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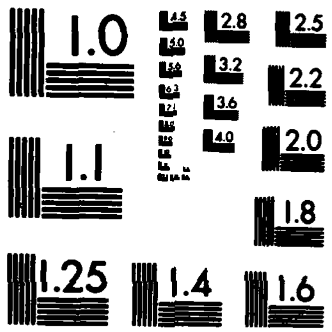

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SCIENCE APPLICATIONS, INC.
Post Office Box 1303, 1710 Goodridge Drive, McLean, Virginia 22102, (703) 821-4300

TECHNICAL SPECIFICATIONS
FOR
SPREAD FUNCTION MODEL

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May 1983

Prepared by:

C. W. Spofford
Ocean Acoustics Division

Prepared for:

R. Farwell
Naval Sea Systems Command

SCIENCE APPLICATIONS, INC.
1710 Goodridge Drive
P. O. Box 1303
McLean, VA 22102
(703) 821-4300

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Section 1

INTRODUCTION AND BACKGROUND

In order to design and accurately estimate the performance of a candidate passive sonar system the systems engineer needs considerably more information than the standard terms in the passive sonar equation. The sonar equation typically deals with the mean values of the total signal and noise fields. All departures from these means are considered only in the time domain as fluctuations in signal excess which lead to the probabilistic description of the detection process in terms of ROC curves, etc.

As a first refinement of this approach, still in the mean value sense however, a higher resolution description of these fields is sought. In terms of propagation loss for passive systems the traditional loss (TL(r, Z_S, Z_R, f) summed across all paths as a function or range (r), source and receiver depths (Z_S and Z_R) and frequency (f)) must be replaced by the mean values of the path-by-path contributions to the total field: the path amplitudes, A_j, their travel times, T_j, and their vertical arrival angles, θ_j. All paths which are potentially separable in space or time (or due to differential Doppler in frequency) must be represented. (For ambient noise, the corresponding refinement would include the average noise directionality, both vertical and horizontal.)

In order to estimate array signal gain, processor gain, and detection and localization performance additional information beyond these means is required on the spreads of these values. Specifically the vertical, σ_θ, and azimuthal, σ_ϕ, ensemble-averaged spreads of each arrival angle are needed. (For simplicity these are described in terms of their standard deviations. If such a Gaussian description is inappropriate other parameters or the actual distribution functions need to be provided.) These angle spread functions are simply the wave-number transforms of the corresponding spatial mutual coherence functions. Similarly path-by-path arrival time spreads, σ_τ, and frequency spreads, σ_f, are required for broadband and narrowband systems, respectively. While σ_τ and σ_f have corresponding conjugate (transform) variables in frequency and time, respectively, these two spreads do not form a conjugate pair themselves. Their separate, consistent treatment is appropriate to best support analyses for broadband and narrowband systems, respectively. The distinction between these spreads and gradual changes, "wander", must be made in terms of the space/time/frequency resolutions of the systems of interest.

This paper addresses the technical specifications for a set of models to support these requirements. For this treatment only second moments (distributions for angles, decorrelation times, frequency spreads) will be considered. While higher-order moments are desirable, their general treatment is beyond the scope of the present effort. In some special cases, such as the distribution of intensity (a collapsed fourth-order moment), estimates may be possible and are considered.

The emphasis of these specifications is on signal characteristics (Section 2) since they tend to drive system design. Ambient noise (Section 3) is less modelable and tends to be treated quasi-empirically (that is in a "model" where a number of the driving parameters are measured, rather than based on more basic-physical principles).

In each area, short-term approaches and long-term issues are identified. These are summarized in outline form in Section 4.

Section 2
SIGNAL MODELING

The signal will be considered in terms of its individual path components. In most instances a "path" will correspond to a geometric arrival as predicted by ray theory (approximately extended to include diffraction effects). In a few instances, such as surface and subsurface ducts, the "path" may actually correspond to a group of modes. In other cases, such as precursor leakage arrivals from ducts, a mixed ray and mode view may be appropriate.

For each of these "paths" we wish to estimate the spreads due to "random" effects. By "random" we mean those effects not directly predicted by the underlying "path" model. There are two separable sources for spreads associated with random effects: small motions of the receiver and source, and scattering associated with random variations in the environment (surface, volume, and bottom). From a modeling point of view it is convenient to treat these separately. There is, however, an interaction between, for example, the angular spread of a signal due to internal wave scattering, and the decorrelation time of the signal for that path as the receiver moves through that spread field.

2.1 THE COMBINED-EFFECTS SPREAD-FUNCTION MODEL

No one model exists which can reliably predict all of the individual paths, let alone their spreads. For this reason a modular approach to both the path and spread models is appropriate. Figure 2-1 illustrates the overall structure

