ACOUSTIC PROPAGATION MODELS AS VIEWED BY THE SONAR SYSTEMS DESIGNER

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ABSTRACT

The purpose of this paper is to consider the efforts performed in the development of ray acoustic propagation analyses from the viewpoint of advanced sonar system design. In particular, those parameters required of such analyses for the enhancement of sonar system design and performance are identified and elaborated upon. A simple ray acoustic shallow water propagation model is used as a vehicle for identifying and relating to a number of areas in which propagation results may be utilized to significantly improve operational sonar system effectiveness. In the development of these examples, the spatial distribution of the acoustic energy together with fluctuations in the received signal energy receive prime consideration. Expanding upon this simple basis, a sonar design concept is developed by analytically incorporating propagation features that can be provided by suitable models.

The orientation of my discussion today is somewhat different from those that have been presented so far in this conference. I intend to talk not as an underwater acoustician actively involved in propagation analysis and the development of ray trace programs.

Rather, from my view point as an engineer faced with the problem of developing sonar systems to operate with maximum efficiency in the ocean medium, I wish to present some of my requirements for information on propagation phenomena.

My reasons for attempting such a presentation are to outline to representatives of the propagation community those aspects of propagation which bear directly on design decisions, and to indicate why simple measures of the energy lost by a signal propagating through the sea are not in themselves sufficient inputs to the sonar design process. In doing this, I hope to indicate to you some specific design-related parameters which characterize propagation phenomena and about which relatively little information exists. Specifically, it is my objective to illustrate why the spatial and temporal behaviour imposed on signals by the medium present inputs to the sonar design process equal in importance to a knowledge of the propagation loss between two points. I hope that this overview will encourage studies in which attention is focused on developing more information about the mechanisms governing these spatial and temporal characteristics which currently are often "washed out" or ignored in analyses directed at developing numbers to characterize average propagation loss.

The general points I wish to consider are outlined in Fig. 1. The usual goals of a programme to develop propagation models, using either ray tracing techniques or normal mode analysis, are twofold, namely:

1. To delineate, on the basis of velocity profiles and other environmental data, the dominant paths via which acoustic signals propagate from source to receiver.
2. To develop a means for estimating the average acoustic power lost by a signal as it propagates between two points. The loss mechanisms involve accounting for geometrical spreading of the wavefront, reflection/scattering, and absorption effects within the medium or at its boundaries.

Once these goals are accomplished, the sonar designer can readily estimate:

1. The average value of the signal present at his array; and
2. The depths at which he can expect high and low levels of signal power.

In general, however, a comprehensive sonar design process requires more detailed knowledge concerning the influences of the medium upon the signal. Specifically, the designer would like to have at his finger tips:

1. The spatial distribution of the signal arrivals at the array.
2. The statistics of both spatial and temporal fluctuations imposed on the signal by the medium; and
3. In the case of short term (transient or pulse) signals, the "impulse response" of the medium; i.e., a measure of the time and frequency dispersion imposed on the original signal.

For the remainder of this paper, I intend to focus on the three areas listed above, and illustrate, by some simple examples, how knowledge of these phenomena may be incorporated into the sonar design process. In particular, I wish to concentrate on the active sonar problem since this area is most urgently in need of more sophisticated techniques.

As a starting point, I would like to consider a simple example to illustrate how a knowledge of the spatial distribution of signal arrivals can impact on the design of a sonar array. The specific case of interest here is one where the impact is greatest, namely, a vertical array for use in a shallow water environment. As used here, the term shallow water implies those instances where propagation takes place over ranges very large relative to water depth, and where the water depth itself is large compared with the wavelength of the signal being propagated.

In such instances (particularly when ranges are such that little energy arrives via a direct path), the signal arrives via multiple surface and bottom reflections. These multiple arrivals imply that the dominant signal energy is distributed over a range of arrival angles rather than being concentrated at a single angle. If this range of angles is known, then the array can be designed to spatially "match" this angular window, and thus insure that maximum signal power is captured by the array.

This can easily be illustrated by use of a very simple ray trace model, which describes the gross features of propagation in a shallow water environment. This model is similar to the one devised by McPherson and Daintith [Ref. 1], and elaborated on by Smith [Ref. 2]. The salient features of this model (which is based on averaging over ray cycles) are shown in Fig. 2.

The details of the model on which the results to be presented are based can be found in the references. Basically, it treats the large number of rays involved in transporting energy from source to receiver as a statistical ensemble. The major features of the propagation mechanisms are preserved, but by use of spatial and temporal averaging over the ranges and depths involved, fine details (i.e., Lloyd's mirror interference phenomena) are smoothed out. However, the fundamental postulates and assumptions which guide the analysis are indicated in the figure.

