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BOOK REVIEWS

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Sound Propagation Through the Stochastic Ocean

John A. Colosi

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More than 35 years ago, a book "Sound Transmission through a Fluctuating Ocean" was published by a group of members of the JASON study group.[1] That book presented a number of theoretical ideas about the effects of oceanic internal waves on acoustic propagation. These ideas were taken from other fields of physical sciences. An example is the studies of twinkling starlight due to propagation through atmospheric turbulence. These studies were adequate for the development of adaptive optics. Such ideas are a reasonable starting point for developing an understanding of some features of ocean acoustic propagation. Unfortunately, these ideas were subsequently treated as lore, rather than as conjectures to be tested by a rigorous application of the scientific method.

The current book is an update of that previous book. Much of the theoretical conjecture from the previous book is again presented as fact, and the justification is still missing. The ocean case is quite different from the starlight case for a number of reasons. Two major reasons are that the wavelengths in the optics case are much smaller in relation to the medium fluctuation than are they in the acoustics case and the oceanic correlation scales in the vertical are much smaller than in the horizontal, and propagations of interest in the topic of this book are mostly horizontal.

The propagation is conveniently split into two aspects. The "wander" (as this lore uses in practice) is the variation $\delta\varphi$ of the phase $\varphi = \int(\omega/c)dl$ evaluated along the unperturbed ray, due to fluctuations of the sound speed c, and the "spread" is the remainder of the effects on the received sound. The wander is proportional to the frequency, and is therefore manifested as a time shift that wanders as the internal waves evolve. The wander is the major effect of the large-scale internal waves, while smaller scales dominate the spread. Many effects of internal waves in deep water may be dominated by the wander, and straightforward expressions are easily obtained. For example, the wander contribution to a second moment is

$$\langle p_1 p_2^* \rangle = p_{01} p_{02}^* \langle \exp\left(i\,\delta\varphi_1 - i\,\delta\varphi_2\right)\rangle,$$

where the subscripts 1 and 2 refer to rays that may be displaced in time, position, and/or frequency. For fluctuations modeled as a Gaussian process

$$\langle p_1 p_2^* \rangle = p_{01} p_{02}^* \exp\left(-\frac{\langle(\delta\varphi_1 - \delta\varphi_2)^2\rangle}{2}\right).$$

The evaluation of the results are apparently considered too messy to be evaluated accurately in a given model of internal waves, and approximations of unknown accuracy are a significant part of the book, as are complicated ways of getting the straightforward expressions. A special case, when 1 and 2 are the same ray, $\delta\varphi_1 = \delta\varphi_2$, and thus the intensity is $\langle I \rangle = I_0$.

The cause and effects of spread are attributed to "microrays." (These are often referred to as "micromultipaths," but the use of the word path as a ray path and the use of all paths as in the path integral has caused confusion.) The microray conjecture is described as "the critical physical concept" in the book. This conjecture is that the ray in the absence of internal waves becomes multiple rays of similar intensities and random phases with internal waves present. "Partial saturation" occurs when there are only a few such microrays, and "full saturation" is when there are enough for the central limit theorem to give nearly an exponential intensity distribution. A cartoon of this conjecture is shown on p. 178. On p. 19 some relevant data are shown. The data looks nothing like the cartoon. The data shows a single arrival; only the caption states that we are seeing microray interference.

Indeed, the concept of rays is prominent throughout the book. Even for weak scattering, rays are accepted as describing the propagation. The book states on p. 52 "…ray theory provides the conceptual picture that is the foundation of many other approaches to sound scattering such as Born and Rytov theory…". Indeed, when the Born approximation [Eq. (2.95) in the book] is manipulated, rays are implicitly and explicitly used to derive Eq. (2.96). The Born approximation requires small phase perturbations and ray tracing requires short wavelengths[2] that have large phase perturbations. The conceptual picture of the Born approximation should be the Bragg condition, not the direction of the phase gradient.

Acoustic propagation is a deductive subject—there is agreement on the applicability of the fundamental wave equation (in most cases), which is linear and thus amenable to accurate treatment. The propagation theories involve various approximations to this equation. The other aspect of making predictions is the sound speed field in the ocean, which is the result of nonlinear and natural phenomena, and much harder to know in detail. The acoustics part of theories can be tested in ways that do not involve actual experiments for which failure can be blamed on insufficient knowledge of the oceanic sound speed field.