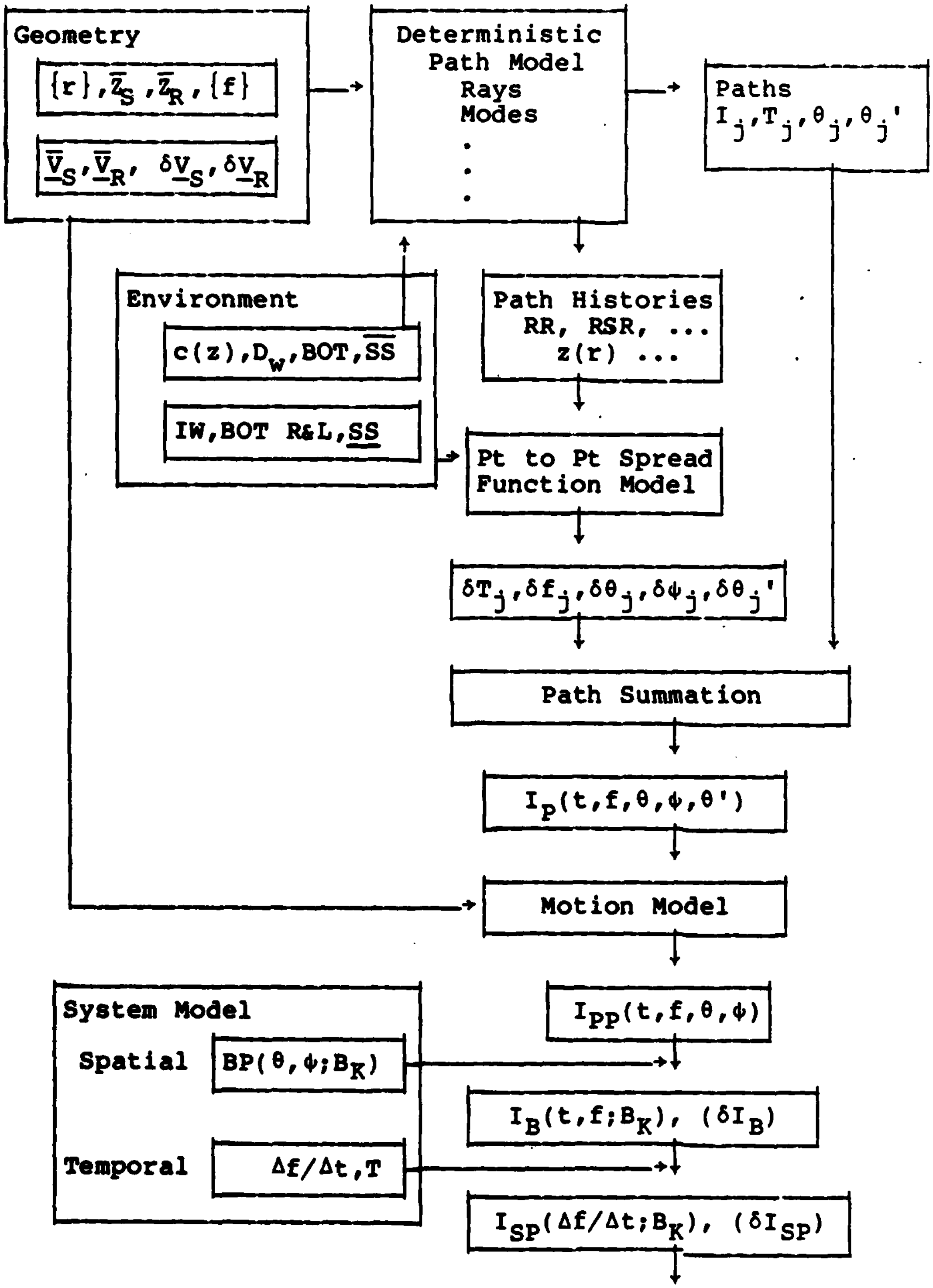

Figure 2-1. Combined-Effects Spread-Function Model.

and flow of this Combined-Effects Spread-Function Model. The final output of the Combined-Effects Model is the average beam intensity (I_{SP}) with corresponding frequency/time spreads (for narrowband or broadband systems, respectively) for a given source-receiver geometry including the effects of motion and random scattering. Previously computed estimates of spreads in angle before all processing effects, I_{PP}, and prior to the incorporation of motion effects, I_P, are also available.

2.1.1 Inputs

The basic inputs required are indicated in the three large boxes on the left-hand side.

(1) Geometry

(a) Deterministic parameters are the set of ranges $\{r\}$ and CW frequencies* $\{f\}$ of interest given the average source and receiver depths, $\overline{z_S}$ and $\overline{z_R}$, respectively.

(b) Motion parameters affect the spread spectra, specifically the mean source and receiver vector velocities, $\overline{\underline{V}_S}$ and $\overline{\underline{V}_R}$, and their spreads, $\delta\underline{V}_S$ and $\delta\underline{V}_R$, respectively. (These are velocities with respect to the fixed sea floor. Relative

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* In this discussion, until the application of the temporal signal processor model, the signal will be referred to as cw. If a broadband signal (system) is being considered, at least center-frequency values would be computed. Where individual paths might show significant frequency dependence, full-band averages might be required.

velocities are inadequate when describing bottom and surface scatter.)

(2) Environment

(a) Deterministic environmental parameters are the sound-spread profile, $C(Z)$, the water depth, D_W, the sea state (or mean wave height $\overline{SS}$), and the gross bottom properties (either a geo-acoustic model or bottom-loss tables, as appropriate). (Range dependence in the mean environment is being ignored for now, and $\overline{SS}$ is meant to represent enough of a description of the sea state to provide loss estimates for the coherent, specularly reflected path.)

(b) Random environmental parameters are the internal wave (and fine structure) volume descriptions, IW, bottom roughness and layering data, BOT R&L, and sea-state directional spectrum, $\underline{SS}$.

(3) System Model

(a) The spatial processing capabilities of the system are represented by the beam response pattern BP for beam B_k as a function of plane-wave incident angles in elevation, θ, and azimuth, ϕ. (These patterns should reflect reasonable distortion effects and are likely to be specified with respect to the platform axis, hence requiring translation to the mean azimuth of interest.)

(b) The temporal processing capabilities represent either coherent narrowband processing leading to frequency bins of width Δf, or broadband processing with time intervals Δt, and incoherent integration for both types of processing over an interval T.

