearity of range versus travel time apparently is not much perturbed by eccentricities in velocity structure nearer the surface. The implications of the near-linearity to the implementation of data reduction are obvious.

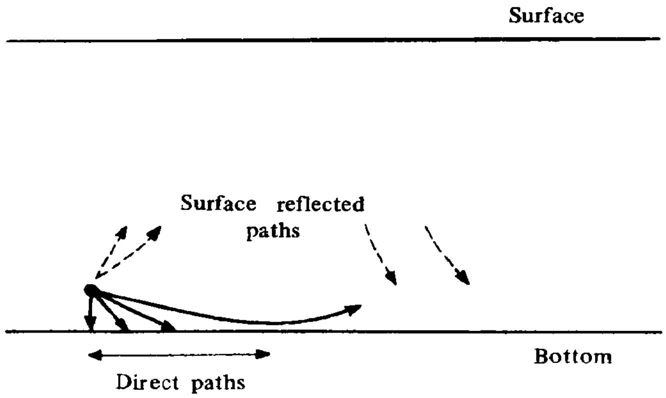

FIG. 8. — Ray paths for deep-towed system.

Ray paths for the deep-towed system configuration are indicated schematically in figure 8. All the rays from a deep source are bent upward. Consequently, the range at which the direct rays can reach the bottom is severely dependent on the height of the source above the bottom (8). For modest source heights, up to a few hundred feet above a 15 000-foot bottom, although the paths are perceptibly curved, the relation between range and travel time is quite closely linear, as shown by the computed results plotted

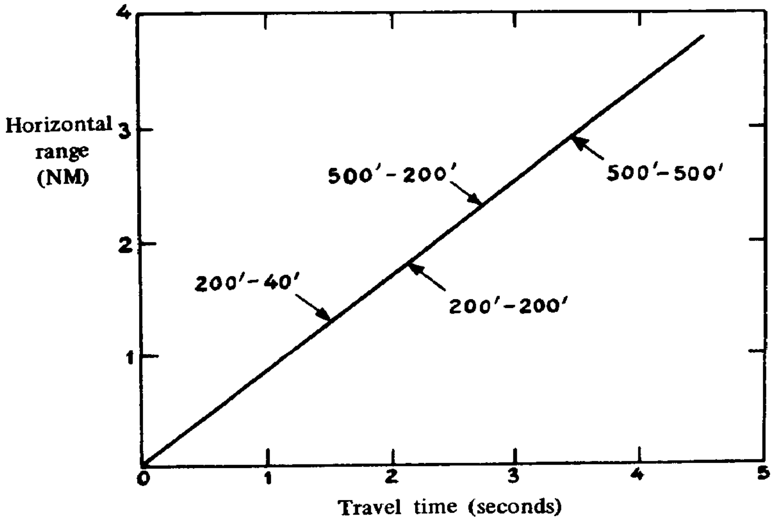

FIG. 9. — One-way travel time and horizontal range for direct ray path of deep-towed system.

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(8) The entire transponder is rarely if ever placed directly on the bottom. This would subject the acoustic paths to the effects of local topography, in the event the transponder is positioned in a depression. The usual practice, whenever feasible, is to moor the acoustic portion of the transponder a modest distance above the bottom by means of a short cable and buoyant element (liquid or solid) suitable for submersion to great depths.

in figure 9. Points are marked along the graph to indicate the maximum range corresponding to various combinations of source and receiver height above the bottom. When the sound source and receiver heights are not the same, the range-travel time curve does not remain linear near the point of origin in figure 9.

When a sound source is close to the ocean surface or bottom, rays reflected from the surface or bottom, respectively, pursue paths which follow closely the direct paths. This is indicated schematically in figure 10. Because the difference in path length between direct and reflected rays is so small, the difference in their travel times also is small, as shown in figure 11 — where the computed delay in milliseconds between direct and reflected paths is plotted as a function of horizontal range for sources 20 feet and