The postulates are self explanatory; the assumptions are found to be reasonable within the objectives of the analysis, namely, a gross prediction of the propagation loss which preserves the basic sensitivity of the result to the dominant environmental parameters. These are:

1. Water depth.
2. Sound speed profile.
3. Surface loss.
4. Bottom loss.

Although sound velocity profiles are seldom observed to have equal velocity at all depths, the isovelocity model often predicts results close to those observed experimentally in shallow water. The most significant departure from isovelocity behaviour occurs for strong surface ducts and severe upward or downward refraction. The model can, however, be readily extended to include these cases.

The geometry for a simple isovelocity situation is shown in Fig. 3, along with the results of the analysis.

In the isovelocity case β, the loss per cycle from boundary reflection for a ray with initial angle θ, is found to be

$$\beta = b_s \theta + b_b \theta = b(\theta) \qquad (\sin\theta = \theta, \quad \cos\theta = 1)$$

where

$$b = b_s + b_b \quad .$$

The results of Smith's analysis [Ref. 2] show that the ray cycle method gives the following value of transmission ratio $\tau(r)$ under the isovelocity assumption. (The transmission ratio is the ratio of the intensity at range r to that at 1 yd) and is given by:

$$\tau(r) = \frac{2}{rD} e^{-\alpha_v r} \int_0^{\theta_f} e^{-\frac{rb\theta^2}{2D}} d\theta$$

The expression in the figure contains twice the integral from 0 (horizontal) to a limiting angle θ_f. For the symmetrical situation, this is equivalent to including all rays from $-\theta_f$ to $+\theta_f$. Note that this integral is of the form of the area under a Gaussian (normal) curve. In their paper, McPherson and Daintith [Ref. 1] obtained a similar isovelocity result by analysing the number of bounces, rather than working with ray cycles. They showed that the result is the same for the sloping bottom case if average depth is used for D. In addition, they derived equations that are quite similar to those shown here for propagation loss under negative gradient conditions.

The distribution of signal arrival angles as determined from the equation for the transmission ratio per radian is shown in Fig. 4.

Note that in isovelocity water the received energy is normally distributed in arrival angle about a mean angle $\theta = 0$ with a standard deviation σ that increases with increasing depth and decreases with increased range and bottom absorptivity. The upper limit of the integral for an omnidirectional receiver is $\pi/2$ corresponding to the two cut-off points shown in the figure.

The implications on array design are immediately evident. First, if one designs a vertical array to have a beamwidth of θ_B between say, the 6 dB down points, when steered to the maximum response axis, the choice of θ_B should be dictated by the distribution of signal arrivals as shown in the figure. These, in turn, depend upon the water depth, the range between source and receiver, and the combined bottom and surface losses. While the first two parameters are usually definable for the conditions over which an array must operate, the determination of the surface and bottom losses is not so easily made. However, it is interesting to note that sufficient information for the designer is obtained by developing estimates of average bottom and surface losses over the ocean area of interest. Thus, a useful effort would be to continue work aimed at developing estimates of average bottom and surface losses, parameterized in terms of controlling physical mechanisms (i.e., windspeed, etc.) in areas of interest to the sonar community.

The preceding example results in conclusions which may seem somewhat obvious to people versed in propagation analysis. However, this simple example was intended mainly to illustrate the coupling which exists between the design process and a knowledge of medium effects; the two cannot be separated, nor can simple estimates of energy loss suffice. In this case, the spatial distribution of the energy arrivals impact on design choices; in turn, the design impacts on guiding the propagation analysis by delineating the environmental parameters of importance.

This analysis also points out the types of shallow water propagation models of use to the sonar designer. Essentially, he looks for a model which provides maximum visibility of the physical parameters of the ocean environment which influence sonar performance. In this context, a simple approximate model, which can be rapidly executed may be favoured over an elaborate ray trace model which requires large computer facilities. At the same time, the designer is aware of the limitations of such simple approximate models. In the one employed here, for example, the use of incoherent energy addition of ray paths precludes accounting for spatial phase cancellation effects among rays (e.g., the Lloyd's mirror effect). However, as long as the designer is aware of the model limitations, he can use various sub-models to investigate "fine structure" effects as required. Basically, this amounts to an iterative application of propagation models; i.e., begin with the simplest physical model available, and then expand the analysis through the use of sub-models as the design development dictates.

Of even more relevance to the sonar designer are data concerning the characteristics of fluctuations imposed on the signal by the medium. Sound fluctuations in the ocean are observed for virtually every type of propagation; surface ducts, deep sound channels, sea surface or bottom reflected paths — to name a few. All of these propagation paths can be characterized by an observed mean value of propagation loss around which instantaneous values of transmitted energy are distributed.