2.1.2 Deterministic Path Model

The deterministic geometric and environmental parameters are then used by the Deterministic Path Model to estimate the intensities, I_j, travel times, T_j, arrival, θ_j, and launch, θ_j', angles for each path connecting the source and receiver at a given range. (Questions remain to be resolved about treatment of mode-like fields, and T_j is meant to represent the sum of any discrete phase shifts a path might suffer as well as its basic travel time.) An additional output for each of these paths is its "history". Depending upon the complexity of the Point-to-Point Spread Function Model (or submodels) as described below, this history might include descriptions as simple as path type (RR, RSR, SRBR, with n full loops, and n_S and n_B surface and bottom reflections) or as detailed as its entire trajectory ($Z(r)$).

2.1.3 Point-to-Point Spread Function Model

This model combines the path histories with the random environmental inputs to yield the spreads in time, δT_j, frequency, δf_j, arrival, $\delta\theta_j$, azimuthal, $\delta\phi_j$, and launch, $\delta\theta_j'$, angles for each path. (The launch angle spread will be necessary when source motion is included.)

This model is the heart of the Combined Effects Model and is described in much more detail in Section 2.2.

These spreads are then combined with the basic deterministic paths to lead to a point-to-point description of the intensity I_p as a function of time, frequency, and angles. Whether in fact the intensities of all scattered fields in all time, frequency, angle bins are summed or not at this point depends upon how the scattered fields are described. If they can be described by parametric spreads (even with correlation between spread components), that parametric description should probably be retained. The required resolution in time, frequency, and angle may make this array enormous, otherwise.

A concern raised at this point is how to combine these fields. Virtually all of the second moment models must discard precise phase information for the spread fields. Clearly we cannot totally neglect phase since for shallow sources and/or receivers at low frequencies and sufficiently near the surface, phase effects lead to significant changes in the mean field (some enhancements of 3-6 dB and very near the surface large degradations). Approximate ways to include phase for the scattered fields may be possible but remain to be demonstrated and verified. At present it seems likely that any coherent phase effects will be applied to the deterministic paths for average intensities. All other coherent phase effects are probably best represented in terms of the corresponding multipath fluctuations (i.e., statistically rather than deterministically).

2.1.4 Motion Model

The effects of source and receiver motion may be treated locally in terms of the differential Doppler shifts acquired by each "path" (deterministic or scattered) as the source or receiver moves past the fixed field points at their respective ends of the track. The relatively small Doppler content of the signal prior to this (due only to the moving surface and perhaps internal waves) will now be substantially broadened due to the path-by-path differential Doppler.

2.1.5 Application of System Parameters

The intensity field after motion has been included (I_{pp}) is now integrated against the corresponding beam patterns $\left(BP(\theta,\phi;B_k)\right)$ to yield the beam intensities with their spreads in frequency or time.

Once paths have been combined on each beam, there is a potential for multipath interference. The corresponding fluctuation distribution, δI_B could be estimated. Fluctuations between interfering, scattered fields may be difficult to estimate. For the surface-reflected scattered field, the surface motion should average out such fluctuations, probably much more rapidly than any source motion. Hence distributions of these interferences may be inappropriate. For bottom scattered paths off large-scale roughness there is no intrinsic time dependence, and motion will drive the fluctuation rates with potentially large distributional spreads depending upon the duration of processing.

The temporal signal-processor characteristics will take the detailed beam intensities in time and frequency and average them according to the processing bandwidths and the integration times. These intensities (I_{SP}) will then have distributions and fade rates (δI_{SP}) representative of the output of the entire spatial and temporal processing suite.

2.2 THE POINT-TO-POINT SPREAD FUNCTION MODEL

A modular approach to the spread-function model will allow engineering estimates to be made at an early date using empirical values (data), with more sophisticated estimates possible as various component sub-models are developed and validated for specific applications. The principal assumption in this model is that, for a path encountering more than one scattering phenomenon (i.e., surface <u>and</u> volume scatter), the spreads will be small enough that a linear multiple scatter model will be reasonable. Hence the net effect of several <u>types</u> of scatter will be estimated by convolving the appropriate spreads for each type, estimated separately (and independently).

Figure 2-2 illustrates the flow for this linear, convolution spread function model. The path histories consist of the number of surface and bottom interactions, n_S and n_B, and the associated mean (deterministic) grazing angles, $\overline{\theta_S}$ and $\overline{\theta_B}$. The volume histories may include up to the entire trajectory. Based upon these inputs (plus other required environmental inputs such as wave, bottom and volume conditions), spreads in vertical and azimuthal angle plus frequency and time are computed. Certain spreads are likely to be negligible. For bottom scatter there is no frequency spread, and for volume scatter the