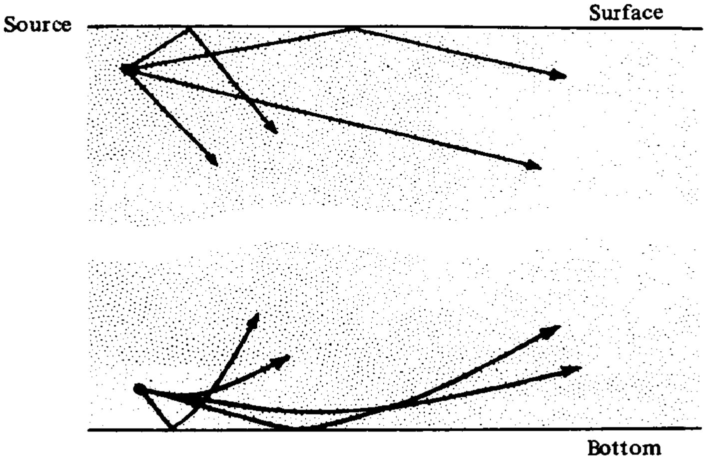

Fig. 10. — Comparison of direct ray paths and paths reflected from surface and bottom boundaries.

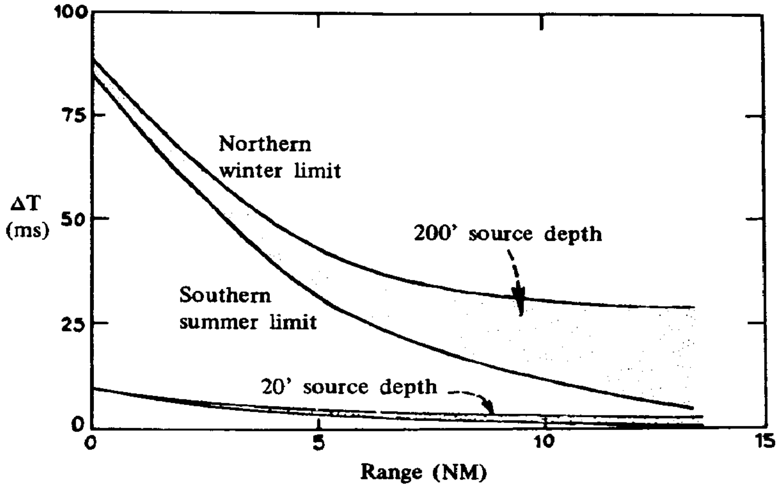

Fig. 11. — Difference in travel time (milliseconds) between direct and reflected ray paths plotted as a function of horizontal range.

200 feet below the surface or above the bottom. As will be seen later, reflections from nearby boundaries cause effects which must be avoided or minimized by suitable selection of system parameters.

PROPAGATION LOSSES AND SEA NOISE

The question of losses along the propagation paths must next be considered. Although, as indicated in the preceding figures, the variable refractive index of the ocean introduces substantial complexity into the geometry of the propagation, spreading losses along the direct paths follow closely an inverse square law. In engineering terms, the level decreases 6 decibels (dB) per distance doubled. In addition, there is an attenuation or heat loss which is exponential in character, that is, at a given frequency it will be a constant number of decibels per mile. At frequencies below one kilocycle per second, (9) attenuation is nearly negligible for ranges less than 20 miles ; at frequencies somewhat above 1 kc/sec it becomes

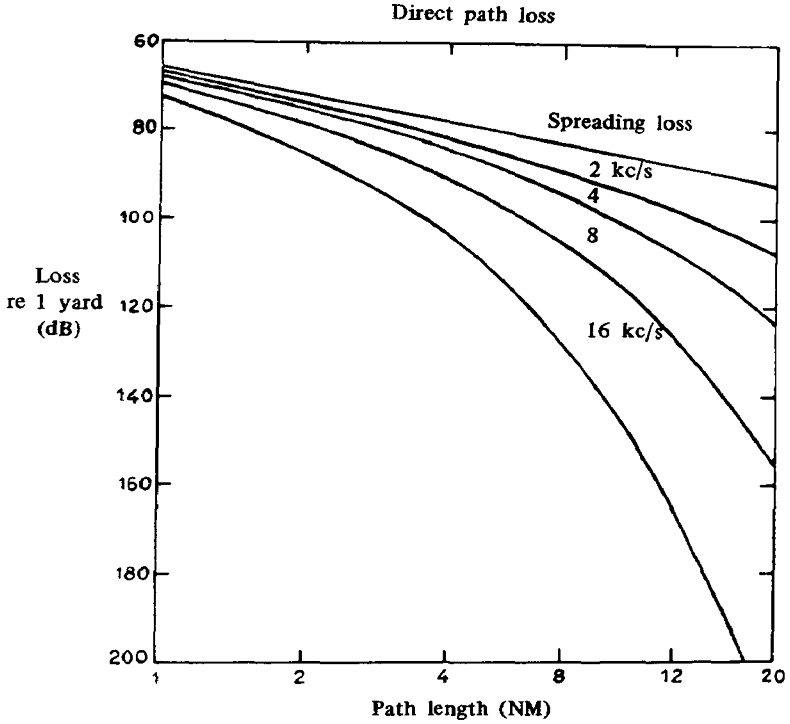

FIG. 12. — Propagation loss along direct ray path in decibels relative to reference distance of one yard plotted as a function of path length in nautical miles.