Too often, modelling efforts are focused on predicting the mean values, with little or no attention given to estimation of the fluctuating components. Yet, often the fluctuations are of primary interest to the sonar designer, in that they impact on his selection of processing times and his estimations of the spatial stability of the signal over the array aperture. Recent work, such as that of Nichols and Young [Ref. 3], and Dyer [Ref. 4] have provided considerable information on the character and statistics of fluctuations; however, more extensive studies are needed if an adequate data base is to be established.

As an example of how such information may be incorporated into the sonar design process, consider the problem of estimating the spatial phase stability of a signal over the aperture of a sonar system. Here, it is important to understand that the degree to which a sonar array can improve signal-to-noise gain and provide directional information is directly related to the degree of stationarity of the phase of the signal wavefront over the array elements. When the array is "steered" to the direction from which the signal arrives, any "jitter" or fluctuations in phase among elements of the array can cause a degradation in performance, in the sense that the signal is not perfectly "in phase" at every element of the array.

This can be illustrated by considering the response of a simple two-element array to a signal arriving from an angle, θ, as shown in Fig. 5. The two identical receivers each generate an output voltage e_0 in response to the incoming wave. However, the difference in signal path length between the two receivers results in a spatial phase difference between their outputs. Referenced to the geometric center of the two-element array, the sum of the voltages from the two hydrophones is given as

$$e_T = 2e_0 \cos\left(\frac{kd}{2} \sin\theta\right) = 2e_0 \cos(\omega\tau)$$

where $k = \frac{2\pi}{\lambda}$, d = element spacing.

Since $k = \omega/c$, where ω is the angular frequency and c the velocity of sound in the medium, the phase term can be written as

$$\cos\left(\frac{\omega d}{c} \sin\theta\right) = \cos \omega\tau$$

where $\tau = \dfrac{d \sin\theta}{c}$ represents the time delay between constant phase (spatial) arrivals at each hydrophone. Note that when the signal arrives at an angle $\theta = 0$ (i.e. broadside), there is zero time delay, and the output voltage of the array is a maximum; i.e. $2e_0$. Suppose, however, that fluctuations in the medium produce a fluctuation in the delay time, such that $\tau = \tau_0 + \tau(t)$; i.e. the delay is characterized by a mean value and a fluctuation about that mean. In this case, for a signal incident along maximum response axis ($\theta = 0$), $\tau_0 = 0$, but $\tau(t)$ may be finite. The output of the array in this case is given as

$$e_T = 2e_0 \cos[\omega\tau(t)]$$

where $\tau(t)$ may be treated as a random variable.

To develop an average response we are interested in the expected value of $\cos[\omega\tau(t)]$. This value is given as

$$\langle\cos[\omega\tau(t)]\rangle = \int_{-\infty}^{\infty} p(\tau) \cos \omega\tau \, d\tau$$

where $p(\tau)$ is the probability distribution of the time delay fluctuation. If we assume that the values of $\tau(t)$ are Gaussianly distributed, and have a zero mean, then

$$\langle\cos[\omega\tau(t)]\rangle = \frac{1}{\sqrt{2\pi}\,\sigma_\tau} \int_{-\infty}^{\infty} \cos \omega\tau \, e^{-\tau^2/2\sigma_\tau^2} \, d\tau$$

The result of the integration yielding

$$\langle\cos[\omega\tau(t)]\rangle = e^{-\omega^2\sigma_\tau^2/2} .$$

Since we assumed the amplitudes of the arrivals to be constant, the expected value of the array output voltage is

$$\langle e_T\rangle = 2e_0 \, e^{-\omega^2\sigma_\tau^2/2} .$$

Note that as $\sigma_\tau \to 0$, the array response is maximum. However, as the magnitude of the fluctuations increase, as reflected in increasing values of σ_τ^2 of the value of $\langle e_T\rangle$ decreases from $2e_0$ for "on-beam" arrivals.

Intuitively, one might expect the magnitude of the phase fluctuations to increase in proportion to the separation between elements. Thus, one might assume $\sigma_T^2 \propto d$, i.e. $\sigma_T^2 = \gamma d$, where γ is the constant of proportionality. In this case, the expected output voltage of the ideal two-element array is given as

$$\langle e_T \rangle = 2e_0 \, e^{-\gamma \frac{\omega^2 d}{2}} .$$

Note that the degradation in response increase as the frequency, as well as with increased element spacing.