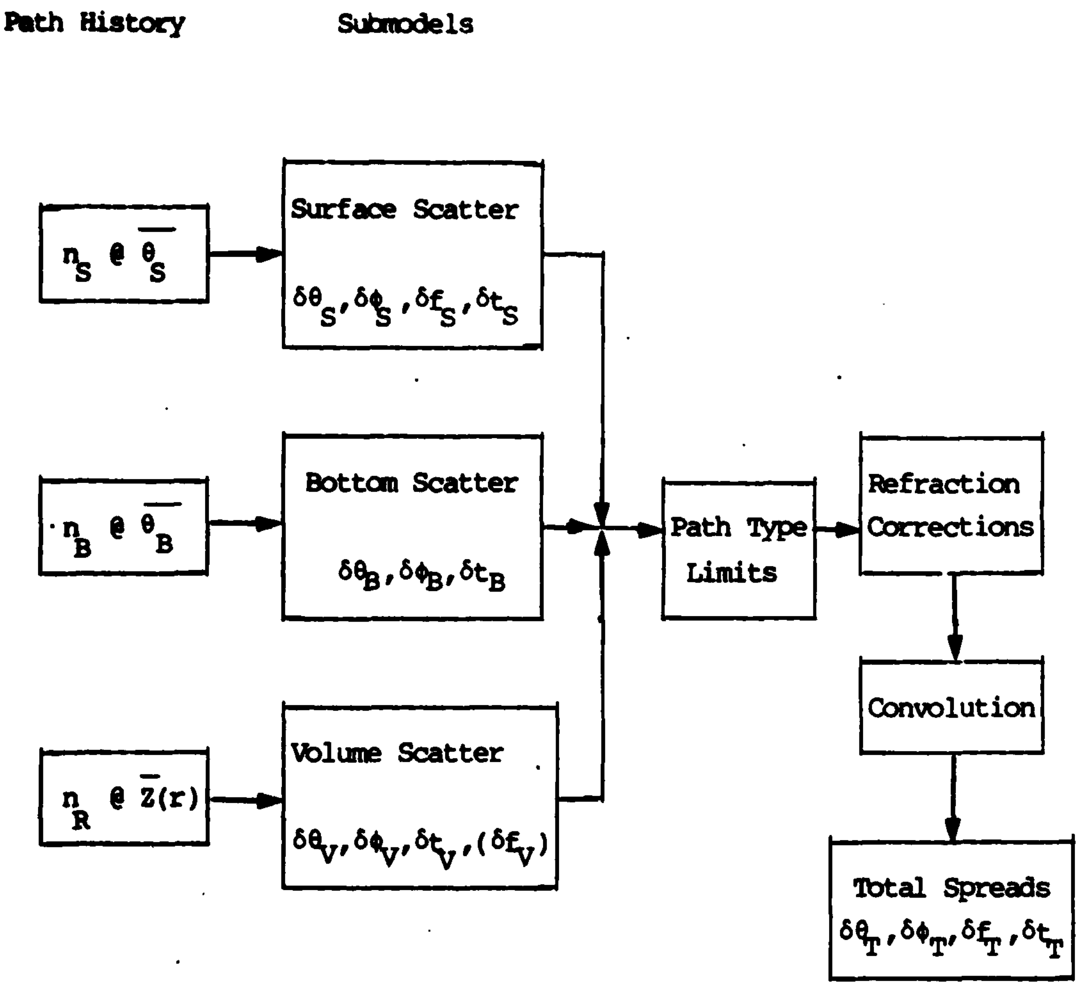

Figure 2-2. Linear, convolution point-to-point spread function model.

temporal evolution of internal waves is so slow that the corresponding frequency smearing is nearly nil.

In early versions of this model it is likely that these spread functions will take on fairly simple forms such as tables or Gaussian distributions whose parameters are determined from elementary modeling and/or available data. The complexity of the more powerful coherence models makes it unlikely that they will actually be employed for each case of interest. Probably they will be used on representative environments to generate these tables (or functional parameters if still appropriate).

These spread functions may then need to be modified to reflect certain constraints on the various types of paths. For example, the surface-scattered RSR path may be scattered into so large an angle that it interacts with the bottom and essentially changes type. Initially such crossovers are likely to be disallowed. In refined models they may be possible. As another example a ducted path may scatter to a high enough angle to leave the duct. The corresponding surface scattering rate should then be reduced to that of an RSR or SRBR path.

The vertical distribution of scattered energy (say at the surface) must then be adjusted for changes in angle due to refraction. Assuming a linear treatment of multiple interactions, the resulting distributions for each interaction are then convolved to obtain the total spreads, $\delta\theta_T$, $\delta\phi_T$, δf_T and δt_T. The definition of "interaction" will depend upon the sophistication of the model. It can be shown that for isolated interactions such as surface reflections, the effect of n_s such events is, to first order, an n-fold convolution of the corresponding distribution for one event. This should also be true for bottom scattering, except the angles may get so large that some of the approximations break down. For volume scatter an "event" might be the net result of multiple scatter along the ray for one full cycle, with convolutions used to treat multiple cycles.

The following subsections describe recommended approaches to treating each of the scattering submodels. In most cases the models do not exist per se, but results presented at the stochastic workshop indicate that the basic components are, or could be, available. In each case the subject is divided into two parts: a short-term approach, and the research issues which need to be resolved in either 6.1 or 6.2 to achieve an improved long-term solution. The time frame envisioned for developing the short-term approach is one year (probably 2 man years) for each scattering submodel, plus 1 concurrent man year for integration into the linear, convolution point-to-point spread function model.

2.2.1 The Surface Scatter Submodel

Surface scatter over the frequency range of interest evolves from the low frequency Bragg-like diffractive scatter off a fully illuminated surface to a high frequency specular scatter off facets of a highly shadowed surface. At very high frequencies bubbles near the surface may play a role. (Such high frequencies are not being treated in this paper.)

At the very low frequencies the Rayleigh approximation may be used, leading (to first order) to Bragg scattering off each component in the directional surface-wave spectrum. Because the wave spectrum has a long-wave (low frequency) cut-off, much of the scattered energy is at large enough angles to be forced to interact with the bottom. The energy which doesn't scatter into the bottom is scattered quite far in azimuth from the specular component. As a result, at the lowest frequency in a multiple-bounce environment the initial and final large-angle scatters in the immediate vicinity of the source and receiver are probably the only ones of interest.

At high frequencies, the Kirchoff approximation leads to scattering off facets, controlled by the distribution of surface slopes that the incident ray can "see" (i.e., including shadowing effects). The resulting scattering function tends to be concentrated around the specular direction.

At intermediate frequencies, composite-surface scattering models indicate that the Bragg "lines" from the "small" surface pick up spreads due to the tilts of the "large" surface carrying the smaller ripples.