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(9) In this paper, frequencies are expressed in cycles per second (cps) and kilocycles per second (kc/sec) rather than in Hertz and kilohertz, partly in deference to the large established bulk of literature in the older terms, and partly by the author's preference.

important; and at frequencies of 10 kc/sec and higher, it becomes dominant. This is shown in figure 12, a plot of loss in dB (relative to an equivalent reference distance of one yard) versus range along the path in nautical miles. The uppermost curve represents spreading loss alone and is also a good approximation to the actual loss curve at very low frequencies. The remaining curves show, at successively higher frequencies, generally accepted values for observed losses in sea water.

Another vital feature of underwater acoustics is the background noise against which signals must be discerned. Like all spatial noise fields which arise from a multiplicity of small disturbances, ambient sea noise is highly statistical, showing both rapid and long-term fluctuations between wide limits. In figure 13, the spectrum level of the noise — the pressure level in decibels relative to one microbar (one dyne per square centimeter) for a one cycle bandwidth — is shown for the range of frequencies of interest to acoustic navigation.

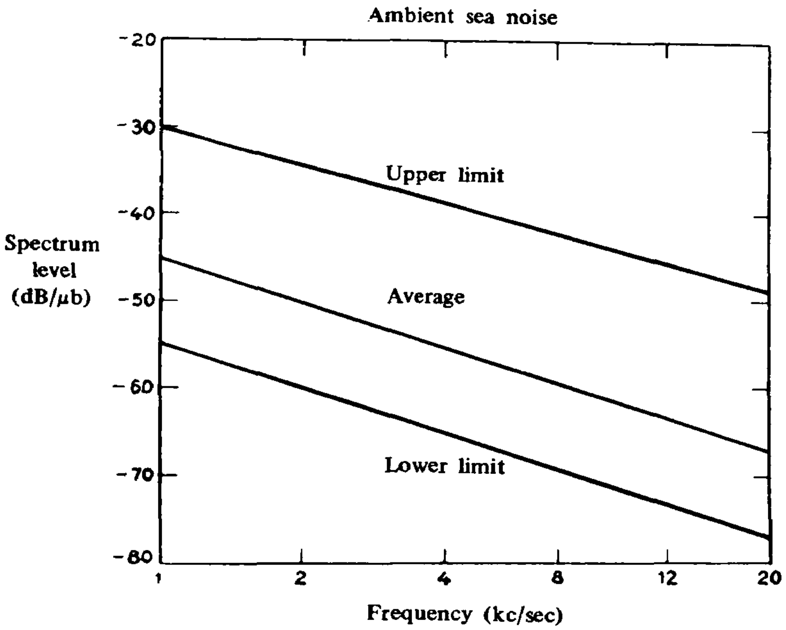

FIG. 13. — Spectrum level of ambient noise — in decibels relative to one microbar per one-cycle bandwidth for range of frequencies of interest to acoustic navigation.

Taken by themselves, the loss curves of figure 12 and the ambient noise curves of figure 13 do not convey immediate meaning for the design of underwater acoustic systems. Two specific examples will be helpful to give perspective on the power and signal-to-noise limitations encountered in the construction of practical systems. The first example, shown in figure 14, portrays the situation for a carrier frequency of 4 kc/sec. For two different source levels, the received level in dB/μb is plotted versus path length in nautical miles. A source level of 82 dB/μb at one yard corresponds to approximately 10 acoustic watts radiated omnidirectionally. The 102-dB source level corresponds to approximately one kilowatt radiated