One way is to estimate the next order terms when the theory can be expressed as the first term in a Taylor series, often in the form of an expansion parameter where the coefficients of the powers of this parameter are of order 1. For example on p. 283, a parameter for the expansion of a moment equation starting with a Markov approximation is presented. To start with, the author incorrectly defines the Markov approximation. That approximation is that the correlated pairs of interactions can be assumed unaffected by any intervening interaction; the author takes it to mean a rather crude evaluation of the correlation function. He then comments on my work, calling its conclusion a "feeling," an inappropriate reason for a scientific conclusion. I had estimated the expansion parameter (for a particular experimental geometry) following van Kampen,[3] for a version of a moment equation known as the "equation without memory" (Markov) and found it to be about a thousand times smaller than the expression in the book, which is the expansion parameter for the "equation with memory"(non-Markov).[4] (Interestingly, van Kampen[3] demonstrates that the equation without memory is not less accurate than that with memory but did not comment that it could be much more accurate.) However, it does not matter to the book, as the author does not report the values of either parameter for the experiments he discusses, and does not report the parameter for his crude approximation.

Another way acoustic approximations can be tested is by comparison with other approaches whose approximations are some, but not all, of the approximations of the theory. The remaining approximations are valid only if the results agree. This is one use of simulations, which avoid the approximations made in deriving formulas for ensemble averages.

A major theory presented in the book is the saddle point approximation to the path integral. It is termed the path integral method, which is somewhat misleading because the path integral is a formal solution of the moment equation.[5] This theory is really that the same approximation that gives ray tracing in a deterministic problem[6] can be used to calculate statistical moments. In particular, with the approximations used in the book, the second moments are predicted to be given by the wander contribution discussed above.

A peculiar result of the saddle point approximation is that the mean intensity at a point is the unperturbed intensity, i.e., the wander contribution. An intuitive expectation is that scattering spreads out the mean intensity, causing it to be lowered in regions of high intensity and increased in regions of low intensity. Simulations agree with that intuitive expectation, and disagree with the saddle point approximation.[7] Thus, the saddle point approximation is inaccurate enough to miss a simple physical effect. There are well-known ways of getting corrections to the saddle point approximation,[8] which could be used to improve the predictions and to test the approximation. In addition, the other approximations used in predicting that the wander contribution is all there is should be tested.

There is a comparison of a number of theories, including the saddle point path integral, with a wave simulation and some data on transverse horizontal correlations (p. 297). If this were taken as a test of the theories, they would have to be discarded, as the data are far from the theoretical results; significant correlation in the data extends well beyond that of the theories. For example, at a separation of 2 km, the saddle point path integral predicts a correlation of about 1%, the simulations predict about 25%, but the data value is about 60%. Saddle point path integrals and wave simulations are presented by Vera.[9] The simulations all show simulations larger than the saddle point path integral, and some show larger discrepancies than the example of the book.

It is unlikely that this discrepancy can be attributed to lack of knowledge of the details of the ocean's sound speed field; an additional structure is likely to increase the decorrelation, not decrease it. Therefore, it should be a good test of the theories. The saddle point path integral theory gives the simple wander result, which generalizes the mean intensity result. The book first states "The source of this large discrepancy is not known.", and then "Clearly other factors such as ray chaos may be important as well." These excuses only cover up that it seems very likely that the theory fails at the frequency and range of these data.

There are many mistakes in the book. One example is that a subsection starting on p. 351 is about an approach to equipartition of mode "energy," and relates it to the growth of microrays, "approach to saturation." To start with, if there were equipartition, it would be mode intensity (energy flux), rather than mode energy density, that would be equipartitioned. Elsewhere [p. 346, Eq. (8.42)], energy density is referred to as intensity, so it appears that the two quantities are confused. Generally, intensity cascades from low modes to high modes. Equipartition would only occur if this cascade were blocked, analogous to how flat water on a river occurs on the reservoir behind a dam. Simulations often have a moderate number of modes, and the mode cascade is blocked by the absence of higher modes. Thus the simulation will (assuming no loss process) approach equipartition, but in nature, the modes extend all the way to vertically propagating modes that send intensity into the solid earth.

In the 35 years since the first book was published, definitive tests of the theories should have been made. Some approximations have domains of validity; for example, ray tracing and the saddle point path integral at sufficiently high frequency and short range. The domain of validity ought to be mapped out. When conditions of validity are known (e.g., Markov approximation), those conditions should be tested. Crucial tests of the theories should be proposed as the basis for experiments.

In summary, this book is not a presentation of what we know about propagation of sound in the ocean, but rather one view of what might be. Oceanic acoustic propagation should be treated as a science, not as lore.

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