2.2.1.1 Short-Term Approach

The low-frequency scattering theories currently being developed by Dashen and Spofford should be combined with the composite-surface work of Brown et al. and the Kirchoff work of Berman and McDaniel to yield an approximate, but continuous transition from diffractive to geometric scattering. For surface ducts and shallow water, where the ray picture is really not applicable there is some suggestion that scattering treatments based on rays may still yield reasonable spread functions. Details of such an approach need to be worked out.

2.2.1.2 Long-Term Issues

a. Refined Plane-Wave Scattering Models

Contributions from higher-order scatter (i.e., second and higher terms in the Rayleigh expansion) and first-order scatter off the non-linear parts of the surface-wave spectrum need to be considered. (In radar work these are essential to describing the spectrum of backscatter beyond the simple Bragg "line".) While the material exists to do this it is probably beyond the scope of the short term solution.

b. Scattering Near Focal Regions

Scattering in the caustic regions of convergence zones requires further work. Holford is currently studying this problem, but again it is not likely to impact the short-term solution.

c. Scattering and Refraction

The joint effects of refraction and scattering have not been treated. The adequacy of present plane-wave theories to treat scattering of a refracting non-plane wave at shallow, spatially varying grazing angles needs to be addressed.

d. Surface Ducts and Shallow Water

A reasonable treatment of mode-mode coupling with frequency and angle spreading needs to be developed for these cases where ray theory is least applicable. The propagation of coupling matrices as developed by McCammon seems closest at this point.

e. Surface Statistics

More information on the two dimensional spectrum of short wavelength surface waves is required. More sophisticated models will require this, and there seems to be some controversy over what is known.

f. Numerical Evaluation

Evaluation versus exact or nearly exact numerical solutions should be attempted. Available candidate solutions are those of Holford (plane waves, periodic surface); Dozier (rough surface PE; approximate but useful for vertical forward scatter including refraction), and Boyles (rough surface coupled modes; under development now but available soon and able to treat large-angle and backscatter as well as refraction for the vertical problem).

g. Data Comparison

There is very little reliable bi-static scattering data with which to evaluate emerging theories. Ambiguities associated with source and receiver beam patterns are especially troublesome. Concurrent, directional wave spectra are almost non-existent.

2.2.2 The Bottom Scatter Submodel

There are three distinct and somewhat separable aspects to bottom scatter: scatter off roughness (in many but not all ways, similar to the surface-scattering problem), scatter from multiple thin layers near the surface of the sediments, and scatter from inhomogeneities in the bulk of the sediments. Promising theoretical models are under development in all three areas. The major short-term problem is that even when these models are fully developed we are likely to be very short of critical inputs. The short-term solution to this problem will be to use the models and the best available data to deduce (basically by acoustical inversion) approximations for these inputs. Whatever geographic or topographic dependence that can be inferred will be used to extrapolate these parameters to other areas. The models will then be used to evaluate their effects at different frequencies and for different geometries than the data can support. The approach, while obviously heuristic, has two merits: first, if the specific models under development do not test out adequately, the interpreted data may be used to support a pure interpolation submodel; second, the approach will yield agreement with the few data we have.

2.2.2.1 Short-Term Approach

For each path of interest the effects of one or more of the types of scatter must be evaluated. Where more than one type is important, say scattering, from thin near-surface layers in undulating terrain, the total scattering will be gotten from convolution of the appropriate submodel results.

a. Roughness Submodel

Because of large-scale roughness at least in areas of thin sediments, the roughness scattering submodel must cover the limits from Rayleigh to Kirchoff and include shadowing. Brown's composite surface model seems most promising, however some issues related to forward scatter need to be resolved.

The missing input is the bottom roughness spectrum (2-dimensional, though an isotropic assumption may be reasonable). Very little data on bottom roughness at the wavelengths of interest are available. Scripps Deep Tow data may be the best but has not been processed. The MACS spread function data from rough areas should be used to deduce an appropriate power spectrum. A parameterized spectrum of the form $S(k) = B/k^n$ might be reasonable where B and n were determined essentially by acoustical inversion. (This approach has been used by those studying linear radar backscatter with some success.) Both B and n would be expected to depend on bottom composition and topography.

b. Thin Near-Surface Layer Submodel

The transport equation model of Besieris and Kohler presently treats time spreads, but should be easily extendable to spatial coherence as well. There is a distinction between realizations and ensemble averages which is not trivial and which needs to be resolved. The transport-equation approach provides ensemble-averaged time spreads. If the horizontal correlation length of the thin layers is as large as some data suggest, then over time scales appropriate to signal processors, the ensemble may never be sampled. In fact only one realization may be sampled. In this case, rather than use a smooth autocorrelation function the received signal may be more appropriately described as a shot process, with corresponding statistics. Deterministic (Monte Carlo) simulations may be better at describing these statistics than a transport equation. (The distinction between these averages may be difficult to discern in data depending upon the bandwidth of the signals used.)

Assuming that the transport-equation approach surmounts these obstacles, the problem of inputs must be addressed. The MACS data on time spreads versus frequency and grazing angle should be adequate to "fit" the corresponding parameters of the random layers (sound-speed and density variances, and correlation lengths, and attenuation). Angular spreads from these near surface layers should be very small. If the data show variations in angular spread this may be evidence of bottom roughness. It would be preferable to attempt to use data sets where the bottom is known to be very flat to eliminate roughness spreads.

c. Volume Scatter Submodel

At this point it is not clear that volume inhomogeneities are large enough to cause significant scatter. In the short term some data sets should be examined to decide how important this phenomenon is. (Hanna and Dozier are doing this currently with a data set from the Indian Ocean. The MACS data have limited sampling in angle and may not be useful for these purposes.) If the problem can be shown to be significant, the transport equation of Besieris and Kohler should apply to it. To the extent that deep sediment-penetrating paths are used in performing the inversions for surface roughness and thin-layer effects, the decorrelating properties of the sediment volume may already be incorporated in their estimates. If this phenomenon is to be included, the inputs are likely to come from inversions, and such effects must be carefully separated.

