COMPUTER MODELS FOR UNDERWATER SOUND PROPAGATION

F.R. DiNapoli

Naval Underwater Systems Center
New London Laboratory
New London, Connecticut 06320

ABSTRACT

The state of affairs of computer models for underwater sound propagation loss estimation is discussed from the viewpoints of two segments of the sonar community; i.e., (1) those who develop the models and are primarily concerned with the accuracy of the estimations and (2) those who use such models and view propagation loss as only one of many areas in which sub-models are required. A list of propagation models, classified according to the analytical methods used in their derivations, is presented. The features and shortcomings of each class are then discussed in broad terms. Various sonar applications for which knowledge of propagation loss is needed are briefly delineated to indicate their diversity. Also, a number of practical considerations (in addition to accuracy) are listed that influence the user's selection of a propagation loss model for a particular application. Finally, various aspects of model assessment are addressed and a method for the quantitative assessment of comparative model accuracy (now in formative stages of development) is presented. The use of this methodology is discussed through illustrative examples.

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During the process of writing this paper recollections of a book by the American psychologist Lawrence LeShan, entitled The Medium, Mystic, and the Physicist (the cover of which is presented in figure 1), came to mind and it seemed that this would perhaps be an appropriate subtitle for my paper. I am positive that certain segments of the sonar community look upon the developers of models for underwater sound as being the most outrageous perpetrators of mysticism ever encountered. There are still others who believe that confronting the model developer with a very straightforward question about his work evokes about the same response one would obtain from a medium if he were asked where his information comes from. Of course, the model developers believe that the situation is the reverse, i.e., in their dealings with the rest of the sonar community they feel they have somehow had a mystical experience.

Clearly, this situation has something to do with the various connotations of the term "reality." LeShan observed that serious mystics and modern theoretical physicists seem to have a common understanding of reality. To prove his point he asks the reader to determine whether statements summarizing viewpoints of reality were written by physicists or mystics. Figure 2 contains a few of those quotations with the name of the originator and the letter P or M to indicate whether he is a physicist or mystic.

After reading all of the quotations supplied by LeShan, I came to agree with his contention that there is a general consensus among mystics and physicists regarding the perception of reality. Although this point is interesting in its own right, especially in view of the diverse fields involved, I use the term reality in this paper because it is my contention that different segments of the sonar community have (at a minimum) different interpretations of reality. This appears on the surface to be a rather obvious point. However, it is often overlooked by all concerned parties in the conduct of their daily business and a fair amount of confusion results. Perhaps not so obvious is why this fact is overlooked. I will expand on this theme as the paper develops by delineating two perceptions of reality currently popular in the U.S. It is hoped that this discussion will help the reader understand the reason for the confused state of affairs.

Up to this point I have spoken rather vaguely about various sectors of the sonar community. The remainder of the paper will deal with computer models of underwater sound and with reality in terms of the two types of sonar scientists and engineers identified in Figure 3.

To the left of the figure are those scientists and engineers who are actually engaged in the development of models. There are at least two types of models that can be discussed. The first consists of models for the individual terms in the sonar equation such as propagation loss, ambient noise, reverberation, etc., which might properly be termed sub-models. The second emphasizes sonar analysis and is concerned with combining the sub-model accounting for medium induced effects and sub-models for the system related terms in the sonar equation to form a total sonar systems model; henceforth, this will be referred to as the generic model. A distinguishing feature of this effort is that the type of funding that usually supports it is identified as research or exploratory development.

The group at the right of figure 3 might be called the model users or customers. (In some instances they may describe themselves as the reluctant model users.) It is not uncommon to find the sonar analyst previously identified also operating in this sphere. These people are usually involved in system analysis, performance prediction, and system design. The funding for their work is usually associated with advanced development and engineering. Whereas the perception of reality for the group to the left revolves around predictions or estimations, reality for the users is governed by applications. In both instances the actual understanding of reality has many aspects that are usually not precisely defined.

Since the model is common to both groups, it ostensibly emerges as the bridge connecting two historically distinct and separate groups within the sonar community. Recent experience in the U.S. suggests that although the concept appears to be sound, the bridge is far from complete (see figure 4).

One reason for this situation is that a generic model for mobile sonar systems does not currently exist. A major difficulty involved in constructing such a model is designing a computer architecture flexible enough to accommodate the different and often conflicting understandings of reality by the two groups. I will have more to say on this subject later. Finally, there is the difficult problem of assessment. Given that a generic model could be constructed and that the developer and user have reached a common understanding of what constitutes reality, the question remains as to whether the model predictions bear any resemblance to the accepted concept of reality. Toward the end of this paper I will discuss our current thinking on the subject of model assessment.

I would now like to address the subject of computer sub-models of underwater sound phenomena from the standpoint of the model developer. I should first explain that the compilation shown in figure 5 is not meant to be comprehensive but, instead indicative of the different types of propagation models existing in the U.S. sonar community classified according to the analytical methods used in their derivations. I will discuss the features and shortcomings of the models in rather general terms, according to class; to do otherwise would require examination of each model separately. Such an examination is best done by the model developer himself but, unfortunately, model documentation rarely contains statements about shortcomings. (The reason for this should become evident as we proceed.) Thus, a general approach to the subject may be the best that can be achieved at this time.

I have begun the compilation with the semi-empirical/semi-analytical class because they are significantly different from the other models on the list. A common characteristic of this class is that the models result from an attempt to fit, or explain, a rather broad base of experimental data. The perception of reality is then intimately related to the scope and quality of the experimental data set. In most cases this constitutes a rather limited outlook on underwater acoustics. The AMOS experiment, for example, consisted of approximately 100,000 data points obtained at various locations in the Atlantic, but the primary subject of investigation was surface duct propagation. The COLOSSUS II experiment was primarily intended to examine shallow water acoustics. This type of model development has, for the most part, disappeared for two reasons, one economical and one technical. The cost of conducting large scale experimental programs such as AMOS or COLOSSUS today is prohibitive. Moreover, advances in computer technology have made it possible to obtain detailed results for specific environmental situations that appear to be more attractive to both the user and the model developer.

A summary of the main features and shortcomings of these models is provided in figure 6. Although limited in scope, they generally have the attribute that answers can be obtained in an extremely short (computer) time. For some applications this feature is of paramount importance, eclipsing even the need for accuracy. The equations involved are generally very simple expressions involving terms that have a semi-analytical flavor, such as the expression labeled $G\ (Z_t, Z_x)$, and terms that have an empirical flavor, such as the attenuation coefficient α .

The shortcomings stem from the intrinsic natures of the models. One expects to find a large variance between the model predictions and data from any single experimental run because the model is an attempt to summarize data obtained from many runs involving different environmental conditions. One should also expect the applicability of the models to be governed by the range of the parameters associated with the experimental data set. If one found agreement between AMOS predictions and surface duct data at 1000 Hz, it would be a fortuitous occurrence.

Another natural shortcoming is the inability to predict the detailed features of propagation loss as illustrated in figures 7 and 8. In both cases the experimental source was located at a depth of 20 ft and emitted CW pulses centered at 3.125 kHz. The receiver depth for figure 7 was 50 ft; i.e., both source and receiver were located in the surface duct. Although the AMOS prediction seems to adequately portray the mean level of the data, it gives no indication of the rather definitive interference structure exhibited in the data. The results shown in figure 8 represent a cross-layer case with the source in the duct and the receiver well below the duct. The agreement in this case is generally quite poor even in mean level and using the AMOS results to obtain an estimate for the detection range would be judged unsatisfactory.

This is an appropriate time to mention that I have arrived at the shortcomings of this class of models (and those that will be discussed shortly) from the viewpoint that the primary interest of the sub-model developer is to produce accurate answers. If the primary interest is not accuracy, as might well be for the model user, the entries on this list would be considerably different.