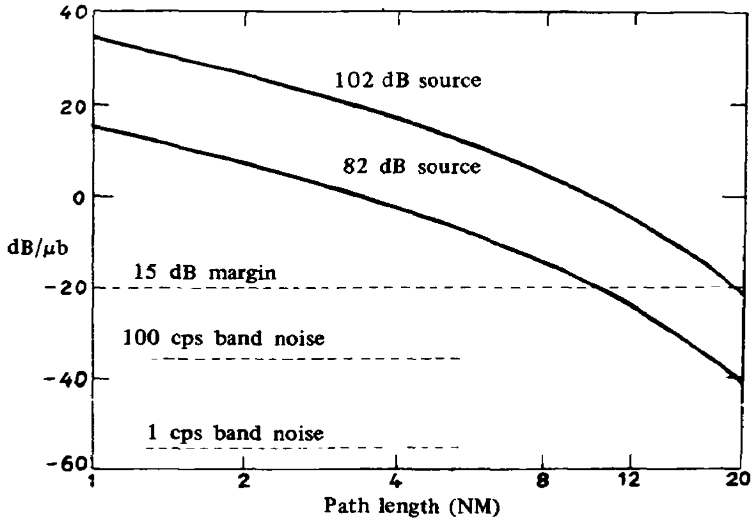

FIG. 14. — Power and signal-to-noise limitations for a carrier frequency of 4 kilocycles per second. (Acoustic levels at receiver 4 kc/sec; no directivity).

omnidirectionally. The decrease of level with increasing range is in accordance with the 4 kc/sec curve of figure 12. Also on figure 14 is plotted the spectrum level or 1-cps band noise level at 4 kc/sec. For a receiving bandwidth of 100 cycles per second (a reasonable choice), the receiver noise level would be 20 dB above the 1-cps level, as shown. Finally, a still higher line is drawn at which there would be a 15-dB margin against the 100-cps receiving band noise.

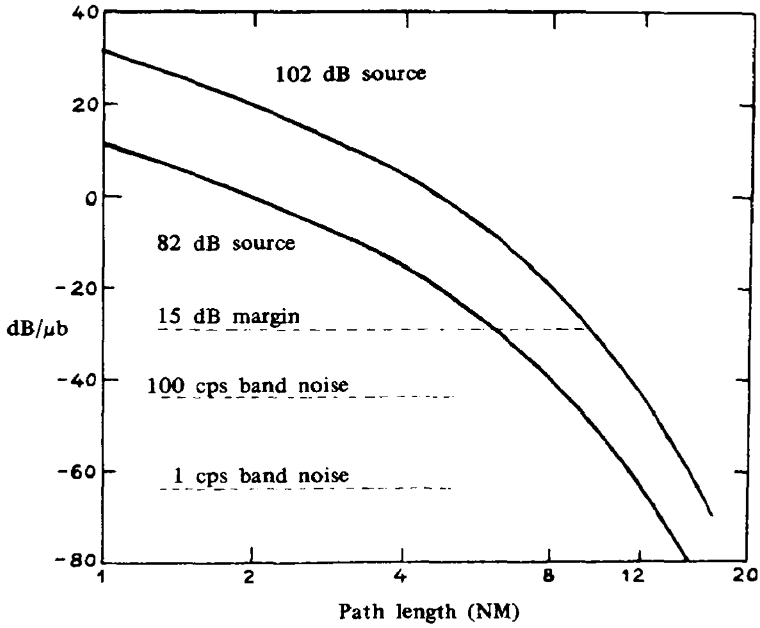

FIG. 15. — Power and signal-to-noise limitations for a carrier frequency of 12 kilocycles per second. (Acoustic levels at receiver 12 kc/sec; no directivity).

It is apparent that even with the 102-dB source, the received level at a range of about 20 miles barely provides the 15-dB margin above noise, while the 82-dB source falls substantially short of this figure.

The second example shown in figure 15 portrays the situation at a carrier frequency of 12 kc/sec. The noise levels are somewhat lower, but the attenuation is higher, and the net effect is that the ranges are somewhat less than at 4 kc/sec for the same margin with respect to ambient noise.

The examples are greatly oversimplified and there are a number of neglected factors that will modify the figures. No account has been taken of the directivity which could possibly be provided at the interrogator and transponder, both in transmitting and receiving. By its very nature, an acoustic positioning system must cover a very wide angle of view, and it is therefore impractical to provide more than a very modest amount of directivity. A practical limit would seem to be about 5 dB corresponding to a cardioid response, with the null pointing into the bottom at the transponder and upward into the surface at the interrogator. This would provide an additional 10 dB of margin against the noise. Another neglected factor is the fact that the acoustic noise field in the ocean does not correspond to smooth white noise. In addition to the relatively steady resultant of a multitude of small random noise sources, there are isolated, sporadic bursts of local noise, either man-made or biological in origin. A margin of 15 dB for a system whose function is to detect pulses from an interrogator or transponder is therefore often inadequate.