2.2.2.2 Long-Term Issues

In all the above areas the best theoretical models will rapidly become input limited. The inversion approach is only an interim solution and by its circular reasoning cannot be used to fully test these models. This issue plus others are listed below for each scattering process.

a. Roughness Submodel

a1) Scatter from a Rough Solid

The effects of roughness are treated as an impedance boundary condition (perhaps with a phenomenological loss term) but not as actual interaction of an incident wave with a rough, elastic solid. For surface sediment roughness the sediment may be treated as a fluid, rather than a solid. Tolstoy has begun some work on this problem.

a2) Bottom Roughness Spectra

The Scripps Deep Tow data may be the only basement roughness data from thin sediment areas. For smoother areas, narrow-beam 12KHz echo-sounder data may be adequate. Appropriate spectra with representative directionalities need to be developed.

a3) Comparisons with Data

It has yet to be demonstrated that the combination of bottom roughness, sediment properties, basement elastic properties and the corresponding scattering theories can quantitatively account for even the observed loss versus grazing angle and frequency of bottom-reflected signals, let alone their spreads. Good acoustical data with concurrent environmental measurements are needed to evaluate this capability.

b. Thin Near-Surface Layer Submodel

b1) Layering Data

For several sites with good acoustical data, echo-sounder and core data need to be examined to determine representative values and ranges for the near-surface acoustical properties. Values measured in situ may differ significantly from those based on extracted cores.

b2) Continuous versus Discrete Changes

The transport equation of Besieris and Kohler assumes a continuous random process for the sound speed and density variations in near-surface layers. Core data suggest more nearly discontinuous, discrete changes similar to a shot process. Greene is currently investigating the significance of this distinction.

c. Volume

c1) Models

Assuming volume effects are found to be significant the appropriate model should be considered. In addition to

Besieris and Kohler's extended transport equation approach, Dozier's master equations and various techniques used in the ocean volume-scattering problem should be considered.

c2) Inputs

Data on the scattering strengths and their spectra would be needed.

d. Shallow Water

In shallow water both sediment roughness and layering may be significant. Coupled-mode approaches may be most applicable, especially when simultaneously including effects of surface roughness.

2.2.3 The Volume Scatter Submodel

For volume scattering, the physical processes (internal waves) have sufficiently slow time variability that the corresponding frequency spreads are probably overwhelmed by source-receiver motion effects. Hence angle spreads and the time spreads associated with the scattered paths in a "frozen" internal-wave field are of interest.

In terms of models, the JASON approach might appear to be the leading candidate. The NRL approximate vertical and horizontal coherence models (COVERT and COHORT), and the NRL "Exact" model (all based upon the transport equation for the mutual coherence function) and Tappert's direct transport equation model are also available (or nearly so). The relationships between these approaches are becoming clearer, and work in all quarters is continuing on relating them and understanding their respective limitations.

Each model is likely to have its domains of validity and utility. The JASON model has been extensively compared with time and frequency spread data. While the results are cast in terms of formulae, the expressions in these formulae are difficult to evaluate (especially for spatial coherence) and may be quite sensitive to the particular ray path of interest. The effort involved in evaluating the JASON formulae appears to be comparable to, or larger than, the effort required to evaluate the approximate NRL models. The "exact" NRL model (CEM) and Tappert's model may require the most effort. The NRL models are essentially low-frequency and long-range. For these reasons the following short- and long-term approaches are suggested.

2.2.3.1 Short-Term Approach

The JASON model should be exercised for a wide variety of environments, ranges and paths (including RSR, RBR, and SRBR after appropriate extensions). The purpose of these runs would be to gain familiarity with the sensitivity of the predicted spreads to the various controlling parameters. Extensive running would also shake out any significant bugs and provide a clear indication of the running times associated with such runs.

Based upon the results of these runs two options should be considered:

Option 1 - "Data Base" Approach

Representative values of spreads for various path types, frequencies, ranges, etc. could be developed with fairly simple interpolation/extrapolation algorithms to cover the spaces of interest. The advantages of this approach are:

(a) It would allow development of the Combined Effects Model to procede, expecting a fairly simple "black box" component for volume spreads.

(b) It would certainly be fast.

(c) It would, by construction, be able to handle all paths, yielding bounded, and in a sense, known ("sailor-proofed") results.

(d) If the JASON approach were found to be inadequate for some paths, similar "data" could be assimilated from other models.

Its principal disadvantage is that it might oversimplify the phenomena. If the extent of oversimplification were too severe Option 2 might be required.

Option 2 - In-Line Model Approach

The full JASON model (or actually system of models) could be incorporated as a component of the Combined Effects Model. For each range (and depth-pair) of interest the JASON model would find the eigenrays, their geometric intensities, and their spreads. The principal advantages of this approach are resolution and internal consistency. The disadvantages are:

(a) Lack of diffraction corrections for fields near caustics,

(b) The possible erroneous treatments of spreads near caustics,

(c) Erroneous impressions from undersampling (in range) a complicated phenomenon,

(d) Possibly prohibitive running time, and

(e) Removal of the scientific filter between the model and the user (non "sailor-proof").