The understanding of reality for the remaining classes of propagation models would appear to be the result of a compromise between what the modeler would like to achieve (namely, the ability to produce accurate answers for propagation loss) and what the state-of-the-art of mathematics and computer technology will allow him to accomplish. The basis for all of the remaining classes is not experimental data but rather the wave equation shown in figure 9. Of course, this equation and the associated boundary conditions also represent a limited scope of reality. That is, this equation represents a linearized version of the fundamental equations, which assume the transmission of energy is a purely deterministic process. Also, it is assumed that the source of energy is concentrated at a single point in space and continuously puts energy into the medium. Lastly, the sound speed profile is assumed to vary only with depth and the boundaries are taken to be horizontal and smooth. Although these assumptions appear to be restrictive, in some cases they are only the beginning of what appears to some to be a never-ending list.

The first of these modifications involves the class of models which I have termed "ray theory with corrections" (figure 10). One may look upon this class of models as an approximate solution for the wave equation, the accuracy of which increases with increasing frequency. It is difficult, however, to state beforehand under precisely what conditions the solution will break down. The practice usually followed at the Naval Underwater Systems Center (NUSC) is to compare the results of a ray and non-ray model for the same case. If agreement is found we are then fairly confident in proceeding to obtain additional ray theory predictions. Recently, significant advancements have been made in automating corrections to the ray theory solution for known artifacts stemming from the nature of the approximate solution. This work involves correcting the solution in the vicinity of caustics. In particular, we have Keller's geometrical theory of diffraction (asymptotic ray theory), the various modified ray theories, and generalized ray theory. Each of these extensions has its own virtues and limitations. For example, the various modified ray theories attempt to make ray theory valid at caustics but each caustic correction seems to be different. The FACT model uses the non-uniform Brekhovskikh caustic correction for smooth caustics while the NISSM II program applies the uniform Ludwig correction. When these corrections are compared against wave theory results, for which caustic corrections are not required, the results are favorable in some cases but not all. In addition to the Brekhovskikh and Ludwig corrections there is the Davis extended modified ray theory and the corrections made by Levey and Felsen in terms of incomplete Airy functions.

In spite of such progress, the use of ray theory in a surface duct, in shallow water, and at low frequencies generally remains a method of dubious accuracy. Another area of concern is the use of ray theory when interaction with the sub-bottom is of significance. This is a relatively new application in underwater acoustics but an old concern for the seismic community. They have made considerable progress in extending ray theory for this application. However, as Cerveny and Ravindra point out in their book, entitled "Theory of Seismic Head Waves," the extensions are not generally applicable when interference effects become important as in thin layers of thicknesses less than, or comparable to, the wavelength.

Thus, it would seem that additional modifications will be required for future applications. It is also clear that a user is likely to have difficulty in interpreting the meaning of these mathematical expressions in terms of classical ray theory.

In spite of the inherent uncertainties concerning its validity, ray theory is widely used and in many instances preferred over other types of solutions; this is not likely to change in the near future. One reason is that the ray diagram can be easily interpreted in a gross fashion to indicate where high or low intensity regions are likely to be found. Furthermore, the ability to provide the user with information about the effects of directivity, surface loss, reverberation, and the like, seem more easily dealt with in terms of ray theory than by wave related solutions. Considerable progress has also been made in reducing the computing time needed to make ray theory predictions. In this regard, the FACT program is quite remarkable. The primary motivation behind the development of the NISSM II model was not speed but to provide the user with predictions for boundary and volume reverberation, signal to noise ratios, and probability of detection in addition to propagation loss values. As such, it is a limited version of a generic model for surface ship sonars.

Let me now summarize the features and shortcomings of this model class (figure 11). One of the reasons for the popularity of ray theory is that the ray diagram itself is a conceptually appealing link between the mathematics involved and the final plot of propagation loss versus range, which can be appreciated by almost every segment of the sonar community.

Another important feature is the ability to routinely provide more information than merely propagation loss to a point receiver. Information about travel time, angle of arrival, reverberation and ambient noise levels, beamformer output, etc., is viewed as essential by many users. The relative speed with which modern ray theory programs provide answers is an important feature for many applications.

The major disadvantage of ray theory is that it is difficult to precisely determine when it should not be used because of invalid results. Caution should be used in applications to shallow water, surface ducts and low frequencies in general and, especially, in cases where sub-bottom interaction may be significant. The need for corrections then follows naturally and the second item results rather naturally from the first. Corrections have been implemented for two and three ray system caustic formations. However, modifications to account for such things as the lateral wave phenomenon need to be implemented.

The perception of reality for the third class of models (see figure 12) is based upon the assumption that the solution for the wave equation can be adequately represented in terms of normal mode theory. The solution is described mathematically in terms of eigenvalues where the eigenvalue spectrum is composed of possible complex, but strictly discrete, eigenvalues. Herein is the first modification this class imposes in terms of reality because the solution to the wave equation (in terms of eigenvalues) generally has both a discrete and a continuous spectrum. Proponents of this type of solution would argue that the contribution from the continuous portion of the spectrum is of nugatory significance. For some applications this is true, but it is generally not true for all mobile sonar applications. As was the case with ray theory, it is difficult to ascertain a priori the significance of the error incurred by neglecting the continuous portion of the spectrum. Therefore, when these programs are routinely run, it can only be hoped that the error will be insignificant.

There is a practical problem involving the numerical location of the discrete eigenvalues common to all general purpose normal mode programs. For some combination of water depth and frequency, the numerical scheme for determining the location of the eigenvalues in the complex wave number space will eventually break down. It is difficult to ascertain precisely when this breakdown will occur without first running the program for the specific case under consideration. Thus, there is a difficulty in determining the high frequency limit to which normal mode calculations can be confidently used.

Once these questions have been dealt with, the solution is essentially complete except for the number of modes to be included in the final summation. This decision is somewhat analogous to choosing the angular sector examined in ray theory. Pedersen and Bartberger have examined the question of which modes are of importance for specific cases and have provided significant insight. However, a great advantage of normal mode theory is that once the significant eigenvalues have been determined, the solutions for any source and receiver combination can be easily obtained. One would like to know the total number of eigenvalues that must be located to satisfy all possible source and receiver combinations of interest. Various rules of thumb exist, e.g., Gordon suggests that the maximum mode number is approximately 1-1/2 times the frequency. Williams suggests that for shallow water the rule of thumb is H/λ, where H is the water depth and λ the wavelength.

In the final analysis, however, the procedure that is most often used is to run the program for a given number of different modes and examine the behavior of the solution as more modes are added. The same would be true in ray theory calculations when trying to determine both the angular sector of rays to be traced and the angular difference between rays. There are parameters similar to these associated with every model; they lack precise definition and make the complete automation of general purpose propagation models a very intricate and complex process. From the users' standpoint, the degree to which a model can be automated by a non-expert is an important concern.

Generally speaking normal mode programs can be broken into two sub-classes depending upon the manner in which the depth-dependent wave equation is solved. One technique is to assume that the ocean is stratified with depth and that within each stratum the sound speed varies in a predetermined fashion. In this case the solution to the depth-dependent wave equation within each stratum will be given in terms of one of the special functions of mathematical physics.

Satisfaction of the continuity of impedance condition at each interface can then be expressed in terms of equations that cascade the known impedance condition at the surface and at the last boundary to the layer in which the source is located. The dispersion equation, or the Wronskian (if Green's function terminology is preferred) results from trying to satisfy the source conditions. There are then two distinct possibilities for the source and receiver locations. Either they are located in the same layer or the receiver is located in a layer that lies below the source. The second alternative approach is to make a guess at the value for the eigenvalue and then numerically integrate the depth dependent wave equation to determine if the boundary conditions are satisfied. Problems related to the numerical convergence of the solution are encountered in both approaches.

Further modifications to the normal mode reality are sometimes made as by Kanabis, Ingenito, and others. They assume that the only significant modes are those whose associated eigenvalues are purely real. This assumption reduces both the required computing time and the applicability of the solution. The advantages and shortcomings of this class of models are summarized in figure 13.

Once one is satisfied that the continuous spectrum can be neglected and that the numerical calculations are stable and accurate, the job is essentially complete and confidence in the results is extremely high. Unlike ray theory, the intermediate steps leading to the final mode summation provide little insight except to those who have labored over normal mode theory for some time. As was the case with ray theory, it is difficult to say in advance precisely when the solution will not be applicable. Finally, information other than propagation loss is difficult to obtain and not usually provided.