The result derived here, although for a simple, if not trivial, case is illustrative of how such fluctuation information can be used by the sonar designer. The analysis techniques can be readily extended both to include multi-element large arrays, and also to allow for fluctuations in the amplitude of signal arrivals. The main point here, however, is the indication of a need for better measurements of characteristic delay time fluctuations induced by the medium, and most importantly the development of propagation models that incorporate and predict these parameters.

Up to this point, I have been stressing the parameters required of propagation models, in addition to signal attenuation, to produce a driving influence on the sonar design and advanced development process. All too often it seems that the signal processing people proceed independently of the environmental people with the result that the idealizations that appear to perform so well in radar fail to reach expectations in the underwater medium. My message then is that although the question of the best mathematical fit to a sound velocity profile is important, the character of the outputs in both space and time that are obtained from a propagation model are of perhaps greater importance.

As a final example to illustrate this point, I wish to consider a problem in the active sonar area. In general, as the threat becomes more quiet, active sonar must greatly increase its capability to enable more likely detections to occur in a shorter time frame; thereby reducing the threat of counter detection and localization. To achieve this increase in capability in the face of reverberation it appears that more than just an increase in source level will be required. In particular, it seems reasonable that increased gains in signal processing must be obtained. These gains in turn can only result from increased knowledge of the environmental conditions and their effect on the transmitted signal.

Proceeding from this point, let us conceptualize a hypothetical system that might be realizable in the not too distant future. Such a system is shown in block diagram form in Fig. 6. We hypothesize an advanced active sonar sub-system capable of transmitting and receiving sonar signals and displaying the processed results. In addition, we include an environmental measurement sub-system capable of providing real time environmental parameters including measurements of the sound velocity profile. Interfacing these two sub-systems, we envision a ray trace propagation sub-system providing on-site estimates of the signal propagation situation based on the environmental (and historical) inputs. The outputs of the propagation sub-system perhaps with an operator interface dictate the type of sonar transmission mode to be employed, e.g. bottom bounce, direct path, etc., for the mission to be performed and also the type of signal to be transmitted. In addition, the propagation sub-system also determines the type of receiver processing both spatial and temporal to be employed.

To illustrate how these sub-systems might interact, let me consider another simple example, based on some of the propagation modelling that was alluded to earlier in the talk. We assume an environment as depicted in Fig. 7 which might be representative of some generalized area during the winter/early spring months where upward refraction is obtained just below the surface because of the lack of surface heating. Under the assumption of isogradient conditions, one characteristic of the propagation behaviour is that of a deep surface duct as shown in the figure. If a SVP gradient of 0.025/s is assumed then at short ranges the limiting ray of the duct would reach a vertex of about 200 ft. The rays "trapped" within this limiting ray would be surface-reflected and their energy contribution would arrive after that of the limiting ray. The transmission angle of the limiting ray would be much less than 6°, implying that the surface reflected rays are all reflected at grazing angles less than this value. Since surface reflected paths will undergo very little scattering, at reasonable sea states the sea surface reflection may be considered essentially specular. Under these conditions, the surface-reflected rays will all arrive at essentially the same intensity as that of the non-reflected limiting ray.

The travel time for the limiting ray is the smallest among the duct arrivals and consequently the energy travelling this path is the first to arrive from the duct. The energy travelling the remaining ducted paths will arrive in a non-uniform manner following that of the energy travelling the limiting or refracted-only ray. The order of arrival follows the number of surface reflections. In other words, the energy travelling the one surface reflection path will be following by that travelling the two surface reflection paths, and so on. In terms of our system design, it is envisioned that this type of information would be automatically displayed by our hypothesized ray path computer.

As an approximation for illustrating the method by which the receiver processing might be determined by the ray path computer, let us assume that the ducted multipaths arrive uniformly in time with an equal delay of Δ seconds between each path. If the arrivals are assumed of equal intensity the normalized received signal can be expressed as shown by the equation:

$$s(t) = \frac{1}{N} \sum_{i=1}^{N} \cos(\omega t - \Delta i) \; .$$

In this equation the effects of doppler scattering causing shifts in the received frequency are neglected. The energy envelope of the received signal can easily be expressed by noting that it is of the form of the off-axis response of an equally spaced coherent array [Ref. 5]. In particular, the envelope of $s(t)$ is given by

$$S_e^2 = \left[\frac{\sin(N\omega\Delta/2)}{N\sin(\omega\Delta/2)}\right]^2 .$$

In general there will be a large number of arrivals from the duct, and the delay between arrivals can be considered to approach zero. This fact may be incorporated in the expression by letting $N\to\infty$ while $\Delta\to 0$ with $N\Delta\to\tau$, where τ is the total time delay of the duct. Under these conditions

$$\alpha_c = \left[\frac{\sin(\omega\tau/2)}{\omega\tau/2}\right]^2 ; \quad N\to\infty,\ \Delta\to 0,\ N\Delta\to\tau .$$

This expression is termed the coherency factor and represents the normalized energy arriving via the duct as a function of the transmitted frequency and the duct time delay.