At this point Option 1 seems clearly preferable, however, the results of early testing might make a strong case for Option 2.

The rationale for recommending this approach is as follows:

(1) While a number of arguments have been advanced questioning the validity of the JASON theory, it has not been demonstrated that it leads to <u>significant</u> errors in applying it to <u>real</u> <u>ocean</u> problems of acoustical interest.

(2) In comparisons with data (nearly all time and frequency spreads or intensity moments and spectra) it has yielded excellent agreement except for the higher-order statistics at Cobb Seamount (which no model has fully explained to date).

(3) It is the only model presently or imminently available able to predict all the spreads (and

coupled spreads) of interest, and internal consistency may be an important consideration.

(4) Alternative, potentially more precise models may be prohibitively expensive to run, even in the "data-base" option for all the cases of likely interest. They are certainly impractical for the in-line model option.

(5) While spatial coherence (angular spreads) have received nearly no attention, the NRL data suggest that the horizontal spreads are quite small and exceedingly difficult to measure accurately. The JASON model should be exercised on the few cases of measured, significant, degradation to see if comparable results are predicted. In general we expect very small spreads at the low frequencies (where the NRL model should be valid) and short ranges of interest to ACSAS. At higher frequencies the JASON model should be valid.

2.2.3.2 Long-Term Issues

The principal difficulty in selecting a model is the sparse acoustical data with which to compare, and the still unresolved fundamental theoretical issues. Each theory makes certain approximations which are claimed by the respective authors to be reasonable but are, in fact, very difficult to evaluate. Nearly all techniques are ray-based and cannot treat fundamentally modal fields, such as in ducts.

The resolution of the domains of applicability of the various models is difficult because they contain both different scattering theories and different oceanographic models. While CEM, for example, may be the most complete scattering theory, its assumed $\delta c(\underline{x})$ and $\rho(\underline{x},\underline{x}')$ may lead to less accurate spread predictions for real problems of interest.

The data on spatial coherence is so sparse (and contains so little concurrent oceanographic data) that model-data comparisons for angle spreads are unlikely to resolve this problem. (The unprocessed Cobb Seamount data do contain some spatial coherence measurements, however, the poor agreement in intensity statistics with any model raises questions about using this data set. Agreement in the second moments was good, however.)

Given the sparse data, it seems likely that these issues need to be resolved in a carefully chosen set of model-model comparisons. The closest thing to "real" data that is likely would be results from simulated numerical experiments using PE. The following items might form the bases for resolving the key issues:

1. Vertical Angle Spreads

It appears that incorporation of the full GM spectrum for internal waves into CEM would be quite difficult (if it did not lead to totally impractical running times). As a first step, CEM and the JASON model could be compared for "equivalent" oceans (i.e., parameters NRL would derive from a given JASON δc spectrum). The significance of the difference between δc representations could be addressed by modifying the JASON code to treat scattering using the NRL parameters. Significant differences between JASON predictions using the two representations would at least indicate possible problems with the NRL "ocean".

A definitive test of the JASON model using the complete spectrum would probably require numerical simulations using PE. Time-stepped, correlated realizations of internal wave fields could be used to provide vertical angle and frequency spreads for CW signals (frequency spreads being produced by transforming the time-dependent phase differences at points in space). Time spreads would require multiple frequencies, and azimuthal-angle spreads a full 3-D PE, either of which would be a major increase in scope. A few, carefully selected, time-stepped CW cases might substantially resolve these issues.

2. Azimuthal Angle Spread

JASON predictions should be made for several of the NRL test geometries. The code should be modified to provide as additional output the single array-gain (or array-gain degradation) values used by NRL in describing their data. The NRL model should be tested at longer ranges and higher frequencies (preferably where the JASON model is conceded to be accurate) to see if the simple functional form holds up.

3. Time Spreads

Tappert's model could be easily modified to accumulate time as well as vertical-angle spreads. Whether agreement in time spread implies agreement in vertical angle spread should be checked, since so many of the JASON model-data comparisons are in the time domain.

4. Oceanographic Models

Several of the models deal with scattering kernels which are computed from the assumed $\delta c(\underline{x})$ spectrum. Use of the full GM spectrum is unwieldy. Whether an adequate approximate spectrum exists which is more amenable to scattering kernels remains to be determined. These issues, plus the significance of the asymmetric scattering kernel, could be addressed using Tappert's T.E. model.

b. Extensions to Modal Fields

In some instances (surface and subsurface ducts, near axial propagation, very low frequencies) these ray-based models are basically inappropriate. Coupled-mode and master-equation approaches should continue to be examined for their applicability to various spreads in these domains. Time spreads seem the most difficult since these mode codes are so intrinsically mono-chromatic.

Section 3
NOISE MODELING

The noise field against which a system must work consists of locally generated components (machinery, flow, strumming, etc.) plus ambient noise due to weather, shipping, biologics, etc. Measured values for the locally generated, self-noise component exist as a function of operating conditions and should have some platform-to-platform variability (also documented). The hardest part of modeling the noise field is the ambient component. Here representative measured values may be used for omni-directional levels (recognizing inherent large spreads and fluctuations), however very little good data exist on noise directionality. At low frequencies azimuthally directive noise associated with nearby (moving) discrete ships and distant (nearly static) aggregates of ships is most important. At high frequencies, where distributed, nearby surface sources (wind, rain, etc.) dominate, vertical directionality may be most important.