I have called the fourth class of models "total field representations" because they come the closest to solving for the initial understanding of reality expressed in terms of the wave equation for an ocean having a single sound speed profile and flat bottom. An equivalent representation for this reality statement is the integral expression for the pressure field shown in figure 14.

The models of Kutschale and Stickler represent solutions obtained in terms of eigenvalues that include contributions from both the continuous and discrete portions of the spectrum. Kutschale was the first investigator to develop a general model having this capability and it should be noted that the inclusion of the continuous spectrum was viewed as a necessity for his work at very low frequencies in polar or arctic type environments. Another feature of his model is that his strata need not be perfect fluids. This was also necessary to explain propagation in the presence of an ice cover and through the sub-bottom at seismic frequencies. His assumption that the sound speed within each stratum is constant appears to be perfectly adequate at these frequencies. Stickler's model is an all fluid model for which the reciprocal of the square of the sound speed varies linearly with depth within each stratum. Since both of these programs are essentially eigenvalue solutions one should expect them to have the same shortcomings mentioned for the normal mode class, i.e., for some combination of water depth and frequency, problems of numerical accuracy and convergence will be encountered.

The Fast Field Program on the other hand is <u>not</u> an eigenvalue solution but, quite simply, a direct numerical evaluation of the field integral which makes use of the Fast Fourier Transform algorithm. In order to arrive at this point, the single modification to reality that must be introduced (figure 15) is that the Hankel function can be adequately represented in terms of its asymptotic expansion. If this approximation is looked at in isolation, one expects to encounter difficulties at very low frequencies and very close ranges. We have examined such cases, however, and have not been able to detect any significant error. The explanation is perhaps that the approximation should not be examined in isolation but rather as it effects the integration process.

The fact that the FFP is not an eigenvalue solution is an important distinction; we believe this is the reason it provides accurate answers for any combination of frequency and water depth of interest for mobile sonar applications. We have examined the FFP solution for frequencies as low as 1 Hz to as high as 100 kHz and intermediate frequencies as well. Results for a few of the case studies conducted since 1968 that have convinced us of the general applicability of the FFP will be discussed below.

The results shown in figure 16 provide an indication of the error that can be incurred by neglecting the continuous portion of the eigenvalue spectrum. The profile was taken from the Iberian Basin in a water depth of approximately 18,000 ft. The source and receiver were located in a subsurface channel overlaying a second channel at a deeper depth; three results are shown. The line connecting the open circles with dots enclosed and labeled "ARL discrete alone" represent Stickler's results when he neglects the continuous spectrum. The line connecting the open rectangles represent his results when the contribution from the continuous spectrum is added to the normal mode summation. Finally, the line connecting the circles that are filled in are the FFP results for the total field. The neglect of the continuous spectrum results in a substantial error for ranges less than 3 nmi. It is clear that applications exist for which the neglect of the continuous portion of the spectrum could hardly be thought of as a minor concern.

Figure 17 shows the comparison between the FFP predictions and data obtained from an active sonar system operating in the Mediterranean Sea. The agreement within the convergence zone is quite good. This is not the case, however, in the bottom bounce region before the zone. The reason for this is a lack of precise knowledge concerning the bottom loss at this location. The disagreement along the trailing edge of the zone, especially for the deeper hydrophones, is somewhat more difficult to explain. One possibility is that we are comparing the results of two dissimilar sources. The predictions are for an infinite CW omnidirectional source, whereas the experimental data source was directional and emitting LFM pulses. This line of discussion is somewhat premature because such questions are more precisely treated under the heading of assessment. However, it should be noted for future reference that the process of overplotting either predictions from various models or predictions with experimental data and arriving at a subjective conclusion regarding the agreement is a common methodology for assessing the accuracy of model predictions.

The features and shortcomings of the FFP are summarized in figure 18. The FFP is unique in that it is applicable for any combination of frequency and water depth. For this reason, various model developers have found it useful to employ the FFP as a bench mark program when they are testing new models or making improvements to older ones. Physical interpretations or the ability to gain insight are difficult with the FFP because it provides the answer for the total field. The only intermediate information that can be provided is a plot of the absolute magnitude of the kernel of the field integral. The user very often would like to partition the total field in various ways depending on his need. This is possible with the aid of the plot of the kernel but many questions remain about exactly what interpretation should be associated with this partitioning. For this reason, and others, the ability to provide user oriented information about reverberation, ambient noise, surface loss, and the like, appears feasible but it has not been worked out.

Reality for all of the models discussed to this point consisted of an ocean having a flat bottom and a sound speed profile that did not change with range. Since this assumption pertains to the acoustics and not the actual environment of the ocean, it is often difficult to determine beforehand when the assumption will be no longer valid. The measured sound speed profiles and bottom bathymetry for an experimental track from Bermuda to the mid-Atlantic ridge are shown in the upper portion of figure 19. The acoustic data for the case of both source and receiver in the deep sound channel is at the lower left of the figure. A reasonable fit to these data is obtained using an expression that has a 10 log r dependence, implying that predictions from the previously mentioned models would provide reasonable agreement. To the right, however, are the data obtained using a near-surface source and a deep receiver. It is apparent that a single cylindrical spreading model fails to agree with the data over the entire range. The source was located in a surface duct that extended down to approximately 1500 ft near the receiver and gradually decreased in depth as the range increased. It is suspected that this is the cause for the non-cylindrical spreading loss behavior of the data.

A considerable amount of data similar to these now exists that suggests that, for some applications, the single profile, flat bottom perception of reality must be modified. In the past few years considerable progress has been made in implementing solutions that accommodate this modification. The models identified in figure 20 are based on normal mode theory, a combination of mode and ray theory, and straightforward numerical techniques. For the normal-mode approach the ocean is usually laterally sub-divided into uniform segments and the normal modes for each segment are found. There are two major points of difficulty using this approach. The first is to properly account for the coupling of energy from one segment to the next, including the possibility that some energy will travel back toward the source. The second involves the treatment of the boundary condition when the ocean bottom interface is not horizontal. In order to arrive at a solution, various approximations must be made, the validity of which is difficult to determine mathematically. One can resort to comparisons with experimental data. However, this is often not a totally satisfying process because of the lack of completeness of the associated environmental data. More directly, agreement with the data can usually be achieved if adjustments are made to model and experimental data parameters, the values of which have not been determined. Although good comparisons with experimental data are encouraging, more is often learned about the model from cases where agreement is poor. Unfortunately, these cases are very seldom widely publicized.

It is a bit early to arrive at a meaningful list of advantages and shortcomings for this class of models since development work is still in progress. Therefore, a few observations of only a general nature would be appropriate. Most of the current effort seems to be devoted to accounting for acoustic effects caused by the range dependence in the environmental parameters of the water column. This is a natural development considering the types of data available. We believe that applications may soon be apparent for which range dependence of the sound speed and density profiles within the bottom, and the non-parallel nature of the boundaries separating different sub-bottom layers, will be more significant than the range dependence of the corresponding environmental parameters of the water column alone.

Other classes of models exist (figure 21) but time constraints prevent discussing them in detail. It is worthwhile to mention them however. For instance, there is a class of models that, in one way or another, use a combination of wave and ray theory. The mathematics involved is usually, but not always, centered around expanding the kernel for the field integral in terms of an infinite series of integrals that correspond to various types of multiple reflections. This technique dates back at least to Pekeris and Haskell.

There has also been recent interest in predicting the received pressure waveform as opposed to the usual prediction for the energy of a CW signal. General purpose programs have been developed based on both the FFP technique and normal-mode theory.

If by this time the reader is somewhat bewildered at the vast number and types of propagation models, then he is in the proper frame of mind for the remainder of this paper.

So far, the basis of reality as discussed herein has involved strictly the question of accuracy for one sub-model, namely propagation loss. To the sonar analyst interested in developing a generic model (figure 3), this represents just one of many concerns. Thus, he may view the discussion about the relative merits of one propagation model over another as being somewhat esoteric. To provide an understanding for this attitude computer models of underwater sound from the sonar analysis viewpoint will now be discussed. In doing so, it is useful to paraphrase discussions held by the Panel On Sonar Standard Models (POSSM), which is a multi-laboratory effort founded by the Naval Sea Systems Command (NAVSEA) (Code 06H1). NAVSEA was concerned about the confusion expressed by users concerning the proliferation of models and chartered POSSM to make recommendations concerning model usage for NAVSEA programs. The membership of the panel was equally divided between those interested in developing sub-models and sonar analysts in the hope that a common reality would emerge.