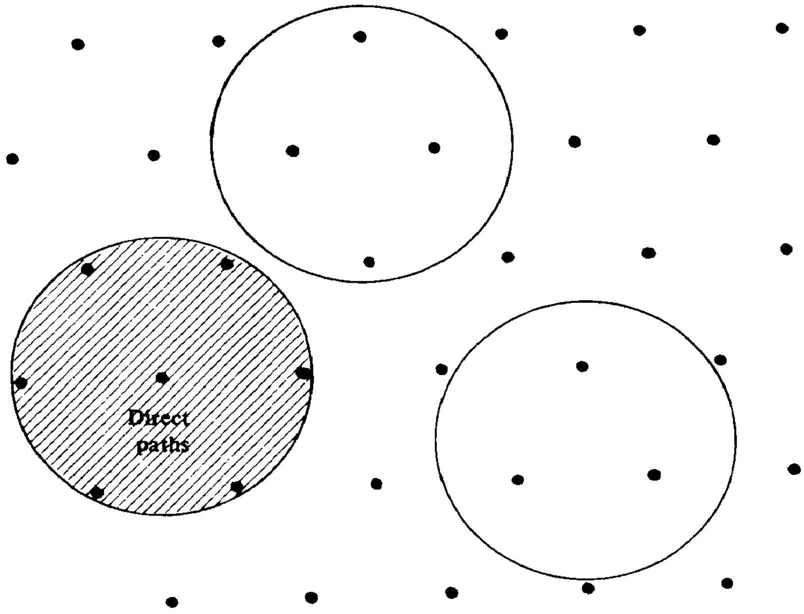

Fig. 16. — Transponder network designed so that direct sound paths from surface can always interrogate at least three transponders — 5-mile spacing for 6000-foot water depth and 12-mile spacing for 15 000-foot water depth.

Even when all of the various detailed factors are taken into careful account, the general conclusion derived from figures 14 and 15 remains valid, namely that the underwater engineering technology must be pushed close to its limits in order to realize effective ranges in deep water out to 10-20 miles, the limit of the direct paths.

The discussion has been concerned thus far with the features of underwater propagation and noise which will influence most the selection of parameters for an operable two-way system between ship-borne equipment and a single transponder. The next logical step is to consider a suitable geometry for a network of transponders, whereby an area of the ocean can be adequately marked for accurate positioning anywhere within it. While there may be no unique geometry that is optimum for all situations, figure 16 suggest a transponder network that may be appropriate for many purposes. It is an equilateral-triangular layout, with the lattice spacing so chosen that the scope of the direct paths from the surface will always include at least three transponders. This would mean a transponder spacing of about 5 miles for a 6 000 foot depth and of about 12 miles for a 15 000 foot depth. From the figure, it is clear that the number of transponders interrogated by direct paths would vary between 3 and 7 depending upon the exact position of the interrogator overhead. The significance of this observation will shortly become apparent.

SIGNAL CODING

It is appropriate to consider next the selection of suitable frequencies and the modulation scheme by which the interrogation and response are carried out. It is axiomatic that the time resolution is directly related to the reciprocal of the system bandwidth. For example, a bandwidth of 100 cps will allow a discrimination or identification of a pulse or leading edge of an impulse function to an accuracy of .01 second or 10 milliseconds, whereas a 1000-cps system will allow resolution to one millisecond. Since the sound velocity in sea water is about 5 feet per millisecond, and since it will generally be undesirable to introduce overall system errors as great as 100 feet purely from inaccuracies of timing, an effective system bandwidth greater than 100 cps is clearly desirable. This is one major reason why acoustic navigation systems have been engineered at carrier frequencies well above 1 kc/sec. Desirable bandwidths cannot be efficiently obtained at lower frequencies. On the other hand, as the carrier frequency is increased, the losses increase rapidly, and a practical upper limit is probably reached between 15 and 20 kc/sec. Also, bandwidths should not be substantially greater than those needed for the required timing accuracy, otherwise the noise level in the receiver is unnecessarily increased.