At this point, we require some knowledge of the environment parameters. From the ray trace sub-system, we are able to determine a value for the average duct time delay. If we use the shallow water propagation model referred to earlier in the talk, this is indeed possible. In fact, Smith has shown that for a shallow water isogradient duct, the average duct time delay can be expressed approximately by

$$\tau = \frac{1}{3}\left(\frac{R}{c}\right)\left(\frac{c_b - c_s}{c}\right) .$$

In this equation R is the range of interest, c_s and c_b are the sound velocity values at the source and the vertex of the limiting ray respectively, and c is the nominal velocity of sound in sea water (5000 ft/s). For a SVP gradient of 0.025/s, a depth difference of 150 ft between the source and the vertex of the limiting ray and for the purpose of illustration a nominal range of 6.5 kyd, then a time delay of 1 ms results.

Given this computation by the propagation sub-system, the sonar operator may determine that the energy transmitted in the duct at least at short ranges is quite concentrated in time. Thus if his sonar can transmit pulse burst transmissions which would generally have pulses long compared to 1 ms he need not concern himself with time dispersion caused by the surface duct transmission. In other words, in this situation he concludes that he need not worry about the time dispersion.

In addition, if all of the reverberation energy associated with the termination of a given pulse decays before the arrival of the next transmitted pulse, then the pulse period within a burst, i.e., the pulse-on to pulse-off duty cycle, should be reasonably stable. All of these results arise from the fact that for a 1 ms duct delay as much as a 100% perturbation caused by medium variations amounts to only a maximum 2 ms delay in the signal time.

At this point, the operator has used the propagation results to indicate the type of propagation to be encountered and the extent of the time delay and in turn has used this information to determine the type of signals he should transmit. Because of the short time delay, he has concluded that gated pulse signals will not be dispersed in time enough to cause them to be distorted greatly. Frequency distortion caused by the multipath situation is another matter of interest to the operator. If he has a range of transmission frequencies available to him he would like to choose a value to minimize the fading characteristics of the signal.

Since the coherency factor has previously been determined this function with the appropriate time delay obtained from the propagation results may be used by the operator to choose from among the frequencies available to him.

Thus, based on calculations provided by the propagation computations the operator may select within the available range, the transmission frequency for which the signal fading is minimized.

The total propagation situation in our example consists of a bottom bounce mode in addition to the surface duct transmission. [See Fig. 7]. In general, the energy arriving via these two paths will interfere and may cause degradation in the total received energy. However, with an adequate ray trace program in the system, it is conceivable that an on-the-spot determination of the arrival time difference between the two paths may be made and that this information could be used to either select an appropriate processing mode to eliminate the effects or by properly assessing the characteristics to use them to advantage. In the former approach, one might select a processor similar to the Rake System in radar which attempts to separate the various energy arrivals and then to coherently recombine them to enhance the total received energy. In the latter technique, by properly assessing the propagation situation, the operator might be able to range on the basis of received signal strength.

Let me consider this latter technique in more detail since it provides a good illustration of incorporating propagation information into the operational problem. Without exact knowledge of bottom topography, it is always difficult to compute the bottom bounce paths; however, a reasonable approach is to assume an essentially flat bottom over the bounce region. If this assumption is made, then for the isogradient case representative calculations indicate that the time delay of the single bottom bounce path relative to the limiting ray (for a gradient of 0.025/s) may be computed to be in the range of 10 ms. This result, of course, is extremely sensitive to parameter changes. However, a good lower bound may be 8 ms with an upper bound as high as 50 ms.

Incorporating this result with the surface channel delay of 1 ms indicates that the total impulse response of the measurement channel in the short range case we are considering consists of the narrow surface duct response plus a bottom arrival impulse (probably a series of bottom arrivals) delayed 8 ms to 50 ms with respect to the surface arrivals. To keep this example simple let us neglect the multiple bottom bounce arrivals on the basis of energy contributions.