The sonar analysts believed that although models for propagation loss could be found in abundance, sub-models for other terms in the sonar equation were, in some cases, nonexistent or at best represented very gross estimates. In order to provide the remainder of the panel with a glimpse of their version of reality the table shown in figure 22, listing the essential ingredients of a generic model, was constructed.

The potential applications for such a model are listed at the left. It was felt that, at a minimum, the sonar analysts needed the capability to conduct performance prediction calculations for both passive and active mobile sonars. The next higher-order use would involve engagement studies employing several platforms. Finally, they would like to conduct statistical analyses of a number of engagement or single platform studies to quantify the merits of new concepts in sonar design. To meet this goal, objective information is required for the medium and system related quantities shown in the columns to the right. The most comprehensive sub-models listed in the fourth column pertain to the signal, noise, and reverberation fields as well as the target model. To adequately model these terms other sub-models, listed in the next column to the right, are required. This dependence continues until we arrive at the last column, entitled "Environmental or System Data."

Few would argue with the view that propagation loss is known with greater accuracy than most of the other items on the chart. Also apparent is that, although accuracy is a concern, it is not the only concern (see figure 23).

The amount of computer time required to run any sub-model is of obvious concern because of the cost involved. Similarly, if the most accurate sub-model requires more core storage than is available, the model is useless. If the sub-model is not available at a facility, additional difficulties will be associated with its implementation. In some cases this may involve time delays that cannot be tolerated. The compatibility of models from one computer to another is a concern that could also result in additional cost and time delays. There are some sub-models that can be run only by the developer and if he is not available for the duration of the study, one might decide to choose another, albeit less accurate, model. Very often it may be possible to decrease the execution time of a model without seriously effecting its accuracy. This would be difficult without extensive documentation. Finally, the sub-model may only provide propagation loss from an omnidirectional source to an omnidirectional receiver when a beamformer output is required.

Of course, these are all practical problems that can be solved with time, money, and manpower. However, they are usually at a premium. Given a multitude of candidates for any sub-model, such as propagation loss, the analyst must arrive at a decision based upon trade-offs between accuracy (and the other items on the list) in the context of the time, money, and manpower available to him.

It became obvious that it would be impossible to recommend a single standard sub-model that would meet the requirements of all potential users. It was thus decided that for each sub-model a matrix of information addressing the items shown in figure 23 be constructed. The analyst or user could then make the required trade-offs himself and select the candidate sub-model best suited for his particular application.

The assessment of accuracy is the most difficult portion of the matrix to complete. One reason for this is that there was unanimous agreement that the methodology adopted had to be significantly more objective than the old technique of graphically comparing predictions and arriving at a value judgment. To accomplish this new ground had to be broken, which was a time consuming process.

The approach currently under consideration is statistical in nature. A given data set is characterized by a sample mean and standard deviation that are functions of the independent variable (e.g., range, azimuth, and time). Two or more data sets are then compared by a variety of statistical techniques yielding quantitative measures of agreement. Although the examples to be discussed specifically deal with transmission loss versus range data, the applicability of the comparison method is not restricted to such data.

Two approaches for finding the range dependent mean have been implemented. The first involves a moving average for which a subjective choice must be made regarding the number of points to be averaged. In the second approach, the entire record is first subdivided into segments based on the presence of predominant interference patterns. The data within each segment are then fitted with various order polynomials to minimize the mean square error. Examples illustrating this approach will be provided in the subsequent figures. All examples pertain to a profile found in the Pacific in about 18,000 ft of water having a surface duct down to 247 ft. Two source and receiver combinations (figure 24) were examined. For one the source and receiver were in the surface layer at depths of 50 ft and for the other the source and receiver were below the layer at 500 and 300 ft, respectively. Model predictions were obtained at frequencies of 50, 500 and 2000 Hz for each configuration. The frequency cases are designated 1 through 6. Experimental data were also available for the source and receiver below the layer at frequencies of 50 and 400 Hz. These have been designated as cases 7 and 8. The models examined are listed in figure 25. Raymode IV, FACT and NISSM II predictions were compared to those of the FFP.

Case 4, with source and receiver below the layer and at 50 Hz, is sufficiently representative so that most major points of interest are manifest. The FFP prediction (figure 26) begins with a Lloyd Mirror Pattern at close ranges followed by a more complex interference pattern in the first bottom bounce region (which extends to about 58 kyd). A double-peaked convergence zone extends to 75 kyd and is followed by the beginning of the second bottom-bounce interference pattern.

The entire range interval was subdivided into five segments. From right to left they are the second bottom-bounce region, then two segments within the convergence zone, a segment capturing the last major interference pattern in the bottom bounce region, and a single segment for the first 35 kyd. The smooth curve in each segment is the range dependent mean obtained using the polynomial fit. The fact that the first 35 kyd were treated as a single segment whereas it could have been subdivided into as many as 10 segments illustrates where subjectivity enters the methodology. The decision as to which features have importance should be based on the user determining which is the feature of least interest for his application. As it turned out, the choice of a single polynomial fit to the FFP for this range interval led to smaller differences between the FFP predictions and those of the other models, which show much less detail.

The polynomial fits to the FACT coherent predictions are shown in figure 27. Note that the abrupt change in the propagation loss at 86 kyd, which would appear to be an artifact, is smoothed by the polynomial fit. The feature between 40 and 50 kyd is significantly reduced in amplitude compared with the FFP value but is, nonetheless, distinguishable.

The next step in the methodology is to subtract the range-dependent mean for FACT from the range-dependent mean for the FFP. The results are provided in figure 28. The large difference at about 38 kyd is caused by the fact that the features occurring in both models just before the convergence zone are displaced from one another in range and have different amplitudes. The two peaks between 60 and 70 kyd result because the double-peaked convergence zone is more clearly defined in the FFP curve. The differences between 80 and

100 kyd are the result of the artifact in the FACT prediction that produced the abrupt increase in propagation loss.

These results serve as a quantitative measure of the difference in accuracy between the two predictions. The measure is not completely objective since, in some instances, the differences between the two means are caused by subjective decisions regarding the subdivision of the data records. In this regard it is felt that the use of a sliding average would be more appealing than subdividing and fitting with polynomials. However, a certain amount of subjectivity will always be present regardless of the technique used to find the range-dependent mean.

Although this information is considered to be a vast improvement over the purely subjective process of overplotting the two predictions, it would have more significance to the user if it could be summarized in a manner that could be easily interpreted. This is a difficult step because it involves finding a link between the realities of the model developer and user. The last set of figures represent an initial attempt at such a summary.

Since it is quite clear that the summary must be range dependent, one can find the mean and standard deviation of the difference curves in various range intervals specified by the user. For the purpose of illustration, 20 kyd intervals have been selected as shown in figure 29. The mean and standard deviation have been tabulated for all of the models considered in case 4. Thus, for the first 20 kyd, the difference between the mean of the FFP predictions and the mean of NISSM II was, on the average, 0.7 dB. Information similar to this would be available for all cases considered in the assessment (which, in this instance, was 6).

Considering that only one profile, two source and receiver combinations, and three frequencies have been used (whereas typical user requirements would entail many more combinations) it was felt that a summary on a higher level was needed. The results shown in figure 30 represent one possible alternative.

The user should assign degrees of importance, first to the various cases and second to the different range intervals, based on the application at hand. Given these weights, which will be taken as unity for this example, the absolute value of the mean plus the standard deviation for the differences is calculated for each case in each range interval. The models are then ranked in accordance with these values. The model with the lowest value receives the rank 1, and so on. In the event that two or more models have the same sum, each is assigned an average rank.

The upper line in each box shows the rankings for cases 1, 2, and 3, respectively; the second line shows the rankings for cases 4, 5, and 6, respectively. The number in parenthesis is the sum of the rankings for the 6 cases. The final column provides the sum of the rankings over all cases and range intervals.