The modulation scheme employed for the pulsed interrogation and response will depend on the number of transponders in the system. A large field of transponders presents an interesting problem of multiplexing the operation so that individual transponders can be properly interrogated and their replies can be properly received and labeled. There are two different ways in which the multiplexing can be accomplished, frequency division and time division (figure 17). In the frequency division scheme, a number of different frequency bands would be established, with an individual band allotted to each species of transponder. In a network such as shown in figure 16, it would clearly be necessary to have at least 7 different species of transponder. Separately interrogated, however, the transponders might reply on a common frequency band. In contrast, the time division scheme could use a common frequency band for all operations of interrogation and response. The various species of transponder differ in that they respond individually to a particular time coding of two or more pulses. If desired for the sake of simplicity, all transponders might reply with a common pulse code.

MULTIPLEX SYSTEMS

FREQUENCY DIVISION

- INDIVIDUAL FREQUENCY BANDS
- DIFFERENT SPECIES OF TRANSPONDER
- COMMON FREQUENCY ONE WAY

TIME DIVISION

- PULSE CODING
- DIFFERENT SPECIES OF TRANSPONDER
- COMMON CODING ONE WAY

FIG 17. — Multiplex system schemes.

In some ways, the time division approach to multiplexing is a more elegant and more powerful approach to the problem, but there are some severe practical difficulties. Figure 18 indicates the nature of the difficulties. A case is assumed where two pulses are transmitted by an interrogator or transponder, with the coding information contained in the precise magnitude of the interval between pulses. At the other end, these two pulses are received along direct paths as pulses 1 D and 2 D, but also received are pulses 1 SR and 2 SR involving a surface reflection, pulses 1 BR and 2 BR from a bottom-reflected path, and pulses 1 SBR and 2 SBR, consisting of both surface and bottom reflections. If the interval between pulses 1 and 2

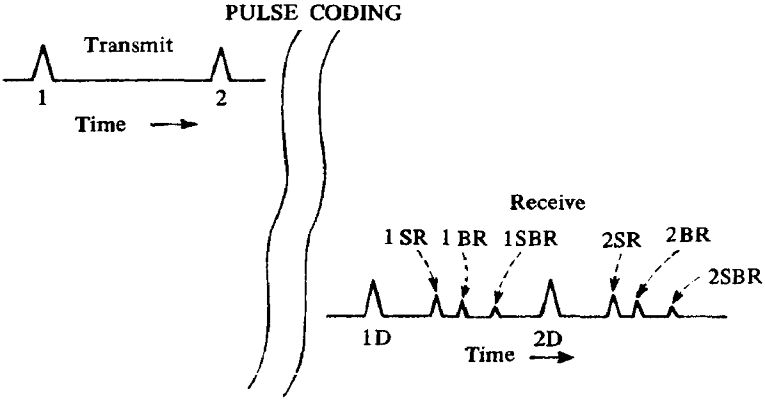

FIG. 18. — Pulse coding in time division approach to multiplexing.

is comparable with the time delay shown in figure 11 for the reflected pulses, the ensemble of direct and reflected pulses will be most confusing and may even defy automatic recognition. This is not to say that the time division scheme is unworkable; rather, it points out the need for careful analysis of the competing paths in relation to the time-coded pulses.

Aside from this difficulty, the advantage of time division in allowing one single frequency band to be used throughout the system is more apparent than real, since the relationship of prevailing ambient noise to the signal power may be such as to require relatively narrow bands in any case. Nevertheless, in spite of the problems presented by spurious signals, problems which thus far have prevented its extensive use, time-division multiplex offers substantial advantages in coding flexibility and interrogation command of the transponder field (10).

SYSTEM CALIBRATION

Another important question concerning the transponder field is the exact localization of each transponder. When the transponders are first planted, it is not safe to assume that their position on the bottom corresponds exactly to the dropping point on the surface. For example, if a one-knot current exists during the free fall to the bottom, the transponder may easily be laterally displaced a substantial fraction of a mile. It is virtually mandatory, therefore, to execute a series of ship runs after the field of transponders is planted, taking data from which the transponders may each be pinpointed to within the inherent accuracies of both the acoustic system and the additional system used for positioning the ship during calibration.

(10) For example, one major advantage is that the transponder will ignore isolated noise peaks, that is, the transponder will be activated to reply only if two or more pulses properly spaced in time are received. This would prevent wasteful power drain and also would make the system less susceptible to undesired interrogation.