Statistical models for the shipping component (Goldman, et al.) exist and have met with some success in predicting low frequency beam noise distributions and decorrelation times. Averaging models (Talham, Cavanagh, et al.) for vertical directionality exist and may be especially applicable to the wind sources. Cavanagh and Renner have shown that under certain reasonable assumptions, vertical directionality near the sound-channel axis may be used to estimate the depth dependence of both the omni-directional level and the vertical directionality. DANES is an elaborate numerical model for predicting at given geographic locations the level and horizontal directionality (and with minor modification, vertical directionality). It does not address fluctuations, and in comparisons with data has shown agreement in mean level of ±3 dB most of the time. Short-term data (daily averages, for example) would be expected to show variations of at least this much.

3.1 SHORT-TERM APPROACH

Noise characteristics should be separated into system/platform related components and ambient. The former should be gotten from available data, recognizing that some components (e.g., levels on a towed receiver) may be geometry dependent. Ambient levels should be estimated using a model such as DANES, with statistical descriptions for fluctuations and for vertical directionality from simple models such as those of Goldman and Cavanagh, respectively. Time and frequency coherence of ambient noise must be gotten from data-supported empirical models.

3.2 LONG TERM ISSUES

a. Fluctuation Models.

No consistent model for the correlations in angle-time fluctuations of noise exist. Clearly for fluctuations dominated by nearby shipping such correlations are present. For short enough ship ranges the vertical and horizontal directionality variations are correlated. Proper modeling of these "path" properties might have to include their spreads, similar to the corresponding signal spreads. Before extensive work in this seemingly endless problem is initiated, a clear need for this level of detail should be demonstrated.

b. Level Models

The major unresolved noise-level issue concerns the depth dependence of noise in surface (and perhaps, sub-surface ducts). Very limited data (Urick, et al.) suggest that much higher levels (5-8 dB) may be found in the ducts relative to below-duct levels than the above-mentioned models can predict. The frequency dependence of these differences is consistent with the injection of distant energy, but mechanisms are inconsistent with known (or at least suspected) source directionality.

c. Coherence Models

In the simplest sense the noise spectrum (omni, beam, etc.) yields a first estimate of the time coherence of the ambient field. No more complicated models for this are known, however clearly if the noise field is dominated by a few broadband sources their echoes via multipaths would impact time coherence. Frequency coherence would seem to be a low-frequency issue controlled by harmonically related lines in the spectrum.

Section 4
SUMMARY OF APPROACHES

The following outline summarizes the recommended approaches.

1. Signal - Combined Effects Spread Function Model

    1.1 Geometry model (with motion spreads)

    1.2 Environment model
        1.2.1 Deterministic environment
        1.2.2 Random descriptors
            1.2.2.1 Surface waves
            1.2.2.2 Internal waves
            1.2.2.3 Bottom, roughness and layering

    1.3 Path model (rays and some modes)
        1.3.1 Mean properties
        1.3.2 Path histories

    1.4 Point-to-point spread function model
        1.4.1 Surface scatter
            1.4.1.1 Low frequency (Rayleigh)
            1.4.1.2 High frequency (Kirchoff)
            1.4.1.3 Composite surface (Brown)
            1.4.1.4 Multiple bounce (Dashen)
        1.4.2 Bottom scatter
            1.4.2.1 Roughness (composite surface)
            1.4.2.2 Layering (Besieris and Kohler)
            1.4.2.3 Inputs via data inversion

- 1.4.3 Volume scatter (JASON)
  - 1.4.3.1 Data base
  - 1.4.3.2 In-line (if needed)
- 1.4.4 Refraction correction
- 1.4.5 Combination by convolution

1.5 Path summation

1.6 Motion model
- 1.6.1 Deterministic frequency spreads
- 1.6.2 Micro motion spreads

1.7 System model
- 1.7.1 Beam pattern averaging
- 1.7.2 Time/frequency processor averaging

2. Noise

2.1 System noise
- 2.1.1 Flow, system, etc. from data
- 2.1.2 Geometry corrections, if necessary

2.2 Ambient noise
- 2.2.1 Levels and horizontal directionality
- 2.2.2 Vertical directionality (FANM or DANES)
- 2.2.3 Fluctuations, horizontal (Goldman)
- 2.2.4 Time/frequency coherence (data)

Long-Term Issues

1. Signal

- 1.1 Mean levels
  - 1.1.1 Surface and subsurface ducts with scatter
  - 1.1.2 Bottom reflected/scattered "loss"
  - 1.1.3 Shallow angle forward scatter "surface loss"
- 1.2 Spreads
  - 1.2.1 Convolution of components
  - 1.2.2 Surface scatter
    - 1.2.2.1 Refined plane-wave models
    - 1.2.2.2 Scattering near focal regions
    - 1.2.2.3 Scattering and refraction
    - 1.2.2.4 Scattering of modes
    - 1.2.2.5 Surface statistics (directional)
    - 1.2.2.6 Evaluation versus "exact" results
    - 1.2.2.7 Evaluation versus data
  - 1.2.3 Bottom scatter
    - 1.2.3.1 Roughness
      - 1.2.3.1.1 Scatter from a rough solid
      - 1.2.3.1.2 Bottom roughness spectra
      - 1.2.3.1.3 Comparisons with data
    - 1.2.3.2 Layering
      - 1.2.3.2.1 Bottom layering data
      - 1.2.3.2.2 Continuous versus discrete changes

- 1.2.3.3 Volume (bottom), if necessary
  - 1.2.3.3.1 Model(s)
  - 1.2.3.3.2 Inputs (geophysical)
- 1.2.3.4 Shallow water models

1.2.4 Volume scatter

- 1.2.4.1 Relationships between theories
- 1.2.4.2 Comparisons with numerical experiments
- 1.2.4.3 Mode-scattering models

2. Noise

2.1 Fluctuation models (ambient)

2.2 Level models (in- versus below-duct)

2.3 Coherence models (time and frequency)

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