It is apparent that, for these cases, the FACT model employing the coherent phase addition shows the closest overall agreement with the FFP. In terms of the the total ranking provided in the last column, the FACT model using incoherent phase addition and the NISSM II model using coherent phase addition are essentially equal. The final three models (Raymode IV with coherent phase addition, Raymode IV with incoherent phase addition, and NISSM II with incoherent phase addition) show significantly less agreement with the FFP model.

When coupled with information about the other items in the matrix, data of this type should provide the user with a reasonable basis upon which to arrive at an objective selection for a sub-model.

In discussing the state of affairs of computer models for underwater sound, it has been helpful to outline the perceptions of reality of those who develop such models and those who use them. Such perceptions, unlike those of the mystic and modern theoretical physicist, are often in conflict, and a fair amount of confusion results. The ideal solution would be either that the user acquire an understanding of the detailed mathematics involved in deriving the various sub-models or that the developer acquire an appreciation for the arts of system analysis and design. A more reasonable alternative would be to establish a line of communication between the two groups so that each could learn to appreciate the realities of the other. The model, whether it be a sub-model or of the generic type, is common to both groups and could serve to bridge the gap. Before this can happen, however, an objective methodology for assessing models must be developed and tested. Some thoughts on such a methodology have been presented, but they are still in the formative stage and require additional exposure and use by both groups. Time does not permit a discussion of experimental data but there are many reasons, not the least of which is relative sparseness, why experimental data cannot be the final reality. Finally, there are perhaps some who would like to know how to avoid finding themselves in a similar predicament. I can offer no advice in this regard for it almost seems inevitable that if you have a computer of any size, you will soon have two or more models that give different answers and, most probably, none will fully represent the reality you had hoped to model. The model will always bear the same relation to reality as a shadow bears to the object that casts it.

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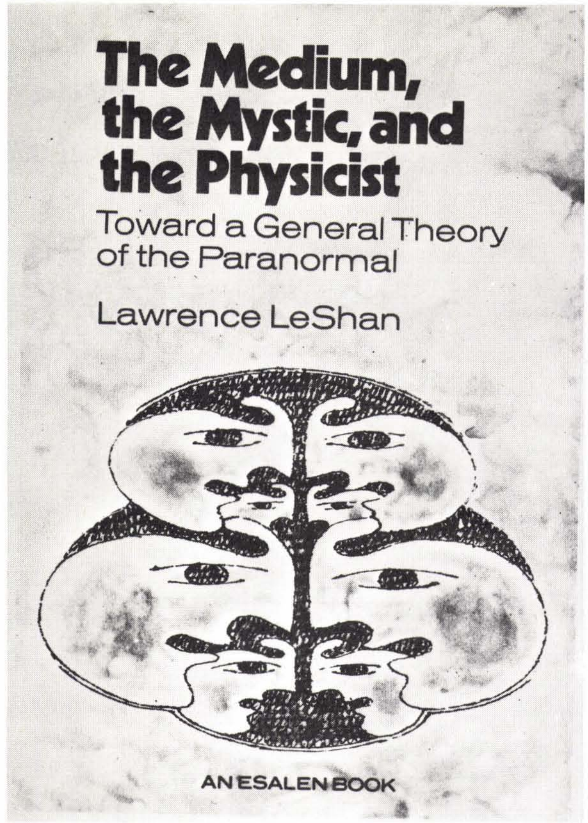

FIG. 1
COVER OF LESHAN'S BOOK

"WHEN WE THOUGHT WE WERE STUDYING THE EXTERNAL WORLD, OUR DATA WERE STILL OUR OBSERVATIONS; THE WORLD WAS AN INFERENCE FROM THEM" DINGLE (P)

"IT IS THE MIND WHICH GIVES TO THINGS THEIR QUALITY, THEIR FOUNDATION, AND THEIR BEING" DHAMMAPADA (M)

"PURE LOGICAL THINKING CANNOT YIELD US ANY KNOWLEDGE OF THE EMPIRICAL WORLD, ALL KNOWLEDGE OF REALITY STARTS FROM EXPERIENCE AND ENDS IN IT. PROPOSITIONS ARRIVED AT BY PURELY LOGICAL MEANS ARE COMPLETELY EMPTY OF REALITY" EINSTEIN (P)

" . . . MAN IS THE MEETING POINT OF VARIOUS STAGES OF REALITY" EUCKEN (M)

"AS FAR AS THE LAWS OF MATHEMATICS REFER TO REALITY, THEY ARE NOT CERTAIN; AND AS FAR AS THEY ARE CERTAIN, THEY DO NOT REFER TO REALITY" EINSTEIN (P)

FIG. 2
SIMILAR VIEWPOINTS ON REALITY

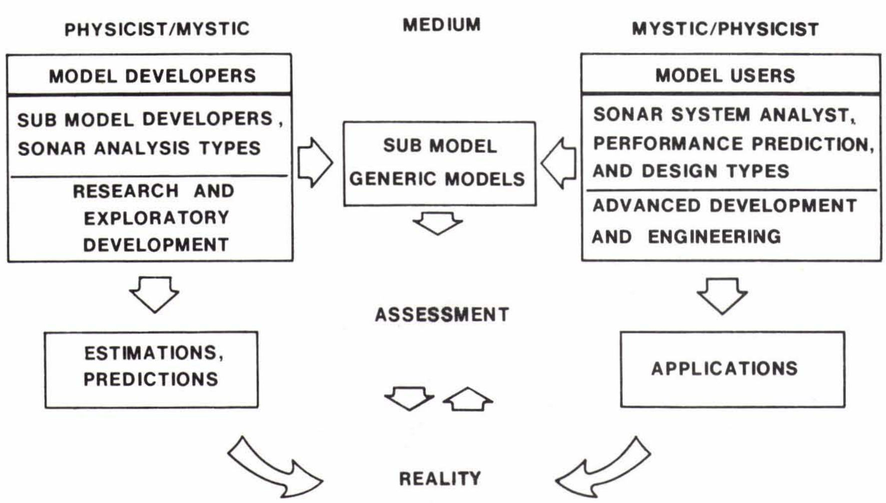

FIG. 3
TWO APPROACHES TO SONAR

CONCEPT

- GENERIC MODEL CAN BE THE BRIDGE BETWEEN THE DEVELOPER AND USER

PROBLEMS

- GENERIC MODEL FOR MOBILE SONAR SYSTEMS DOES NOT EXIST
- DEVELOPERS AND USERS HAVE DIFFERENT PERCEPTIONS OF REALITY
- ASSESSMENT METHODOLOGY IN PRIMITIVE STAGE

FIG. 4 CONCEPT AND PROBLEMS

A. SEMI - EMPIRICAL / SEMI-ANALYTICAL
  1.) AMOS
  2.) COLOSSUS

B. RAY THEORY WITH CORRECTIONS

C. NORMAL MODE THEORY

D. TOTAL FIELD MODELS

E. RANGE DEPENDENT MODELS

F. GENERALIZED/RAY MODELS

G. TIME DOMAIN (WAVE FORM PREDICTION) MODELS

H. EXACT SOLUTIONS

FIG. 5 FIRST CLASS OF PROPAGATION MODELS

FEATURES:

- EQUATIONS ARE SIMPLE, MINIMAL EXECUTION TIME REQUIRED

$$H = 20 \log (1000\, R / R_0) + \alpha R + (r/r_1)\, G(Z_t, Z_x)$$

$$G(Z_t, Z_x) = \begin{cases} .1 \times 10^{2.3(Z_t - Z_x)} (f/25)^{1/3}, & Z_t - Z_x < 1 \\ 20\,(f/25)^{1/3}, & Z_t - Z_x \geq 1 \end{cases}$$

SHORT COMINGS:

- LARGE VARIANCE
- VALIDITY GOVERNED BY DATA BASE
- UNABLE TO PREDICT FINE STRUCTURE OF PROPAGATION LOSS

FIG. 6 SEMI-EMPIRICAL/SEMI-ANALYTICAL CLASS

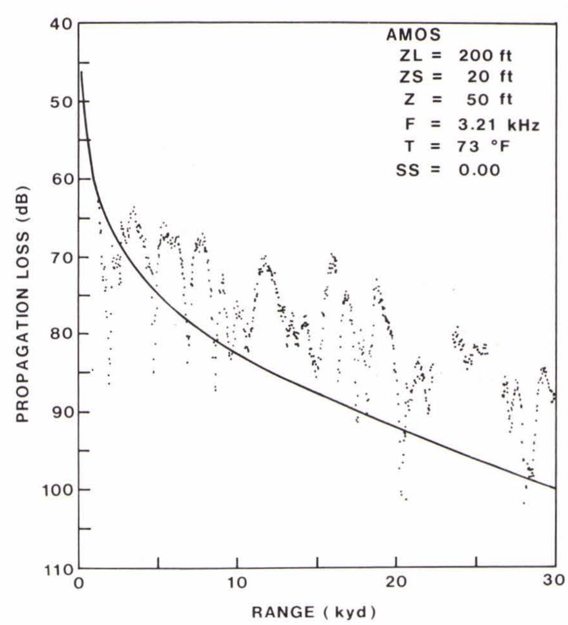

FIG. 7
PROPAGATION LOSS VERSUS RANGE (RECEIVER DEPTH 50 ft)

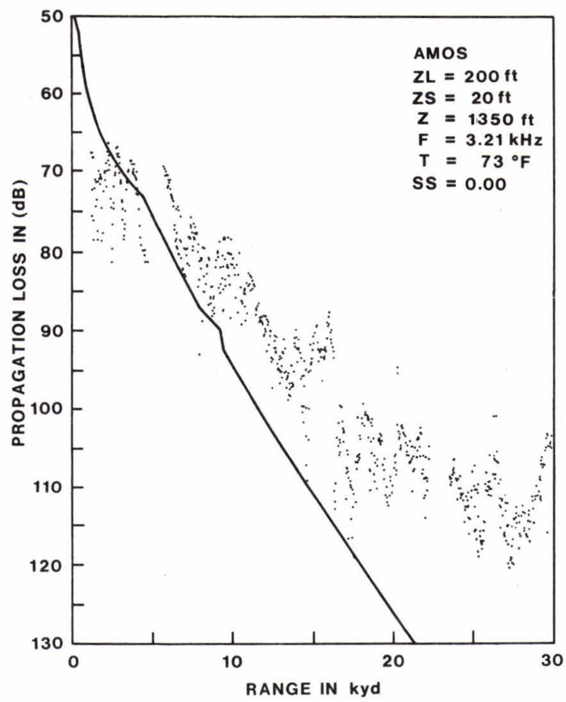

FIG. 8
PROPAGATION LOSS VERSUS RANGE (RECEIVER DEPTH 1350 ft)

TIME INDEPENDENT WAVE EQUATION

$$\nabla^2 \psi + k^2 \psi = - \delta (z - z_0) \frac{\delta (\rho)}{\rho}$$

+ BOUNDARY CONDITIONS (FLAT BOTTOM, SINGLE SSP)

FIG. 9
REALITY FOR THE SUB-MODEL DEVELOPER

A. SEMI - EMPIRICAL / SEMI - ANALYTICAL

B. RAY THEORY WITH CORRECTIONS
   1. FACT
   2. NISSM II

C. NORMAL MODE THEORY

D. TOTAL FIELD MODELS

E. RANGE DEPENDENT MODELS

F. GENERALIZED RAY MODELS

G. TIME DOMAIN (WAVE FORM PREDICTION) MODELS

H. EXACT SOLUTIONS

FIG. 10
SECOND CLASS OF PROPAGATION MODELS

FEATURES:

RAY DIAGRAM EASILY INTERPRETED

ADDITIONAL USER ORIENTATED INFORMATION AVAILABLE

SIGNIFICANT REDUCTION IN EXECUTION TIME AND STORAGE REQUIREMENTS

SHORT COMINGS:

LIMITS OF APPLICABILITY DIFFICULT TO DETERMINE

ADDITIONAL CORRECTIONS ARE REQUIRED

FIG. 11 SUMMARY OF RAY THEORY WITH CORRECTIONS

A. SEMI - EMPIRICAL / SEMI - ANALYTICAL

B. RAY THEORY WITH CORRECTIONS

C. NORMAL MODE THEORY

1. GORDON, PEDERSEN
2. BARTBERGER
3. BUCKER, MORRIS
4. BLATSTEIN

SPECIAL FUNCTIONS OF MATHEMATION PHYSICS

$$\frac{d^2\beta}{dz^2} + (k^2(z) - \xi^2)\beta = 0$$

5. KANABIS, INGENITO

NUMERICAL INTEGRATION

D. TOTAL FIELD MODELS

E. RANGE DEPENDENT MODELS

F. GENERALIZED RAY MODELS

G. TIME DOMAIN (WAVE FORM PREDICTION) MODELS

H. EXACT SOLUTIONS

FIG. 12 THIRD CLASS OF PROPAGATION MODELS

FEATURES

CONFIDENCE IN THE RESULTS

SOLUTION FOR ANY SOURCE AND RECEIVER DEPTH COMBINATION IS OBTAINED AT LITTLE EXTRA EXPENSE.

SHORT COMINGS:

PHYSICAL INTERPRETATION DIFFICULT

LIMITS OF APPLICABILITY DIFFICULT TO ASCERTAIN PRECISELY

ADDITIONAL USER-ORIENTED INFORMATION DIFFICULT TO OBTAIN

FIG. 13 NORMAL MODE THEORY

A. SEMI - EMPIRICAL / SEMI - ANALYTICAL

B. RAY THEORY WITH CORRECTIONS

C. NORMAL MODE THEORY

D. TOTAL FIELD MODELS

1. KUTSCHALE
2. STICKLER

EIGENVALUE SOLUTION (MODES PLUS BRANCH CUT)

$$\psi(z,r) = \int_{-\infty}^{\infty} G(z, z_0, \xi)\, H_0^{(1)}(\xi r)\,\xi\, d\xi$$

3. FAST FIELD PROGRAM (FFP)
4. KUTSCHALE VERSION OF FFP

NON EIGENVALUE SOLUTION

E. RANGE DEPENDENT MODELS

F. GENERALIZED RAY MODELS

G. TIME DOMAIN (WAVE FORM PREDICTION) MODELS

H. EXACT SOLUTIONS

FIG. 14 FOURTH CLASS OF PROPAGATION MODELS

$$H_0^{(1)}(\xi r) \cong e^{i\xi r}/\sqrt{\xi r}\ , \quad (\xi r) >> 1$$

$$\psi(z,r) \cong \frac{1}{\sqrt{r}} \int_{-\infty}^{\infty} G(z_1\, z_0, \xi)\,\xi^{1/2} e^{i\xi r} d\xi$$