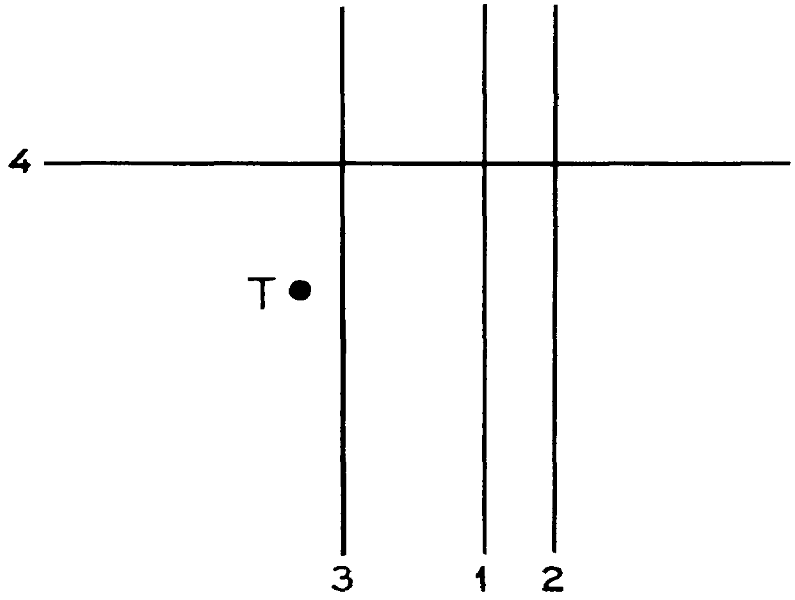

FIG. 19. — Plan view of ship tracks during transponder localization tactics.

Figure 19 suggests the way in which the ship runs should be conducted with respect to a particular transponder. A first run should be made along a line which is offset from the estimated position by an amount perhaps equal to

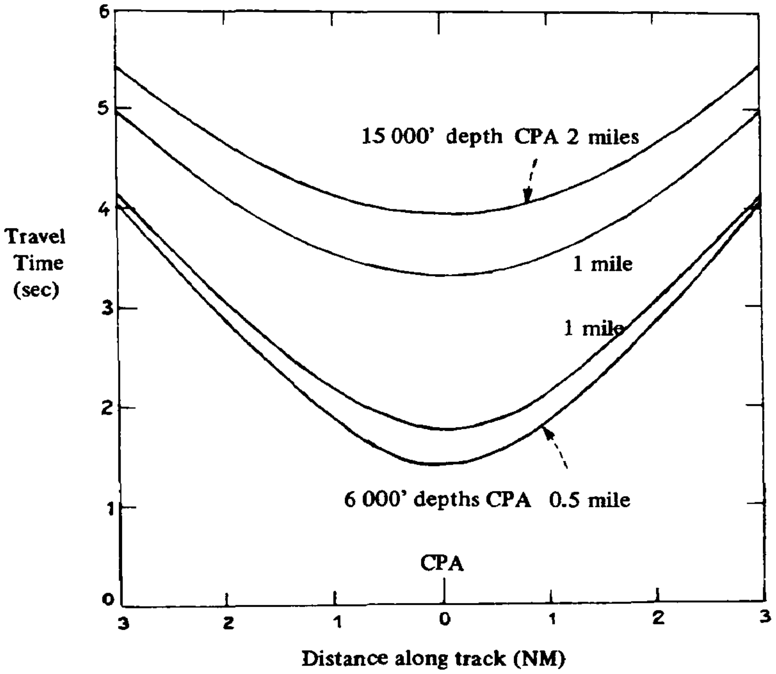

FIG. 20. — Transponder localization data illustrating axis of symmetry for points of closest approach along each track.

the water depth. A second run should be made along a nearby parallel track, not only to accumulate additional data but also to make certain on which side of the previous track the transponder really lies. A third run should be made approximately over the transponder in order to determine its exact depth. Finally, a fourth run at right angles will give the position as a cross-fix relative to runs 2 and 3.

During all these runs, it is assumed that the ship maintains a steady known heading at constant speed and that electronic means are provided for accurate determination of the ship's position. Throughout a run, the transponder is interrogated at frequent intervals, and the delay time is determined for each point along the track. The data will then resemble the curves shown in figure 20, with an axis of symmetry about the point of closest approach (CPA). From the blunt shape of the curves, it is apparent that the localization will have good accuracy only when a cross fix is obtained between two runs approximately at right angles.