In the duct, the incoherent energy E_{IC} is given by the incoherent addition of the energy of each multipath arrival E_p. This implies that E_{IC} is given by the number of significant arrival paths times the energy per path,

$$E_{IC} = NE_p \ .$$

The coherent energy, on the other hand, is given by

$$E_C = N^2 E_p \alpha_c \ .$$

In this equation α_c is a measure of the coherency. If α_c is 1, the energy arrivals are coherent and maximum energy is obtained. Eliminating N from the two equations results in the equation shown for the coherent energy.

$$E_c = \frac{E_{IC}^2 \alpha_c}{E_p} \ .$$

If one bottom arrival is considered, then it contributes the energy per path E_p modified by the bottom loss factor β. Thus, the ratio of the bottom to duct energy is given by

$$RBD = \frac{E_p/\beta}{E_{IC}^2 \alpha_c / E_p} \ .$$

Since the source is common, the RBD ratio can be expressed in decibels in terms of the duct and bottom path transmission losses. This expression is given below. It expresses the ratio of the bottom to duct energy in terms of the duct and bottom transmission losses, the duct coherency factor and the bottom loss parameter

$$RBD = 2(TL_b - TL_d) - 10 \lg \alpha_c - 10 \lg \beta \ .$$

To utilize this expression, we determine duct and bottom transmission losses from the shallow water (range much greater than depth) propagation loss model of Smith [Ref. 2]. An approximate expression for the transmission loss in an isogradient duct is

$$TL_d = 10 \lg \left(\frac{2\theta_\ell}{L} \frac{e^{-\alpha R_d}}{R_d} \right) .$$

In this equation R_d is the horizontal range between the source and the receiver, α is the volumetric attenuation coefficient as a function of frequency, L is the depth of the duct measured from the surface to the limiting ray, and θ_ℓ is the angle of the limiting ray at the source which is determined by the equation

$$\theta_\ell = \left[\frac{2(c_b - c_o)}{c_o}\right]^{1/2} .$$

Using a sound speed gradient of 0.025/s in these equations and an assumed duct depth of 200 ft, we determine that

$$\theta_\ell = \left(\frac{2(5)}{5000}\right)^{1/2} = \frac{1}{\sqrt{500}} .$$

In addition, for the 200 ft duct we determine the duct transmission loss as

$$TL_d = -28 - 10 \lg R_d - 4.34 \alpha R_d .$$

For the bottom transmission loss assume spherical spreading with a range of essentially the same as that of the duct and a volumetric attenuation α. Thus, the simple spherical spreading loss is

$$TL_b = -20 \lg R_d - 4.34 \alpha R_d .$$

From our previous calculations a representative value of the coherency factor may be determined to be -28 dB. Thus, we may combine our results to obtain the expression for the ratio of the bottom and duct energy,

$$RBD = 2(28 - 10 \lg R_d) + 28 - 10 \lg \beta .$$

Choosing a short horizontal range of 6.5 kyd,

$$RBD = 6 - 10 \lg \beta .$$

A reasonable bottom loss value in the range 4 dB to 9 dB may be chosen from Urick [Ref. 6] for a sand type composition. Using this range of values yields the range of RBD values of from 0 dB to -3 dB. Thus, on the basis of these calculations it may be expected that the duct and bottom energy arrivals are of the same order of intensity. This is a significant result for the sonar operator in that it implies that pulse spreading caused by the bottom arrival is of the same order of intensity as that of the duct arrivals.

The combination of the duct and bottom arrivals at a receiver implies a time spreading of an individual pulse and the generation of an interference pattern in the region of time overlap. The magnitude of this interference is most simply investigated by the simple Lloyd's Mirror type of pattern generated by two arrivals of the same frequency. A plot of the expected envelope in the region of overlap is shown in Fig. 8 as a function of operating frequency and the difference between the path arrival times. The curve is also parameterized by the relative intensities of the two arrivals.

An interpretation of this diagram is as follows. Assuming that the energy envelope of the initial pulse arrival is at zero dB (for convenience) when the energy arrives on the second path, an interference pattern is established during the duration of overlap of the two pulses. The magnitude of the envelope during this overlap period is a function of the degree to which the arrivals coherently add (measured by $f\tau$) and their relative intensities (measured in dB) and may be found from the diagram. When time progresses beyond the overlap period, the envelope of the response reduces to that of the second arrival. In terms of the results we have found for the surface duct and bottom path, since the two arrivals are at essentially the same energy, one would expect a relatively continuous pulse with a discontinuity (either an increase or a decrease depending on the $f\tau$ product) during the period of overlap. From previous calculations the difference between the duct and bottom arrivals can be expected to be on the order of 8 ms to 50 ms. In these ranges one would expect both increases and decreases during the overlap of the duct and bottom arrivals. In addition, of course, the pulse will be spread in time by the later bottom arrival.

Although the computations we have presented may seem somewhat complicated, in reality, of course, they could easily be programmed on a mini-computer. In this manner, the operator could, at least ideally, be presented with an indication of the type of pulse distortion that he might expect and could either alter his frequency or signal shape accordingly.