FIG. 15 ONE MODIFICATION TO REALITY

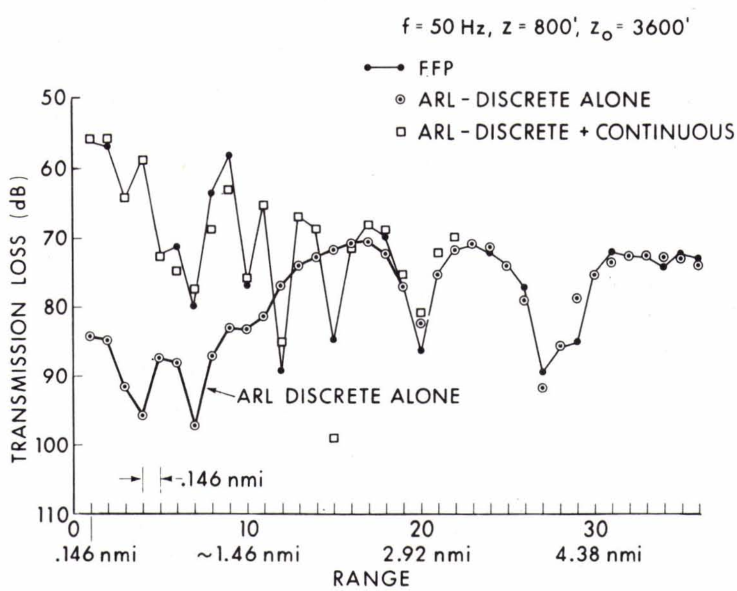

FIG. 16 GENERAL APPLICABILITY OF THE FFP

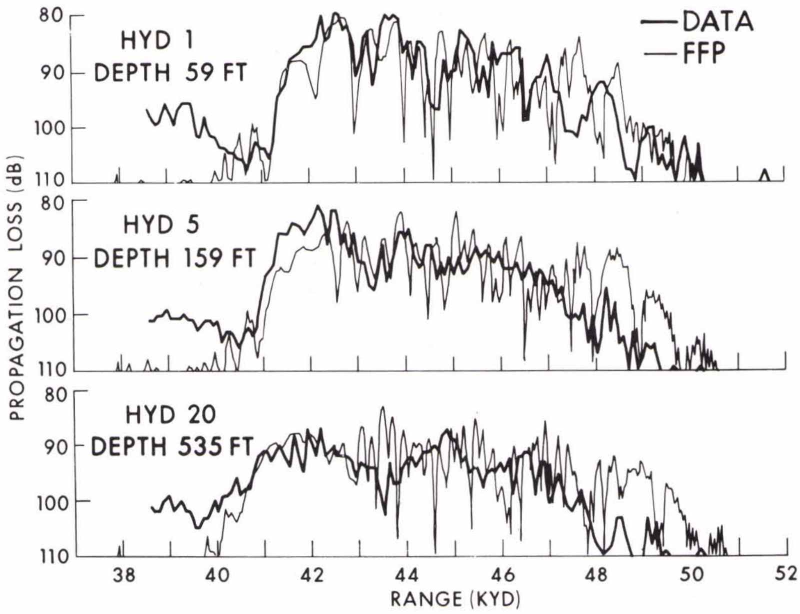

FIG. 17
COMPARISON OF FFP PREDICTIONS AND ACTIVE SONAR SYSTEM DATA

FIG. 18
TOTAL FIELD MODELS (FFP)

FEATURES:

- APPLICABLE FOR ANY FREQUENCY / WATER DEPTH COMBINATION
- IS USED AS A BENCHMARK PROGRAM

SHORT COMINGS:

- PHYSICAL INTERPRETATION DIFFICULT
- ADDITIONAL USER-ORIENTED INFORMATION DIFFICULT TO OBTAIN

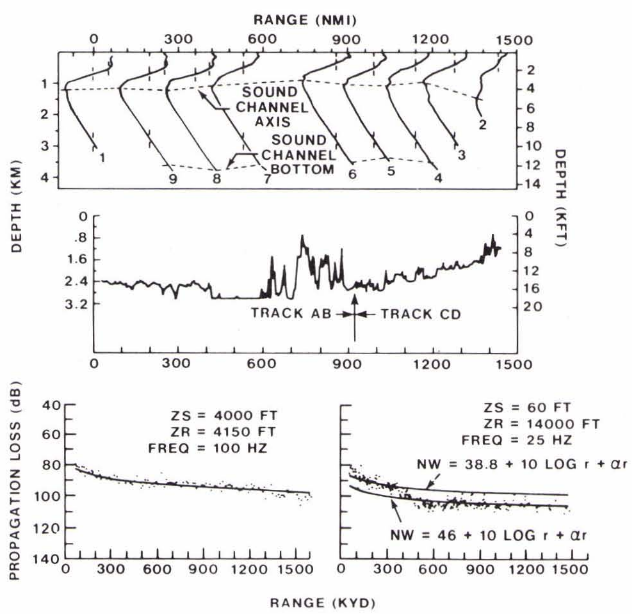

FIG. 19
ACOUSTIC DATA FOR SOURCE AND RECEIVER

A. SEMI EMPIRICAL / SEMI - ANALYTICAL

B. RAY THEORY WITH CORRECTIONS

C. NORMAL MODE THEORY

D. TOTAL FIELD MODELS

E. RANGE DEPENDENT MODELS
   1. KANABIS NORMAL MODE
   2. WEINBERG 3 D NORMAL MODE
   3. PARABOLIC EQUATION MODEL

F. GENERALIZED RAY MODELS

G. TIME DOMAIN (WAVE FORM PREDICTION) MODELS

H. EXACT SOLUTIONS

FIG. 20
FIFTH CLASS OF PROPAGATION MODELS

A. SEMI EMPIRICAL / SEMI - ANALYTICAL

B. RAY THEORY WITH CORRECTIONS

C. NORMAL MODE THEORY

D. TOTAL FIELD MODELS

E. RANGE DEPENDENT MODELS

F. GENERALIZED RAY MODELS
   1. RAY MODE
   2. RAY WAVE
   3. WEINBERG

G. TIME DOMAIN (WAVE FORM PREDICTION) MODELS
   1. TIME DOMAIN FFP
   2. TIME DOMAIN NORMAL MODES (PORTER, GUTHRIE)

H. EXACT SOLUTIONS

FIG. 21
SIXTH CLASS OF PROPAGATION MODELS

← MODEL APPLICATIONS			DEPENDENCE →				
STATISTICAL	ENGAGEMENT	PERFORMANCE PREDICTION	MAJOR MODELS	MAJOR COMPONENTS	MINOR COMPONENTS	SUB COMPONENTS	ENVIRONMENTAL OR SYSTEM DATA
ENGAGEMENT STATISTICS MODEL ASSESSMENT CONCEPT COMPARISON	MULTI-PLATFORM	PASSIVE ESTIMATION ACTIVE TRACKING RANGING	SIGNAL NOISE REVERBERA-TION TARGET	XMIT ARRAY RESPONSE RECEIVE ARRAY RESPONSE PROP. LOSS TARGET STRENGTH RADIATED NOISE SEA NOISE SHIPPING NOISE BIO. NOISE SELF NOISE BOTTOM REVERB. SURFACE REVERB. VOLUME REVERB. PASSIVE PROC. ESTIM. PROC. ACTIVE PROC. TRACKER RANGE PROC. CLASSIFIER TMA	BOTTOM STRUCTURE SURFACE LOSS ATTENUATION BAFFLE WINDOW BOTTOM SCAT. STR. XMIT BEAM PATTERN RECEIVE BEAM PATTERN SIGNAL PROC. DATA PROC. INFO. PROC. DISPLAY	POWER AMPLIFIER WAVE HEIGHT BOTTOM ROUGHNESS VELOCITY PROFILE VOLUME SCATTERING PROFILE FILTER CORRELATOR AVERAGER NORMALIZER SPECTRUM ANAL.	XMIT WAVEFORM HYDROPHONE LOCATION XDUCR LOCATION SEA STATE WIND SPEED BOTTOM SLOPE SHIPPING DISTRIBUTIONS TEMPERATURE PROFILE SALINITY PROFILE BOTTOM SCATTERING CONST. SURFACE SCATTERING CONST.

FIG. 22 ESSENTIAL INGREDIENTS OF GENERIC MODEL

A. ASSESSMENT OF ACCURACY

B. RUNNING TIME

C. AMOUNT OF COMPUTER MEMORY REQUIRED

D. EASE OF IMPLEMENTATION

E. COMPLEXITY OF PROGRAM EXECUTION

F. EASE OF EFFECTING SLIGHT ALTERATIONS TO THE PROGRAM

G. AVAILABLE ANCILLARY INFORMATION

FIG. 23
FACTORS INFLUENCING MODEL SELECTION

CASE NUMBER	FREQUENCY (Hz)	SOURCE DEPTH (ft)	RECEIVER DEPTH (ft)
1	50	50	50
2	500	50	50
3	2000	50	50
4	50	500	300
5	500	500	300
6	2000	500	300
7	50	500	300
8	400	500	300