SYSTEM ACCURACY

A final topic deserving brief review is the influence of the various acoustic factors and broad engineering limitations as they affect the overall accuracy of a navigation or positioning system. Figure 21 summarizes the key ideas. The term accuracy is used broadly to include all factors which will determine reliability and day-to-day repeatability of the performance.

Fundamental limitations are imposed by the ocean medium and by the very nature of the navigation system and its component parts. Except over very short distances, it is not possible to achieve and maintain a bandwidth greater than a few thousand cps and it is not generally practical to exceed 1000 cps. This puts definite limitations on the time resolution of received pulses and on the degree of sophistication in coding the signals. Propagation losses, out to ranges of 10 or 20 miles along direct paths, are high enough so that it is difficult to maintain a generous margin against all statistical fluctuations of ambient noise. Only a low directivity can be tolerated in the acoustic transducers, or otherwise the system would not respond suitably over a wide field of view.

There are also some general engineering limitations. The acoustic power which can be radiated is distinctly limited, particularly in the transponder, where it is necessary to conserve battery power in order to have a long operating life. There are severe problems in designing equipment to withstand the environment of the deep ocean and to provide reliable unattended operation of the transponders. There also are limitations in the complexity of installation procedures that can be successfully carried out at sea. Finally, all phases of designing, manufacturing, installing and operating an acoustic positioning network are critically dependent upon the amount of money, available ships, trained personnel, and the needed facilities to carry out the various necessary tasks. In this respect acoustic navigation systems are similar to other kinds of marine systems now being studied and used within the broad subject area of ocean engineering.

ACOUSTIC NAVIGATION ACCURACY

FUNDAMENTAL LIMITATIONS

BANDWIDTH

LOSSES

DIRECTIONALITY

PRACTICAL LIMITATIONS

POWER

HARDWARE DESIGN

INSTALLATION

ECONOMICS

SYSTEM ACCURACY

"ULTIMATE" – 25 FEET 10 FEET ?

PRACTICAL – 100 FEET 50 FEET ?

FIG. 21. — Summary of factors affecting acoustic navigation accuracy.

In spite of the many uncertainties and limitations, it is worthwhile to attempt an estimate of system accuracy that can be achieved with present-day technology. Some guesses are hazarded in the lower part of figure 21. These are not meant to be accuracies which are attainable under very special conditions, but accuracies which are inherently or practically obtainable under average conditions in the deep ocean in areas remote from land (11).

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(11) No attempt has been made here to distinguish between self-consistent accuracy within a self-contained acoustic system and accuracy of relating points on the ocean bottom to well-established points on the nearest land masses. Remarks about repeatability and accuracy of acoustic positioning apply only to the self-contained case of locating a point on the bottom with respect to other nearby points on the bottom or to points on the ocean surface. Relating these points in turn to more remote points on the earth's surface must involve other approaches and other kinds of navigational systems.

CONCLUDING REMARKS

In summary, the foregoing discussion has endeavored to bring out, or at least to imply, the following points :

(1) Ray paths must be determined and studied as an essential ingredient of system design for deep-water navigation. Ray paths can be readily determined by computerized ray tracing.

(2) Propagation losses and ambient sea noise must be known for the ocean area in question; these parameters form another important input to system design.

(3) Operating frequencies and signal coding must be selected with full regard for losses and noise, and, in the case of a large transponder field, with proper attention to the systems engineering problem of multiplexing.

(4) System calibration, the determination of the true geometry, is essential to reliable operation of an acoustic positioning network.

Several important points that should be made about underwater acoustics and its future application to marine geodesy are the following. Acoustic transmission and noise are as variable as the deep oceans themselves. In almost every instance where a new ocean area is being explored, it will be necessary to measure the ambient noise and either to measure the acoustic propagation or determine those physical quantities which will allow the propagation to be calculated. Without such specific measurements, the performance of an ideally designed navigational system in a new ocean area is likely to be disappointing or even entirely unsatisfactory. However, with sufficient, preliminary, acoustic field investigations our present understanding of underwater acoustics is entirely adequate to guide the design of successful systems. Therefore it can be predicted with some confidence that acoustic positioning will be one of the building blocks in the future development of marine geodesy.

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