In summary, I have tried to indicate the importance of propagation models from the view-point of sonar design and future sonar systems. In doing so, I have tried to emphasize that simple predictions of transmission loss are not sufficient for these purposes. Rather, more emphasis must be placed upon the temporal and spatial influences of propagation, the fluctuations encountered, and the interference effects that may occur in transmitted signals. I hope that these remarks may serve to stimulate the direction of future work and operation.

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DISCUSSION

When asked whether sonars should not be designed for more general use than just shallow-water operation, the author said that the trend was toward more specialised sonars, otherwise the necessary compromises become too difficult.

PROPAGATION ANALYSIS: USUAL OBJECTIVES

1. DELINEATE DOMINANT PATHS OF ENERGY TRANSMISSION
2. ESTIMATE LOSS IN ENERGY AS SIGNAL PROPAGATION FROM SOURCE TO RECEIVER

PROPAGATION ANALYSIS: ADDITIONAL OBJECTIVES

1. SPATIAL DISTRIBUTION OF SIGNAL ARRIVALS (MULTIPATH EFFECTS)
2. STATISTICS OF SPATIAL AND TEMPORAL FLUCTUATIONS IMPOSED ON SIGNAL BY MEDIUM
3. IMPULSE RESPONSE OF MEDIUM AS IT INFLUENCES SHORT TERM (PULSE OR TRANSIENT SIGNALS)

FIG. 1

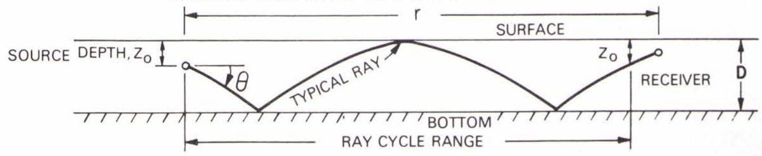
SIMPLE SHALLOW WATER PROPAGATION MODEL

REFERENCES: SMITH, P.W. Jr., "SOUND TRANSMISSION IN SHALLOW WATER; PART I: ANALYSIS," BB & N REPORT NO. 1563, OCT. 24, 1967
McPHERSON, J.D., AND DAINTITH, M.J., "PRACTICAL MODEL OF SHALLOW WATER ACOUSTIC PROPAGATION," J. ACOUST. SOC. AM. VOL. 41

RAY CYCLE MODEL (AFTER SMITH)

POSTULATES
1. ENERGY TRAVELS ALONG RAY PATHS
2. ENERGY IS BOTH CONTINUOUSLY ATTENUATED (VOLUME) AND INTERMITTENTLY ATTENUATED (SURFACE + BOTTOM REFLECTION/SCATTERING)
3. ENERGY TRAVELS AT LOCAL SOUND SPEED ALONG RAY

FIG. 2



ASSUMPTIONS
1. ONLY RAYS IN WATER CONTRIBUTE (NO BOTTOM REFRACTED PATH)
2. ENERGY SCATTERED TOO FAR OUT OF BEAM ESSENTIALLY LOST
3. BULK OF ENERGY RECEIVED CLUSTERED ABOUT IDEAL RAY PATHS
4. SOURCE-SEQUENCE OF IMPULSES, RECEIVED SIGNAL p^2 (t); i.e. SUPERPOSITION OF ENERGY ARRIVALS (NO INTERFERENCE EFFECTS)

ISOVELOCITY CASE

LOSSES

$\beta = b_s\theta + b_b\theta = b\theta$

$b = b_s + b_b$

b_s = surface loss per ray cycle per radian

b_b = bottom loss per ray cycle per radian

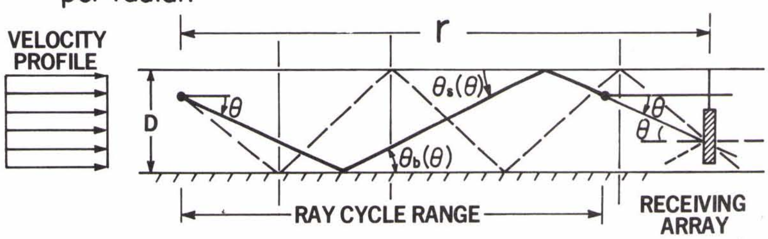
TRANSMISSION LOSS

$N_W = 10 \log \tau$

where

$$\tau = \frac{2}{rD} e^{-\alpha_v r} \int_0^{\theta_f} e^{-\frac{rb\theta^2}{2D}} d\theta$$