FIG. 24
TWO SOURCE AND RECEIVER COMBINATIONS

CASES 1–6: FAST FIELD PROGRAM (FFP) WITH

- **RAYMODE IV**
- **FACT**
- **NISSM II**

CASES 7,8: PARKA DATA WITH

- **FFP**
- **RAYMODE IV**

FIG. 25
CASES 1 THROUGH 6

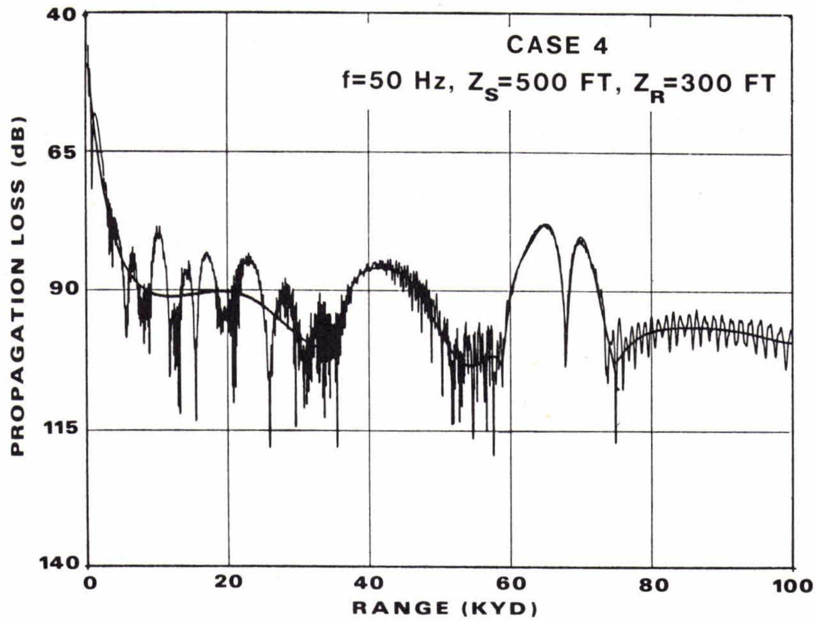

FIG. 26
FFP PROPAGATION LOSS

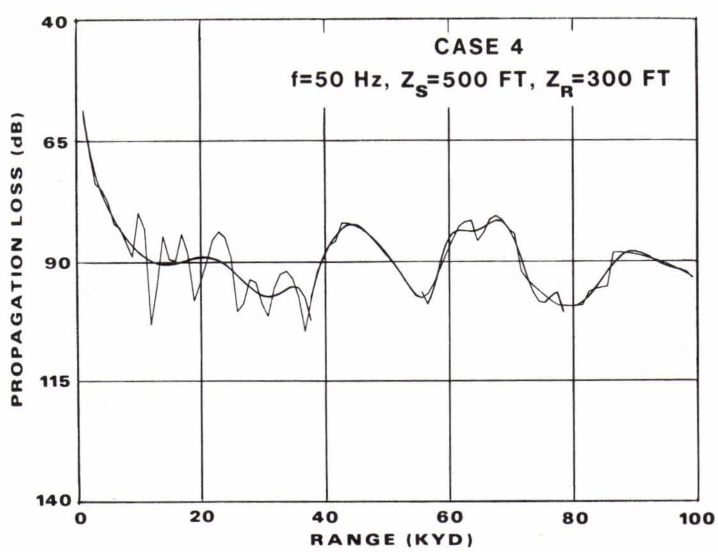

FIG 27
FACT COHERENT PROPAGATION LOSS

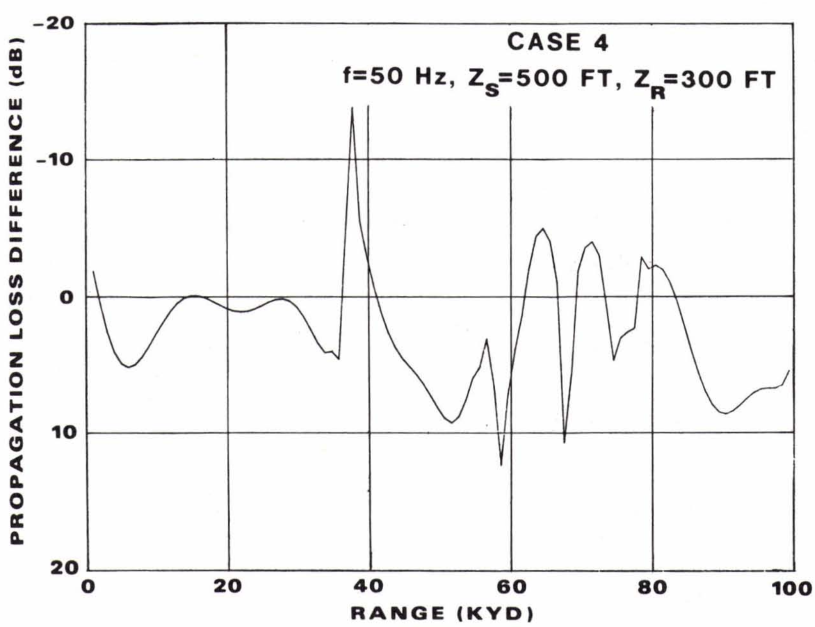

FIG. 28
FFP POLYNOMIAL MINUS FACT COHERENT POLYNOMIAL

CASE 4

RANGE INTERVAL (Kyd)	0-20		20-40		40-60		60-80		80-100		0-100	
MEAN AND STANDARD DEVIATION (dB)	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
FFP POLYNOMIAL MINUS RAYMODE COHERENT POLYNOMIAL	3.1	4.0	-4.3	3.7	0.3	8.2	1.0	8.3	-3.6	2.5	-7.0	6.4
FFP POLYNOMIAL MINUS RAYMODE INCOHERENT VALUES	4.0	1.9	1.1	4.4	3.1	8.9	2.8	5.7	-2.3	1.3	1.7	5.6
FFP POLYNOMIAL MINUS FACT COHERENT POLYNOMIAL	1.8	2.1	0.0	4.1	5.9	3.0	0.1	4.1	5.0	3.6	2.6	4.2
FFP POLYNOMIAL MINUS FACT INCOHERENT VALUES	3.7	2.2	4.2	4.2	6.2	6.2	0.5	4.8	1.4	3.3	3.2	4.7
FFP POLYNOMIAL MINUS NISSM COHERENT POLYNOMIAL	0.7	1.4	-0.1	1.8	-2.4	4.0	-6.9	10.3	-2.0	3.3	-2.2	5.9
FFP POLYNOMIAL MINUS NISSM INCOHERENT VALUES	3.3	1.6	3.6	4.3	5.1	7.0	-3.2	6.9	-1.0	4.3	1.5	6.0

FIG. 29 COMPARISON OF PROPAGATION LOSS MODELS WITH THE FFP

RANGE INTERVAL	0-20	20-40	40-60	60-80	80-100	TOTAL
RAYMODE COHERENT	4 4 3 6 5 2 (24)	6 3 4 5 5 6 (29)	5 5 4 2 6 6 (28)	3½ 2 3½ 4 1 1 (15)	5 1 6 5 6 6 (29)	125
RAYMODE INCOHERENT	6 3 1 4½ 6 6 (26½)	5 4 3 3 4 1 (20)	6 4 3 4 5 4 (26)	6 1 3½ 3 5 4 (22½)	6 2 5 1 5 5 (24)	119
FACT COHERENT	1 2 2 2 4 3 (14)	2 2 1½ 2 6 5 (18½)	1 2 2 3 3 3 (14)	1 3½ 2 1 2 2 (11½)	2 5 2 6 2 2½ (19½)	77½
FACT INCOHERENT	2 1 4 4½ 3 5 (19½)	3½ 1 1½ 6 3 4 (19)	4 1 1 6 4 5 (21)	5 5 1 2 3 3 (19)	4 3 1 2 4 4 (18)	96½
NISSM COHERENT	3 5 5 1 1 1 (16)	1 6 5 1 1 3 (17)	2 6 5 1 2 1 (17)	2 3½ 5 6 6 6 (28½)	1 6 3 3½ 1 2½ (17)	95½
NISSM INCOHERENT	5 6 6 3 2 4 (26)	3½ 5 6 4 2 2 (22½)	3 3 6 5 1 2 (20)	3½ 6 6 5 4 5 (29½)	3 4 4 3½ 3 1 (18½)	116½

FIG. 30 RELATIVE STANDING OF EACH MODEL ON THE BASIS OF $|\mu| + \sigma$ FOR CASES 1–6