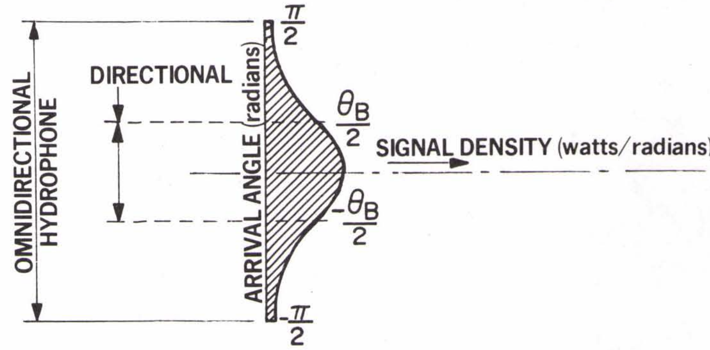
FIG. 3

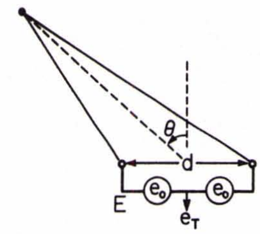


SIGNAL ARRIVAL ANGLES FOR ISOVELOCITY CASE

$$\frac{d\tau}{d\theta} = \frac{2}{rD} e^{-\alpha_\nu r} e^{-\frac{\theta^2}{2\sigma_\theta^2}}, \quad \sigma_\theta = \sqrt{\frac{D}{br}}$$

FIG. 4





$$k = \frac{2\pi}{\lambda} = \frac{\omega}{c}$$

FIG. 5

$$e_T = 2e_0 \cos\left[\frac{kd}{2}\sin\theta\right] = 2e_0 \cos[\omega\tau]$$

$$= 2e_0 \text{ when } \tau = 0$$

However, when $\tau = \tau_0 + \tau(t)$

$$\langle e_T \rangle = 2e_0\, e^{-\frac{\omega^2\sigma_\tau^2}{2}} = 2e_0^{-\frac{\gamma\omega^2 d}{2}}$$

for $\tau_0 = 0$

σ_τ^2 = Variance of distribution of $\tau(t)$

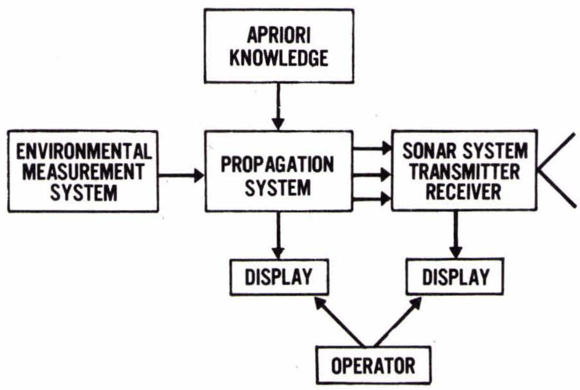
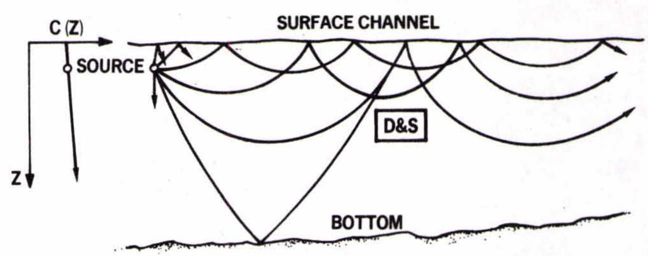


FIG. 6

POSITIVE ISOGRADIENT SHORT RANGE PROPAGATION

FIG. 7



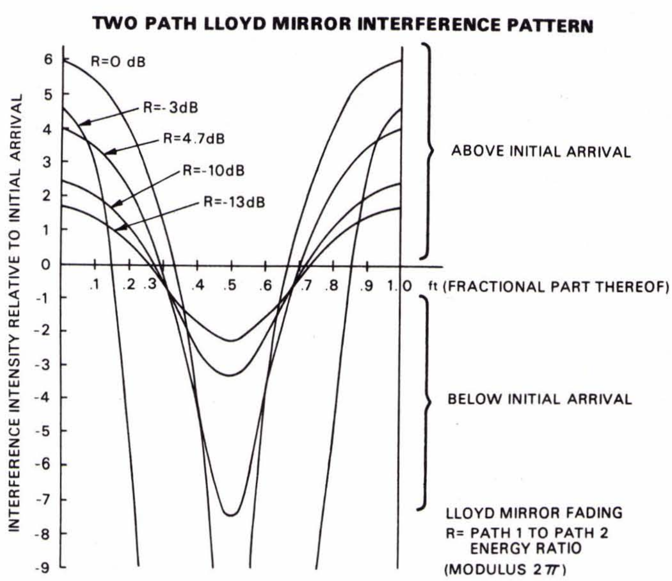


FIG. 8